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Multi-Objective Optimization for Energy, Comfort, and Daylighting in High-Rise Residential Buildings

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Abstract

This study addresses the multi-objective conflicts in daylighting, thermal comfort, and energy efficiency inherent in balcony design for high-rise residential buildings. A climate-responsive synergistic optimization framework is proposed, integrating parametric modeling and multi-objective genetic algorithms to systematically analyze the coupled effects of balcony design parameters—including window-to-wall ratio (WWR), shading depth, and thermal properties of building envelopes—across diverse climatic zones (cold, tropical, and hot-summer/cold-winter regions). Key findings reveal: In cold regions (e.g., Xining), enhanced insulation ($U \leq 0.35$ W/m^{2}K) is critical, with glazed door width ($ST = 0.61$) dominating heat gain/loss balance. Tropical regions (e.g., Singapore) require synergistic shading depth ($ST = 0.58$) and ventilation; 0.5m horizontal overhangs with vertical louvers reduce radiant heat gain by 34%. Adjustable shading components in hot-summer/cold-winter zones (e.g., Changsha) reduce annual severe overheating hours (sGA) by 65% while maintaining daylight sufficiency (sDA ≥ 55%), demonstrating feasible tri-performance synergy (thermal-daylight-energy). A rapid assessment tool integrating Building Information Modeling (BIM) and machine learning algorithms is developed, providing theoretical and practical pathways for low-carbon retrofits in high-density urban residential contexts.

Keywords

Multi-objective Optimization; Thermal-Daylight-energy Synergy; Climate-Responsive Design; Passive Design Strategies; High-Rise Residential Buildings.

1. Introduction

The building sector, accounting for approximately 30% of global final energy consumption (Chen et al., 2021), represents a critical domain for energy use and carbon emissions. Under the dual pressures of carbon neutrality goals and intensifying extreme climates, passive design strategies have emerged as a core pathway to reduce operational energy consumption in buildings. Balconies, serving as transitional spaces within the building envelope, integrate multiple functions—including solar shading, heat collection, ventilation buffering, and spatial expansion—and are increasingly recognized as key elements for enhancing building sustainability (Loche et al., 2024). Empirical studies demonstrate that optimizing balcony design parameters (e.g., depth, orientation, envelope construction) significantly improves comprehensive building performance: in hot-summer/cold-winter regions, south-facing balconies with a 2.1 m depth reduce summer cooling loads by 12.3% (Yang and Li, 2021), while enclosed balconies in severe cold regions reduce winter heat loss by up to 29% (Wang, 2025). However, balcony design involves complex multi-objective trade-offs—increased depth enhances shading but may compromise natural daylighting (Loche et al., 2024), and glazed railings improve daylight penetration but exacerbate thermal bridging effects (Grudzińska, 2020). These performance trade-offs vary markedly across climate zones, necessitating systematic research to clarify parameter-performance relationships.

This study investigates the integrated impact of balcony design parameters on building energy efficiency, thermal comfort, and daylight performance. We establish a comprehensive framework covering geometric parameters (depth, aspect ratio), construction parameters (railing type, glazed door configuration), and spatial parameters (layout, orientation) (Loche et al., 2024; Wang, 2025). Research objectives include: (1) Integrating empirical data from multiple climate zones (severe cold, cold, hot-summer/cold-winter, subtropical) to quantify parameter sensitivity; (2) Proposing climate-responsive design guidelines and algorithmic optimization frameworks; (3) Identifying research gaps (e.g., insufficient long-term performance monitoring) and future directions (e.g., aging-adaptive design) (Li et al., 2024). Performance evaluation spans three dimensions: Measured via heating/cooling loads (kWh/m^2); Analyzed using PMV-PPD models and adaptive theory; Evaluated via spatial daylight autonomy (sDA$_{300/50\%}$) and daylight glare probability (DGP) (Hilliaho et al., 2016).

2. Theoretical Framework and Performance Correlation Mechanisms

As transitional interfaces between indoor and outdoor environments, balconies enable systematic enhancement of building performance through parametric design. This study constructs a three-dimensional theoretical framework—"Design Parameter Layer → Performance Objective Layer → Regulation Mechanism Layer"—to elucidate causal relationships between parameters and performance from an interdisciplinary perspective.

2.1. Design Parameter Layer

This layer encompasses three core elements: geometric morphology, construction attributes, and interface relationships.

