BASELINE: Benchmarking Scenarios for Environmental Layouts and Integrative Neighbourhood Evaluation

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Abstract

Urban microclimatic analysis is essential in addressing challenges of urbanization and climate change, particularly the Urban Heat Island (UHI) effect. Urban areas often experience significantly higher temperatures than their rural surroundings due to the concentration of built surfaces and reduced vegetation. Studies estimate that UHI can increase daytime temperatures in U.S. cities by approximately 1°C to 7°C and night-time temperatures by about 2°C to 5°C. (Drukenmiller, 2024)This research introduces a framework employing canonical urban geometries to bridge the gap between theoretical microclimatic principles and practical urban design applications. Developed through a systematic study of urban typologies, these geometries represent diverse layouts, incorporating metrics like Sky View Factor (SVF), Aspect Ratio (AR), and Vegetation Cover.

Unlike traditional EPW files, which lack the granularity required for microclimatic precision, this approach enhances simulation accuracy by integrating localized urban configurations. Canonical geometries capture critical interactions between urban form and environmental factors, enabling comprehensive evaluations of wind flow, heat retention, and cooling strategies. Through a comparative analysis of global urban layouts, this research demonstrates how tailored geometries can inform sustainable design interventions, mitigate UHI impacts, and optimize urban energy performance.

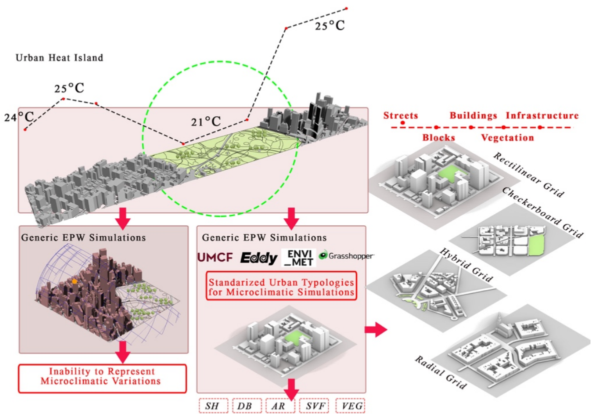


Figure 1: graphical abstract

Keywords: Canonical Urban Geometries, Urban Microclimate, Microclimate Simulation, Heat Retention, Thermal Comfort.

1. Methodology

1. The research begins with an assessment of the effect of urban heat islands (UHIs), which focuses on temperature changes, thermal comfort and energy consumption in urban environments. This establishes the importance of addressing UHI through urban design.
2. This study identifies and examines key microclimatic parameters to understand how urban morphology affects thermal comfort, energy efficiency, and cooling performance.
3. The evolution and development of urban layouts across the globe are analysed to discern their impact on heat accumulation, airflow dynamics, and shading patterns.
4. *Step 2 and 3* informed the selection of canonical grids, ensuring they serve as a comprehensive repository representing diverse urban typologies for microclimatic analysis.
5. Canonical grids were developed to represent a variety of urban typologies, including rectilinear, radial, organic, checkerboard, and hybrid layouts. These grids serve as simplified models for systematically assessing the microclimatic impacts of different urban configurations.

2. Introduction

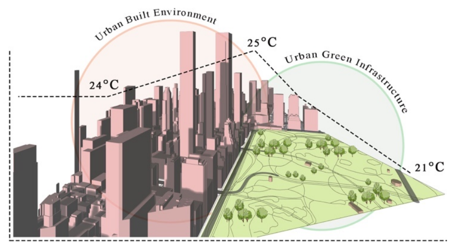


Figure 2: UHI

Urban microclimate analysis has become increasingly important due to rapid urbanization and climate change. Urban areas often experience the Urban Heat Island effect (UHI), where the temperature is higher than in the surrounding rural areas. (Tsoka, Tsikaloudaki, Theodosiou, & Bikas, 2020)
The effect of UHI has become one of the major problems of urban environment and human health. (Ren J, 2023). Urban regions account for more than 70% of the global energy use, largely due to the intricate microclimatic conditions that dominate the urban environment. (Edenhofer, 2015). In many cities, the urban heat island intensity (UHII) reaches about 5 °C (Ren J, 2023). The construction sector is a leading contributor mainly because of the high energy requirements of heating and cooling. (Mahdavinejad, 2014) . Notably, office buildings account for 23% of non-residential buildings and account for more than 48% of the annual energy consumption of urban heating and cooling. (Javanroodi & Nik, 2019) . The Urban Heat Island effect (UHI) increases ambient temperatures, increases building cooling requirements and, consequently, increases energy consumption. According to the research, UHI can increase the average cooling energy consumption by 19% and reduce heating energy consumption by 18.7% (Li X. Z., 2019).

