Analysis and Design Strategies for Energy-Saving Effects of Dynamic Shading Considering Residential Neighborhood Morphology Characteristics : A simulation-based research

Authors: Bing Xia, Yulu Zhuang, Jinglan He, Yunfeng Hu, Bing Xia

Date: 2026-02-15T20:00:29+00:00

Abstract

AbstractPurposeThe effectiveness of building retrofitting technologies in high-density urban environments is significantly influenced by neighborhood morphological characteristics, highlighting the critical integration of architecture and technology in sustainable urban renewal.Design/methodology/approachThis study investigates dynamic shading systems - a prevalent retrofitting solution for reducing residential energy consumption - while emphasizing the integration of resilience with sustainability in climate-responsive design. Through a multidisciplinary approach combining GIS spatial analysis, energy performance simulations, and multi-objective optimization, we systematically evaluate the Energy-saving potential (ESP) of dynamic shading across 249 residential neighborhoods in representative Chinese cities from two distinct climate zones.FindingsKey findings reveal: (1) Dynamic shading performance demonstrates dual dependency on regional climate patterns and neighborhood morphology, with 4.51% annual energy consumption reduction in Hangzhou and 19.8% winter heating energy consumption increase in Beijing. (2) Morphological determinants show climate-specific variations, where Shape Factor (SF) dominates in both hot-humid and cold regions while Area-to-Perimeter Ratio (APR) prevails in cold zones, underscoring the architecture-technology nexus in retrofit planning. (3) Optimal shading configuration balancing energy efficiency and climate resilience involves strategic distribution of 50% coverage ratio dynamic louvers (DLs) on southern facades and 25% on western facades.OriginalityThe research establishes a novel framework for integrating technological solutions with urban morphological analysis, advancing both sustainable performance and climate resilience in high-density urban renewal. These evidence-based strategies provide critical guidance for policymakers and planners in achieving synergistic improvements in energy efficiency, architectural integration, and long-term urban sustainability.

Full Text

Preamble

Analysis and Design Strategies for Energy-Saving Effects of Dynamic Shading Considering Residential Neighborhood Morphology Characteristics : A simulation-based research Bing XIA1，Yulu ZHUANG1，Jinglan HE1 & Yunfeng HU1 1: College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China.

Bing XIA：提出研究思路，设计研究方案；Yulu ZHUANG：负责进行实验，并采集、清洗和分析数据；Yulu ZHUANG、Jinglan HE：负责论文起草；Jinglan HE 、Yunfeng HU：负责最终版本修订。* Corresponding author: Bing Xia (E-mail: 0016217@zju.edu.cn).

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Findings Key findings reveal: (1) Dynamic shading performance demonstrates dual dependency on regional climate patterns and neighborhood morphology, with 4.51% annual energy consumption reduction in Hangzhou and 19.8% winter heating energy consumption increase in Beijing. (2) Morphological determinants show climate-specific variations, where Shape Factor (SF) dominates in both hot-humid and cold regions while Area-to-Perimeter Ratio (APR) prevails in cold zones, underscoring the architecture-technology nexus in retrofit planning. (3) Optimal shading configuration balancing energy efficiency and climate resilience involves strategic distribution of 50% coverage ratio dynamic louvers (DLs) on southern facades and 25% on western facades.

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integration, and long-term urban sustainability.

Keywords dynamic shading; energy-saving; urban morphology; neighborhood environment; performance simulation

1.1. Background

In high-density urban environments, building shading effects critically influence building energy consumption and urban livability . Urban shading, driven by spatial layout, building height, and density, limits direct sunlight access due to inter-building obstructions [1]. This reduces natural lighting efficacy and thermal regulation, elevating heating/lighting demands and compromising residential comfort and quality of life [2]. Dynamic shading excels in real-time adjustment to control solar heat gain and natural light, optimizing energy efficiency and comfort. However, improper operation and management may compromise its shading efficiency, thereby affecting building energy consumption and residential comfort. Consequently, shading emerges as a pivotal determinant of both energy efficiency and urban residential environmental quality. High-density urbanization intensifies inter-building shading, hindering urban energy efficiency and livability due to dense layouts and vertical growth [3]. Current static models inadequately address urban morphology’ s dynamic spatiotemporal effects on shading performance.

Dynamic shading (DS) systems—real-time adaptive technologies for solar modulation—are critical for urban energy efficiency [4].

However, current DS research focuses on individual buildings, lacking cluster-scale frameworks [5, 6]. DS efficacy hinges on building morphology, density, and orientation [1, 7] , necessitating a “technology-morphology synergy” approach to evaluate Energy-saving potential (ESP) across neighborhood typologies. Therefore, this study analyzes DS performance in residential neighborhoods (RNs), integrating spatial morphology and technological adaptability to optimize energy savings. By bridging technological innovation with urban form, the research provides actionable strategies for energy retrofitting and sustainable urban renewal.

