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AI-Driven Parametric Design for Performance-Oriented Northern Residential Buildings

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Abstract: ***In this article, the application of artificial intelligence (AI) and boundary design methods combine algorithmic AI with boundary design tools, and we introduce a new workflow for creating and evaluating housing plans in the initial design phase. By extracting database status and parameters, many design solutions can be quickly created, with a focus on automating the design process. Evaluate these alternative solutions using energy simulation data to determine the most effective solution. This article introduces the Grasshopper for automatically generating flat graph levels, and the results show that compared with current design methods, the repetition time of charts is greatly reduced, and energy efficiency is improving.***

Keywords: Parametric Design, Artificial Intelligence, Performance Optimization, Residential Buildings, Energy Efficiency.

1. Introduction

The construction industry is currently undergoing a transition towards digital technology and artificial intelligence (Amnesty International). Due to the increasing demand for resources and environmental issues, improving energy efficiency has become the first choice. Residential buildings in northern China are facing significant energy challenges, with heating and cooling accounting for a significant portion of total energy consumption. The latest research shows that since 1995, the energy consumption of residential buildings in northern Chinese cities has increased fivefold, accounting for only about 74% of the total energy consumption of urban residential buildings. Therefore, we need a performance oriented design approach that prioritizes energy efficiency.

The design process of traditional furniture is based on the subjective experience of architects, which can produce excellent results. The general approach involves repetitive guidelines between design concepts, performance simulations, and feedback modifications. This process not only takes time, but also cannot fully utilize the shape of the building and potential energy planning room. The latest advances in artificial intelligence and boundary design provide promising solutions to these challenges through the implementation of workflow design driven data automation.

In this article, based on performance oriented residential buildings in northern China, artificial intelligence (AI driven) framework boundary design is at the forefront. The main objectives are: (1) to develop automated design workflows in the early stages of residential planning, using artificial intelligence and boundary design tools to generate and evaluate various design solutions; (2) to integrate performance data (such as energy consumption, thermal comfort) into the design process and implement data based on decision-making. (3) The proposed framework has been validated through case studies, demonstrating its effectiveness in improving energy efficiency and reducing redundant designs. This research is of great significance in introducing artificial intelligence driven methods, fundamentally changing residential practices, and improving design efficiency and performance. Through automated design processes, architects can focus on higher-level decisions to ensure compliance with environmental building standards.

2. Related Work

2.1 Parametric Design in Architecture

Boundary design becomes the cornerstone of digital architecture and can generate complex shapes through logical algorithms. The early concept of border design can be traced back to Luigi Moretti's work in the 1940s, which focused on the relationship between design parameters and engineering. [3] Computer aided design (Canada) emerged in the 1960s, driving the practice of border design. Using modern boundary design tools such as Grasshopper and Dynamo, designers can dynamically create building shapes by manipulating parameters.

2.2 AI Applications in Building Design

Artificial intelligence technology, especially genetic algorithm learning machines, has become a powerful tool in architectural design. Inspired by natural selection, genetic algorithms (GA) are used to improve building shape and enhance energy efficiency. For example, Jin and others used genetic algorithms to improve the shape of buildings to reduce external convection, resulting in significant energy savings. [4] Wang et al. also used multi-objective genetic algorithm to improve packaging structure standards and demonstrated that it can enhance energy efficiency. [5] Sedura and Strulia (6) developed a Building Information Modeling (BIM) interior design framework in a computer-readable form to describe the rules of interior design so that users can automatically create interior design models. By defining the irregular shape of each room and the neighborhood relationships between rooms, Article [7] creates an irregular structure. Wang et al. (8) created an urban design tool called the "City Engine", which generates a city structure similar to the surrounding community by creating syntax and procedural rules. Zhang et al. (9) developed an urban planning generation algorithm that allows users to generate design solutions based on the original features of the site, such as sunlight, water, and landscape density.

Other applications of artificial intelligence include neural networks for predicting energy consumption and generating reverse network designs (GAN) automatically. Through these technologies, designers can browse large areas of design and effectively determine the best solution.

2.3 Performance-Oriented Design Methods

Design performance guidelines, using simulation tools to evaluate and improve building performance during the design process. Energy simulation software, such as Energy Plus and DST, can provide a detailed understanding of a building's energy consumption and guide planning and decision-making. However, the traditional simulation driven design process often requires a large amount of manual input and frequent adjustments, which limits its usefulness. Recent research has investigated the integration of artificial intelligence and performance simulation tools. For example, Li et al. This study provides a fast bidirectional optimization method based on artificial intelligence, which can greatly shorten the repetition time. Based on these advances, this article combines cutting-edge design driven artificial intelligence with performance simulation to form performance automation driven by the design process.

