



## Microclimate Simulation-Based Architectural Learning Model in Urban Design Studio: A Quasi-Experimental Approach to Enhancing Design Quality and Thermal Comfort

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### ABSTRACT

Urban overheating and outdoor thermal discomfort have become critical challenges in rapidly urbanizing tropical cities, significantly reducing the environmental quality, usability, and livability of public spaces. Despite the growing emphasis on climate-responsive and performance-based urban design, the integration of environmental simulation into urban design education and spatial decision-making processes remains limited. This study aims to evaluate the effectiveness of a simulation-informed urban design learning model in improving both design quality and outdoor thermal comfort performance. A quasi-experimental approach was employed within an urban design studio involving 40 architecture students divided into control and experimental groups. The experimental group applied a simulation-informed workflow using ENVI-met and Ladybug Tools, while the control group followed conventional urban design methods. Design quality was evaluated through spatial organization, public-space quality, climate responsiveness, vegetation integration, and design coherence. The results demonstrate that the experimental group achieved a 39.6% improvement in overall design quality, with the highest increase observed in climate responsiveness (60.7%). In terms of thermal performance, the simulation-informed approach reduced air temperature by 4.3°C and MRT by 9.5°C, while increasing shading coverage by 30%. Statistical analysis confirms that the differences between groups are significant ( $p < 0.05$ ). The findings indicate that environmental simulation substantially enhances spatial responsiveness and thermal performance by enabling iterative and evidence-based design decisions. This study contributes to performance-based urban design and architectural pedagogy by establishing a quantitative relationship between microclimate simulation, spatial quality, and outdoor thermal comfort within a tropical urban context.

**Keywords:** Urban Design; Microclimate Simulation; Outdoor Thermal Comfort; Performance-Based Design; Tropical Urban Environment

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### INTRODUCTION

Rapid urbanization in tropical cities has significantly intensified the Urban Heat Island (UHI) phenomenon, resulting in elevated air temperatures, increased thermal stress, and declining outdoor thermal comfort. The expansion of impervious surfaces, reduction of vegetation coverage, and high-density urban morphology contribute substantially to heat accumulation and reduced environmental quality in urban public spaces [1], [2], [14]. In tropical environments characterized by high solar radiation and humidity, thermal discomfort directly affects the usability, livability, and social functionality of public spaces [3], [27], [30]. Previous

studies have demonstrated that outdoor thermal comfort is strongly influenced by environmental variables such as air temperature ( $T_a$ ), Mean Radiant Temperature (MRT), humidity, wind velocity, and solar exposure [23], [24], [25]. Among these variables, MRT is widely recognized as one of the most dominant parameters affecting human thermal perception in outdoor environments [3], [28].

From an urban design perspective, thermal conditions are not merely environmental outcomes but are closely related to spatial configuration, vegetation distribution, shading strategies, and urban morphology [7], [31], [32]. Research by Santamouris [18] and Taleghani [7] demonstrated that passive cooling strategies, urban greening, and shading interventions can significantly reduce urban thermal stress and improve outdoor comfort. Similarly, Ng et al. [39] and Yuan and Ng [40] emphasized that vegetation density, urban porosity, and building configuration play a critical role in regulating urban microclimates in high-density tropical cities. In addition, Ali-Toudert and Mayer [44], [45] found that street orientation, aspect ratio, and shading elements substantially influence outdoor thermal comfort by controlling solar exposure and radiant heat gain.

The relationship between thermal comfort and urban livability has also been widely discussed within urban design and public-space theory. Gehl [10] argued that environmental comfort strongly influences public activity intensity and social interaction in urban spaces. Jacobs [62] and Whyte [63] further emphasized that the success of public spaces depends on their ability to support human comfort, activity, and social engagement. Similarly, Lynch [61] highlighted the importance of spatial quality and environmental perception in shaping urban imageability and user experience. These perspectives suggest that climate-responsive urban design is not only an environmental concern but also a critical factor influencing spatial quality and public-space usability.

In response to growing urban thermal challenges, environmental simulation technologies have increasingly been integrated into urban climate studies and performance-based design approaches. Simulation tools such as ENVI-met enable detailed three-dimensional analysis of surface-plant-air interactions within urban environments [35], [36], while Ladybug Tools support environmental analysis and climate-responsive parametric design workflows [47]. Previous studies have demonstrated that simulation-informed approaches can effectively evaluate urban thermal conditions and optimize environmental performance through modifications in urban morphology, vegetation strategies, and spatial configuration [33], [34], [37]. Moreover, performative and performance-oriented design theories argue that environmental performance should function as an active design parameter rather than merely a post-design evaluation criterion [48], [49], [50].

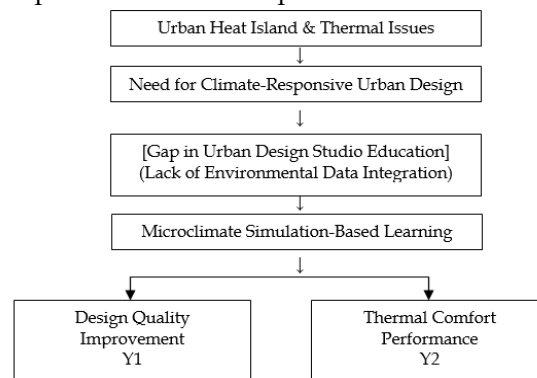
Despite these advancements, several critical limitations remain. First, most previous studies primarily focus on post-design environmental evaluation in real urban environments rather than integrating simulation as an active decision-making tool during the design process itself [33], [37]. Second, existing studies generally examine professional urban planning practices or built urban environments, while empirical research investigating the integration of microclimate simulation into architectural education and urban design studio pedagogy remains limited [6]. Third, although previous research has demonstrated the effectiveness of climate-responsive strategies in improving thermal conditions, there is still insufficient quantitative evidence explaining how simulation-informed approaches influence design quality, spatial coherence, and environmental performance simultaneously within a controlled educational setting. Furthermore, quasi-experimental studies comparing conventional design methods and simulation-informed urban design processes are still scarce, particularly in tropical contexts where thermal stress significantly affects public-space usability and urban livability.