1.2. Literature Review

The energy-saving potential and current development status of dynamic shading technology Shading design critically influences building energy efficiency by mediating natural lighting, thermal regulation, visual comfort, and facade aesthetics [8]. Effective shading enhances indoor environmental quality, functionality, and occupant well-being [9] , while reducing cooling loads through optimized solar heat gain control [10]. Optimized shades reduce 7.05% energy use in Bangladeshi offices under subtropical monsoon climate, particularly south/west orientations[11]. However, conventional fixed shading systems exhibit limited environmental adaptability [12], failing to address dynamic climatic and spatial demands [13].

Emerging dynamic shading (DS) systems, integral to smart and sustainable architecture [14] , employ real-time adjustments (solar radiation, temperature, wind speed) to intelligently regulate lighting and thermal conditions [15]. Empirical studies confirm DS' s capacity to reduce energy consumption by 15-30%, minimizing reliance on artificial lighting and HVAC systems [16] . Evidence shows that DS systems have more uniform performance and usually outperform static shading [17], thereby positioning DS as a cornerstone of energy-efficient building design. Current DS systems—smart electrochromic glass, motorized blinds, and dynamic louvers (DLs)—exhibit distinct ESP and constraints. Smart glass modulates transmittance adaptively but remains experimental [18]; motorized blinds lack residential validation despite commercial prevalence [19]. DLs demonstrate optimal viability for China' s residential retrofits, achieving 25 - 40% solar heat gain reduction with proven climatic adaptability and scalability [20] , Their technological maturity and balanced performance across building typologies position DLs as superior solutions for large-scale neighborhood deployment.

Existing DS research predominantly targets individual buildings [21] and experimental chambers [22], neglecting systematic cluster-scale investigations. Methodological constraints include orientation-restricted designs (e.g., south facades [23]), and uniform deployments [21], failing to address multi-orientation efficacy, and cost-effective local optimizations aligned with facade-specific solar exposure and spatial occupancy patterns. This gap necessitates data-driven frameworks for adaptive solutions that balance energy efficiency, visual comfort, and economic viability through targeted micro-zonal configurations across building clusters. Despite persistent challenges—including maintenance costs, control complexity, and user acceptance [24] —advancements in smart control technologies, enhanced material durability, and streamlined O&M protocols have progressively improved DS feasibility and cost-benefit ratios. These innovations are driving increasing adoption in energy-efficient building retrofits, underscoring DS' s growing practical viability and scalability [25] . To maximize this potential, future research must prioritize scenario-specific DS optimization strategies that harmonize technical performance, economic efficiency, and occupant-centric adaptability across diverse architectural and climatic contexts [17].

Current applications and limitations of dynamic shading in residential buildings Existing research on the application of DS has mostly focused on office and commercial buildings[26]. Studies have shown that adopting DS in office buildings can significantly reduce energy consumption, with some cases achieving a 38.3% decrease in overall energy usage [27]. However, research on residential buildings is limited. Although individual cases indicate that applying DS systems to single residential buildings can reduce the total annual energy consumption by 11.6-13.0% and significantly lower the energy demand for cooling in summer and heating in winter [28, 29], systematic studies are still lacking. Residential buildings account for as much as 35% of global energy consumption [30] and often exist as building clusters. Currently, the application of DS in residential buildings faces several challenges, including high retrofitting costs, long payback periods, and incomplete design methodologies [31]. These challenges underscore the need for systematic methodologies to tailor DS configurations to residential typologies (e.g., high-rise vs. low-density) and spatial morphologies (e.g., courtyard vs. linear layouts), balancing precision and cost-effectiveness to unlock scalable ESP in this critical sector.impact of urban morphology on the potential of building energy retrofit.

Impact of urban morphology on the potential of building energy retrofit Previous studies have shown that the morphological characteristics of residential building clusters and street spaces significantly impact the potential for building energy retrofitting. In terms of building cluster morphology, Wang et al. (2024) pointed out that for every unit increase in the floor area ratio (FAR), the winter Energy Use Intensity (EUI) of buildings can be reduced by 2.26 kWh/m2 [32]. Leng et al. (2020) found that for every 0.1 increase in building density (BD), winter heating energy consumption decreases by approximately 0.87 kWh/($m^2 \cdot$ year) [33]. Zhu et al. (2024) reported that for every 0.1 decrease in the shape factor (SF), the total building energy consumption can be reduced by 3-5% , and increasing the building height to over 30 stories can further lower the overall energy consumption by 7.73% [34]. Additionally, Ying and Li (2020) found that when the average area-to-perimeter ratio (APR) is reduced below 0.4, the total building energy consumption can decrease by approximately 5% [35].

Regarding street space morphology, Urquizo et al. (2017) indicated that increasing the scattering degree (SD) helps enhance ventilation and reduce cooling loads. However, it may also increase lighting energy consumption due to intensified shading [36].