3. AI-Driven Parametric Design Framework

3.1 Case Library and Parameter Extraction

3.1.1 Case Library Development

The foundation of the proposed framework is a comprehensive case library of northern residential buildings. This library comprises 345 high-quality residential floor plans sourced from design standards, industry practices, and academic research. Each case is tagged with key performance metrics, including energy consumption, thermal comfort, and spatial efficiency. The case library serves as a knowledge base for the algorithm, enabling it to learn from existing design patterns and generate new solutions.

Table 1: Basic Information of Case Library

Floor plan type	Count	Percentage
1Stair+2Suites	128	37.1%
1Stair+3Suites	33	9.6%
1Stair+4Suites	69	20%
1Stair+5Suites	10	2.9%
1Stair+6Suites	3	0.9%
1Stair+8Suites	4	1.2%
Single Suite	98	28.4%
Total	345	

3.1.2 Parameter Extraction Methodology

To automate the design process, critical design parameters are extracted from the case library. These parameters include: 1) **Spatial Layout Features**: Room dimensions, traffic space organization, and functional relationships. 2) **Performance Metrics**: Energy consumption coefficients, thermal bridging effects, and window-to-wall ratios. 3) **Architectural Constraints**: Building codes, zoning regulations, and user-defined design requirements. The extraction process involves a combination of manual annotation and automated feature recognition. Machine learning techniques, such as clustering and dimensionality reduction, are employed to identify recurring patterns and optimize parameter ranges.

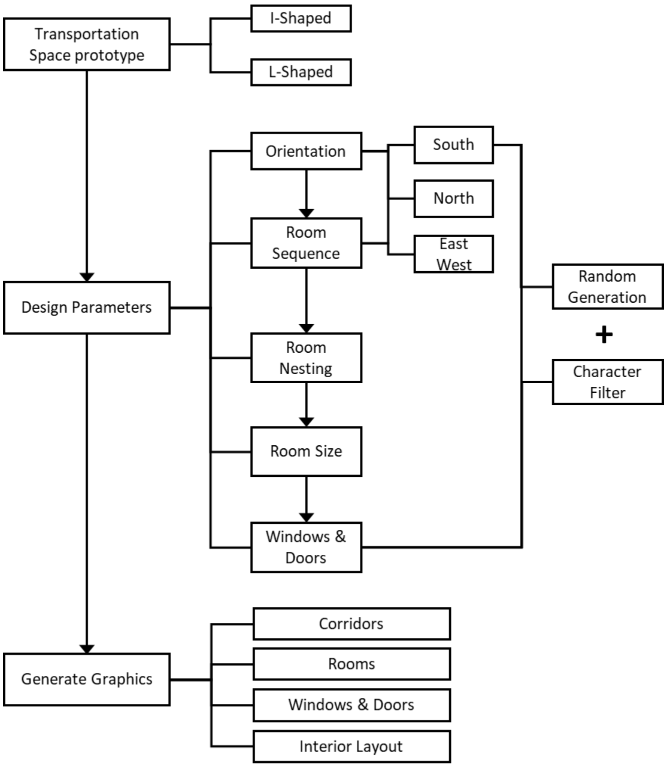

Figure 1: The algorithmic logic for AI generating floor plans

3.2 Algorithm Development for AI Design Generation

The algorithm is developed using Grasshopper, a parametric design plugin for Rhino, and Python for custom scripting. The architecture consists of three main components: 1) **Input Module**: Accepts user-defined design parameters (e.g., building area, room count, climate zone). 2) **Processing Module**: Generates design alternatives through parametric rules and AI-driven optimization. 3) **Output Module**: Visualizes results and evaluates performance metrics. The Algorithm workflow is structured as follows:

1) **Parameter Initialization:** User inputs design requirements, and the algorithm initializes design variables.

2) **Design Generation:** Using parametric rules, the algorithm generates multiple design alternatives. Each alternative is evaluated against predefined performance criteria.

3) **Performance Simulation:** EnergyPlus is integrated to simulate energy consumption and thermal comfort for each generated scheme.

4) **Optimization:** Genetic algorithms (GA) are applied to iteratively refine designs, prioritizing energy efficiency and spatial functionality.

5) **Result Visualization:** Results are visualized in Grasshopper, providing architects with intuitive feedback on design performance.

3.3 Integration of Performance Simulation Data

The simulation setup employs EnergyPlus to simulate heating and cooling loads of residential floorplan schemes. Incorporating meteorological data from EnergyPlus databases, thermal transmittance values (U-values) for walls, windows, and roofs, and occupancy patterns that mirror typical usage in northern residential buildings. The integration of performance simulation data into the design workflow is seamless and systematic. EnergyPlus outputs are parsed and imported into Grasshopper, forming the foundation for performance evaluation (Figure 2). Each design alternative undergoes rigorous scoring based on energy efficiency and thermal comfort, ensuring that only high-performing designs are retained for further optimization. This feedback loop eliminates the need for manual iterations, streamlining the design process and enabling architects to focus on refining the most promising solutions. The framework thus bridges the gap between simulation and design, creating an iterative and efficient workflow that enhances both the quality and sustainability of architectural outcomes.

