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Performance-Oriented Parametric Design Method and Tool for Residential Buildings in Northern China

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Abstract: ***In the context of rapid digital technology and artificial intelligence development, the construction industry faces a new technological revolution. Green energy efficiency is a practical requirement due to increasingly severe resource and environmental problems, with residential energy conservation in northern China being particularly important. This paper addresses practical problems in current domestic residential design, including insufficient performance optimization in early design stages and deviation between actual building performance and design targets. Focusing on green performance targets in the early design stage of northern residential buildings, this research combines energy-efficient design with AI technology, exploring the application potential of parametric digital technology and intelligent design. The paper constructs a green performance-target-oriented, human-machine collaborative design method based on performance simulation data and an architect-oriented technical collaboration tool platform. A residential standard floor plan automatic generation algorithm and a simplified intelligent optimization algorithm are developed based on parametric generative design methods and genetic algorithms. An intelligent green design tool platform, "TH-Green House Designer", is developed for architects. The method and tools are validated through a case study of the Beijing Vanke Emerald Garden demonstration project, achieving an 18.1% reduction in total energy load compared to the original scheme.***

Keywords: Green residential building; Building performance; Parametric design; Genetic algorithm; Early design stage.

1. INTRODUCTION

Green energy efficiency is a practical requirement for the construction industry due to increasingly severe resource and environmental problems [1]. Research has shown that the early design stage is critical for green building performance optimization, with over 40% of energy saving potential originating from this stage [2,3]. Predicting and optimizing building performance in the early design stage can significantly improve residential energy efficiency by optimizing building form, spatial layout, and envelope structure with almost no additional cost.

Residential energy consumption in northern China accounts for approximately 74% of total building energy consumption [4]. The current heating area in northern urban areas is 8.8 billion square meters, with winter heating consuming 153 million tons of standard coal, representing about one-quarter of total building energy consumption [5]. Therefore, improving the energy efficiency of residential buildings in northern China is a national priority.

Conventional residential green design processes face two main problems: (1) disconnection between schematic design and green performance optimization – energy simulation is often introduced after the basic scheme is determined, failing to guide early-stage optimization; and (2) simulation tools are not conducive to repeated feedback due to high time costs and technical difficulty, preventing full exploitation of the energy saving potential of building forms [6,7].

To address these issues, this research develops a performance-oriented parametric design method and tool platform for residential buildings in northern China. The objectives are: (1) to establish a "reverse", data-driven design process; (2) to develop a parametric automatic generation algorithm for residential standard floor plans; (3) to develop a simplified genetic algorithm (GA) based optimization algorithm; and (4) to create an architect-oriented intelligent green design tool, "TH-Green House Designer".