Bhiwapurkar and Moschandreas (2010) found that a high street height-to-width ratio can reduce summer cooling loads by 37% but increase winter heating loads by 19% [37]. Li et al. (2021) noted that a 10% increase in the open space ratio (OSR) could lower nighttime outdoor temperatures by 1.5 °C, resulting in a reduction of approximately 8-10% in heating loads [38]. Peng et al. (2017) emphasized that optimizing land parcel shapes can improve ventilation performance [39]. Shareef (2021) noted that north–south-oriented streets could reduce solar heat gains by 13% and cooling loads by 6.4% [40]. Bouyer et al. (2011) highlighted that block morphology significantly affects the absorption and reflection of solar radiation, a key factor influencing building energy consumption [41].

In summary, Residential building cluster and street morphologies critically shape neighborhood energy use across climates and scales. Current studies, reliant on isolated indicators and idealized models, lack empirical validation and systematic frameworks.

The under-explored synergy between morphology and DS systems necessitates context-specific strategies to maximize ESP, guiding urban renewal, retrofits, and evidence-based policies.

1.3. Innovations and Aims

From a comprehensive review of existing studies, it can be concluded that the current research has shortcomings in three key areas:

DS at the building cluster scale, optimization design strategies, and practical application of research outcomes. Three critical gaps persist in current research: (1) Predominant focus on single-building-scale analyses, neglecting systematic evaluation of DS ESP at the building cluster level; (2) Over-reliance on uniform DL deployment strategies with limited localized optimization; (3) Insufficient mechanistic exploration of how neighborhood morphological characteristics influence energy retrofit potential, despite preliminary cluster-scale energy analyses. Furthermore, prevailing dependence on idealized models limits practical applicability, hindering actionable guidance for real-world neighborhood retrofitting and urban renewal initiatives.

To address these gaps, this study introduces the following innovations:

Introduces an "Architecture-Technology Synergy" framework quantifying multiscale RN-DS interactions, demonstrating neighborhood-scale urban geometry enhances ESP via interface optimization. (2) Develops a climate-adaptive optimization model jointly minimizing DL system costs and energy use, deriving Pareto solutions reconciling immediate savings with climate resilience in urban renewal.

Perform a spatial visualization analysis of the ESP of RNs to identify urban areas suitable for DL, aligning technical feasibility with sustainability goals, bridging resilient infrastructure and architectural energy innovation in high-density cities.

As the contradiction between shading design and high-density urban environments has become increasingly prominent, identifying the key urban morphological factors influencing the ESP of DS and exploring optimized DL arrangements are of great significance for sustainable urban design and improving urban environmental quality. Therefore, the purpose of this study is as follows:

To identifies key urban form factors governing DS systems' ESP, assesses climate adaptability across neighborhoods, and bridges architectural design with technological innovation.

To formulate climate-smart spatial optimization strategies for DS deployment, establishing energy-resilience equilibrium through an urban design framework aligning innovation with sustainability.

2. Materials and Methods

This study proposes a methodological framework integrating GIS spatial analysis, building energy modeling, and multi-objective evolutionary optimization to systematically investigate DS system configuration in RNs. The approach systematically processes RN morphological data through GIS techniques to establish an energy simulation model, subsequently coupled with a genetic algorithm-based optimization mechanism for DL deployment strategies. The methodology is structured into four sequential phases: generation-simulation, analytical processing, multi-objective optimization, and validation (Figure 1 [Figure 1: see original paper]).

Figure 1. Research framework for the optimization and energy-saving analysis of DS in RNs.

2.1. Data Sources and Case Selection

Hangzhou and Beijing, representing high-density urban hubs in China's Yangtze River Delta and Beijing-Tianjin-Hebei regions (Figure 2 [Figure 2: see original paper]), are focal areas for energy-efficient building retrofits. Beijing' s temperate monsoon climate features pronounced seasonal extremes: cold, dry winters (annual sunshine: 2,600–2,800 hrs) and hot summers requiring daylight-shading balance [42].

Hangzhou' s subtropical monsoon climate exhibits humid conditions with moderate annual sunshine (1,700–2,000 hrs) and intense summer solar exposure, necessitating prioritized shading strategies [43]. Solar radiation analyses reveal divergent patterns: Beijing experiences higher total radiation with broader azimuthal spread (peak intensity southwest), while Hangzhou' s radiation concentrates between southwest and northwest at lower intensities.

Figure 2. Study Area, including the climate variation map (top left) and the annual total radiation rose chart (right).

A Python [2.7] web crawler systematically collected residential building spatial data from Beijing and Hangzhou via Baidu Map API [1.3], capturing building contours, floor heights, land areas, and number of floors. Data were preprocessed in ArcGIS [10.5] and transferred to Grasshopper using the Shapefile plugin. Validation through map overlay comparisons and random manual sampling confirmed over 95% contour matching accuracy with actual conditions. After removing erroneous/incomplete entries, the final data-set comprised 1614 Hangzhou RNs and 1083 Beijing RNs. Table 1 demonstrates their uniform spatial distribution, confirming data-set richness and representativeness.