This research gap is significant because architectural education plays a critical role in shaping future urban design practices. Without systematic integration of environmental analysis into the design-learning process, urban design education risks continuing to produce visually acceptable but environmentally unresponsive spatial solutions. In rapidly urbanizing tropical cities, this limitation may further exacerbate urban overheating, reduce public-space

usability, and weaken urban livability [1], [18]. Therefore, developing a simulation-informed and evidence-based urban design learning framework is essential not only for improving educational outcomes but also for advancing climate-responsive urban design practices in tropical environments.

Addressing these gaps, this study aims to develop and empirically evaluate a microclimate simulation-based learning model within an urban design studio using a quasi-experimental approach. Specifically, the research investigates whether the integration of ENVI-met and Ladybug simulations into the urban design process can significantly improve both design quality and outdoor thermal comfort performance compared to conventional design methods. Design quality is evaluated through spatial organization, public-space quality, climate responsiveness, vegetation integration, and design coherence, while environmental performance is assessed through air temperature (Ta), Mean Radiant Temperature (MRT), and shading coverage.

Figure 1 illustrates the conceptual framework of the proposed microclimate simulation-based learning model in urban design studio. The framework demonstrates the logical relationship between urban thermal challenges, the limitations of conventional intuition-based design approaches, and the integration of simulation-informed environmental analysis within the design process. The framework positions microclimate simulation as an iterative decision-support mechanism connecting environmental data, spatial modification strategies, and performance evaluation. Through this framework, environmental variables such as thermal stress, solar exposure, and shading performance are systematically translated into urban design decisions involving building orientation, vegetation distribution, open-space configuration, and material selection. As shown in Figure 1, the integration of environmental simulation is expected to improve both spatial quality and outdoor thermal comfort performance, thereby contributing to the development of climate-responsive and livable urban environments.



**Figure 1. Conceptual framework of microclimate simulation-based learning model in urban design studio**

The novelty of this study lies in its integration of microclimate simulation as an active generative component within the urban design learning process rather than merely as a post-design evaluative tool. Unlike previous studies that mainly assess environmental performance after design completion, this research establishes a simulation-informed iterative workflow in which environmental data directly shape spatial decisions throughout the design process. Furthermore, this study contributes one of the few quasi-experimental investigations that quantitatively link microclimate simulation, design quality, and thermal performance within an educational urban design framework in a tropical context. By combining environmental simulation, architectural pedagogy, and performance-based urban design into a unified methodological framework, this research contributes to the advancement of climate-responsive urban design education and provides a structured approach for developing more adaptive, livable, and sustainable tropical urban environments.

## METHOD

This study employed a quasi-experimental research design to evaluate the effectiveness of a simulation-informed urban design learning model in improving design quality and outdoor thermal comfort performance. Quasi-experimental approaches are widely used in educational and design-based research to compare different interventions within controlled environments while maintaining realistic studio-learning conditions [8], [9]. The research was conducted over one academic semester (approximately 14–16 weeks) within a fifth-semester urban design studio involving undergraduate architecture students at Universitas Pelita Bangsa, Indonesia.

A total of 40 students participated in the study and were equally divided into two groups consisting of a control group and an experimental group. To ensure methodological validity and group equivalence, participants were assigned using a balanced grouping approach based on academic performance (GPA) and baseline design scores. Students were first ranked according to their academic and design performance, then alternately distributed into both groups to ensure proportional representation of high-, medium-, and low-performing participants. This approach was intended to minimize bias and maintain comparable baseline competencies between groups.

The control group followed a conventional urban design process involving site analysis, spatial composition, precedent studies, and design development based primarily on intuition, formal composition, and qualitative environmental considerations. In contrast, the experimental group applied a simulation-informed design process integrating microclimate analysis directly into spatial decision-making. This approach utilized ENVI-met and Ladybug Tools as the primary environmental simulation platforms. ENVI-met is a three-dimensional microclimate simulation model capable of simulating surface–plant–air interactions in urban environments [35], [36], while Ladybug Tools supports climate-responsive parametric analysis and environmental performance evaluation within computational design workflows [47].

The simulation-informed design workflow consisted of iterative environmental analysis and spatial modification processes. Simulation outputs were continuously translated into urban design decisions, including building orientation, vegetation placement, shading strategies, surface material selection, open-space configuration, and pedestrian-space optimization. This process reflects the principles of performance-based and performative design approaches, where environmental performance actively informs spatial form and design development [48], [49], [50].

The study was conducted within a high-density tropical urban context characterized by compact urban morphology, limited vegetation coverage, extensive impervious surfaces, and high solar exposure. The selected study area ranged between 5–10 hectares and represented typical urban conditions in rapidly urbanizing tropical cities. Both groups received the same urban design brief focused on improving public-space quality, environmental comfort, and urban livability within tropical climatic conditions.