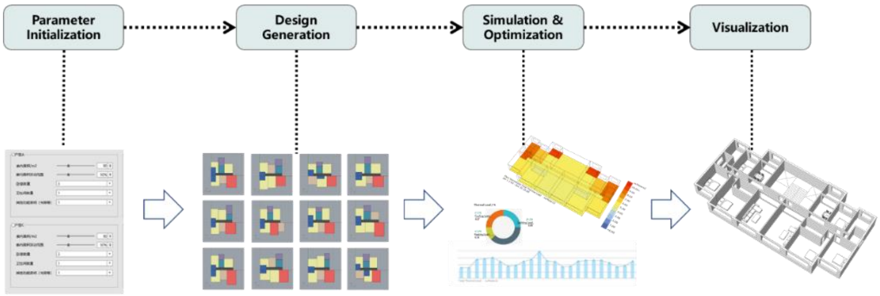

Figure 2: Algorithm workflow

4. Case Study: Automated Generation of Residential Floor Plans in Beijing

The algorithm was brought to life within the Grasshopper platform, aided by Python scripting. The process began with setting up parameters, where input variables like building area and room count were defined alongside performance targets. This was followed by the generation of 1,595 design alternatives for a 25-story residential building in Beijing, showcasing the algorithm's ability to produce a multitude of options (Figure 3). Each of these alternatives was then put through energy simulations using EnergyPlus, allowing for a detailed assessment of their performance. To fine-tune the designs and pinpoint the highest-performing ones, a genetic algorithm (GA) was applied, acting as a refining tool for the generated schemes.