Geometric morphology parameters (e.g., balcony depth, width, depth-to-length ratio (A/L); Figure 1) directly determine shading efficiency and daylight penetration (Lefoche et al., 2024). Empirical studies show that balconies with 1.5–2.0 m depths reduce cooling energy use by 28% in subtropical climates (Yang et al., 2021), while depths >2.5 m attenuate daylight factors by 40% (Zheng et al., 2021).

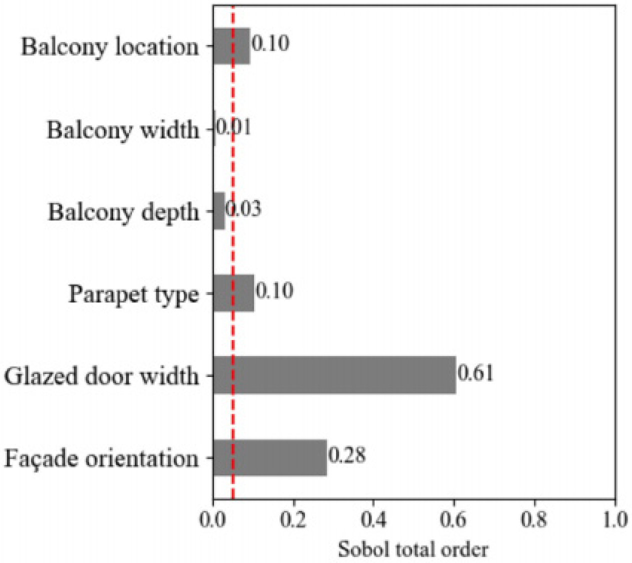

Figure 1. Daylight availability (sDA) (Loche et al., 2024)

Construction attributes include thermal properties of envelopes (U-value), visible transmittance (VT) of glazed doors, and railing types (glazed/opaque), significantly influencing heat gain and visual connectivity. For instance, glazed railings improve visual comfort (sGA) by 0.12 but increase summer overheating risks (Elgohary et al., 2015).

Interface relationship parameters (e.g., window-to-wall ratio (WWR), façade orientation, floor height) regulate solar radiation intake and microclimate. South-facing balconies in temperate winters can achieve triple the radiant heat gain of north-facing ones (Grudzińska, 2020), while high-rise balconies enhance ventilation efficiency due to increased wind velocity (Mohamed et al., 2014).

2.2. Performance Objective Layer

This layer focuses on three target dimensions: thermal environment, light environment, and energy efficiency.

Thermal environment performance is characterized by operative temperature (T_{op}) and predicted percentage dissatisfied (PPD). Balconies' thermal buffering reduces adjacent-room HVAC loads by 13.5% (Pang and Yang, 2023), but excessive enclosure may induce greenhouse effects (Ribeiro et al., 2020).

Light environment performance is evaluated via spatial daylight autonomy (sDA) and glare probability (sGA). When WWR > 60%, sDA can reach 75%, but requires horizontal shading to suppress direct glare (Abd-Alhamid et al., 2023).

Energy efficiency performance manifests as air-conditioning usage (ACU) and photovoltaic (PV) integration potential. For example, east/west-facing balconies with 5 m-wide PV glazed doors reduce cooling energy use by 48% (Xiang and Matusiak, 2022).

2.3. Regulation Mechanism Layer

This layer deciphers nonlinear parameter-performance relationships. **Climate-responsive mechanisms** emphasize synergistic design of balcony depth and shading elements to balance daylighting and heat dissipation in humid-hot climates (Omrani et al., 2017). In Singaporean HDB housing, 0.5 m overhangs with vertical louvers increase useful daylight illuminance ($UDI_{100–2000\ lx}$) compliance by 20% (Gamero-Salinas et al., 2021).

Multi-objective optimization mechanisms resolve parameter conflicts via sensitivity analysis. Sobol indices indicate that glazed door width ($S_T = 0.61$) and orientation ($S_T = 0.28$) contribute more significantly to daylight performance than balcony position ($S_T = 0.10$) (Lefoche et al., 2024).

Human behavior feedback mechanisms drive modular configurations: integrated housekeeping-drying-greening modules increase balcony space utilization by 35%, while smart shading systems reduce summer radiant heat gain by 29% (Pang and Yang, 2023).

