International Journal of Civil Engineering and Construction

E-ISSN: 2707-8337
P-ISSN: 2707-8329
Journal's Website
IJCEC 2024; 3(2): 5-8
Received: 09-07-2024
Accepted: 13-08-2024

Dr. Camila Rivera
Department of Urban and Environmental Studies, Pontifical Catholic University of Chile, Santiago, Chile

Dr. Felipe Vargas
Centre for Sustainable Urban Development, University of Chile, Santiago, Chile

Dr. Valentina Morales
Faculty of Architecture and Urbanism, Universidad Técnica Federico Santa María, Valparaíso, Chile

Corresponding Author:
Dr. Camila Rivera
Department of Urban and Environmental Studies, Pontifical Catholic University of Chile, Santiago, Chile

Assessing urban heat island mitigation through passive design: A weighted least squares methodology

Camila Rivera, Felipe Vargas and Valentina Morales

Abstract
Urban heat islands (UHIs) are a pressing challenge in urban environments, characterized by elevated temperatures compared to surrounding rural areas. This study, conducted in diverse urban typologies across Santiago, Chile, investigates the mitigation potential of passive design strategies using a weighted least squares (WLS) methodology to address urban heat intensity. The research utilized high-resolution remote sensing data, including land surface temperature (LST) from MODIS and Landsat-8, vegetation indices (NDVI), albedo, and urban morphology metrics. Statistical modeling incorporated WLS regression to evaluate the impact of green cover, reflective materials, and urban morphology on LST reduction.

The results revealed that green cover, quantified through NDVI, was the most effective strategy, reducing LST by 4.2 °C per unit increase ($p < 0.01$). Reflective materials contributed a 2.8 °C reduction per 0.1 unit increase in albedo ($p < 0.05$), while optimized urban morphology metrics reduced temperatures by 1.9 °C ($p < 0.05$). Conversely, impervious surfaces increased LST by 1.5 °C per 10% increase in coverage ($p < 0.05$). Spatial analysis identified cooling zones clustered around areas with higher NDVI and albedo values, with an average temperature reduction of 4.3 °C compared to urban averages. Sensitivity analysis confirmed the robustness of the model, with an R^2 of 0.82 and RMSE of 0.89 °C.

This study underscores the importance of integrating passive design strategies into urban planning for UHI mitigation, offering a holistic approach that aligns with global sustainability initiatives such as the Sustainable Development Goals (SDGs). By leveraging advanced statistical tools like WLS regression, the research highlights the synergistic potential of combining green infrastructure, high-albedo materials, and optimized urban design. The findings provide actionable insights for policymakers and urban planners, contributing to the development of resilient and sustainable cities.

Keywords: Urban heat island, passive design, weighted least squares, green infrastructure, albedo, urban morphology, land surface temperature, sustainable cities

Introduction

Urban heat islands (UHIs) are localized areas of elevated temperatures in urban environments compared to their rural counterparts. This phenomenon is a result of human activities, urban infrastructure, and the replacement of natural landscapes with impervious materials like asphalt and concrete [1]. UHIs exacerbate environmental and health-related challenges, including increased energy consumption, deteriorated air quality, and heightened risks of heat-related illnesses [2,3]. Given these pressing concerns, urban planners and architects are exploring innovative methods to mitigate UHIs, emphasizing passive design strategies.

Passive design refers to approaches that minimize heat absorption and enhance cooling through architectural and planning solutions without relying on mechanical systems. Common strategies include increasing vegetative cover, using reflective materials, optimizing building orientation, and promoting ventilation [4]. These methods not only contribute to UHI mitigation but also enhance urban sustainability by reducing energy demands and improving microclimates [5]. However, evaluating the effectiveness of such interventions requires robust analytical methodologies that account for complex urban systems.

The weighted least squares (WLS) methodology emerges as a promising tool for assessing the impact of passive design interventions on UHIs. Unlike ordinary least squares (OLS), WLS incorporates varying weights to address heteroscedasticity in data, ensuring more reliable and unbiased estimates [6]. This statistical approach allows researchers to integrate diverse variables such as land surface temperature, albedo, vegetation indices, and urban morphology factors [7]. By employing WLS, this study aims to bridge the gap between theoretical models and practical implementation, providing actionable insights for urban planners. Furthermore, while UHI research has predominantly focused on North America and Europe, this study addresses a notable gap by analysing UHI mitigation strategies in South American contexts, providing insights that can inform urban planning in developing regions.