The research procedure consisted of four primary stages:

1. Baseline design development
2. Microclimate simulation and environmental analysis
3. Design modification based on simulation outputs
4. Final design and performance evaluation

This structured workflow ensured that environmental data were systematically integrated into the design process and enabled direct comparison between conventional and simulation-informed approaches.










The independent variable in this study was the application of the simulation-informed urban design process, while the dependent variables included design quality (Y1) and outdoor thermal comfort performance (Y2). Design quality was evaluated through five criteria:

- spatial organization
- public-space quality
- climate responsiveness

- vegetation integration
- design coherence






These criteria were adapted from urban design quality and public-space evaluation frameworks proposed by Gehl [10], Lynch [61], and Jacobs [62].

**Table 1. Research Variables and Indicators**

| Variable Type  | Variable   | Indicators   | Measurement           |
|--|--|--|-----------------------|
| Independent<br>     | <b>Simulation-informed Urban Design Process</b><br> | Integration of microclimate simulation into design workflow<br>  | Applied / Not applied |
| Dependent (Y1)<br>  | <b>Design Quality</b><br>                           | Spatial organization, public-space quality, climate responsiveness, vegetation integration, design coherence<br> | Score (1–5)           |
| Dependent (Y2)<br> | <b>Thermal Comfort Performance</b><br>             | Air Temperature (Ta), Mean Radiant Temperature (MRT), Shading Coverage (%)<br>                                 | Simulation results    |

Design quality assessment was conducted using a structured evaluation rubric consisting of five performance criteria. Each criterion was evaluated using a 5-point Likert scale ranging from very poor (1) to excellent (5). The assessment was performed independently by three experts in urban design and architectural education to ensure objectivity and inter-rater reliability.

**Table 2. Design Evaluation Rubric**

| Criteria  | Description  | Scale |
|---|--|-------|
|  <b>Spatial Organization</b>   | Clarity and structure of urban layout                | 1–5   |
|  <b>Public-Space Quality</b>   | Functionality, accessibility, and user comfort       | 1–5   |
|  <b>Climate Responsiveness</b> | Shading, solar control, and environmental adaptation | 1–5   |
|  <b>Vegetation Integration</b> | Ecological and thermal contribution of vegetation    | 1–5   |
|  <b>Design Coherence</b>       | Overall spatial integration and consistency          | 1–5   |

Microclimate simulations were conducted under representative tropical climatic conditions during peak daytime thermal periods to capture maximum thermal stress

conditions. Simulation parameters included spatial grid resolution, boundary conditions, vegetation configuration, material properties, and time intervals corresponding to morning, midday, and afternoon periods. These settings were selected to capture temporal variations in outdoor thermal conditions and ensure comparability between design alternatives.

Outdoor thermal comfort performance was evaluated using air temperature ( $T_a$ ), Mean Radiant Temperature (MRT), and shading coverage percentage, which are widely recognized indicators in outdoor thermal comfort studies [3], [24], [27], [32]. MRT was emphasized as a critical parameter because radiant heat significantly influences thermal perception in tropical outdoor environments [23], [28]. In addition, shading coverage was analyzed because shading strategies are considered one of the most effective passive cooling approaches in tropical urban design [1], [7], [39].

Quantitative data analysis was performed using an independent sample t-test to determine whether differences between the control and experimental groups were statistically significant [9]. This statistical method was selected due to the comparative nature of the quasi-experimental design. Prior to hypothesis testing, baseline equivalence analysis and homogeneity of variance tests were conducted to ensure the validity of group comparison. In addition, percentage improvement analysis was employed to evaluate the effectiveness of the simulation-informed learning model in improving both design quality and thermal performance.

The methodological framework developed in this study was designed not only for studio-based educational application but also for broader implementation within performance-based urban design practice. By integrating environmental simulation, spatial analysis, and iterative design modification into a unified workflow, the proposed approach provides a structured framework for developing adaptive, climate-responsive, and livable urban environments in tropical contexts.

## **RESULT AND DISCUSSION**

The results of this study are presented based on the analysis of participant characteristics, baseline conditions, design quality improvement, and outdoor thermal comfort performance. The findings are interpreted by linking experimental validity, design processes, environmental mechanisms, and performance outcomes within a simulation-informed urban design framework.

### **Participant Characteristics and Baseline Equivalence**

The study involved 40 undergraduate architecture students enrolled in a fifth-semester urban design studio course. All participants had completed prerequisite courses related to architectural design, urban studies, and environmental analysis, ensuring relatively homogeneous levels of spatial understanding and technical competency. To minimize bias and maintain internal validity within the quasi-experimental framework, participants were distributed into control and experimental groups using a balanced grouping approach based on Grade Point Average (GPA) and baseline design scores.

**Table 3. Participant Characteristics**

| Variable               | Control Group (n = 20)   | Experimental Group (n = 20) |
|------------------------|--------------------------|-----------------------------|
| Number of Participants | 20                       | 20                          |
| Academic Level         | 5 <sup>th</sup> Semester | 5 <sup>th</sup> Semester    |
| Study Program          | Architecture             | Architecture                |
| Prior Design Courses   | Completed                | Completed                   |
| Mean GPA               | 3.20                     | 3.18                        |
| Initial Design Score   | 3.05                     | 3.08                        |

Both groups show comparable academic background and initial design performance, indicating baseline equivalence before the intervention.