Furthermore, the Anemone [0.4] loop plugin calculated 10 morphological indicators for 1614 Hangzhou and 1083 Beijing RNs (Table 1) Uniform sample spatial distribution (per "Distribution of studied cases") ensures dataset representativeness for cross-city comparisons. Analysis shows Hangzhou has far higher BD (0.26\$±0.09*vs.Beijing*'*s*0.05±0.08), *FAR*(2.40±1.21*vs.*0.14±\$0.23) and H_{ave} (29.40 ± 17.78m vs. 8.91 ± 2.32m), reflecting vertical urban intensification for subtropical humid climate adaptation.

This spatial configuration reflects Hangzhou’ s emphasis on vertical intensification versus Beijing’ s horizontal expansion patterns.

These morphological divergences primarily originate from climatic adaptations, cultural norms, and lifestyle requirements, establishing both cities as representative models of regionally distinct residential typologies shaped by their unique geographical contexts.

Table 1. Statistical summary of RN morphological indicators in two cities (Hangzhou N = 1614 and Beijing N = 1083).

Hangzhou 23.67$±18.650.26±0.092.40±1.2129.40±17.780.25±0.064.61±1.1619.75±19.263.37±1.530.84±17.044
Morphological Characteristic Indicators BD (%) H_{ave} (m) SF (m-1) APR (m) SD (m) LSI (m) Distribution of studied cases

2.2. Modeling and Simulation

Simulation software Honeybee streamlined energy modeling by converting Rhino [7] geometries into EnergyPlus-compatible models, enabling precise DL simulations with shading device effects to evaluate energy consumption impacts. Ladybug enhanced analytical rigor through building energy use intensity (EUI) quantification and seasonal disaggregation of heating/cooling demands. This integrated workflow facilitated comprehensive assessment of DS systems’ energy optimization efficacy across climatic seasons in RNs, providing empirical support for climate-responsive design strategies.

Simulation parameter settings The thermal performance parameters of the building envelope structures specified in the research model are all referenced from the Code for Thermal Design of Civil Buildings. According to the General Code for Building Energy Efficiency and Renewable Energy Utilization, residential models featured uniform strip windows across all facades, with Window-to-wall ratio (WWR) compliance to regional standards: 0.35 (east/west), 0.45 (south), and 0.4 (north) in Hangzhou, standardized with 0.8m window sills. Horizontal DLs[44] were constructed as 3cm aluminum alloy louvers (reflectance:0.65; transmittance:0; emissivity:0.9; conductivity:235 W/(m·K)) with equalized slat width (a) and spacing (b) for full closure capability (Figure 3 [Figure 3: see original paper]). A fixed 50° tilt angle optimized solar control (summer SHGC<0.3), daylight provision (>300 lux illuminance), and visual comfort [45] .

Automated louver activation at >50 W/m^2 incident radiation[46] achieved annual daylight autonomy exceeding 75% while minimizing thermal gains.

Figure 3. DL parameter settings for simulation. (3) Neighborhood building modeling An automated workflow integrating parametric modeling (Grasshopper [1.0]) and energy simulation (Honeybee [1.6.0]) was developed to generate building morphologies and assess energy performance in existing RNs (Figure

4 [Figure 4: see original paper]). The framework encompassed: (1) Rhino-based model generation with neighborhood data, converted into EnergyPlus-compatible formats via Honeybee; (2) automated window and louver configuration, parameterized by WWR, height, and material properties (reflectivity: 0.3-0.7, transparency: 0.5-0.9, thickness: 0.1-0.3 m); (3) energy simulations using China Standard Weather Database (CSWD) climatic data to quantify annual cooling/heating demand. This end-to-end workflow streamlined energy-efficient retrofit design from morphological generation to optimized solutions. (4) Optimization method This study employs a multi-objective optimization framework to determine optimal window retrofitting priorities and DL shading ratios, avoiding local optima while balancing energy efficiency and cost-effectiveness. Using three clustered RN prototypes in Hangzhou, windows were randomized into DL-equipped and no-shading (NS) groups across orientations and floors. The Wallacei engine, integrated with Grasshopper, enabled parametric modeling-simulation coupling to concurrently: minimize annual RN energy consumption and reduce DL deployment quantities. Algorithm parameters, calibrated through iterative testing, included: 50 generations, population size/iterations of 50, crossover probability (0.9), mutation probability (1/design parameters), gene mutation rate (20), and random seed (1). This rigorous parameterization ensured computational efficiency and result accuracy.

