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High-Density Block Generation and ENVI-met Microclimate Evaluation Based on Pix2Pix GAN

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Abstract

Rapid urbanization has precipitated the development of high-density urban blocks, particularly in metropolitan regions facing land scarcity. While high-density living offers economic efficiency, it often exacerbates the Urban Heat Island effect and compromises outdoor thermal comfort. Traditional urban design methodologies, which rely heavily on manual iteration and intuition, struggle to balance the complex trade-offs between floor area maximization and microclimatic performance. This research proposes an automated generative design framework integrating a Conditional Generative Adversarial Network, specifically the Pix2Pix architecture, with ENVI-met microclimate simulation. By training the neural network on a dataset of existing high-density urban morphologies and their corresponding layout constraints, the model learns to generate realistic block typologies. Subsequently, these generated forms are subjected to Computational Fluid Dynamics simulations via ENVI-met to evaluate their thermodynamic and aerodynamic performance. The study demonstrates that the Pix2Pix model can successfully synthesize urban textures that adhere to spatial constraints while simulation results reveal specific morphological traits that enhance wind permeability and reduce thermal stress. This interdisciplinary approach bridges the gap between artificial intelligence and sustainable urban planning, offering a robust decision-support tool for architects and planners.

Keywords

Generative Adversarial Networks, Urban Microclimate, High-Density Housing, ENVI-met, Artificial Intelligence.

1 Introduction

The acceleration of global urbanization has led to a paradigm shift in city planning, emphasizing vertical expansion and increased building density to accommodate growing populations within limited geographical footprints. This phenomenon is particularly evident in East Asian metropolises, where high plot ratios are necessitated by economic and spatial constraints. However, the densification of the urban fabric fundamentally alters the surface energy balance and aerodynamic roughness of the city, frequently leading to the deterioration of the local microclimate [1]. The prevalence of deep street canyons and the reduction of vegetative cover contribute significantly to the Urban Heat Island effect, which impairs the livability of outdoor spaces and increases building energy consumption due to higher cooling loads [2]. Consequently, the optimization of urban block morphology to facilitate natural ventilation and solar regulation has become a critical objective in contemporary urban design. Traditionally, the design of high-density blocks relies on the tacit knowledge of architects and iterative manual adjustments. While simulation tools such as ENVI-met have been widely adopted to validate design performance, they are typically employed at the final stages of the design process due to their high computational cost and time requirements [3]. This linear

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workflow limits the exploration of the solution space, as designers cannot easily evaluate the microclimatic impact of numerous morphological variations in real-time. There is a pressing need for methodologies that can rapidly generate diverse design options while simultaneously considering environmental performance indicators [4]. Recent advancements in Artificial Intelligence, specifically in the domain of computer vision and deep learning, offer promising avenues for automating portions of the urban design process. Generative Adversarial Networks have demonstrated remarkable capabilities in image synthesis and style transfer, enabling the generation of complex spatial structures from limited input data [5]. Among these, the Pix2Pix architecture, a conditional GAN framework, is particularly suited for image-to-image translation tasks, such as converting land-use diagrams into detailed building footprints. By learning the underlying statistical distribution of architectural features from a training dataset, Pix2Pix can produce novel urban layouts that retain the stylistic and functional characteristics of the source examples [6]. This research aims to establish a novel framework that couples the generative capabilities of Pix2Pix with the analytical precision of ENVI-met. The primary objective is to investigate whether a GAN-based model can generate high-density block layouts that are not only morphologically coherent but also conducive to improved microclimatic conditions. Unlike pure optimization algorithms that search for a single optimal solution, the proposed method focuses on generating a diverse range of viable design alternatives that can be rapidly screened for environmental performance [7]. By integrating these distinct computational domains, the study seeks to enhance the efficiency of sustainable urban design and provide a scalable methodology for climate-responsive planning.

2. Literature Review

2.1 Urban Microclimate and High-Density Morphology

The relationship between urban morphology and microclimate has been extensively documented in building physics literature. High-density urban forms influence local climate primarily through the modification of wind patterns and solar access. Studies have shown that the orientation, height, and spacing of buildings directly determine the roughness length and zero-plane displacement height, which are critical parameters in urban wind profiles [8]. In high-density contexts, the obstruction of prevailing winds often leads to stagnation zones and poor pollutant dispersion. Conversely, appropriately designed breezeways and variable building heights can enhance air permeability, thereby mitigating thermal stress [9]. Thermal comfort in outdoor spaces is frequently assessed using indices such as the Physiological Equivalent Temperature or the Universal Thermal Climate Index. Research indicates that shading is the dominant factor reducing daytime heat stress in hot-humid climates, while ventilation plays a crucial role in removing trapped heat during the night [10]. However, achieving an optimal balance is challenging; for instance, narrow street canyons provide desirable shading but may impede radiative cooling and ventilation [11]. The complexity of these interactions necessitates the use of sophisticated simulation tools. ENVI-met has emerged as a standard in this field due to its holistic model that couples fluid dynamics, thermodynamics, and plant physiology, allowing for the detailed simulation of surface-atmosphere interactions at the micro-scale [12]. Despite its accuracy, the computational intensity of ENVI-met remains a bottleneck for iterative design optimization.

