Optimizing Morphological Design in High-Density Residences in Hong Kong to Enhance Mental Health

Zijun Wang
School of Landscape Architecture, Beijing Forestry University, China

Keyword: High-Density Urban Living, Mental Well-Being, Urban Morphology, Visual Exposure, Thermal Comfort, Wallacei Optimization.

Abstract: This study addresses the challenges of enhancing mental well-being in high-density residential environments, with a specific focus on Hong Kong. Employing a 3D model in Rhino and parametric design in Grasshopper, we used the Wallacei plugin for multi-objective optimization to balance four critical factors—visual exposure, direct sun hours, Universal Thermal Climate Index (UTCI) standard deviation, and building volume—across four building typologies: East-West oriented dot-and-row forms, North-South oriented dot-and-row forms, crossing layouts, and loop-shaped layouts. This process generated six locally optimal configurations for each typology. We then examined how variations in building morphology and street configurations influenced these factors and, in turn, emotional responses. The results indicate that wider streets and a greater number of street intersections enhance visual emotional impact, while narrower streets yield a lower UTCI standard deviation, thereby improving thermal comfort. Typological differences underscore the need for context-specific design strategies to balance these factors. Our findings provide insights for optimizing building configurations to promote emotional well-being in high-density urban settings.

1 INTRODUCTION

1.1 Context

High-density urban living, especially in cities such as Hong Kong, poses unique challenges to mental well-being owing to limited open spaces, extreme urban density, and various environmental stressors. (Wong et al., 2016).

A growing body of research has examined the relationship between urban environmental factors—such as visual exposure, greenery, and thermal comfort—and mental health. Building on this foundation, the present study explores the specific impact of building typologies and morphology on mental well-being in high-density environments.

1.2 Research Gap

Although prior studies have examined the influence of urban morphology on microclimates and energy efficiency, there is a paucity of research on using morphological designs to balance key factors—such as visual exposure, sunlight exposure, thermal comfort, and residential density—relative to mental health in high-density residential areas.

1.3 Research Aim

The primary aim of this research is to use parametric modeling to control building morphologies and street configurations, evaluating the combined impact of different morphologies across various typologies on visual and thermal exposure—factors that directly affect environmental comfort.

The ultimate goal is to enhance mental health in high-density urban settings.

1.4 Framework

The framework of the study is as follows: after the introduction, the second section will provide a literature review covering four key areas relevant to the study. The methodology follows, consisting of three steps: parametric modeling, environmental simulation, and multi-objective optimization.

In the parametric modeling step, four building typologies will be parameterized. The primary decision variables that influence these typologies will

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be defined, and relevant constraints—such as dimensional limits and design features—will be identified for each variable.

For environmental indicators simulation and quantification, the Isovist plugin in Grasshopper will first be used to generate five visual exposure metrics for each layout, while Ladybug will be employed to calculate thermal metrics. Basic operations will also be performed to determine the overall volume. Notably, a mathematical model will establish the relationship between visual metrics and visual emotional value, while thermal metrics and volume will serve as direct optimization objectives.

The key step, multi-objective optimization, will utilize the Wallacei multi-objective optimization tool, incorporating the NSGA-II (Non-dominated Sorting Genetic Algorithm II). This tool will balance environmental indicators and identify configurations that maximize positive mental health outcomes. Simulations will be conducted for each building typology, yielding six representative locally optimal solutions per typology. A post-hoc analysis will then be performed on these solutions within each building type, uncovering consistent findings. Last by not least, a conceptual approach to exploring the improvement saturation effect will be proposed, which could be used for further investigation in the future.

2 LITERATURE REVIEW

2.1 Mental Health and Urban Density

Urban living and city-based upbringing affect human neural responses to social stress. (Lederbogen et al., 2011). Crowding, noise, and prolonged exposure to dense environments further exacerbate stress and anxiety (Tost et al., 2015).