Urban microclimate conditions are widely recognized for their substantial influence on broader urban climates, urban comfort, and building energy performance (Javanroodi & Nik, 2019). At the micro level, urban areas have lower average wind speeds and more complex air flow patterns than rural areas. (Oke, 2017) . Additionally, the Urban Heat Island (UHI) effect contributes to higher average air temperatures in cities (Huidong Li, 2019). These wind speed and temperature fluctuations have a major impact on the technical applications of various urban environments, particularly in the field of building design and performance.

Furthermore, high urban temperatures not only cause discomfort for pedestrians but also aggravate air pollution. Higher temperatures promote the formation of ozone at ground level, the main component of smog, and can aggravate respiratory disorders such as asthma and chronic bronchitis. Overheating and deterioration of air quality often result in high rates of hospitalization and death during heat wave. (Tong S, 2021).

These findings underscore the critical importance of addressing urban microclimate challenges at the design stage itself to enhance energy efficiency in buildings, improve urban comfort, and mitigate the broader impacts of urbanization on climate systems.

Consequently, these impacts are often overlooked in urban Energy Performance Simulation (EPS) studies that use standard climatic data, such as EnergyPlus Weather (EPW) files. These files are generally created from localized weather data representing typical years, such as the Typical Meteorological Year (TMY) or the Weather Year for Energy Calculation (WYEC), which are designed to capture the average long-term climate conditions of a given location. (Janjai, 2009). However, these weather files do not represent local micro-data and extreme weather conditions, introducing large peak loads and causing an average increase in total energy demand. (Moazami, 2019). Budgetary and time constraints in construction projects make it impractical to generate weather datasets for an entire urban area at an hourly resolution using Computational Fluid Dynamics (CFD) simulations or long-term local measurements. Conversely, architects and urban designers often rely on commercial building energy simulation tools during the early design stages. Therefore, providing them with more design-oriented methods and user-friendly workflows that leverage existing simulation engines would be highly beneficial. (Javanroodi & Nik, 2019). In addition to refining simulation tools, employing predefined city typologies—standardized models representing various urban layouts—can be advantageous. By applying simulation engines to these typologies, designers can assess energy performance and other critical factors before construction begins. This approach allows for the identification of specific needs and potential challenges associated with different urban configurations, facilitating informed decision-making and optimized design outcomes.

3. Research Goal

To establish a comprehensive framework of canonical urban geometries that improves the accuracy of urban microclimatic simulations. This framework provides researchers with a robust repository for analysis and equips urban designers with actionable insights to develop sustainable solutions by quantifying and evaluating the impacts of various urban typologies on thermal comfort, energy performance, and UHI mitigation.

4. Hypothesis

The canonical urban geometry provides more accurate microclimate predictions than general climate data and provides effective solutions to local environmental challenges in cities. This approach addresses granular problems, demonstrating that the integration of these geometries into urban design improves thermal comfort and energy efficiency, while at the same time mitigates the impact of the Urban Heat Island (UHI).

5. Literature Review

Urban form exerts a significant influence on the microclimate of cities, shaping factors such as heat retention, wind patterns, and solar exposure. By strategically designing the physical and spatial components of urban areas—negative microclimatic impacts can be mitigated and enhance overall urban liveability and sustainability.