2. METHODOLOGY

2.1 Reverse Design Process

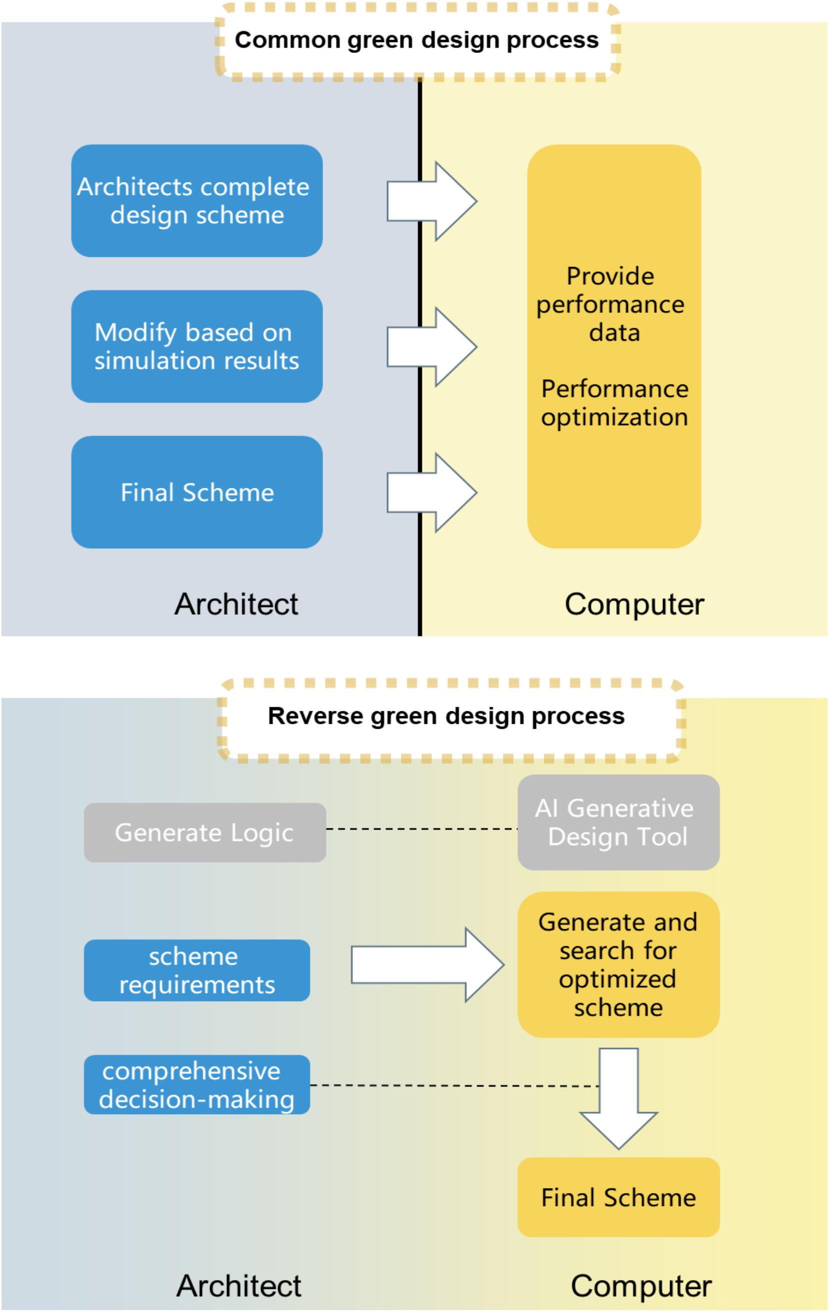

Figure 1: Forward vs. reverse green design processes

Conventional green design follows a "forward" process: design → simulation → feedback → modification → re-simulation. This involves repetitive work and often results in insufficient performance optimization [8]. This research adopts a "reverse" or target-oriented design process (Figure 1), where architects input design conditions and performance targets, and the computer automatically generates and provides solutions that meet performance requirements. This approach fundamentally solves the time-lag problem between design and simulation, allowing designers to complete highly complex multi-objective optimizations [9].

2.2 Parametric Automatic Generation of Standard Floor Plans

Based on parametric generative design methods, an automatic generation algorithm for residential standard floor plans was developed using Grasshopper and Python. The algorithm simulates architects' design thinking and follows three main steps: (1) feature extraction from a case library of 300 excellent northern residential designs, (2) parametric scheme generation, and (3) constraint-based filtering [10]. Figure 2 shows the algorithm framework.

The algorithm includes four modules: automatic generation module, constraint filtering module, energy simulation module, and visualization module. Qualitative elements (spatial configuration, room adjacency) and quantitative elements (room dimensions, window sizes, envelope properties) are parameterized. Constraint filtering ensures compliance with design codes, functional rationality, and user-defined subjective rules. Energy simulation is performed via Honeybee calling EnergyPlus.