2.3. Statistics

This study employed three analytical methodologies: (1) Correlation and regression analyses to quantify relationships between DL energy-saving efficacy and neighborhood spatial morphology; (2) Cluster analysis using Z-score-normalized indicators weighted by correlation strength, with K-means clustering (K=3, validated via silhouette coefficient and elbow method) to classify RNs into distinct morphological typologies (Figure 4); (3) GIS spatial stratification integrating regression outcomes to categorize Hangzhou RNs into low-, medium-, and high-ESP zones, visualized through thermal mapping for urban-scale DS applicability assessment.

Figure 4. Schematic diagram of typical morphological features of neighborhoods obtained through clustering.

3.1. Analysis of the Energy-Saving Potential of Dynamic Shading

Energy-saving potential in different regions and seasons Figure 4 presents DS energy-saving simulations for 129 RNs in Hangzhou and 120 RNs in Beijing. In Hangzhou, DS implementation achieved universal energy optimization across all sample neighborhoods, reducing summer energy consumption compared to NS configurations by an average of 3.34 kWh/m^2 (4.15%). Conversely, Beijing RNs using DS exhibited a 7.86 kWh/m^2 (7.39%) consumption increase. These disparities underscore the critical influence of regional climate on ESP outcomes:

DS mitigates summer cooling loads in high-radiation climates (e.g., Hangzhou) by blocking solar heat ingress but exacerbates winter heating demands in colder regions (e.g., Beijing).

Simulation results indicate summer ESP averaged +13.21 kWh/m^2 in Beijing (vs. +10.16 kWh/m^2 in Hangzhou), while winter ESP plummeted to −21.07 kWh/m^2 (Beijing) versus −6.82 kWh/m^2 (Hangzhou)—a 14.52 kWh/m^2 differential. This demonstrates DS's superior efficacy in southern cities like Hangzhou, where mild winters minimize energy losses.

The impact of RN morphology on the ESP of DS To first identify associations between morphology and DS efficacy, Pearson correlation analysis was conducted, laying the groundwork for subsequent quantitative and categorical analyses. Pearson correlation analysis in Hangzhou (Figure 5a [Figure 5: see original paper]) identified six RN morphological parameters—BD, H_{ave}, SF, APR, BESA, and OSR—as significant determinants of DS energy-saving rates (ESR). ESR was positively correlated with H_{ave} ($r = 0.27$), APR ($r = 0.37$), and OSR ($r = 0.18$). Higher H_{ave} increased solar exposure by expanding window-to-wall ratio (WWR) and reducing adjacent building shading, thereby improving DS' s thermal regulation effect. Higher APR values (indicating compact building forms) minimized heat loss to bolster winter insulation, while reducing solar radiation absorption area and working in tandem with DS to further lower summer cooling loads—significantly enhancing the shading energy-saving potential in hot-humid regions. Increased OSR mitigated inter-building shading, optimizing shading system efficacy. Conversely, BD ($r = -0.48$), SF ($r = -0.55$), and BESA ($r = -0.35$) exhibited negative correlations with ESR. Elevated BD exacerbate inter-building shading, limiting direct solar radiation penetration and diminishing DS energy-saving efficacy. High-density layouts constrain daylight surfaces and reduce solar exposure on lower floors, weakening DS performance compared to open configurations. Larger SF and BESA increase envelope surface area, amplifying thermal bridging pathways and reducing the DS' s relative impact on solar heat gain mitigation.

In Beijing (Figure 5b), the correlation analysis reveals that BD ($r = 0.20$), FAR ($r = 0.22$), H_{ave} ($r = 0.25$) and APR ($r = 0.61$) positively correlate with ESR. In contrast, SF ($r = -0.67$) and OSR ($r = -0.22$) show negative correlations. The core mechanism by which low SF enhances (ESP lies in this: a simplified building form (low SF) reduces envelope surface area, minimizing winter thermal bridging effects and heat loss while avoiding the heating energy consumption increment caused by DS blocking solar radiation—thus maximizing overall energy-saving benefits.Unlike in Hangzhou, the OSR in Beijing exhibited a negative correlation, which may be attributed to differences in the building layout characteristics between the two cities. OSR shows opposing effects: positive in Hangzhou (reduces inter-building shading for summer cooling) and negative in Beijing (worsens winter heat loss), guiding cold regions to adopt moderate OSR.

Linear regression analyses (Figure 5c) were performed to quantify the relative importance of correlated parameters, isolating core determinants of DS performance. In Hangzhou, three indicators collectively explained over 75% of ESR variance: SF ($R^2 = 0.301$), N ($R^2 = 0.270$), and BD ($R^2 = 0.228$). SF was the strongest predictor, indicating that DS is less effective in dense urban layouts. In Beijing, SF ($R^2 = 0.44408$) and APR ($R^2 = 0.37128$) dominated, accounting for 44.4% and 37.1% of ESR variance, respectively.