Urban form encompasses the physical elements and spatial organization of cities, shaping how they function, evolve, and interact with their inhabitants and the environment. A built urban fabric typically consists (figure3):

1. **Streets:** These serve as the main pathways for movement within a city, enabling transportation and ensuring connectivity. (Živković, 2019). The layout and orientation of streets and blocks influence wind flow and solar access.
2. **Blocks:** Defined by the grid of streets, blocks are parcels of land that can contain multiple plots or buildings.
3. **Buildings:** Structures erected on plots serve various functions, including housing, commerce, and industry. The design, height, and placement of buildings shape the city's skyline and influence environmental factors like sunlight penetration and wind flow (Živković, 2019)
4. **Public Spaces and Vegetation:** Parks, plazas, and green roofs (Živković, 2019) introduce vegetation that facilitates evapotranspiration, providing cooling effects and mitigating the UHI phenomenon (Li, Mao, Ouyang, & Zheng, 2022).
5. **Infrastructure:** Urban infrastructure, including transportation networks and utilities, influences microclimatic conditions. For example, extensive paved surfaces can increase heat absorption, while elevated structures may alter wind patterns. (Salih K, 2024)

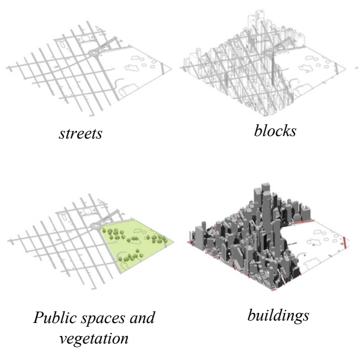


Figure 3: Morphological elements

To establish optimal test geometries for microclimatic simulations that can comprehensively represent diverse urban configurations, it is essential to leverage insights from existing research on the relationship between urban form and microclimatic factors. By analysing patterns in wind flow, solar radiation, shading, and thermal comfort across various urban layouts, key typologies can be identified that highlight these interactions. These selected geometries will act as representative models, enabling a systematic assessment of their microclimatic performance and their potential to guide sustainable urban design strategies. This approach ensures that the geometries are both theoretically robust and practically applicable to addressing urban climate challenges.

1) Standard Deviation of Building Heights (SH) (figure 4) & Average Distance Between Nearby Buildings (DB) (figure 5) : Urban geometry, such as the height, distance, and orientation of buildings, has a direct impact on wind flow patterns. Tall buildings and compact urban forms create low-speed winds, storms, and low-wind areas, affecting the natural ventilation needed for heat dissipation.
   High-rise buildings can effectively channel the wind if they are aligned with the dominant wind direction, creating "wind corridors" that cool urban areas. (A. Kubilay D. S., 2023)

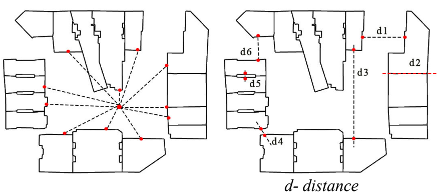


Figure 4: SH

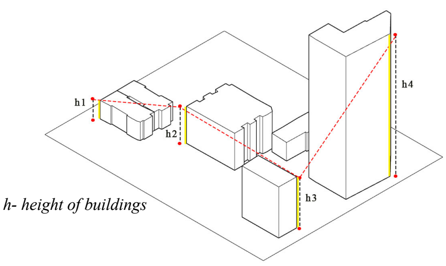


Figure 5 : DB

2) Aspect Ratio (AR) (figure 6): The height-to-width ratio (H/W) of urban canyons influences heat retention by controlling the amount of solar radiation that penetrates during the day and the rate of heat dissipation at night. Narrow and deep canyons retain less heat during the day due to shading but can trap heat at night because of limited radiative cooling. (Johansson, 2006) Wide and shallow canyons allow more sunlight during the day, increasing surface temperatures but facilitating better night-time cooling due to greater exposure to the sky. (A. Kubilay D. S., 2023)

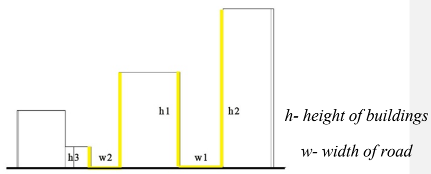


Figure 6: AR

3) Sky View Factor (SVF) (figure 7): The Sky View Factor (SVF), which quantifies the portion of the sky visible from the ground, influences the balance between solar heat absorption and longwave radiation dissipation. Lower SVF values decrease solar heat gain during the day but also hinder night-time cooling by restricting longwave radiation escape. Urban forms with reduced SVFs, such as narrow streets or courtyards, help lower daytime temperatures by limiting solar exposure but can impede heat loss at night due to obstructed radiation pathways. (Mahmoud, 2019)
   Higher SVFs (e.g., open plazas or wide streets) allow better heat dissipation at night but increase solar radiation during the day, requiring additional shading solutions.