Urban planning increasingly focuses on enhancing visual and thermal comfort to mitigate these stressors (Liu et al., 2024).Urban parks, for example, enhance visual openness and regulate local climates in dense settings (Chiesura, 2004), while abundant greenery aids stress recovery (Ulrich et al., 1991) and improves overall emotional well-being (Xiang et al., 2021), particularly benefiting older adults (Luo et al., 2024). These findings align with the concept of “affective atmospheres,” which suggests that urban green spaces optimized for visual and thermal comfort can effectively reduce stress (Deitz et al., 2018).

However, integrating green spaces often conflicts with the demand for additional living areas in high-density cities, such as Hong Kong. This trade-off necessitates alternative strategies, such as optimizing building morphologies and street layouts.

2.2 Visual Exposure and Emotion

Visual exposure plays a key role in emotional well-being in dense urban environments.

Visual openness has been shown to reduce stress (Stamps, 2005), while individuals' perceptions of it significantly shape emotional responses (Yang et al., 2024). In addition, building forms influence visibility in crowded settings (Giseop et al., 2019); specifically, moderate building heights, combined with visible green spaces, enhance emotional comfort (Lindal et al., 2013). Together, these findings highlight the importance of designing urban spaces that enhance visibility to promote mental well-being.

2.3 Thermal Comfort and Emotion

Thermal comfort is critical for mental well-being, particularly in densely populated areas with limited climate control.

Specifically, open spaces and vegetation help improve thermal comfort by reducing the urban heat island effect (Wang et al., 2021), which in turn positively influences both physical and emotional well-being (Yan et al., 2023). Moreover, the configuration of streets and buildings is essential for thermal comfort: narrower streets and taller buildings provide shading that reduces direct sun exposure (Wang et al., 2023), while layouts that minimize temperature fluctuations further enhance comfort (Xu et al., 2019)

2.4 Quantification and Optimization

To optimize urban design for mental well-being, tools such as Rhino and Grasshopper, along with plug-ins like IsoVist, Ladybug, and Wallacei, are invaluable for balancing visual and thermal comfort in high-density settings.

IsoVist expands visibility analysis by capturing three-dimensional spatial relationships, helping to evaluate how building heights and layouts influence accessibility and psychological comfort. Originally developed for 2D analysis (Benedikt, 1979) and later enhanced for 3D relationships, IsoVist is now a key tool in assessing emotional well-being (Giseop et al., 2019).

Ladybug supports climate-based simulations to assess thermal comfort and sunlight exposure across urban layouts, allowing urban designers to refine their designs for improved environmental comfort (Wang et al., 2023).

Wallacei, a genetic algorithm, facilitates multi-objective optimization to enhance spatial efficiency (Xu et al., 2019). In our study, it plays a crucial role in balancing visual exposure, thermal comfort, and urban density in high-density urban environments.

3 METHODOLOGY

3.1 Site Selection

The experimental site is located in To Kwa Wan, Hong Kong, within a residential zone.

Figure 1: Site location.

Chosen for its redevelopment potential, the area features low-density buildings with large footprints that may be replaced by higher-density developments to improve housing capacity and environment. The site's layout comprises regular residential buildings arranged in long, parallel rows along narrow streets and alleys, typical of older urban districts in Hong Kong. With a low floor area ratio (FAR), extensive ground coverage, and minimal building height variation, the area provides an ideal setting for testing different building typologies and exploring how high-density redesigns can optimize visual exposure, thermal comfort, and living space to enhance residents' emotional well-being. The site location is shown in Figure 1.

3.2 Parametric Modeling

Hong Kong's high-density urban environment is characterized by four typical building typologies: East-West oriented dot-and-row forms, North-South oriented dot-and-row forms, crossing layouts, and loop-shaped layouts. To explore their design potential, these typologies were parameterized and simplified for testing. Figure 2 provides an example of the East-West oriented dot-and-row form, with key variables involved in parametric modeling including n (number of divisions along the east-west direction), m (number of divisions along the north-south direction), a (street width), b (alley width), and h (building height).