3. Multi-Climate Zone Empirical Research

3.1. Performance Response Patterns in Cold Climates

In severe cold and cold climate zones (e.g., Xining, Harbin), balcony design prioritizes winter heat gain and thermal insulation. Field measurements in Xining high-rise residences (Wang, 2025) demonstrate that a 1.5 m-deep balcony with high-transmittance glazing (VT = 0.78) elevates south-facing room sDA to 65%, but requires WWR ≤ 45% to mitigate nocturnal heat loss. Enclosed balconies in Harbin (Liu et al., 2020) equipped with double Low-E glazing ($U = 1.2\ \mathrm{W/m^2K}$) and insulated walls ($U = 0.35\ \mathrm{W/m^2K}$) reduce heating loads by 29%, yet exhibit temperature fluctuations of 8.3°C (−12.5 to −4.2°C), necessitating PCM buffer layers (Wang et al., 2023). Sobol sensitivity analysis reveals that glazed door width ($S_T = 0.52$) and envelope U-value ($S_T = 0.41$) significantly outweigh balcony depth ($S_T = 0.22$) in energy efficiency impact (Lefoche et al., 2024).

3.2. Performance Balancing Mechanisms in Hot-Summer/Cold-Winter Zones

Regions like Changsha and Shanghai require seasonal demand coordination (Figure 2). Changsha studies (Yang et al., 2021) confirm that south-facing 2.1 m-deep balconies reduce summer cooling loads by 12.3%, but contribute only 7.8% to winter radiant heat gain. Adjustable shading components (e.g., retractable louvers) lower sGA from 0.35 to 0.12 while maintaining sDA ≥ 55% (Zheng et al., 2021). Modular testing in Shanghai (Pang and Yang, 2023) shows integrated housekeeping-greening modules improve space utilization by 35%, but risk obstructing ventilation paths (18% efficiency reduction). Core conflicts include: increased depth enhances summer shading (Q_{diff} reduced by 37 W/m^2) yet attenuates winter sDA by 22% (Gamero-Salinas et al., 2021).

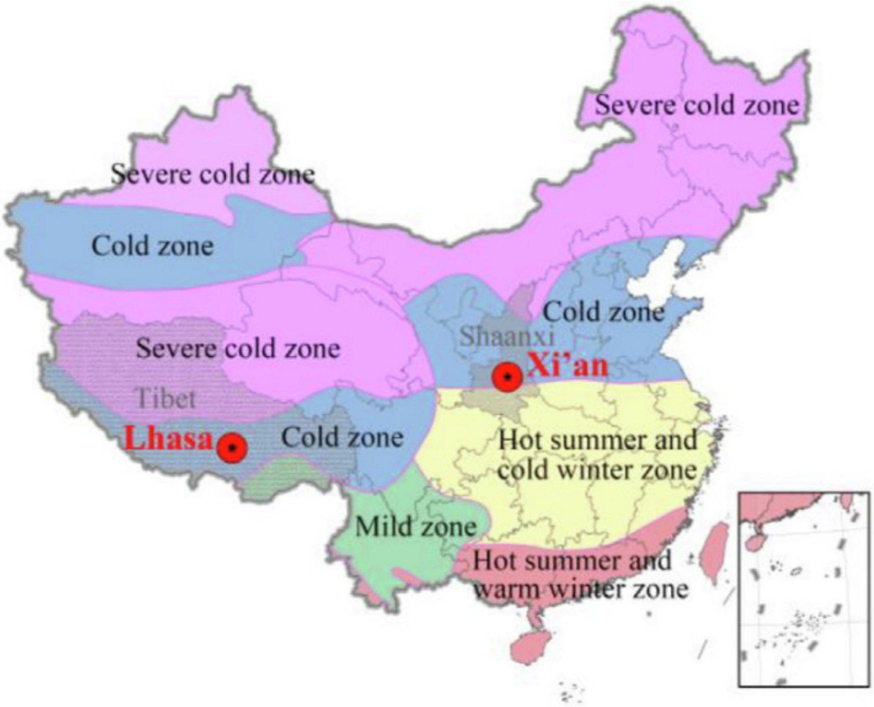

Figure 2. Distribution map of China's climate zones (Zhang et al., 2022)