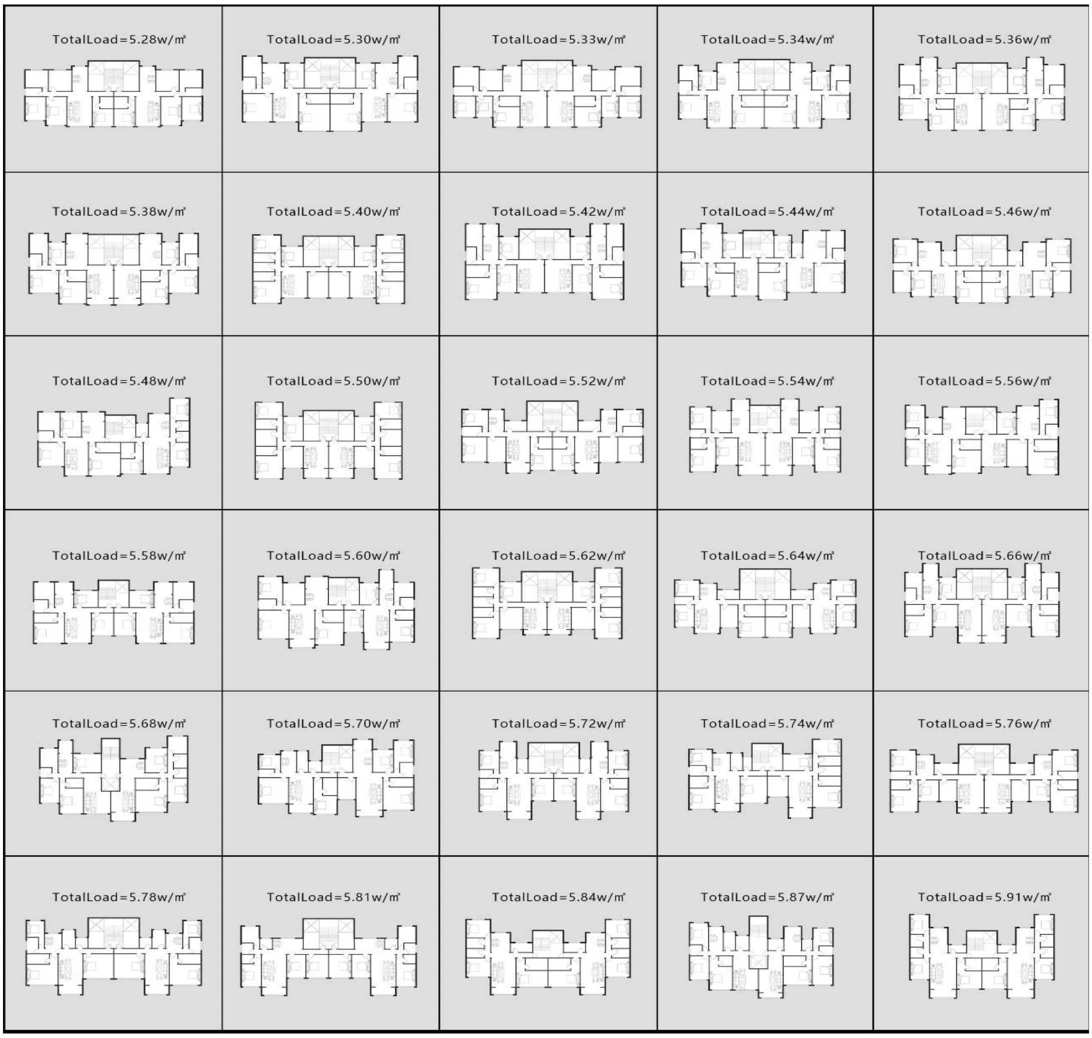

Figure 3: Generated Schemes of Residential Building Case

Validation of the algorithm centered on three key aspects. Energy efficiency was evaluated by comparing the total heating and cooling loads across all design alternatives, seeking the most optimal energy performance. Design feasibility was ensured by checking compliance with building codes and user requirements, guaranteeing that the generated designs were not only efficient but also practical and applicable. Lastly, computational efficiency was measured by looking at the algorithm's runtime and iteration speed, ensuring that the process was not only effective but also efficient in terms of time and resources. This comprehensive validation approach underscored the algorithm's effectiveness in producing designs that were both innovative and grounded in real-world applicability.

The quantitative analysis revealed that the optimal scheme achieved a 4.2% reduction in total energy load in comparison to the baseline design. Moreover, the generated schemes exhibited enhanced spatial organization, effectively minimizing unnecessary concavities and thereby improving thermal performance. A comparative analysis between the algorithm-generated schemes and conventional designs indicated that the algorithm significantly enhanced time efficiency by reducing design iteration time by approximately 70%. In terms of performance gains, the generated schemes demonstrated superior energy efficiency, with their total energy loads being 15.8% lower than those of the poorest conventional design. The sensitivity analysis further identified critical parameters affecting energy performance. Notably, a strong correlation was found between the window-to-wall ratio and total energy load, with a Spearman's ρ value of 0.65. Additionally, room depth was found to have a moderate negative correlation with energy efficiency, with a ρ value of -0.53. These findings underscore the algorithm's effectiveness in producing design alternatives that not only meet but exceed the performance benchmarks of conventional methods, while also highlighting key parameters that can guide future design optimizations.

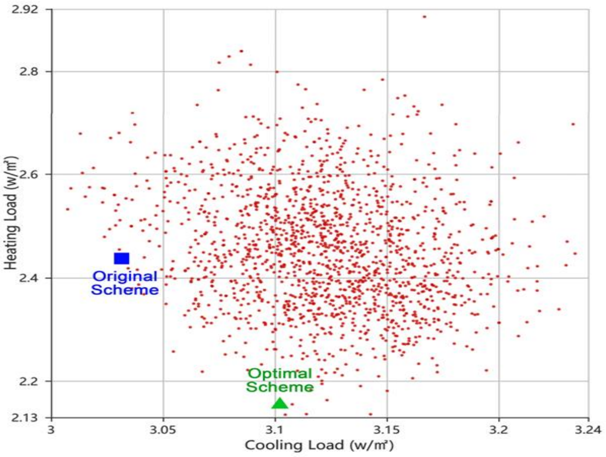

Figure 4: Scatter plot of heating and cooling loads for all schemes

5. Conclusion

The research presented in this paper has charted a new course for AI-driven parametric design in the realm of northern residential architecture. By developing and validating an algorithmic framework that seamlessly integrates performance simulation data with automated design generation, we have demonstrated the potential for transformative change in design practices. The case study served as a crucible for testing the framework's efficacy, revealing not only its technical merits but also its broader implications for the architecture industry.

The AI-driven parametric design framework has proven to be a catalyst for efficiency and innovation. It has shown that the integration of AI into the early stages of design can lead to more sustainable, energy-efficient buildings without compromising on architectural quality. The time savings achieved through automated design iterations are substantial, allowing architects to explore a richer design space and make more informed decisions. This is particularly relevant in the context of northern residential buildings, where energy performance is paramount.

Looking to the future, the framework's scalability and adaptability position it as a versatile tool for addressing the diverse challenges of architectural design. The potential for expansion to include additional performance metrics, such as daylighting and indoor air quality, further enhances its utility. As AI technologies continue to evolve, their role in architecture is likely to deepen, offering new avenues for exploration and optimization.

In conclusion, the AI-driven parametric design framework is not merely a technical advancement but a strategic evolution in how we approach architectural design. It invites architects to embrace a collaborative relationship with AI, leveraging its analytical power while retaining creative control. As the building industry faces increasing demands for sustainability and efficiency, this framework stands as a beacon of innovative potential, ready to guide the next generation of architectural practice.

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