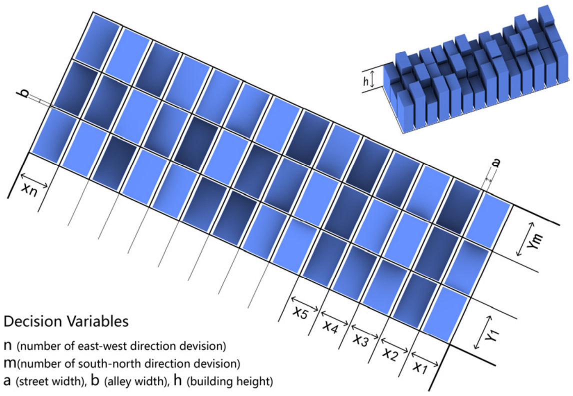


Figure 2: Five decision variables.

These five variables serve as the decision variables for the multi-objective optimization. The parameter constraints for these variables were derived from map distance calculations in Hong Kong and supported by relevant architectural research. The dimensional details are shown in Figure 3.

Type	Base Site Dimensions	n (number of east-west direction devision) (Building Length in East-West Direction)	m (number of south-north direction devision) (Building Length in South-North Direction)
Dot (Row Layout) East-West Axis	100 x 300 m	6 to 12 division (25-50 m)	4 to 6 divisions (15-25 m)
Dot (Row Layout) North-South Axis		12 to 20 divisions (15-25 m)	2 to 4 divisions (25-50 m)
Cross Layout		8 to 10 divisions (25-30 m)	3 to 4 divisions (25-30 m)
Loop Layout		5 to 8 divisions (30-50 m)	2 to 3 divisions (30-50 m)

Type	a (Street Width)	b (Alley Width)	h (Building Height)	Other Dimensions
Dot (Row Layout) East-West Axis	4-16 m	2-6 m	50-100 m	/
Dot (Row Layout) North-South Axis	4-16 m	2-6 m	50-100 m	/
Cross Layout	8-12 m	2-6 m	50-125 m	Narrow side width range: 10-16 m
Loop Layout	8-12 m	4-8 m	50-125 m	Courtyard range: 0.25–0.5L (L=building's exterior length/width)

Figure 3: Parameter constraints.

3.3 Visual Exposure Metrics

Visual exposure was analyzed using the IsoVist plug-in in Grasshopper, enabling both 2D and 3D isovist calculations to simulate visibility across the experimental site. The goal was to understand how different building forms, along with variations in street and alley dimensions, affect the visual experience of residents in a high-density setting.

2D Isovist Calculations: The 2D analysis involved placing observation points uniformly across the site, excluding building interiors to focus solely on the external visual experience. This approach ensured comprehensive coverage of the experimental area, enabling the calculation of average visibility in terms of ground-level access to streets and open spaces. Using the IsoVist 2D tool, three key metrics—drift magnitude, mean radial, and compactness—were generated to support the subsequent Emotional Value Calculation. The results of the 2D Isovist calculations are shown in Figure 4.

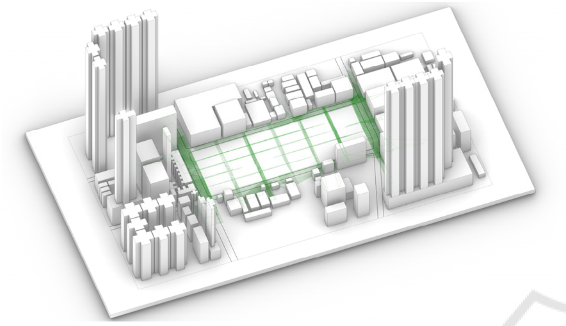


Figure 4: 2D Isovist Calculations

3D Isovist Calculations: For the 3D spatial analysis, four key observation points were selected to capture diverse visibility perspectives within the dense residential layout. In high-density areas with tall, closely packed buildings, street-level visibility is often limited to nearby structures; therefore, the four central points are representative of most viewing angles. This strategy ensures a balanced assessment while optimizing computational efficiency. The four observation points are shown in the figure 5.