2.2 Generative Artificial Intelligence in Urban Design

The application of generative algorithms in architecture has evolved from parametric rule-based systems to data-driven machine learning models. Early generative design relied on evolutionary algorithms or cellular automata, which required the explicit definition of

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geometric rules and fitness functions [13]. While effective for specific optimization problems, these methods often struggle to capture the qualitative and stylistic nuances of complex urban fabrics. The advent of Deep Learning has shifted the focus towards learning design patterns directly from data. Generative Adversarial Networks, introduced by Goodfellow et al., consist of two neural networks, a generator and a discriminator, competing in a zero-sum game. In the context of urban planning, GANs have been utilized to generate street networks, zone maps, and building footprints [14]. The Pix2Pix model, which utilizes a conditional adversarial loss, is particularly relevant because it allows for user control over the generation process through input masks or semantic labels [15]. Previous implementations of Pix2Pix in urban design have successfully demonstrated the ability to generate master plans from site boundaries or transport networks [16]. However, a significant gap remains in the integration of these generative models with environmental performance evaluation. Most existing studies focus on the visual realism or morphological validity of the generated outputs, with limited attention paid to their functional performance regarding wind and thermal comfort [17]. This paper addresses this gap by subjecting the GAN-generated layouts to rigorous microclimatic assessment.

3. Methodology

3.1 Research Framework and Workflow

The methodology adopted in this study follows a sequential workflow comprising three distinct phases: data preparation and model training, morphological generation, and microclimatic evaluation. The initial phase involves the construction of a comprehensive dataset of high-density urban blocks, which serves as the ground truth for training the Pix2Pix model [18]. The dataset includes paired images representing the boundary conditions (input) and the building footprints (target). Following the training process, the generator is deployed to synthesize new block layouts based on hypothetical site constraints. The second phase focuses on the selection of representative generated layouts for detailed analysis. To ensure the validity of the generative process, the outputs are first inspected for topological consistency and adherence to the input constraints. The third phase involves the translation of these 2D raster images into 3D geometric models compatible with the ENVI-met simulation environment [19]. The simulation settings are calibrated to represent a typical summer day in a subtropical high-density city, characterizing a worst-case scenario for heat stress. The results are then analyzed comparatively against existing standard block typologies to quantify the potential microclimatic benefits or drawbacks of the AI-generated designs.

3.2 Pix2Pix Model Architecture and Training

The core generative engine employed is the Pix2Pix architecture, which is based on the Conditional Generative Adversarial Network. The generator network adopts a U-Net structure, an encoder-decoder network with skip connections that connect layers in the encoder directly to corresponding layers in the decoder [20]. This architecture is critical for preserving high-frequency details, such as building edges and street boundaries, which might otherwise be lost during the down-sampling process. The input to the generator is a binary image representing the site boundary and road network, while the output is a predicted building footprint map. The discriminator network utilizes a PatchGAN classifier, which operates on local image patches rather than the entire image at once. This design choice penalizes structure at the scale of patches, encouraging the generation of sharp, high-frequency textures that characterize realistic urban forms [21]. The objective function of the network is a combination of the adversarial loss, which drives the generator to fool the discriminator, and the L1 distance loss, which ensures that the generated image remains close

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to the ground truth in terms of pixel-level accuracy. The training process utilized a dataset of 1,000 paired images derived from satellite imagery of high-density districts, processed to a resolution of 256 by 256 pixels. The model was trained for 200 epochs using the Adam optimizer, with a batch size of 1 to ensure stochasticity in the gradient descent [22].

3.3 ENVI-met Simulation Configuration

To evaluate the microclimatic performance, the generated 2D layouts were extruded into 2.5D models within the ENVI-met (v5.0) interface. The simulation domain was defined with a grid resolution of 2 meters by 2 meters by 3 meters, ensuring sufficient granularity to resolve airflow patterns within street canyons [23]. To avoid boundary effects impacting the core study area, a nesting grid system was employed, adding five additional grid cells around the perimeter of the main model domain. The meteorological boundary conditions were set to replicate a hot summer day. The initial potential temperature was set at 30 degrees Celsius, with a relative humidity of 75 percent. The wind speed at 10 meters height was fixed at 3.0 meters per second, blowing from the prevailing wind direction (southeast) [24]. Solar radiation was calculated based on the geographic coordinates of the target city, including direct, diffuse, and reflected components. Material properties for buildings and ground surfaces were standardized across all simulations to isolate the impact of morphology. Concrete and asphalt were assigned their standard albedo and thermal emittance values found in the ENVI-met database [25]. The simulation duration was set to 24 hours, with the first 6 hours discarded as spin-up time to allow the model to reach numerical stability.