The results indicate that both groups possessed highly comparable academic and design-performance characteristics, with only marginal differences observed across all variables. To further validate baseline equivalence, an independent sample t-test was conducted on the initial design scores across all evaluation criteria.

**Table 4. Baseline Group Equivalence Test**

| Variable               | t-value      | df        | p-value     | Interpretation         | Independent Sample t-test Results (95% Confidence Interval) |             |
|------------------------|--------------|-----------|-------------|------------------------|---|-------------|
| Spatial Organization   | -0.45        | 38        | 0.65        | Not Significant        |   | 0.65        |
| Public-Space Quality   | -0.52        | 38        | 0.60        | Not Significant        |   | 0.60        |
| Climate Responsiveness | 0.48         | 38        | 0.63        | Not Significant        |   | 0.63        |
| Vegetation Integration | -0.41        | 38        | 0.68        | Not Significant        |   | 0.68        |
| Design Coherence       | 0.50         | 38        | 0.62        | Not Significant        |   | 0.62        |
| <b>Average Score</b>   | <b>-0.47</b> | <b>38</b> | <b>0.64</b> | <b>Not Significant</b> |   | <b>0.64</b> |



**Interpretation:**

All variables show p-value > 0.05, indicating no statistically significant differences between the control and experimental groups at baseline. This confirms that both groups have equivalent initial design performance before the intervention.

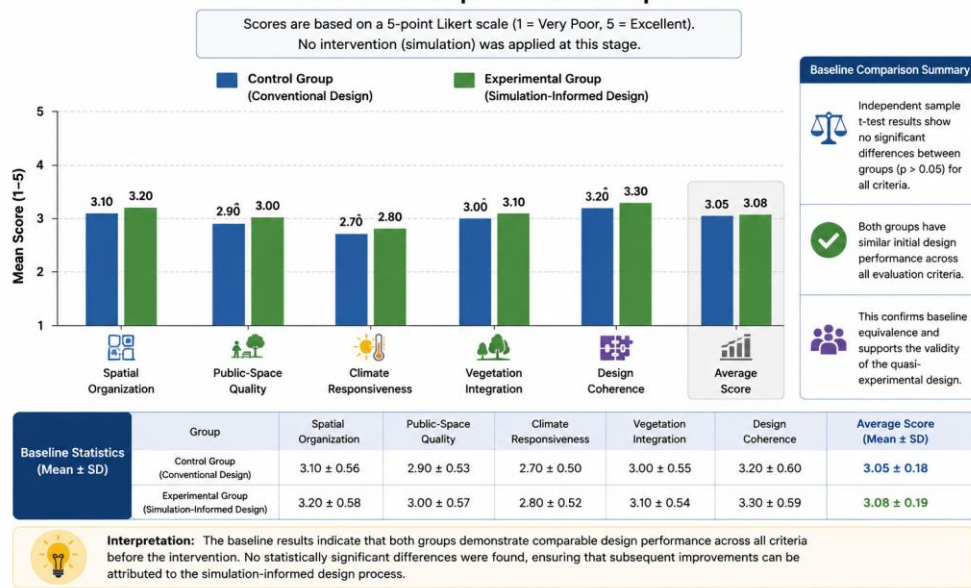


**Conclusion:**

Baseline equivalence is achieved. Subsequent differences can be attributed to the simulation-informed design intervention.

The statistical analysis confirms that there were no significant differences between the control and experimental groups prior to the intervention ( $p > 0.05$ ). These findings indicate that both groups possessed equivalent baseline performance levels, ensuring that subsequent differences in design quality and thermal comfort performance can be attributed primarily to the simulation-informed design intervention rather than differences in participant capability. Figure 2 illustrates the baseline comparison between the control and experimental groups. The chart demonstrates that both groups exhibited nearly identical performance across all

evaluation criteria prior to the intervention, further reinforcing the validity of the experimental framework.



**Figure 2. Baseline Design Performance Comparison Between Control and Experimental Groups**

### Design Quality Improvement

Following the intervention, the experimental group demonstrated significantly higher design quality compared to the control group across all evaluation criteria.

**Table 5. Comparison of Design Quality Scores**

| Criteria               | Control Group | Experimental Group | Improvement (%) |
|------------------------|---------------|--------------------|-----------------|
| Spatial Organization   | 3.2           | 4.1                | 28.1%           |
| Public-Space Quality   | 3.0           | 4.3                | 43.3%           |
| Climate Responsiveness | 2.8           | 4.5                | 60.7%           |
| Vegetation Integration | 3.1           | 4.4                | 41.9%           |
| Design Coherence       | 3.3           | 4.2                | 27.3%           |
| Average                | 3.08          | 4.30               | 39.6%           |

The experimental group achieved an overall improvement of 39.6%, with the most substantial increase observed in climate responsiveness (60.7%), followed by public-space quality (43.3%) and vegetation integration (41.9%). These findings indicate that integrating microclimate simulation into the urban design process significantly improved environmental responsiveness and spatial quality.