3.3. Ventilation-Shading Synergy in Tropical Climates

Humid-hot zones (e.g., Singapore, Guangzhou) prioritize heat dissipation and glare control. Singapore HDB measurements (Gamero-Salinas et al., 2021) indicate that 0.5 m horizontal overhangs with 50%-porosity vertical louvers increase $\mathrm{UDI}_{100\text{–}2000\ \mathrm{lx}}$ compliance by 20% while reducing radiant heat gain by 34%. Balcony position critically alters wind environments—30th-floor balconies exhibit 2.8 m/s higher wind speeds and 40% greater air change rates than 5th-floor counterparts (Mohamed et al., 2014). Guangzhou simulations (Lefoche et al., 2024) show that serrated-planar west-facing balconies (30° protrusions) reduce high-glaze probability (DGP > 0.35) from 45% to 18%, albeit sacrificing 5% daylight uniformity.

3.4. Cross-Climate Parameter Sensitivity Comparison

Sobol global sensitivity analysis reveals climate-dependent parameter contributions (Table 1): **Glazed door width**: $S_T = 0.61$ (dominant in heating/cooling balance) in cold climates vs. 0.42 (ventilation/daylight influence) in tropics; **Balcony depth**: $S_T = 0.58$ (core shading parameter) in tropics vs. 0.19 in cold climates; **Envelope U-value**: $S_T = 0.53$ in cold climates vs. 0.08 in tropics (insulation demand weakened by cooling dominance); **Railing type**: Universal $S_T \approx$ 0.12–0.15 across climates due to consistent visual connectivity requirements.

Table 1. Comparison of Sensitivity Indices for Balcony Parameters Across Multiple Climate Zones

Parameter	Severe Cold Climate (ST)	Hot Summer and Cold Winter Climate (ST)	Tropical Climate (ST)
Glazed door width	0.61	0.49	0.42
Balcony depth	0.19	0.38	0.58
Building envelope U-value	0.53	0.31	0.08
Parapet type	0.15	0.13	0.12
Facade orientation	0.47	0.29	0.35

4. Optimization Strategies

4.1. Parametric Design Strategies

Balcony design requires synergistic optimization of geometric parameters (depth, width, position), thermal properties (glazing type, shading coefficient), and layout parameters (orientation, floor height, WWR). Studies show that depth-glazing interactions critically affect thermal comfort and energy efficiency. For example, Loche et al. (2024) demonstrated that 3 m-wide glazed doors with 2 m-deep balconies in subtropical mixed-mode offices improve visual comfort while reducing HVAC energy by 28%. Railing transparency should align with room depth: transparent railings benefit shallow rooms (≤5.5 m) for daylight enhancement, whereas opaque railings reduce glare in deep rooms (≥7 m) (Loche et al., 2024).

Climate-adaptive strategies diverge significantly: **Severe cold zones** (e.g., Harbin): South-facing balconies require enhanced insulation and WWR ≤ 0.6 to balance heating demands and daylight access (Ma and Zhang, 2023). **Hot-summer/cold-winter zones** (e.g., Changsha): Horizontal shading ≥500 mm projection reduces summer cooling loads by 20% (Li et al., 2023).

4.2. Multi-Objective Optimization Algorithms

Conflicting objectives—daylight utilization (sDA), thermal comfort (PMV/PPD), energy efficiency (EUI)—necessitate advanced algorithms. NSGA-II efficiently generates Pareto-optimal solutions, e.g., Zhou et al. (2023) optimized WWR and balcony depth in high-rises to increase sDA by 16.56% while lowering energy use by 22%. Sensitivity analysis identifies critical parameters: glazed door width dominates daylight performance (S_T = 0.61), while orientation contributes >70% to thermal gains (Loche et al., 2024).

Cross-analysis quantifies parameter interactions: east/west balconies on short-axis façades (7 m rooms) improve visual comfort by 10% through low-angle solar protection (Loche et al., 2024). Algorithm-driven frameworks (e.g., Rhino/Grasshopper) enable rapid solution generation, with TOPSIS models selecting holistic optima (Li et al., 2023).

4.3. AI and Data-Driven Methods

Machine learning enhances predictive accuracy: Random forests forecast balcony temperature distributions (RMSE = 0.8°C) using historical data (Grudzińska, 2021). Deep reinforcement learning (DRL) dynamically controls shading angles, reducing lighting energy by 15% through daylight-heat gain equilibrium (Taser et al., 2023). Generative adversarial networks (GANs) create balcony layouts that maximize PV irradiation while maintaining wind comfort (<2 m/s) in low-density urban blocks (Kabosova et al., 2022). Data-driven workflows (e.g., Ladybug+Honeybee) integrate climate data and performance simulation for rapid iteration (Omrani et al., 2017).