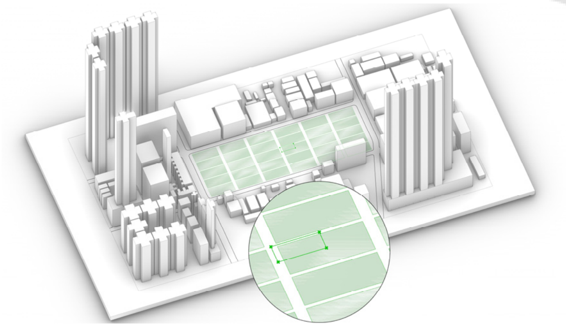


Figure 5: Four observation points for 3D.

The four points include: street-alley intersection, street midpoint, alley midpoint and building center.

When the building layout changes, the street–alley intersection point can be replaced with the midpoint of the building's interior. This adjustment ensures that observation points remain consistent and adaptable, as both serve as diagonal anchors within a rectangular layout, preserving their role throughout the analysis. For each layout type, the 3D visual exposure score is calculated as the average of the values from all four observation points, regardless of building type. This approach ensures a consistent basis for comparing different layouts. For loop-shaped layouts with courtyards, the interior point adds a unique visibility perspective, enabling an evaluation of how the courtyard influences overall visibility compared to layouts with more restricted internal sightlines.

Building on this, 3D Isovist analysis calculates two supplementary metrics—3D object proportion and 3D visual volume—to further quantify visibility.

Figures 6 and 7 illustrate the 3D IsoVist visibility and effective collision points.

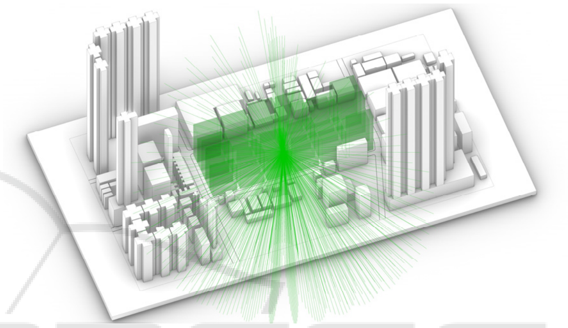


Figure 6: 3D IsoVist visibility.

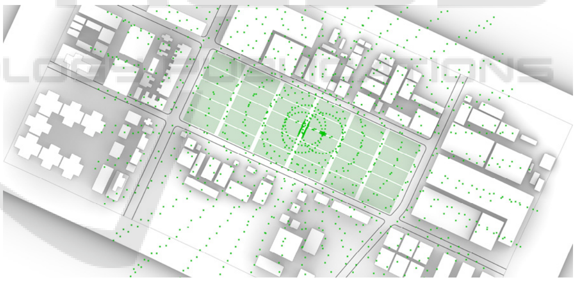


Figure 7: Effective collision points.

The emotional value, derived from these visibility parameters, was calculated using an existing Multiple Linear Regression (MLR) model developed by Xiang et al. This model estimates emotional responses to visual exposure by linking isovist parameters to psychological comfort based on environmental psychology studies. The MLR coefficients for each parameter were applied to compute the overall visual comfort score.

$$Y=1/n\sum_{i=1}^{n}(0.528a_i-0.178b_i+0.29c_i-0.304d_i+0.461e_i)$$

n: total number of observation points randomly placed on the site, a: drift magnitude, b: mean radial, c: compactness, d: 3d object proportion, e: 3d visual volume

3.4 Thermal Comfort Metrics

Thermal comfort was assessed using two primary metrics: direct sunlight hours and the standard deviation of UTCI (Universal Thermal Climate Index). These metrics help quantify residents' thermal comfort in relation to the built environment and weather conditions, particularly important in a hot climate like Hong Kong.

Direct Sunlight Hours: The Ladybug plug-in in Grasshopper was used to simulate direct sunlight exposure on the site, incorporating the experimental buildings, surrounding structures, and local climate conditions. The simulation accounted for building heights and orientations (East-West and North-South) to estimate sunlight exposure for both the buildings and the streets. The site was divided into a 10-meter grid to balance precision with computational efficiency. By including outdoor spaces alongside building facades, the analysis aimed to capture thermal comfort across the entire neighborhood. The focus was on minimizing excessive sunlight exposure, which can significantly reduce thermal comfort in hot climates. Figures 8 illustrates the direct sunlight hours.