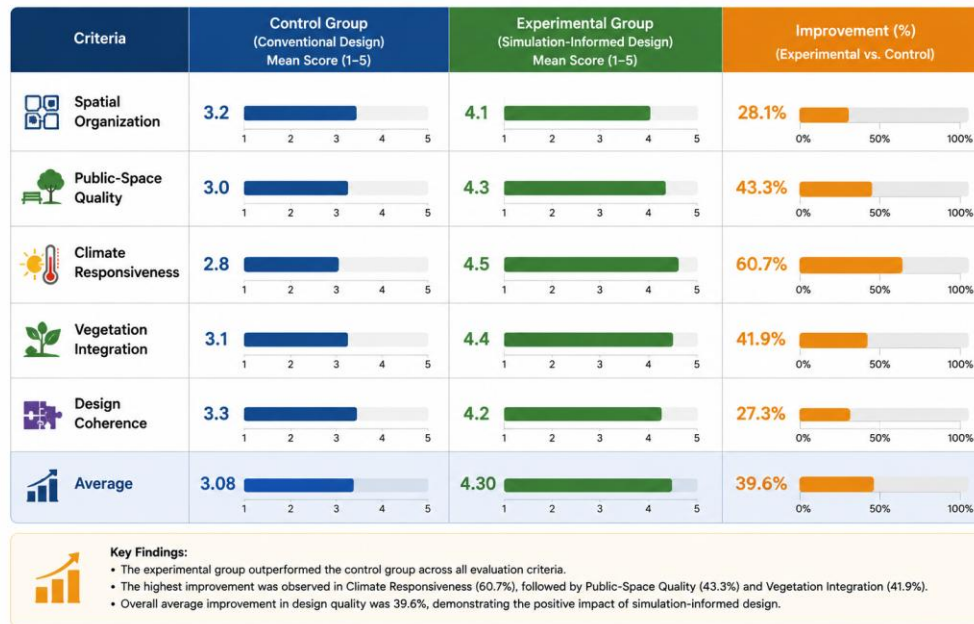
From a design-process perspective, the improvements reflect a transition from intuition-based design toward performance-informed spatial decision-making. In the experimental group, simulation outputs continuously provided environmental feedback regarding thermal hotspots, solar exposure, shading performance, and spatial thermal distribution. This iterative workflow enabled participants to optimize building orientation, vegetation placement, and open-space configuration based on measurable environmental parameters.

In contrast, the control group relied primarily on conventional qualitative approaches emphasizing formal composition and visual arrangement without quantitative environmental evaluation. As a result, environmental considerations remained secondary within the design process, leading to lower climate responsiveness and weaker integration of passive environmental strategies.

Figure 3 presents the comparison of final design quality scores between the control and experimental groups. The chart clearly demonstrates that the experimental group consistently

achieved higher performance across all evaluation criteria, particularly in climate responsiveness and vegetation integration.

**Table 5. Comparison of Design Quality Scores**



**Figure 3. Comparison of Design Quality Between Control and Experimental Groups**

To further illustrate the magnitude of improvement, Figure 4 presents the percentage increase across all design criteria. Climate responsiveness achieved the highest level of improvement, indicating the strong influence of simulation-informed environmental analysis on spatial decision-making and design adaptation.

The findings are consistent with previous studies emphasizing the importance of climate-responsive urban design and environmental simulation in improving spatial quality and urban environmental performance. Santamouris [18] and Taleghani [7] demonstrated that shading strategies, urban greening, and passive cooling interventions significantly improve thermal comfort and environmental quality within urban spaces. Similarly, Lai et al. [32] confirmed that environmental modifications involving vegetation and shading substantially influence outdoor thermal comfort and public-space usability.

The results also align with performative architecture theories proposed by Kolarevic and Malkawi [48] and Hensel [49], which argue that environmental performance should function as an active design generator rather than merely a post-design evaluative parameter. In this study, environmental simulation directly informed spatial configuration and design modification, supporting the transition toward performance-based urban design methodologies.

Furthermore, the improvement in public-space quality and vegetation integration reinforces Gehl's [10] argument that environmental comfort strongly influences public activity intensity and social interaction within urban spaces. Similar perspectives were proposed by Jacobs [62] and Whyte [63], who emphasized that successful public spaces depend heavily on pedestrian comfort, environmental quality, and human-scale spatial experience.

Statistical analysis using an independent sample t-test confirmed that the differences between the control and experimental groups were statistically significant ( $p < 0.05$ ), indicating that the observed improvements were directly associated with the simulation-informed urban design process.

## Thermal Comfort Performance

The comparison of outdoor thermal comfort performance between the control and experimental groups is presented in Table 6.