4. High-Density Block Generation

4.1 Training Results and Morphological Quality

The training process of the Pix2Pix model exhibited stable convergence, with the generator loss decreasing steadily over the first 100 epochs before stabilizing. Visual inspection of the validation set revealed that the model successfully learned the fundamental rules of high-density block organization. The generated layouts respected the road boundaries defined in the input masks and produced building footprints that mimicked the texture and density of the training data [26]. The model demonstrated the capacity to generate diverse typologies, ranging from podium-tower configurations to perimeter block layouts, depending on the nuances of the input constraints.A critical observation was the model ability to infer internal courtyard spaces and secondary circulation paths that were not explicitly defined in the input but were inherent to the logic of the training set. This suggests that the GAN captured the implicit spatial syntax of the urban fabric. However, some generated artifacts were observed, such as unconnected building fragments or ambiguous pixel values at the edges of structures, which required a post-processing step of thresholding and morphological opening to clean the geometry for simulation [27].

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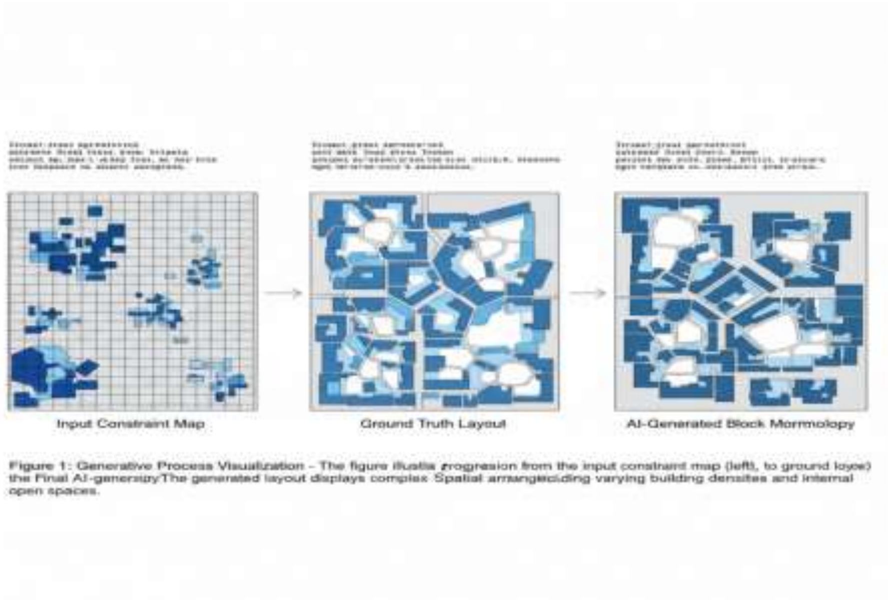

Figure 1: Generative Process Visualization

4.2 Typological Analysis of Generated Blocks

The generated blocks were categorized based on their morphological characteristics. The dominant typology identified was the hybrid block, consisting of a continuous commercial podium with residential towers above. This typology is highly characteristic of the Asian high-density context provided in the training data. The generator also produced variations in building orientation. While the input road network was rectilinear, the internal building arrangements often exhibited slight angular variations, which are beneficial for wind deflection and solar access. Comparative analysis of the building coverage ratio between the generated layouts and the ground truth showed a high degree of correlation, with a mean deviation of less than 5 percent. This indicates that the Pix2Pix model is capable of adhering to density targets implicitly learned from the dataset. However, the floor area ratio of the generated models had to be manually assigned during the 3D extrusion process, as the 2D GAN does not inherently predict building height. For the purpose of this study, a uniform height distribution strategy was applied to generated footprints to facilitate fair comparison [28].