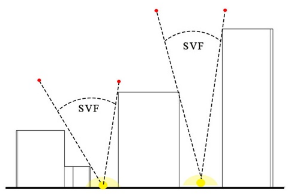


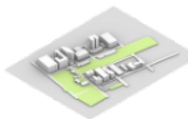
Figure 7 : SVF

4) Vegetation Cover : Kubilay's work emphasizes that building orientation, materials, and vegetative cover influence heat absorption, wind-driven cooling, and moisture exchange.. (A. Kubilay D. D., 2017) Combining reflective surfaces, vegetation, and aligned ventilation corridors can mitigate urban heat and improve thermal comfort by enhancing energy redistribution.

5) Results

Observing the above influences on microclimatic conditions through specific metrics, certain cities were meticulously selected to offer a diverse range of examples for each urban typology. Each city uniquely explores these metrics, highlighting how urban design elements interact with environmental factors. The selected canonical geometries represent a thoughtful synthesis of urban forms that have the most significant influence on microclimatic conditions. These geometries encompass a range of layouts, accounting for variations in Building Height, Aspect Ratio, Sky View Factor and Vegetation coverage. By distilling complex urban configurations into clear and representative forms, these models provide a practical framework for understanding how urban design affects wind flow, heat retention, and overall thermal comfort.

	Urban Typology	*Varieties of Examples*	*Reasons for Example Selection*	*Image*	*Link*
T1	***Rectilinear Grid***	Belo Horizonte, Brazil	**Belo Horizonte's** grid was designed to maximize solar exposure with *north-south* streets offering better shading and reduced heat islands. This grid has a moderate SVF, where street orientations optimize exposure. Uniform SH and DB restrict natural wind flow, while vegetation contribute to localized cooling.		Link
		Chicago, USA	**Chicago's** dense grid layout and predominant east-west streets trap more solar radiation, leading to higher heat accumulation. The SVF is moderate, influenced by consistent street alignments. The AR results in significant solar exposure during the day due to tall buildings.		Link
T2	***Radial Grid***	Doha, Qatar	**Doha's** radial layout intensifies heat accumulation near the central node, where SVF values are lowest due to dense clustering of buildings. The AR is higher in central areas, reducing ventilation and trapping heat. Variable SH and DB disrupt airflow, while sparse vegetation around the city centre amplify heat retention.		Link
		Amsterdam, Netherlands	**Amsterdam's** concentric ring roads and varied street orientations improve shading and ventilation, minimizing heat build-up. The SVF is higher in peripheral areas, allowing heat dissipation. A balanced AR supports solar shading while enabling ventilation.. Diverse SH and DB enhance wind flow.		Link
T3	***Organic Grid***	Casablanca, Morocco Cairo, Egypt	**Casablanca** and **Cairo** both represent organic grids with narrow streets that inhibit airflow, causing significant heat stagnation in densely built-up areas with poor ventilation.		Link

					Link
T4	***Checkerboard Grid***	Manhattan, USA Barcelona, Spain Philadelphia, USA	**Manhattan's** grid leads to urban heat islands due to its dense, east-west street orientation. The SVF is moderate, with limited sky exposure in densely built areas. A balanced AR allows some solar penetration but leads to heat build-up in the absence of shading.		Link
			Barcelona's checkerboard grid, with alternating open spaces and built blocks, improves airflow and reduces heat retention. A moderate to high SVF enhances ventilation, while a balanced AR optimizes shading and heat dissipation. Uniform SH and DB support better wind flow, and ample vegetation enhance thermal comfort.		Link
			Philadelphia's grid strikes a balance, with moderate impacts on the microclimate. A moderate SVF and balanced AR allow for controlled solar penetration. Regular SH and DB aid wind circulation, while sufficient vegetation mitigate heat accumulation.		Link
T5	***Hybrid Grids***	Paris, France Sydney, Australia	**Paris's** hybrid grid balances historical radial streets with modern grid elements, providing improved airflow. The SVF varies, with open areas offering greater sky exposure. The AR is mixed, balancing shading in denser areas and ventilation in open zones. Diverse SH and DB facilitate wind movement.		Link
			Sydney's modern planning integrates efficient ventilation and shading. A high SVF in peripheral areas supports heat dissipation. A mixed AR enhances shading and ventilation. Variable SH and DB create ventilation corridors, while significant vegetation improve cooling and comfort.		Link