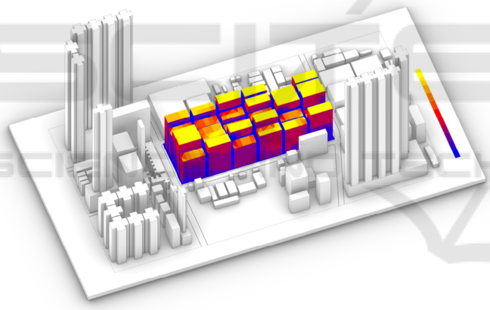


Figure 8: Direct Sunlight Hours.

UTCI Standard Deviation: The Universal Thermal Climate Index (UTCI) measures thermal comfort by accounting for factors like air temperature, humidity, and wind speed. In this study, the standard deviation of UTCI values was used to evaluate temperature variability across the site, prioritizing spatial consistency over average UTCI. Using the Ladybug plug-in in Grasshopper, the site was divided into a 5-meter grid, with UTCI values calculated for each grid cell to capture localized temperature variations in outdoor areas. This approach enabled a detailed analysis of how design elements—such as building dimensions, orientation, and spacing—affect thermal stability. Examining UTCI standard deviation helped identify areas prone to sudden temperature changes, offering insights into how design adjustments can promote stable outdoor thermal comfort. Figures 9 illustrates the UTCI standard deviation.

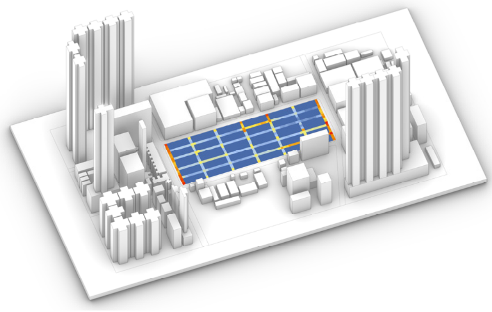


Figure 9: UTCI Standard Deviation.

3.5 Building Volume

The total building volume was calculated to reflect the density and massing of the proposed morphologies. As density is critical in urban planning, this metric was essential for balancing high-density residential needs with emotional well-being. Building volume for each morphology was determined based on height, footprint, and spatial configuration, ensuring that the designs met density requirements.

3.6 Optimization with Wallacei

Metrics for visual exposure, thermal comfort (direct sunlight and UTCI deviation), and building volume were calculated and optimized using the Wallacei plug-in. This tool employed a genetic algorithm to balance competing factors—visual access, thermal comfort, and building density—across four building typologies. The optimization process aimed to maximize visual exposure, minimize excessive sunlight, maintain stable thermal comfort, and achieve higher density.

4 EXPERIMENTAL RESULTS

4.1 Overview

Using Wallacei X, which integrates the built-in genetic algorithm with NSGA-II (Non-dominated Sorting Genetic Algorithm II), each of the four typologies underwent 15 generations, with 30 individuals per generation.

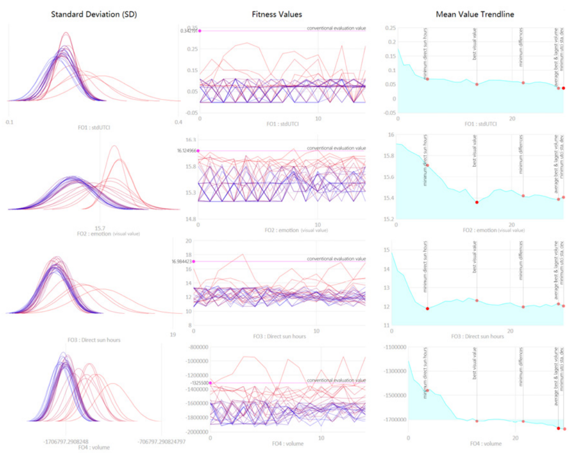
Taking the East-West Oriented Dot and Row form as an example (Figure 10), the first column illustrates the evolution of the curve from red (initial generations) to blue (subsequent generations), while the left-to-right progression indicates progressively better results.