4.4. Practical Applications and Validation

Engineering validation is critical: Prefabricated balcony systems enable modular configurations (base, optional, add-on modules). Housekeeping-greening composites increase space utilization by 40%, while smart shading cuts summer overheating duration by 30% (Pang and Yang, 2023). Wind tunnel tests and CFD simulations verify extreme climate adaptability. Generalized extreme value (GEV) distributions accurately model peak wind pressures on solar collectors at 55° tilt angles (Mao et al. (Mao Dan), 2023). Field monitoring confirms algorithmic efficacy: optimized temperature correction coefficients ($\alpha = 0.5$) in Xining reduce heating load deviation from 22% to 5% (Ma and Zhang, 2023).

5. Challenges and Future Directions

5.1. Technical Challenges

Multi-objective optimization conflicts represent the core challenge in balcony design. Balconies must simultaneously fulfill daylighting, thermal comfort, ventilation, and energy efficiency goals, yet parametric adjustments often trigger trade-offs. For instance, increasing WWR enhances daylight but exacerbates heating/cooling loads (Fang and Cho, 2019), while shading optimizations may impede natural ventilation (Liu et al., 2020). Furthermore, inadequate climate change adaptability exposes limitations in current models. Most studies rely on static climate data, overlooking long-term warming impacts on building thermal performance (Dosio et al., 2018). Projections indicate a 3–4°C global temperature rise by 2050 (IPCC, 2023), yet few balcony thermal designs incorporate such dynamic variables (Chen et al., 2021b).

Complex system modeling also constrains precision. Integrating BIPV or hybrid ventilation systems requires coupling Building Energy Modeling (BEM) with CFD simulations, but multi-scale modeling incurs high computational costs and error propagation risks (Liang and Xiang, 2024). For example, energy yield of adaptive PV façades is highly sensitive to local shading and orientation, yet existing tools struggle to quantify self-shading effects on curved structures (Shi et al., 2022).

5.2. Socioeconomic Challenges

Cost-benefit imbalances hinder technology adoption. High initial investments in advanced materials (e.g., PCM glazing) and smart controls (e.g., MPC) face weak market incentives due to insufficient policy support (Otasowie et al., 2022). South African construction case studies show <20% utilization of circular economy materials without subsidies (Aigbavboa et al., 2021). User behavior uncertainty further complicates design—elderly adaptive behaviors (e.g., window-opening frequency) are influenced by health status and cultural habits, but predictive models fail to integrate these variables effectively (Lee et al., 2023).

5.3. Interdisciplinary Collaboration Needs

Future research demands strengthened cross-disciplinary integration. Collaborations among architecture, environmental engineering, and social sciences can break down technical silos. Real-time monitoring of occupant thermal feedback (e.g., via wearables) enables dynamic shading angle adjustments (Huang et al., 2023). Aligning with the EU's "Renovation of 35 Million Building Units" initiative (Cuffe, 2023), subsidy-certification linkage mechanisms for balcony retrofits should be established. Combining drone IR thermography with machine learning allows rapid thermal bridge identification and insulation optimization (Videras Rodríguez et al., 2021).

6. Conclusion

This study synthesizes empirical multi-climate data and algorithmic optimization frameworks to systematically reveal balcony design parameter-performance relationships, yielding the following conclusions:

Cold climates (e.g., Xining): Prioritize insulation ($U \leq 0.35$ W/m^{2}K), with glazed door width ($S_T = 0.61$) dominating heat gain/loss.

Tropical climates (e.g., Singapore): Rely on shading depth ($S_T = 0.58$) and ventilation synergy; 0.5 m overhangs with vertical louvers reduce radiant heat gain by 34%.

Hot-summer/cold-winter zones (e.g., Changsha): Balance seasonal conflicts; adjustable shading components lower sGA by 65% while maintaining sDA ≥ 55%.

Balcony design is transitioning from experience-based to data-driven paradigms. Future efforts must deepen convergence among building science, environmental engineering, and social sciences. Through three-dimensional synergy—climate-responsive algorithm libraries, low-cost prefabrication technologies, and policy-financial instruments—we can achieve sustainable building transformation characterized by **quantifiable performance, scalable technology, and user engagement**.

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