**Table 6. Thermal Comfort Performance Comparison**

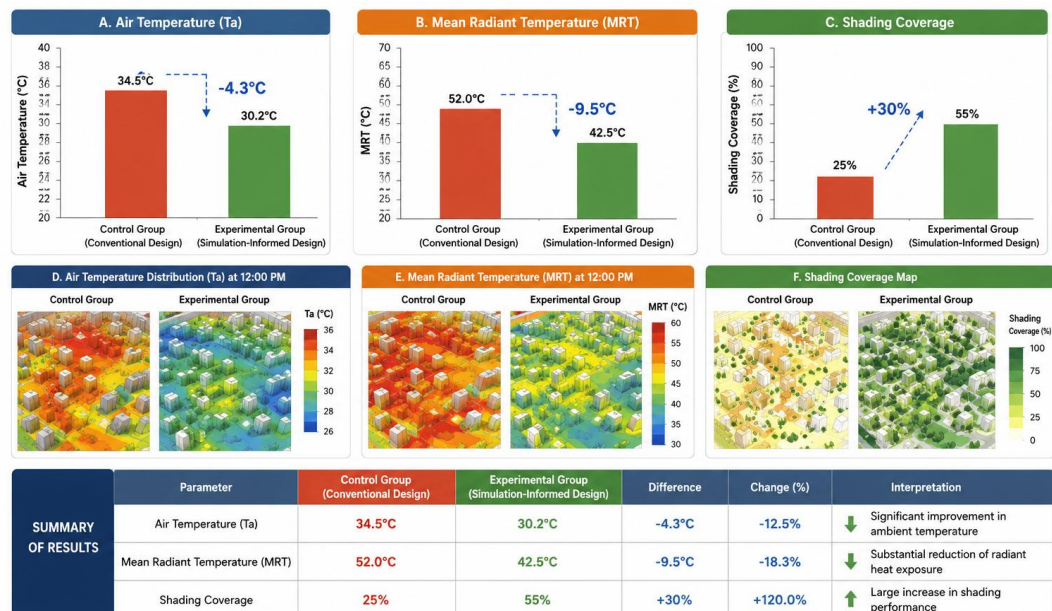
| Parameter                      | Control Group | Experimental Group | Difference |
|--------------------------------|---------------|--------------------|------------|
| Air Temperature (Ta)           | 34.5°C        | 30.2°C             | -4.3°C     |
| Mean Radiant Temperature (MRT) | 52.0°C        | 42.5°C             | -9.5°C     |
| Shading Coverage               | 25%           | 55%                | +30%       |

The experimental group achieved substantially improved thermal conditions compared to the control group. Air temperature decreased by 4.3°C, while Mean Radiant Temperature (MRT) decreased by 9.5°C. In addition, shading coverage increased by approximately 30%, demonstrating the effectiveness of passive environmental strategies implemented through the simulation-informed workflow.

The greater reduction in MRT compared to air temperature suggests that the primary impact of the design intervention involved controlling solar radiation and radiant heat exposure rather than modifying ambient air conditions. This finding is particularly important because MRT is widely recognized as one of the dominant variables influencing outdoor thermal perception [23], [24], [28].

The substantial reduction in MRT strongly correlates with the increase in shading coverage achieved within the experimental group. Vegetation integration, shading devices, and optimized building orientation collectively reduced direct solar exposure and radiant heat accumulation. Similar findings were reported by Ali-Toudert and Mayer [44], [45], who found that shading configuration, urban geometry, and street orientation significantly influence thermal comfort by reducing solar radiation exposure within urban canyons.

Figure 5 compares the thermal comfort performance between the control and experimental groups. The chart demonstrates substantial reductions in air temperature and MRT accompanied by a significant increase in shading coverage within the experimental group.

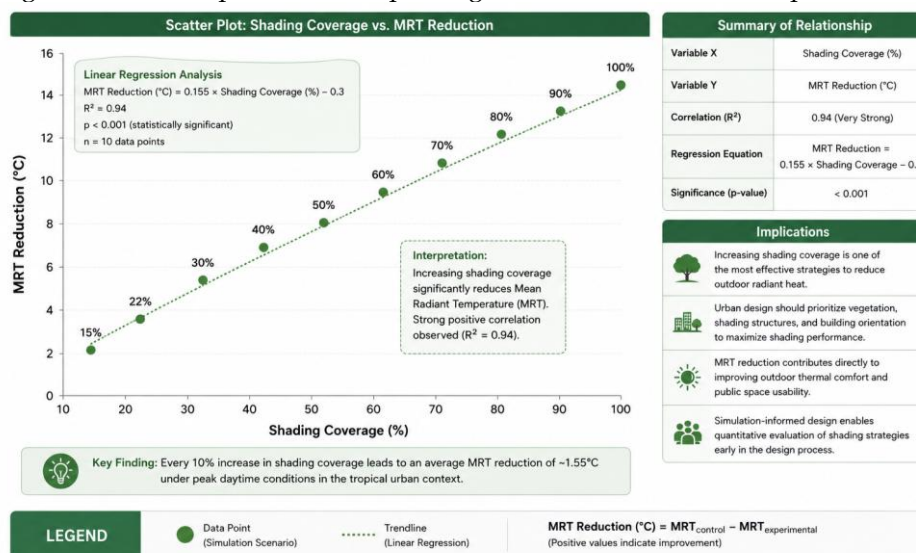


**Figure 3. Thermal Comfort Performance Comparison**

The findings are also consistent with studies conducted by Emmanuel and Johansson [42], [43], who demonstrated that urban morphology and vegetation distribution strongly influence outdoor thermal conditions within tropical urban environments. Likewise, Ng et al.

[39] emphasized that increasing urban greenery and shading coverage significantly improves thermal comfort in high-density tropical cities.

Figure 6 further illustrates the relationship between shading coverage and MRT reduction. The regression trend indicates that increasing shading coverage contributes directly to reducing radiant heat exposure and improving outdoor thermal comfort performance.



**Figure 4. Relationship Between Shading Coverage and MRT Reduction**

From a performance-based urban design perspective, the findings indicate that thermal comfort is not merely an environmental outcome but a direct consequence of spatial configuration, vegetation strategy, and solar-control integration. This supports Hensel's [49] argument that environmental performance should be embedded within the core logic of architectural and urban design processes.

Moreover, the results demonstrate that improved thermal comfort directly contributes to enhanced urban livability and public-space usability. Previous studies by Chen and Ng [30] and Nikolopoulou and Steemers [28] similarly concluded that outdoor thermal conditions strongly influence pedestrian activity, spatial perception, and social interaction within public urban spaces.