The second column shows the changes in the values of each optimization objective, where the values decrease from red to blue, reflecting improved optimization outcomes. The conventional evaluation values are also annotated on the graph, demonstrating that the majority of optimized results are lower than the initial values, thus validating the effectiveness of the optimization.

The third column depicts the trend of the objective variables across generations, showing a gradual reduction, which further supports the success of the optimization process. Additionally, it also highlights the specific values of six outstanding individuals and the time they first appear.

Similarly, the other three typologies were also optimized, and six local optimal individuals were selected for each typology, including the Average Best, Minimum Difference, and the local optima for the four key criteria (Minimum UTCI Std. Dev., best visual emotion value, minimum direct sun hours, and largest volume). After obtaining the final shapes of the selected individuals, a preliminary analysis was conducted to explore the relationship between the individual shapes and the four indicators.

This analysis examined the impact of street (alley) width and number on visual exposure, UTCI standard deviation, and direct sunlight hours, as well as the influence of typology-specific differences on these factors. Additionally, the conventional building shapes and the corresponding evaluation values were also presented across all four groups of results to further validate the reliability of the optimization outcomes.



Note: The lower the value shown in the image, the better the corresponding indicator. The value of building volume should be converted to a positive number for practical use.

Figure 10: Result of the Wallacei genetic algorithm.

4.2 East-West Oriented Dot and Row

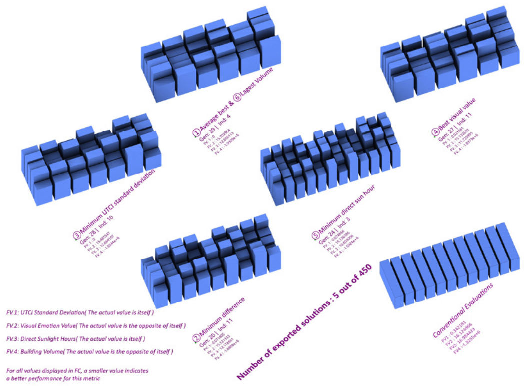


Figure 11: Local Optimal Solutions (Type 1).

Street Width Impact: Comparing configurations ① and ④, we find that with the same number of streets and alleys, wider streets improve the visual emotion value ($p<0.05$).

Number of Streets and Alleys: With consistent street width (①, ②, ③, ⑤), an increase in street count enhances the visual emotion value, indicating that a higher street density may promote emotional well-being.

Sunlight and UTCI: Consistent street width (①, ②, ③, ⑤) shows that more streets correlate with longer minimum direct sun hours, impacting thermal comfort. However, the effect on UTCI Std. Dev. is inconsistent.

Building Dimensions: With the same number of streets and alleys (① vs. ④), larger buildings mitigate direct sun exposure but increase UTCI Std. Dev.

All optimized results for the four indicators are below the conventional values, demonstrating the effectiveness of the optimization.

4.3 North-South Oriented Dot and Row

Street Width and Emotion Value: Similar to East-West forms, wider streets (④ vs. ⑤) enhance visual emotion value.

Street Count and Emotion Value: With consistent alley width, more streets increase visual emotion value, suggesting a positive relationship between urban density and emotional well-being.

Contradiction in UTCI: The negative effect of street width on UTCI Std. Dev. contradicts the findings from Experiment 1, highlighting the need for further investigation into this discrepancy.

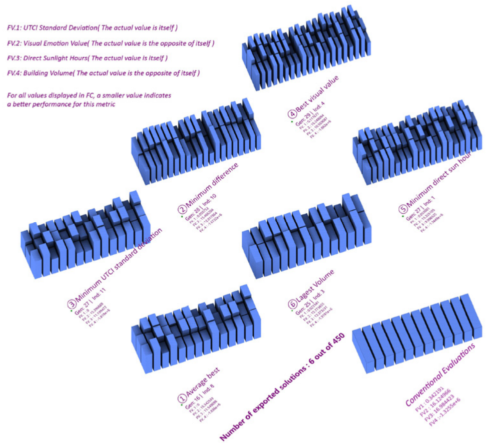


Figure 12: Local Optimal Solutions (Type 2).