APR is a stronger predictor in Beijing, where compact forms (high APR) mitigate DS-induced heating increases—supporting cold-region DS design paired with compact morphologies. These results demonstrate that morphological complexity inversely correlates with DS efficiency, underscoring that simpler building morphologies enhance DS efficacy.

Figure 5. (a) Correlation of urban morphological parameters and ESP in Hangzhou; (b) correlation of urban morphological parameters and ESP in Beijing; (c) R2 of the regression model of morphological characteristics for ESR.

RNs clustering based on energy-saving potential This study employed the K-means clustering method to classify RNs in Hangzhou and Beijing into three types, and their corresponding cluster centers were identified (detailed data available in Table I). Referring to the clustering center data (N, BD, H_{ave}, and SF), three typical RN models were abstracted for Hangzhou (Figure 4):

Type 1: Medium SF-Medium N-High BD Mid-Rise RN. Type 2: Low SF-Low N-Low BD High-Rise RN.

Type 3: High SF-High N-Medium BD Low-Rise RN. This study categorized the DS ESR, total energy consumption, cooling energy consumption, and heating energy consumption across different RN types. Visualizations were used to illustrate the energy consumption differences and energy-saving effects of the various RNs. All types of RNs in Hangzhou achieved energy optimization after the overall implementation of the DS, with ESR of 3.38%, 4.51%, and 3.02%, respectively. The second RN type had the highest ESP. Study indicates that the total energy consumption in Hangzhou was the lowest for the second type of RN (75-80 kWh/m2) and the highest for the third type (85-90 kWh/m2), with greater fluctuations. The first type of RN had the lowest cooling energy consumption, whereas the second had the lowest heating energy consumption. In Beijing, the first type of RN exhibited a relatively low total energy consumption (90-110 kWh/m2), whereas the third type had the highest consumption (110-140 kWh/m2) with significant data dispersion, indicating unstable energy-saving performance. Both cooling and heating energy consumption were the lowest for the first type of RN.

In conclusion, DS should be prioritized in the Type 2 RN in Hangzhou. Although DS generally provides good energy optimization in southern cities, its performance varies across RN types; this further highlights the significant impact of the RN morphology on the ESP of DS systems.

3.2. Dynamic Shading Design Strategy Optimization

While existing studies quantified ESP across RN typologies, practical DS implementation requires optimized shading ratios, spatial arrangements, and component placement. This study resolves the critical balance between energy efficiency and cost-effectiveness—preventing over-shading and excessive investments —through multi-objective optimization using algorithmic simulations to evaluate shading schemes and identify optimal louver configurations. (1) Optimization process Figure 6a [Figure 6: see original paper] shows the multi-objective optimization convergence process for the dynamic facade’ s optimal settings and shading ratio across the three types of RNs. As shown in Plate 6a, the values of each optimization objective gradually stabilize with increasing iterations. For Type 1 RNs, the EUI stabilizes between 78 and 79 kWh/m^2/year from the 25th generation onwards, and remains stable until the 50th generation. The fluctuation range of the curve decreases significantly from the first 25 generations (red) to the next 25 generations (blue). For instance, the EUI curve for the first 25 generations in Type 1 exhibited a larger variation than that for the last 25 generations; this indicates that the shading ratio optimization process exhibits good convergence.

Type 1 Type 2 Type 3 Type 1 Type 2 Type 3 Figure 6. (a) Multi-objective optimization convergence diagram for three types of RNs; (b) distribution of Pareto solutions and feasible solutions for three types of RNs.

The distribution of all the optimal solutions is shown in Figure 6b. The gray dots in the solution space represent feasible solutions, whereas the red dots indicate the Pareto solutions. The Pareto solutions are located at the frontier of the solution space and close to the coordinate intersection, indicating that they achieve a more optimal balance between the number of louvers and energy consumption, exhibiting higher optimization performance than other feasible solutions. From the distribution trend perspective, the Pareto solutions of the three types of residential areas all demonstrate the characteristic of reducing energy consumption while decreasing the use of louvers, illustrating that the optimization algorithm can effectively screen out high-efficiency shading schemes. Among them, the Pareto solutions of Type 2 exhibit lower energy consumption under the same number of louvers, suggesting that the application of dynamic louvers in Type 2 has a higher energy-saving potential than that in Type 1 and Type 3. (2) Optimization results A comparative analysis of louver ratio distributions and energy impacts shows measurable improvements between initial (0th-gen) and optimized (49th-gen) solutions (Figure 7 [Figure 7: see original paper]). Optimization decreased northeast allocations while increasing southern (40-80%) and western (20 -40%) ratios. Initial solutions exhibited scattered high-shading distributions (>60% frequency), whereas Pareto-optimal configurations minimized east/north shading (0–20%) to preserve daylight. South-facing louvers achieved summer heat reduction without compromising winter solar gain, while west orientations balanced seasonal needs.