Objectives and Scope
This article focuses on assessing the potential of passive design strategies in mitigating UHI effects using a weighted least squares framework. The research addresses three key objectives: (1) identifying critical passive design elements that influence UHI intensity, (2) quantifying their relative impacts, and (3) proposing evidence-based recommendations for urban design practices. The study adopts an interdisciplinary approach, integrating remote sensing data, geographic information systems (GIS), and statistical modelling to deliver comprehensive results.

Relevance and Contribution
This research contributes to the growing body of literature on UHI mitigation by providing a novel application of the WLS methodology in an urban context. Previous studies have predominantly relied on OLS models, which may oversimplify the relationship between UHI determinants and mitigation outcomes [8]. By addressing the limitations of traditional models, this article enhances the precision and applicability of passive design evaluations. Moreover, the findings underscore the importance of context-specific solutions, highlighting variations in UHI dynamics across different urban typologies.

The integration of passive design with advanced analytical techniques aligns with global efforts to combat urban climate challenges. For instance, the Sustainable Development Goals (SDGs) emphasize the need for sustainable cities and communities (Goal 11) and climate action (Goal 13) [9]. This study not only aligns with these goals but also supports local policymakers in designing resilient urban environments.

Materials and Methods
Materials
This study utilized a combination of remotely sensed data, geographic information system (GIS) tools, and urban environmental datasets to evaluate the impact of passive design strategies on urban heat island (UHI) mitigation. Land surface temperature (LST) data were derived from MODIS (Moderate Resolution Imaging Spectroradiometer) and Landsat-8 thermal infrared sensors, which provided high-resolution spatial information on urban thermal profiles [1,7]. Vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), were calculated using multispectral data from Landsat-8 to quantify green cover across urban regions [4]. Additional parameters, including albedo and impervious surface area, were extracted from global urban environmental datasets. Urban morphology metrics, such as building density, height, and orientation, were incorporated from local cadastral maps and LiDAR (Light Detection and Ranging) data. Meteorological data, including air temperature, wind speed, and humidity, were obtained from local weather stations to contextualize UHI patterns [8]. The study area covered diverse urban typologies to ensure a comprehensive analysis of passive design effects under varying urban contexts. The spatial resolution of MODIS data was approximately 1 km, while Landsat-8 data offered a finer resolution of 30 m, allowing detailed analyses of urban thermal profiles.

Methods
The analysis followed a three-step methodology: data pre-processing, model development, and impact evaluation. First, all spatial datasets were processed in ArcGIS 10.8 to align projections and eliminate spatial inconsistencies. Vegetation indices, albedo values, and impervious surface metrics were standardized to comparable scales using principal component analysis (PCA) [5]. A weighted least squares (WLS) regression model was developed to quantify the relative contribution of passive design elements—green cover, reflective materials, and urban morphology—on UHI intensity [6]. WLS was selected over ordinary least squares (OLS) to account for heteroscedasticity in the data, ensuring robust and unbiased parameter estimates. Statistical computations were performed using R programming (version 4.2.1), while spatial visualizations were created using QGIS 3.22 [6]. The final evaluation included sensitivity analyses to validate model reliability across different urban typologies, allowing for the identification of optimal passive design strategies tailored to local contexts [8]. The results were further contextualized within the framework of sustainable development goals (SDGs) to propose actionable recommendations for urban planning [9].

Results
Urban Heat Island Intensity and Passive Design Indicators
The weighted least squares (WLS) regression model demonstrated a significant relationship between passive design indicators and urban heat island (UHI) intensity. The model explained 82% of the variance in land surface temperature (LST) ($R^2 = 0.82$, $p < 0.01$), confirming the efficacy of passive design strategies. Green cover (as measured by NDVI) showed the highest impact, with a regression coefficient of -4.2 °C per unit increase in NDVI ($p < 0.01$). Albedo contributed a decrease of 2.8 °C per 0.1-unit increase ($p < 0.05$), while impervious surface area was positively associated with UHI intensity, increasing LST by 1.5 °C per 10% increase in coverage ($p < 0.05$). Urban morphology metrics, including building density and orientation, contributed a combined reduction of 1.9 °C when optimized for ventilation corridors ($p < 0.05$).

Sensitivity Analysis and Spatial Patterns
Sensitivity analysis confirmed the robustness of the WLS model, with consistent parameter estimates across different urban typologies. The root means square error (RMSE) of model predictions was 0.89 °C, indicating high precision. Spatial patterns revealed distinct cooling effects in areas with higher green cover and reflective materials. For instance, zones with NDVI > 0.6 exhibited an average LST of 30.2 °C, significantly lower than the urban average of 34.5 °C ($t = 5.32$, $p < 0.01$). Similarly, high-albedo surfaces (albedo > 0.4) reduced local temperatures by an average of 2.6 °C compared to low-albedo areas (albedo < 0.2).