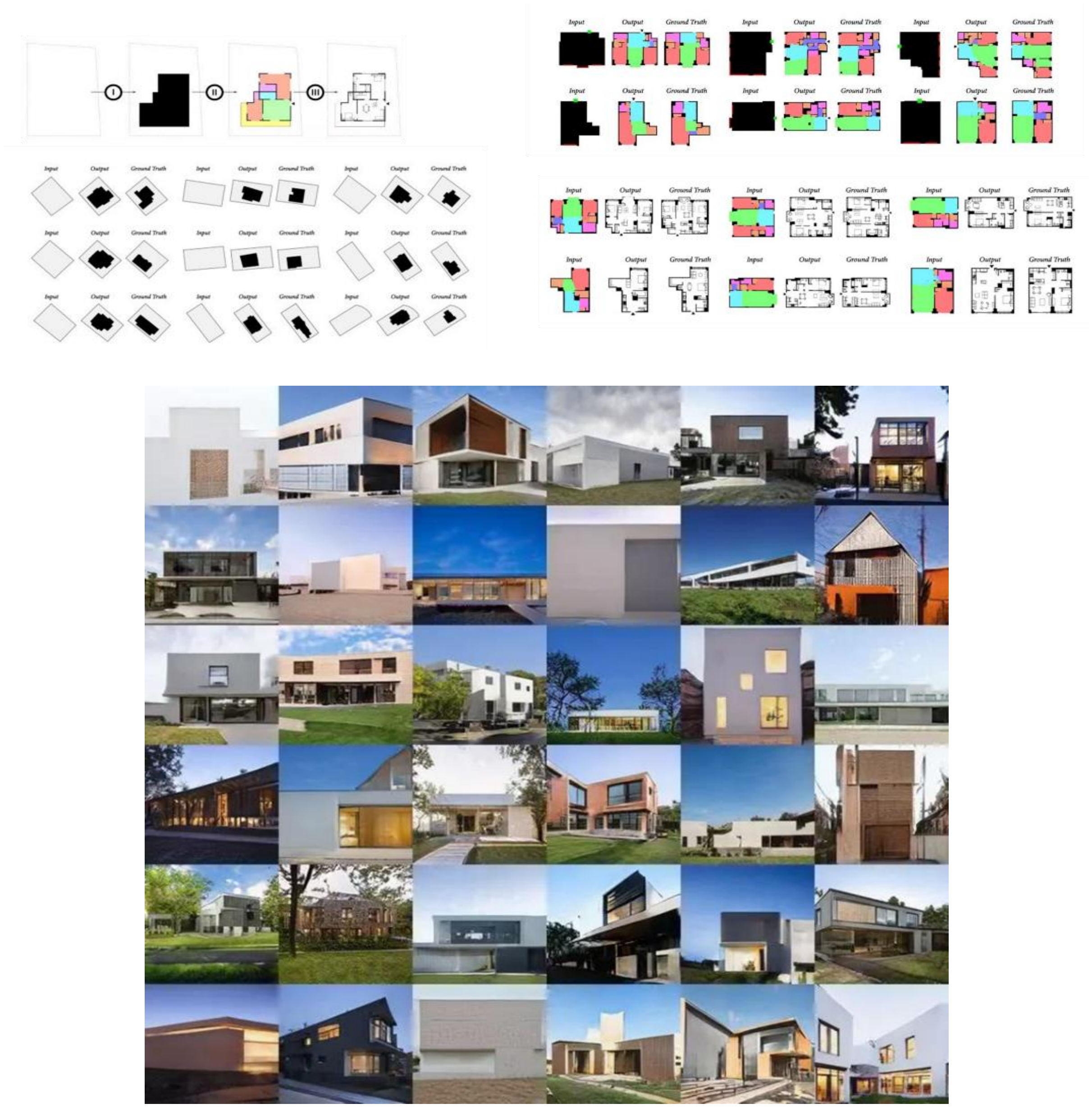

Figure 2: Algorithm framework for residential standard floor plan automatic generation

2.3 Performance-Oriented Optimization Using Genetic Algorithm

To simplify the optimization process for existing residential schemes, a “one-click” intelligent optimization algorithm was developed based on genetic algorithms (GA) [11,12]. The algorithm automatically identifies variable parameters (room dimensions, window-to-wall ratio, window height, envelope thermal properties), builds parametric models, calls EnergyPlus for energy simulation, and performs GA optimization. The technical route is shown in Figure 3.