5. Microclimate Evaluation Results

5.1 Thermal Environment Analysis

The ENVI-met simulation results provided detailed spatial maps of potential air temperature and mean radiant temperature. The analysis focused on the pedestrian level, specifically at a height of 1.5 meters. The comparison between the generated block layouts and a control set of conventional grid-based blocks revealed distinct thermal behaviors. The generated layouts, which often featured irregular building spacing and internal courtyards, demonstrated a capacity to create localized cool islands. Specifically, the mean radiant temperature in the generated blocks was frequently lower during peak solar hours (14:00) compared to the standard grid layouts. This can be attributed to the complex self-shading geometry produced by the GAN, which mirrors the organic evolution of urban forms found in the training data. The irregular street widths in the generated designs provided intermittent shading that reduced the cumulative heat storage of pavement surfaces. However, in areas where the generator produced excessively dense clusters of buildings, heat entrapment was observed,

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leading to elevated night-time temperatures due to the reduced sky view factor hindering radiative cooling.

5.2 Ventilation and Wind Environment

Wind flow analysis highlighted the aerodynamic implications of the AI-generated morphologies. The standard grid layouts, while efficient for land use, often created long, straight street canyons that acted as wind tunnels at high velocities or stagnation zones when perpendicular to the wind direction. In contrast, the generated layouts displayed a higher roughness variance. This morphological heterogeneity induced turbulence that facilitated air mixing, preventing the formation of stable hot air layers near the ground. Quantitative analysis showed that the ventilation efficiency, measured by the average wind speed ratio at pedestrian level, was slightly higher in the generated blocks for oblique wind angles. The inclusion of small pockets of open space, a feature learned by the GAN, acted as air pressure relief valves, allowing wind to permeate the block interior. Nevertheless, certain generated configurations resulted in dead zones on the leeward side of large building masses, indicating that while the GAN can mimic visual realism, it does not inherently understand fluid dynamics without explicit physics-informed loss functions.

Table 1 Experimental Results of Microclimate Variables at 14:00

Metric	Unit	Standard Grid Block	AI-Generated Block A	AI-Generated Block B
Average Air Temperature	Celsius	34.2	33.8	33.9
Mean Radiant Temperature	Celsius	58.5	55.2	56.1
Average Wind Speed	m/s	1.2	1.5	1.4
Physiological Equivalent Temp	Celsius	44.1	42.3	42.8
Sky View Factor (Avg)	-	0.45	0.38	0.41

6. Discussion

6.1 Interpretation of Generative Performance

The results of this study suggest that Generative Adversarial Networks possess significant potential as auxiliary tools for urban design. The Pix2Pix model demonstrated the ability to rapidly synthesize high-density block configurations that are statistically similar to real-world examples. Crucially, the microclimatic evaluation indicates that these generated forms often perform better than rigid, geometric standard layouts in terms of thermal comfort. This improvement is largely incidental to the training data; since the model was trained on real cities that have evolved over time to adapt to their local climates, the generator implicitly reproduces these climate-responsive features, such as self-shading geometries and porous block structures. However, the lack of explicit environmental parameters during the training phase means that the generation of climate-optimized solutions is stochastic rather than deterministic. The model does not optimized for wind speed or temperature; it optimizes for visual similarity to the training set. Therefore, the current framework serves best as an

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ideation tool that produces a "population" of design variants, which must then be filtered using simulation tools like ENVI-met.

6.2 Limitations and Future Work

Several limitations hinder the immediate applicability of this workflow in professional practice. Firstly, the resolution of the GAN is limited by GPU memory, restricting the output to relatively coarse grids that may miss fine architectural details affecting microclimate, such as balconies or pilotis. Secondly, the translation from 2D footprints to 3D volumes involves significant assumptions regarding building height and facade materiality. A true 3D-GAN approach, utilizing voxel-based representations, would provide a more accurate basis for environmental simulation. Future research should focus on embedding environmental performance indicators directly into the loss function of the neural network. By creating a physics-informed GAN, or by using a surrogate model to estimate ENVI-met results during the training loop, the generator could be incentivized to produce layouts that actively maximize cooling and ventilation. Additionally, expanding the dataset to include diverse climatic zones would allow for the development of a more generalized model capable of context-specific generation.

7. Conclusion

This paper presented a comprehensive framework for generating high-density urban blocks using Pix2Pix GANs and evaluating their microclimatic performance via ENVI-met simulations. The research confirmed that deep learning models can effectively automate the generation of realistic urban morphologies that respect spatial constraints. The subsequent environmental analysis revealed that these AI-generated designs frequently exhibit superior shading and ventilation characteristics compared to standardized grid layouts, resulting in lower physiological equivalent temperatures and improved outdoor thermal comfort. While the generated designs are not inherently optimized for physics, they inherit the successful adaptive traits of the existing urban fabric present in the training data. The integration of generative AI with microclimate simulation represents a significant step forward in the digitalization of urban planning. It allows for the rapid exploration of complex design spaces, offering planners a rich catalog of morphologically valid and environmentally sound options. As computational power increases and neural network architectures evolve, the coupling of creative generation and analytical simulation will likely become a cornerstone of sustainable high-density urban design.

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