6) Conclusion

This research underscores the critical role of canonical urban geometries in advancing microclimatic simulations to effectively address the Urban Heat Island (UHI) effect and promote urban sustainability. These geometries provide a comprehensive framework for analysing the intricate relationships between urban form and environmental factors such as heat retention, airflow dynamics, and thermal comfort. By seamlessly integrating theoretical principles with practical design applications, the proposed approach empowers urban designers and planners with actionable, data-driven insights. The comparative evaluation of diverse urban layouts highlights the necessity of context-specific strategies for sustainable urban design. Moreover, this study advances the field by moving beyond generalized climatic datasets, paving the way for localized, precise, and highly adaptive simulation techniques that cater to the unique needs of varied urban environments.

7) Future Scope

Future research could focus on integrating this repository with Urban Micro Climate Foam (UMCF) simulations. By running UMCF simulations on the proposed canonical urban geometries, this repository could serve as a valuable pre-simulated tool. Such an integration would streamline workflows for users of UMCF, enabling them to access pre-simulated data tailored to various urban typologies. This would significantly reduce the time and computational effort required for microclimatic analysis, making the tool more efficient and user-friendly for urban designers and researchers.

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References

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Drukenmiller, H. (2024, March 14). *Urban Heat Islands 101*. Retrieved from Resource for Future: https://www.rff.org/publications/explainers/urban-heat-islands-101/?utm_source=chatgpt.com

Tsoka, S., Tsikaloudaki, K., Theodosiou, T., & Bikas, D. (2020). Urban Warming and Cities' Microclimates: Investigation Methods and Mitigation Strategie. *Energies* .

Ren J, S. K. (2023). A Review on the Impacts of Urban Heat Islands on Outdoor Thermal Comfort. *Buildings*, 13(6), 1368.

Edenhofer, O. (2015). *Climate change 2014: mitigation of climate change.* Cambridge University Press.

Mahdavinejad, M. a. (2014). Natural ventilation performance of ancient wind catchers, an experimental and analytical study–case studies: one-sided, two-sided and four-sided wind catchers. *International journal of energy technology and policy*, 36-60.

Javanroodi, K., & Nik, V. (2019). Impacts of Microclimate Conditions on the Energy Performance of Buildings in Urban Areas. *Buildings*, 9(8), 189.

Li, X. Z. (2019). Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy*.

Oke, T. R. (2017). *Urban climates.* Cambridge university press.

Huidong Li, Y. Z. (2019). Quantifying urban heat island intensity and its physical mechanism using WRF/UCM. *Science of The Total Environment*, 3110-3119.

Tong S, P. J. (2021). Urban heat: an increasing threat to global health. *BMJ*.

Janjai, S. a. (2009). Comparison of methods for generating typical meteorological year using meteorological data from a tropical environment. *Applied Energy*, 528-537.

Moazami, A. (2019). Impacts of future weather data typology on building energy performance–Investigating long-term patterns of climate change and extreme weather conditions. *Applied Energy*, 696-720.

Živković, J. (2019). *Urban Form and Function.* Climate Action.

Li, J., Mao, Y., Ouyang, J., & Zheng, S. (2022). A Review of Urban Microclimate Research Based on CiteSpace and VOSviewer Analysis. *International Journal of Environmental Research and Public Health*, 19(8), 4741.

Salih K, B. N. (2024). Review of the Role of Urban Green Infrastructure on Climate Resiliency: A Focus on Heat Mitigation Modelling Scenario on the Microclimate and Building Scale. *Urban Science*.

A. Kubilay, D. S. (2023). Assessment of summer outdoor thermal comfort in an urban neighborhood with high-rise buildings. *Journal of Physics*.

Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment*.

Mahmoud, H. (2019). EFFECT OF URBAN FORM ON OUTDOOR THERMAL COMFORT OF GOVERNMENTAL RESIDENTIAL BUILDINGS: NEW ASWAN AS A CASE STUDY, EGYPT. *JES. Journal of Engineering Sciences*.

A. Kubilay, D. D. (2017). Parametric Study of Urban Microclimate Based on a Coupled Approach for CFD, Radiation, Wind-Driven Rain and Heat and Moisture Transport in Building Materials. *Building Simulation Conference Proceedings* .