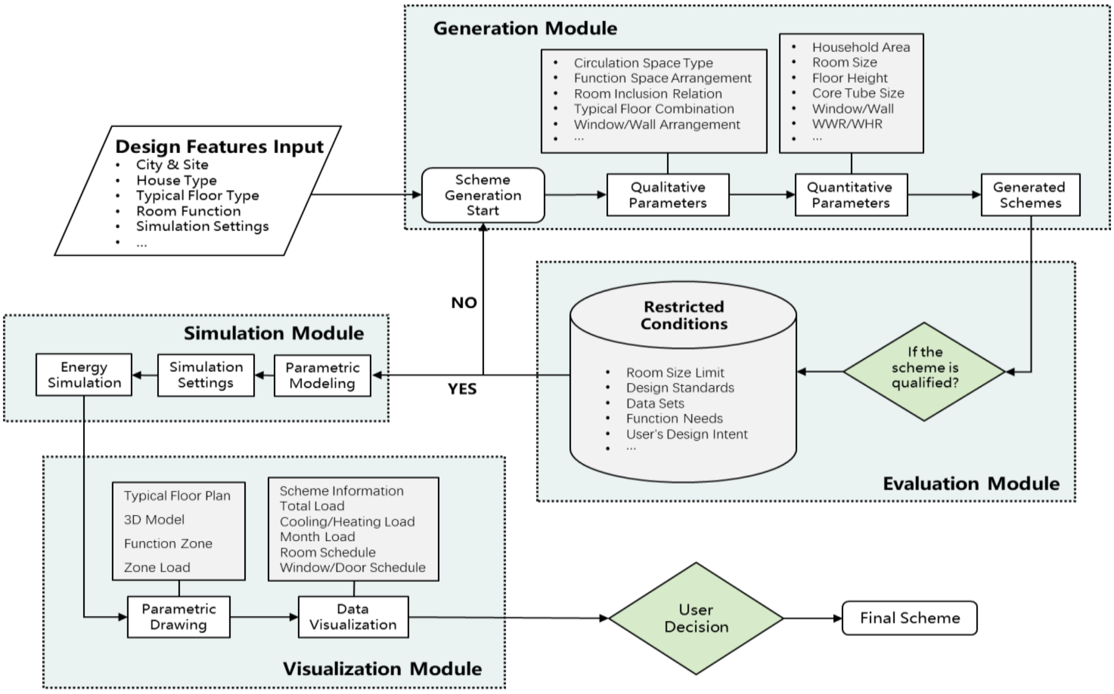

Figure 3: Technical route of one-click intelligent optimization algorithm (Source: Author, original paper Figure 4.8)

The optimization supports both automatic GA optimization and manual adjustment with real-time energy feedback. The objective is to minimize total cooling and heating load per unit area. Variable ranges are defined based on design standards and typical practice.

2.4 TH-Green House Designer Platform

Based on the above methods and algorithms, the "TH-Green House Designer" platform was developed using Grasshopper, Python, and C#. The platform features: (1) performance-oriented reverse design process, (2) parametric automatic generation of standard floor plans, (3) human-machine collaborative one-click green optimization (both automatic GA and manual adjustment), (4) real-time performance visualization, and (5) automatic generation of plans, 3D models, and reports.