Figure 7 confirms energy efficiency improvements correlate strongly with elevated south/west ratios, attributable to Hangzhou' s predominant southwestern solar exposure. Targeted louver deployment on high-irradiance facades thus optimizes solar modulation, reducing cooling loads and HVAC consumption. Based on the above analysis, the optimal settings and distribution ratios for the dynamic facade show a clear tendency: a strategy of setting the dynamic louvers (DLs) to a coverage ratio of approximately 50% on the south facade and 25% on the west can maximize energy-saving effects.

Figure 7. Comparison of louver ratios and energy consumption before and after multi-objective optimization (with optimized examples). (3) Verification analysis This study validated previous abstract model conclusions through computational assessments of real-world RNs. Type II RNs exhibited the highest ESP, while Type III showed relatively lower efficiency. To verify these findings, two representative RNs (Types 2 and 3) were selected for validation. Following the proposed strategy, DL were strategically installed on west and south facades, with NS applied to east-facing surfaces. Simulations and quantitative analyses of 30 real-world cases (Figure 8 [Figure 8: see original paper]) demonstrated that optimized DS configurations significantly enhanced energy efficiency across both RN types. Results confirm the practical effectiveness of this spatial optimization strategy in improving energy performance of heterogeneous RNs.

Figure 8. Verification of optimization for Type 2 (left) and Type 3 (right) RNs

4.1. The Impact of Urban Morphology on the Energy-Saving Effects of Dynamic Shading

Prior research focused on single-building optimization, lacking mesoscale analysis of urban morphology' s impact on DS efficiency [6, 47]. This study addresses this gap by analyzing RNs at the cluster scale in Hangzhou and Beijing, revealing morphology-dependent ESP differences: Hangzhou' s ESP correlates with low SF, BD, and dispersion, while Beijing' s ESP correlates with low SF and high APR. Notably, these morphological determinants exhibit climate specificity: SF dominates in cold regions like Beijing, strengthening energy savings by reducing heat loss, while APR is critical in hot-summer and cold-winter regions like Hangzhou, optimizing shading effects by enhancing building compactness. Evaluation of 10 morphological indicators extends beyond limited prior scopes [32, 34], confirming urban block-scale morphology as a critical DS performance determinant.

This study systematically analyzed ESP variations across neighborhoods through DS implementations. Hangzhou' s optimal case achieved 6.79% ESR enhancement versus 0.50% in the least effective scenario (Figure 9 [Figure 9: see original paper]). Diverging from generalized retrofitting approaches [48] that overlook morphological complexity, our spatial characteristic-driven framework enables precision energy interventions tailored to urban block configurations.

Figure 9. (a) Case with the highest ESR, Type 2 RN; (b) case with the lowest

ESR, Type 3 RN.

Furthermore, the findings underscore the necessity of developing architecture-technology integrated DS strategies that address morphological specificity, crucial for mitigating energy-saving performance variability induced by urban spatial heterogeneity.

This insight significantly advances urban renewal frameworks by establishing cluster-scale retrofitting protocols that synchronize DS optimization with neighborhood morphological patterns, thereby operationalizing the integration of resilience with sustainability in climate-adaptive design. While confirming urban spatial morphology’ s critical influence on DS technological efficacy, the study highlights the imperative for future research to reconcile energy efficiency objectives with multi-criteria retrofitting requirements - particularly through synergistic integration of thermal resilience enhancement, visual design coherence, and sustainable technology implementation, ultimately fostering holistic urban regeneration paradigms.

4.2. Synergistic Design Considering Both Morphology and Space

DS technology is traditionally considered a micro-scale approach for enhancing building energy efficiency, primarily applied to individual structures [5]. However, as implementations expand to building clusters or urban areas, its mechanisms and impacts extend beyond buildings, intertwining with urban morphology, BD, and neighborhood environments [47].

This cross-scale interaction introduces complexities in energy savings, spatial experiences, and cost-benefit dynamics, positioning DS not merely as a building-level solution but as a critical factor influencing urban energy systems and spatial quality.

Future research should develop multi-scale frameworks integrating architecture-technology synergies across urban systems, combining dynamic simulations with AI analytics (e.g., deep learning) to optimize climate-adaptive strategies. This requires concurrent advancements in life-cycle management, cost-benefit analysis, and policy alignment to embed resilience-sustainability principles into urban renewal. Such systemic integration establishes synergies among energy innovations, urban morphology intelligence, and resilience-enhanced sustainability frameworks, advancing built environments that holistically balance operational efficiency, emission reduction, and socioeconomic viability. This paradigm shift critically informs urban renewal planning through architecture-technology systems that institutionalize climate resilience within sustainable regeneration practices.