Statistical analysis confirmed that the differences in thermal performance between the two groups were statistically significant ( $p < 0.05$ ), indicating that the observed thermal improvements were directly attributable to the simulation-informed urban design process.

### Synthesis and Theoretical Contribution

The combined findings reveal a strong interrelationship between environmental performance and spatial quality within the urban design process. Improvements in thermal conditions—particularly MRT reduction and increased shading coverage—were closely associated with enhanced spatial organization, vegetation integration, and public-space quality. These results indicate that environmental performance is intrinsically embedded within the spatial logic of urban design rather than functioning as an isolated technical parameter.

This study demonstrates that integrating microclimate simulation into the design process enables a transition from reactive environmental evaluation toward generative and performance-informed design development. Unlike conventional urban design approaches where environmental analysis is conducted after spatial decisions are finalized, the proposed framework positions environmental simulation as an active decision-support mechanism guiding spatial configuration from the earliest stages of design development.

Figure 7 presents the simulation-informed urban design workflow applied in this study. The framework illustrates how environmental simulation functions as an iterative

process connecting baseline design, thermal analysis, spatial modification, and performance optimization.

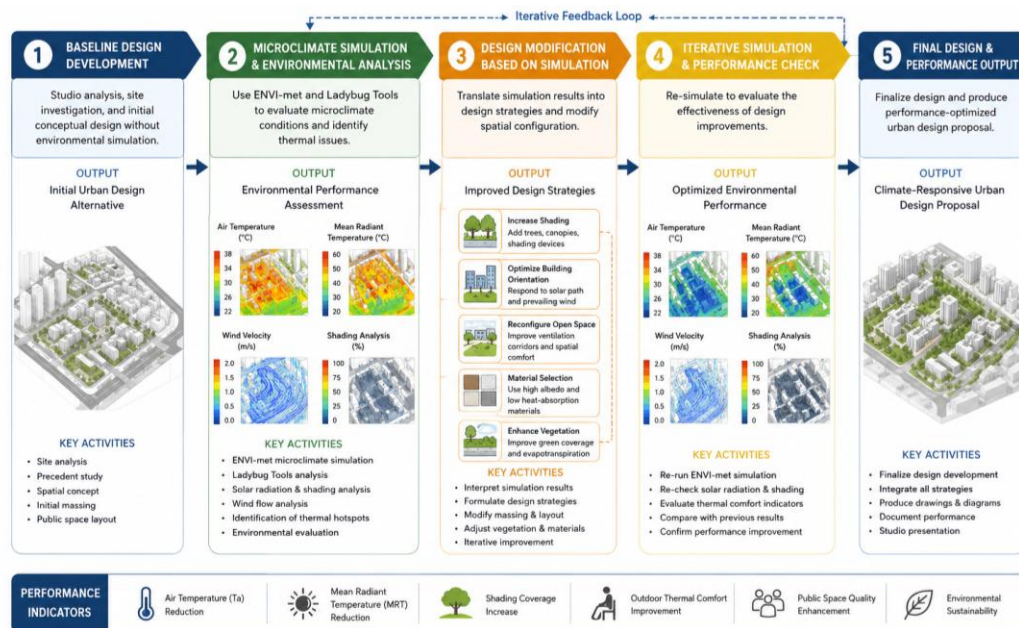


Figure 5. Simulation-Informed Urban Design Workflow

The novelty of this study lies in its integration of microclimate simulation within urban design pedagogy using a quasi-experimental framework that quantitatively links simulation, design quality, and thermal performance. While previous studies primarily focused on environmental evaluation within built urban environments [33], [37], this research extends the discourse by demonstrating how environmental simulation can actively shape spatial decision-making and design learning within architectural education.

The findings also reinforce the theoretical principles of performance-based and performative architecture proposed by Kolarevic and Malkawi [48], Hensel [49], and Hensel and Sørensen [50], which emphasize that environmental performance should become a primary driver of spatial formation and design development.

### Design Implications for Tropical Urban Design

The findings provide several important implications for climate-responsive urban design within tropical environments.

First, shading coverage emerged as the most influential environmental parameter affecting outdoor thermal comfort. Increasing shading coverage from 25% to approximately 55% significantly reduced both MRT and air temperature. Therefore, tropical urban design should prioritize shading integration through tree canopies, shading structures, arcades, and climate-responsive building massing.

Second, vegetation integration plays a dual role in providing shading and evapotranspirative cooling. Strategically positioning vegetation within high-exposure zones such as pedestrian pathways and gathering spaces substantially improves environmental comfort and public-space usability.

Third, building orientation and spatial configuration must respond directly to solar paths and environmental analysis rather than purely formal or aesthetic considerations. Simulation-informed workflows enable designers to quantitatively evaluate thermal performance and iteratively optimize environmental strategies throughout the design process.

Finally, the study demonstrates that integrating environmental simulation into urban design education significantly improves students' capacity to develop evidence-based and

climate-responsive urban design solutions. This finding suggests that simulation-informed learning models should be integrated more systematically into architectural and urban design curricula, particularly within tropical contexts vulnerable to urban overheating and thermal stress.

## DISCUSSION

This study introduces a novel simulation-informed urban design learning model that integrates microclimate simulation directly into the urban design process as an active generative mechanism rather than merely as a post-design evaluative tool. Unlike most previous studies that focus primarily on environmental assessment after the completion of design proposals, this research establishes an iterative framework in which environmental simulation outputs continuously inform spatial decision-making during the design process itself. The integration of ENVI-met and Ladybug within a quasi-experimental urban design studio setting represents an innovative methodological contribution, particularly within tropical architectural education contexts where empirical evidence regarding simulation-based learning models remains limited. The novelty of this study also lies in its quantitative linkage between environmental performance, thermal comfort indicators, and design quality within a unified pedagogical and performance-based urban design framework.