3. CASE STUDY: BEIJING VANKE EMERALD GARDEN

3.1 Project Description

The demonstration project is Building No. 9 of the Vanke Emerald Garden residential complex in Mentougou District, Beijing (cold climate zone, IIA). The building has 25 floors with a north-south orientation, adopting a "two units per floor" pattern. The target unit area is approximately 130 m², with functional requirements: 1 master bedroom, 2 secondary bedrooms, 2 bathrooms, and 1 dining room. Default envelope properties: exterior wall U-value 0.4 W/(m²·K), window U-value 1.5 W/(m²·K), south window-to-wall ratio 0.5, north 0.35, floor height 2.8 m.

3.2 Scheme Generation Results

A total of 536 standard floor plan schemes were generated in approximately 26 hours and 20 minutes. The optimal scheme achieved a total load of 5.28 W/m² (cooling: 3.14 W/m², heating: 2.14 W/m²). Compared to the original scheme (simulated under same conditions: total load 5.46 W/m²), the optimal scheme reduced total load by 3.4%; compared to the worst scheme (5.91 W/m²), the reduction was 11.9%. Figure 4 shows the cooling/heating load scatter plot of all generated schemes. The optimal scheme exhibited a more compact form with less 凹凸 variation, consistent with general energy-efficiency principles.

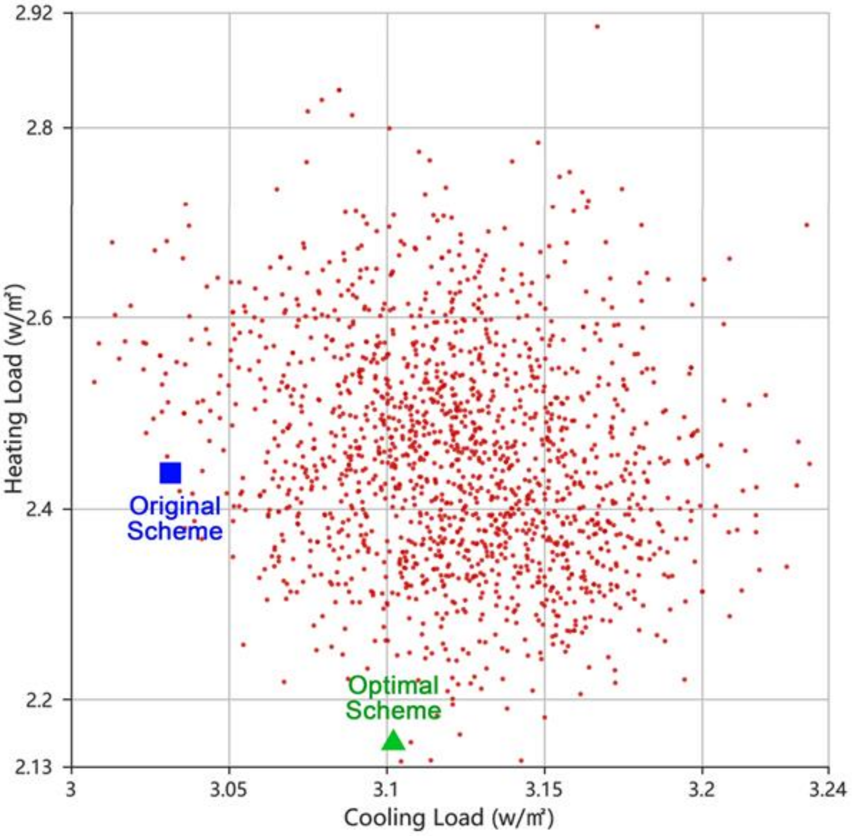

Figure 4: Cooling/heating load scatter plot of all generated schemes

3.3 Optimization Results

Using GA optimization with 27 variable parameters (Table 1), 3,709 valid data sets were obtained. The optimal scheme achieved a total load of 4.74 W/m², an 18.1% reduction compared to the original scheme (5.60 W/m²). Under the most favorable conditions, the reduction reached 48.1%. Table 2 compares the original scheme with three optimal schemes. The optimization was verified using an annealing algorithm, which yielded a very similar optimum (4.75 W/m²), confirming reliability.