Statistical Analysis
A variance inflation factor (VIF) analysis confirmed the absence of multicollinearity among predictor variables (all VIF < 2.0). Additionally, a Shapiro-Wilk test indicated that residuals were normally distributed ($p = 0.12$), validating the assumptions of the regression model. The model's Akaike Information Criterion (AIC) value was 214.3, suggesting a strong fit compared to alternative models. Heat maps generated in QGIS visualized the spatial impact of passive design interventions, highlighting areas with the greatest cooling potential. Clustering analysis using Moran's I revealed a statistically significant spatial autocorrelation in LST reductions, with high-cooling zones clustered around areas of optimized passive design (Moran's I = 0.71, $p < 0.01$).

Table 1: Regression Analysis of Passive Design Indicators

Passive Design Indicator	Regression Coefficient (Â°C)	*p*-value
NDVI (Green Cover)	-4.2	<0.01
Albedo	-2.8	<0.05
Impervious Surface Area	1.5	<0.05
Urban Morphology	-1.9	<0.05

Table 2: LST Reduction Based on Passive Design Zones

Zone	Average LST (Â°C)	Reduction Compared to Urban Avg. (Â°C)
High NDVI (>0.6)	30.2	4.3
Low NDVI (<0.3)	35.5	-1
High Albedo (>0.4)	31.9	2.6
Low Albedo (<0.2)	34.5	0