The findings demonstrate that the simulation-informed design process significantly improved both design quality and outdoor thermal comfort performance. The experimental group achieved an overall design quality improvement of 39.6%, with the highest increase observed in climate responsiveness (60.7%), followed by public-space quality (43.3%) and vegetation integration (41.9%). In terms of environmental performance, the experimental group reduced air temperature ( $T_a$ ) by 4.3°C and Mean Radiant Temperature (MRT) by 9.5°C while increasing shading coverage by approximately 30%. These findings indicate that integrating environmental simulation into the design process enables more adaptive spatial configurations and more effective climate-responsive strategies. The results also confirm that environmental performance is strongly interconnected with spatial quality, demonstrating that thermal comfort enhancement directly contributes to improved usability and livability of urban public spaces.

The findings of this study are consistent with previous research emphasizing the importance of climate-responsive urban design and environmental simulation in improving thermal conditions in urban environments. Santamouris (2020) reported that shading strategies and urban greening significantly reduce urban thermal stress and improve outdoor comfort in high-density cities. Similarly, Taleghani (2021) demonstrated that passive cooling strategies, vegetation integration, and urban morphology modifications contribute substantially to improving outdoor thermal comfort performance. Lai et al. (2023) further confirmed that MRT reduction and shading enhancement are among the most influential factors affecting outdoor thermal perception and public-space usability. In addition, Cheshmehzangi (2021) highlighted that environmental performance should become a central component of sustainable urban development strategies.

Within the field of architectural and urban design education, the findings also align with Salama (2022), who argued that performance-based and evidence-driven learning approaches are increasingly necessary to address contemporary environmental challenges in design education. Similarly, Ng and Ren (2015) emphasized that climatic analysis and environmental simulation should be integrated into urban planning and design workflows to support sustainable urban development. Furthermore, Gehl (2011) stated that the quality and comfort of public spaces directly influence public activity intensity and social interaction, which supports the present finding that improvements in thermal comfort are associated with enhanced public-space quality and usability.

The consistency between this study and previous research can largely be explained by the similar environmental mechanisms underlying thermal comfort improvement. Previous studies consistently demonstrate that shading, vegetation density, and solar exposure control are primary determinants of outdoor thermal conditions in tropical and subtropical climates. In

this study, the integration of simulation tools enabled participants to identify thermal hotspots and optimize environmental strategies more effectively, resulting in substantial reductions in MRT and improved spatial quality. These results reinforce the argument that environmental simulation enhances design precision by allowing iterative evaluation and optimization of climatic performance throughout the design process.

However, this study also differs from previous research in several important aspects. Most earlier studies focus primarily on real urban environments, post-occupancy thermal evaluations, or professional urban planning practices, whereas this research investigates the implementation of simulation-informed approaches within an educational urban design studio using a quasi-experimental methodology. In addition, previous studies generally evaluate environmental performance independently from design quality, while this study quantitatively links spatial quality, climate responsiveness, and thermal performance within a single analytical framework. The stronger improvement observed in climate responsiveness compared to other design criteria may also reflect the direct influence of environmental simulation tools, which provide measurable climatic feedback during the design process. Furthermore, the tropical context of this study may have amplified the significance of shading and MRT reduction due to consistently high solar radiation and humidity levels characteristic of tropical urban environments.

The study contributes significantly to the advancement of performance-based urban design and architectural pedagogy. Theoretically, this research expands the discourse on climate-responsive urban design by demonstrating that environmental performance can function as an active design generator rather than solely as an evaluative parameter. The study also contributes to urban design education by proposing a structured simulation-informed learning framework capable of integrating environmental data, spatial analysis, and iterative design development within studio pedagogy. Methodologically, the use of a quasi-experimental approach provides empirical evidence regarding the effectiveness of simulation-informed design processes, which remains relatively underexplored in existing literature. Consequently, this research helps bridge the gap between environmental simulation technologies and architectural learning processes in tropical urban contexts.

From a practical perspective, the findings indicate that urban designers and educators should integrate environmental simulation tools into the early stages of design development to improve both spatial quality and thermal comfort performance. The results highlight the importance of shading coverage, vegetation placement, and climate-responsive spatial configuration in creating more livable tropical urban environments. For architectural education, this study suggests that simulation-informed learning approaches can strengthen students' capacity to develop evidence-based and environmentally responsive urban design solutions. From a policy perspective, the findings support the incorporation of climate-responsive performance indicators into urban design guidelines, educational curricula, and public-space development strategies, particularly in rapidly urbanizing tropical cities vulnerable to urban overheating and thermal stress.

Despite these contributions, this study has several limitations. The research was conducted within a single academic studio involving a relatively limited number of participants and focused primarily on tropical urban conditions. Future research may expand the investigation by involving larger datasets, multiple institutions, diverse climatic contexts, and more advanced simulation technologies. Further studies may also examine the long-term impact of simulation-informed learning on professional design practice and investigate the integration of additional environmental variables such as wind flow, humidity, energy consumption, and user behavior analysis. These future directions may contribute to the further development of adaptive, evidence-based, and climate-responsive urban design methodologies.

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