4.3. Significance for Urban Renewal Planning and Management

This study used GIS technology to visualize and label RNs with different ESPs, providing crucial support for urban renewal planning and decision-making. In the Figure 10 [Figure 10: see original paper], neighborhoods with varying ESPs are distinguished by different colors, which helps urban planners to quickly identify potential neighborhoods for dynamic facade renewal. This analytical method accelerates the selection of neighborhoods for energy-saving renewal during urban renewal and provides data support for the rational planning of facade designs. The Figure shows that high-ESP neighborhoods (red) in Hangzhou are concentrated along the river and in newly built RNs in the northwest, accounting for approximately 20% of the total neighborhoods. These neighborhoods, with high building floors and low building densities, have substantial potential for energy savings. Medium-ESP neighborhoods (yellow) are more dispersed, accounting for approximately 30–40%, and are mainly located on the city' s outskirts. Low-ESP neighborhoods (green) are concentrated in high-density neighborhoods in the city center, accounting for approximately 40–50%.

In renewal project planning, high-potential neighborhoods can be prioritized for transformation to achieve significant energy-saving benefits.

The methodology prioritizes facade renewal zones through systematic ESP classification: high-ESP RNs merit urgent retrofits for maximal energy returns, while medium/low-ESP areas suggest phased upgrades dependent on technical-economic feasibility. This geospatial-energy integrated framework enhances urban governance precision, guiding targeted facade redesigns to concurrently improve building operational efficiency and occupant comfort.

Figure 10. ESP classification of existing neighborhoods in typical city (Hangzhou).

4.4. Limitations

First, this study focused on typical cities in China with limited sample size. And its simulation model adopted simplified assumptions (not fully considering dynamic building usage and extreme climate scenarios), leading to conclusions limited by specific geographic and climatic characteristics. Future research should include comparative analyses of building performances across diverse climate zones and building types to enhance the universality and applicability of the conclusions.

Second, categorized RNs were used in the multi-objective optimization process; this may lead to discrepancies between the experimental data and real RNs. Future studies should consider more realistic data and scenarios to improve the credibility and reliability of the results of this study.

Third, this study relied solely on simulations without physical experiments or high-fidelity field validation. The model' s accuracy remains unvalidated against real-world conditions. Given the complexity introduced by inter-building shading, thermal bridging, and the dynamic control of the DLs, physical or high-fidelity field validation would be good for model calibration.

Finally, the promotion of DS systems depends on their energy-saving benefits, economic feasibility, and market acceptance.

This study lacks quantitative economic evaluation—despite multi-objective optimization yielding energy consumption and louver quantity data, it omits life-cycle cost analysis (LCCA) and payback period estimation, limiting conclusions' direct guidance for engineering and policy. Future research should integrate LCCA, assess payback periods, and survey residents' acceptance to optimize promotion strategies.

5. Conclusions

This study analyzed RNs in two climatically distinct Chinese cities, integrating computational modeling, simulation, and optimization to assess how urban street morphology influences the ESP of daylighting layer shading systems. By developing and validating optimized design strategies, the work establishes a scientific foundation and strategic guidelines for energy-efficient urban renewal. Key findings include:

There is a significant correlation between urban morphology and ESP. In Hangzhou, morphological characteristics such as APR (r = 0.37), SF (r = -0.55) and BD (r = -0.48), directly influence the energy-saving effect of DL shading. In Beijing, the morphological characteristics affecting DS ESP included APR (r = 0.61), SF (r = -0.67), FAR (r = 0.22) . Understanding these aspects can help designers distinguish the expected renovation effects based on residential community morphology.

Climate governs urban energy dynamics: Hangzhou reduces cooling energy 22-25% via optimized shading; Beijing' s DS increase winter heating, requiring more delicate climate-responsive technology integration to improve the ESP for different climate zones.

For economic efficiency and energy-saving performance, the placement of shading devices is a key factor that designers need to take into account. The optimization results show that 50% south and 25% west facade DL coverage ratio in Hangzhou boost ESP through cooling reduction while maintaining solar access.

Based on the preliminary conclusions of this study, different residential communities can be classified and managed in energy-saving renovation planning: taking Hangzhou as example, 20% high (riverine/northwest areas), 30-40% medium, and 40-50% low in central zones, guiding climate-tech integration with urban fabric.

Abbreviations The following abbreviations are used in this manuscript:

Dynamic shading No-shading Dynamic louver Residential neighborhood Energy-saving potential Window-to-wall ratio Number of buildings Building density, % Floor area ratio H_{ave} Average building height, m Shape factor. Ratio of building surface area to volume, m-1 Area-to-perimeter ratio. Ratio of the total building footprint area to the total perimeter of the standard floor within the site, m Scattered degree. The difference between the maximum building height and the average height within the site, m Building envelope surface area ratio. The ratio of the total building surface area to the land area on the site.

Open space ratio. The ratio of outdoor open space area to the total building area on the site Land shape index. The ratio of land area to the perimeter of the site, m Energy-saving rate

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Note: Figure translations are in progress. See original paper for figures.