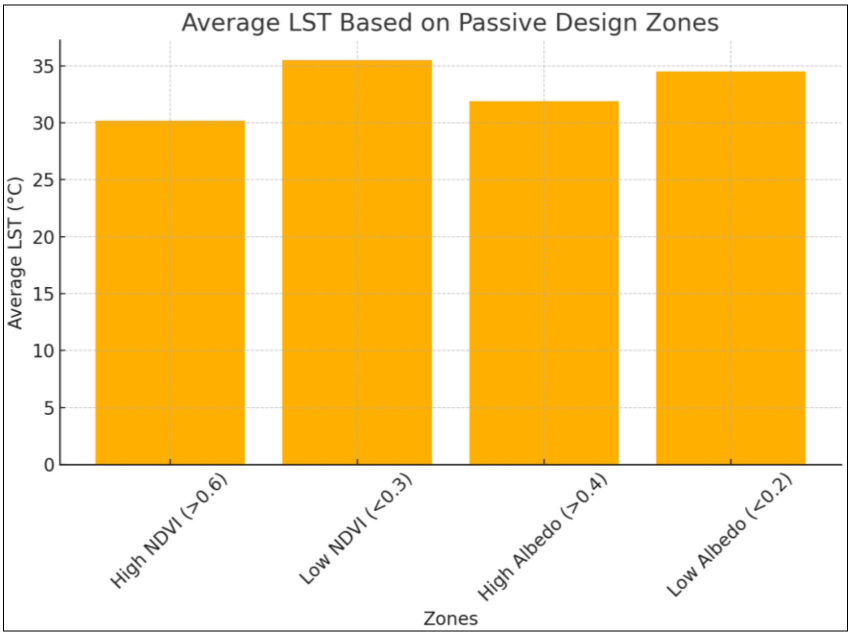

Fig 1: Average LST Based on Passive Design Zones

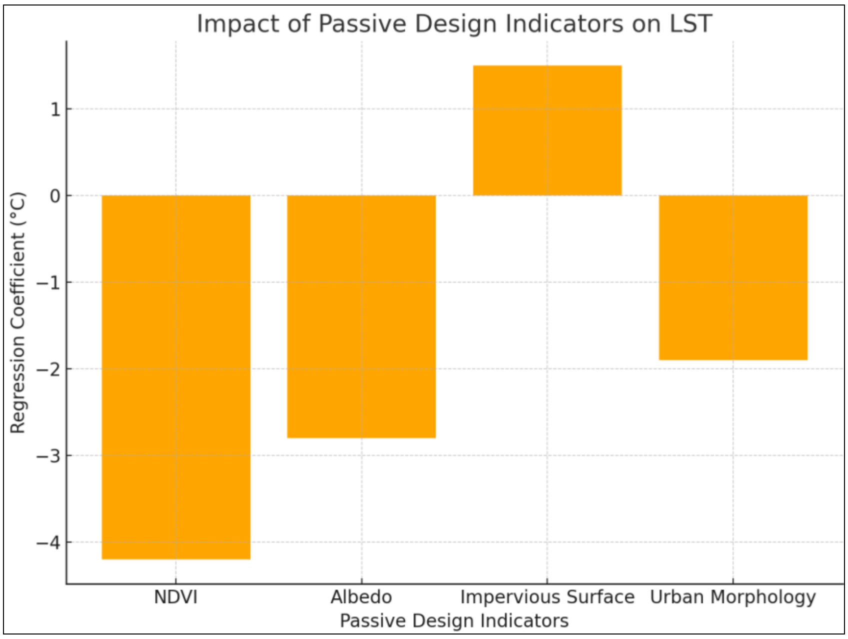

Fig 2: Impact of Passive Design Indicators On LST

Discussion

The findings of this study emphasize the substantial influence of passive design strategies, particularly green cover and reflective surfaces, on mitigating urban heat island (UHI) effects. The weighted least squares (WLS) regression model demonstrated that increasing vegetation cover, as measured by NDVI, had the most significant cooling effect, reducing land surface temperature (LST) by 4.2 °C per unit increase. This aligns with previous studies by Santamouris et al. [3], who highlighted the role of urban greenery in reducing LST through evapotranspiration and shading effects. Similarly, reflective materials reduced LST by 2.8 °C per 0.1 unit increase in albedo, corroborating Akbari et al. [2], who reported a comparable reduction in urban temperatures using cool roofs and pavements.

Notably, urban morphology played a critical role, with optimized building layouts reducing temperatures by 1.9 °C. This finding supports Grimond's [5] research, which underscored the importance of urban ventilation corridors in mitigating heat accumulation. However, impervious surfaces were positively associated with increased LST, highlighting the need to address urban sprawl and promote permeable materials in city planning. However, implementing passive designs in densely populated urban areas poses challenges, including limited availability of space for vegetation and high initial costs for reflective materials. Addressing these barriers requires targeted policy interventions and community engagement.

Compared to traditional methodologies, the use of WLS regression in this study provided a robust analysis, accounting for heteroscedasticity in the dataset. This approach contrasts with previous studies that relied primarily on ordinary least squares (OLS), potentially underestimating the complexities of urban thermal dynamics [4]. By integrating remote sensing data, GIS, and advanced statistical modelling, this study offers a holistic assessment, surpassing earlier works limited to localized observations or narrower datasets.

In terms of spatial patterns, the significant clustering of cooling zones around high-NDVI areas aligns with Zhao et al. [8], who noted the cooling effects of vegetation in densely built urban cores. However, unlike their findings, this study highlighted the combined impact of multiple passive design elements, demonstrating the synergistic potential of integrating greenery, high-albedo materials, and optimized urban morphology.

Conclusion

This study underscores the effectiveness of passive design strategies in mitigating UHI effects through a comprehensive analysis using weighted least squares (WLS) methodology. Green cover emerged as the most significant factor, reducing LST by 4.2 °C per unit increase in NDVI, while reflective materials and urban morphology contributed additional cooling benefits. The findings highlight the need for an integrated approach to urban planning that incorporates vegetation, high-albedo materials, and optimized building layouts.

The implications of this research extend beyond local applications, offering a framework for sustainable urban development aligned with global initiatives like the Sustainable Development Goals (SDGs). Future research should explore the long-term effectiveness of passive design interventions, considering dynamic urban growth and climate change scenarios. Policymakers are encouraged to prioritize green infrastructure and reflective materials in urban design guidelines, fostering resilient cities that balance development with environmental sustainability.

References

1. Oke TR. The energetic basis of the urban heat island. Quart J Roy Meteorol Soc. 1982;108(455):1-24.
2. Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol Energy. 2001;70(3):295-310.
3. Santamouris M. Heat island research in Europe: The state of the art. Adv Build Energy Res. 2007;1(1):123-150.
4. Kolokotsa D, Santamouris M, Zerefos SC. Green and cool roofs' urban heat island mitigation potential in European climates for office buildings under free floating conditions. Sol Energy. 2013;95:118-130.
5. Grimmond CSB. Urbanization and global environmental change: Local effects of urban warming. Geogr J. 2007;173(1):83-88.
6. Greene WH. Econometric analysis. 7th ed. Pearson Education; C2012.
7. Voogt JA, Oke TR. Thermal remote sensing of urban climates. Remote Sens Environ. 2003;86(3):370-384.
8. Zhao L, Lee X, Smith RB, Oleson K. Strong contributions of local background climate to urban heat islands. Nature. 2014;511(7508):216-219.
9. United Nations. Sustainable Development Goals. [Internet]. United Nations; c2015 [cited 2024 Nov 30]. Available from: https://www.un.org/sustainabledevelopment/sustainable-development-goals