4.4 Crossing Layouts

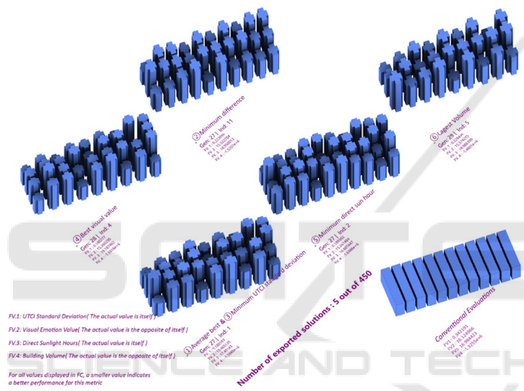


Figure 13: Local Optimal Solutions (Type 3).

Street Width and Visual Emotion: Wider streets (① vs. ④) improve visual emotion value, aligning with other layouts.

Street Count and Thermal Comfort: Increasing street count with consistent width improves direct sun exposure but has an inconsistent impact on UTCI Std. Dev.

Building Dimensions As observed in other layouts, larger buildings mitigate direct sun exposure but increase UTCI Std. Dev.

4.5 Loop-Shaped Layouts

Street Width and Emotion Value: Wider streets (① vs. ④) enhance visual emotion value.

Street Count and UTCI: An increase in street count positively affects UTCI Std. Dev., which contrasts with findings from other experiments, indicating a complex relationship.

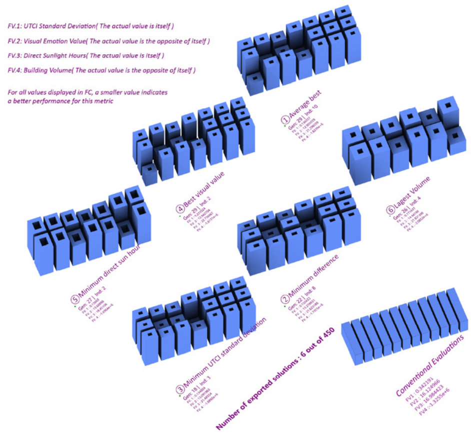


Figure 14: Local Optimal Solution (Type 4).

Atrium Scale Impact: Atrium scale has a more significant positive impact on visual emotion value than street count, suggesting the importance of open spaces in dense urban areas.

5 DISCUSSIONS

By comparing the six locally optimal solutions for each of the four building typologies, a clear pattern emerged: wider streets and higher street counts enhance visual emotion values, while narrower streets help stabilize UTCI Std. Dev., improving thermal comfort. Typology-specific differences were also noted. For example, loop-shaped layouts with atriums had a greater positive impact on visual emotion value than street count. These findings highlight the importance of adjusting designs for individual typologies while adhering to broader principles.

However, the results were validated only within a limited sample. To explore the potential thresholds of influence—such as when changes in decision variables lead to saturation—we propose further investigation. Wallacei genetic algorithm propagates optimal offspring, meaning that decision variables favorable to the objectives appear more frequently, concentrating high-quality solutions. We plan to analyze the optimization data to track variable frequencies. Preliminary analysis offers three key thresholds for further investigation: at what street widths and intersection counts do visual value improvements saturate, and at what widths does thermal comfort reach saturation? Given Wallacei's discrete selection method, we propose reclassifying street widths into smaller intervals (e.g., 0.5 meters) from 4 meters to 16 meters, resulting in 24 intervals. This approach will help track and compare the frequency of intervals, improving accuracy in identifying the ranges where saturation effects occur.

6 CONCLUSIONS

This study explored how optimizing building morphologies and street configurations improves mental well-being in high-density areas by balancing visual exposure, thermal comfort, and urban density. However, the study has limitations. The small dataset may limit generalizability, and the emotional value model (MLR) may not fully reflect local conditions. Additionally, the simplified parametric models and focus on Hong Kong may reduce applicability to other regions. Future research could address these limitations by exploring growth thresholds, expanding the dataset, refining the emotional value model, and incorporating more detailed urban representations to validate and extend the findings.

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