Table 1: Variable parameter ranges in optimization

Parameter	Description	Unit	Min	Max
FloorHeight	Floor height	m	2.8	3.2
LivingR-Width	Living room width	m	4.2	4.8
MainB-Width	Master bedroom width	m	3.8	4.2
NB_Depth	North bedroom depth	m	3.6	4.0
Platform-Depth	Equipment platform depth	m	0	3.0
SWWR	South window-to-wall ratio	%	35	55
NWWR	North window-to-wall ratio	%	20	40
Wall_K_Val	Exterior wall U-value	W/(m²·K)	0.30	0.45
Win_U_Val	Window U-value	W/(m²·K)	1.8	2.4

Table 2: Comparison of original and optimal schemes

	Original	Optimal 1	Optimal 2	Optimal 3
Total Load (W/m²)	5.60	4.74	4.75	4.76
Cooling Load (W/m²)	–	3.14	–	–
Heating Load (W/m²)	–	1.60	–	–
Floor Height (m)	3.00	2.71	2.70	2.73
Wall U-value	0.40	0.25	0.25	0.25
Window U-value	1.50	1.53	1.54	1.56

3.4 Sensitivity Analysis

Spearman correlation analysis was conducted to identify the relationship between design parameters and total load (Table 3). Wall U-value (0.688), window U-value (0.658), and equipment platform window-to-wall ratio (0.653) showed the strongest positive correlations. Room depth parameters showed moderate negative correlations, with equipment platform depth showing the strongest effect (-0.599). Floor height showed a moderate positive correlation (0.482). Interestingly, north-facing window-to-wall ratio had a stronger effect than south-facing ratio, suggesting that architects should pay particular attention to north facade design in cold climates.

Table 3: Correlation coefficients between key design parameters and total load

Parameter	Spearman's ρ	Significance
Wall U-value	0.688**	0.000
Window U-value	0.658**	0.000
Equipment platform WWR	0.653**	0.000
Equipment platform depth	-0.599**	0.000
North bedroom depth	-0.553**	0.000
South bedroom depth	-0.544**	0.000
Floor height	0.482**	0.000

** $p < 0.01$ (2-tailed)

4. DISCUSSION

The case study demonstrates several important findings. First, the reverse design process effectively integrates schematic design with green performance optimization, addressing the disconnection problem common in conventional practice. Second, the parametric automatic generation algorithm successfully produces numerous valid schemes with performance data, enabling data-driven design decisions. Third, the simplified GA optimization algorithm significantly improves residential energy efficiency with minimal additional effort from architects – the 18.1% load reduction was achieved automatically. Fourth, sensitivity analysis reveals that envelope thermal performance is most critical, followed by room depth and window-to-wall ratio. The strong negative correlation of room depth suggests that increasing depth (within limits) can reduce heat loss, likely due to reduced surface area-to-volume ratio.

This research has some limitations. Currently, the algorithm only supports "two units per floor" residential types and focuses solely on heating and cooling load, without considering lighting, ventilation, or carbon emissions. The simulation used simplified models (single floor, adiabatic slabs). Future work will expand to more residential types and multi-performance objectives (daylighting, natural ventilation, carbon emissions, urban heat island) and improve simulation speed using simplified algorithms or machine learning.

5. CONCLUSION

This research constructed a performance-oriented parametric design method and tool platform for residential buildings in northern China. The main contributions include: (1) proposing a reverse, data-driven design process for green residential buildings; (2) developing a parametric automatic generation algorithm for residential standard floor plans; (3) developing a simplified one-click intelligent optimization algorithm based on genetic algorithms; (4) developing the architect-oriented "TH-Green House Designer" platform; and (5) validating the methods and tools through a real demonstration project. The case study showed that the optimal scheme achieved an 18.1% reduction in total load compared to the original scheme, demonstrating the effectiveness of the proposed approach. This research provides a practical and scientific basis for early-stage green residential design in northern China.

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