

# Evaluation of Biomimicry-based Strategies to Improve Exterior Environmental parameters: A numerical Study at Urban Scale in a tropical Climate

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**Abstract.** Due to population growth, cities have expanded their urban areas, causing increased temperatures and vegetative scarcity. Therefore, studies have been carried out on the urban heat island phenomenon, its effect on people's thermal stress, and how to mitigate this problem. This research aims to evaluate the application of biomimetic strategies for improving exterior environmental conditions on an urban scale under a tropical climate through dynamic simulation. The case study takes place in the Casco Antiguo of Panama. Here, two cases were evaluated (base case and proposed case). The proposed case consists of strategies obtained from the application of the biomimetic design methodology. The ENVI-met software was used to evaluate both cases, where the external environmental parameters are compared between both cases for the critical months (March and October) at 15:00. Results showed that the air temperature reached an average reduction for March of 1.9 °C and 2 °C for October, the T<sub>mr</sub> had an increase up to 0.6 °C in March and the PET index decreased 1.7 °C in March and in October 2 °C. Although significant changes were obtained, high levels of discomfort persist due to the narrowness and proximity of the buildings in this urban settlement.

## 1 Introduction

In the last century, the development of urban areas has been based on land occupation, ignoring the deforestation of green areas, their surrounding environments where waterproofing materials used, with high thermal retention, generating, today a high environmental and energy cost.

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In 2018, studies showed that 55% of the world's population lives in urban areas, and it is estimated that by 2050 it will increase to 68% [1], which is the cause of the change in the microclimate of urban regions and will cause an increase in air temperature. So, cities and urban areas will be much warmer than nearby rural areas; this phenomenon is known as the urban heat island (ICU) [2].

According to United Nations studies, in Latin America and the Caribbean, 2018 has one of the highest percentages of urban population with around 81% [3], which indicates that this phenomenon also affects this region.

Panama City and its surroundings also present this situation as it exhibits a disorderly pattern that concentrates a large part of the country's population. In 2010, 65% of the country's total population resided in urban places, which will increase much more in the future. The evolution of the capital is conformed by a vertical development and closed core of tall buildings with designs sustained by the frequent use of electricity, especially in refrigeration and air conditioning [4].

Multiple strategies allow the mitigation of ICU, such as the inclusion of green areas in streets and avenues or the orientation of buildings as studied in [5], through the use of the Envi-Met tool, possible benefits were determined. Also, the use of ecological roofs, cold pavements, and cold roofs that allow the reflection of sunlight can be positive contributions.

Panama has limited energy resources that prevent it from meeting the growing demand. In addition, renewable energy sources are in full development, and the behavior of intermittent nature for this type of energy requires high investment costs [4]. It is necessary to look for other alternatives to be more energy efficient in cities. So, change the mentality and seek the most efficient way to solve problems as nature does, using new strategies called biomimetics.

Biomimetics is imitation engineering that combines biology and engineering whose goal is sustainability for human development and has been a source of inspiration throughout the years. It is divided into three primary levels (form, process, and ecosystem), which can be adapted to the design problem that needs to be solved. Darai Prabhakaran [6] shows in his research how biology can provide bio-inspired ideas in the development of materials for buildings according to the levels of biomimetics presented.

This research is mainly based on the search for strategies based on nature, focusing on the problem of the urban heat island and the thermal comfort of pedestrians in the old town of Panama City. Looking for different functions through which organisms in nature manage to regulate their temperature. These functions will be taken as a reference and define different types of processes and factors that carry it out and species that perform it. Thus, obtaining an appropriate number of strategies to choose those that best adapt to evaluate their performance through dynamic simulation in the Panamanian urban microclimate. In this matter, a recent study presented a biomimicry-based framework for application in Panama's climate [7].

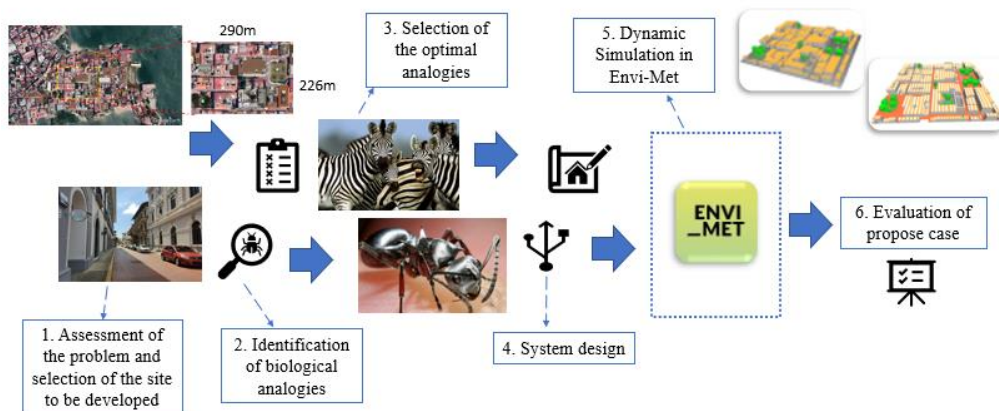
## 2 Materials and methods

For this research, the methodology adopted is based on the problem-based approach (figure 1). It will be developed in the following sections. This methodology implemented can be summarized as follows [8]:

- First, the study site must be identified, based on the problem of urban heat island and lack of comfort for pedestrians.
- Search for biological analogies that best adapted to the problem by studying their behavior, morphology, and physiology (thermoregulation), that is, the most

optimal, to achieve the proposed design.

- Abstraction of biological analogies to adapt it to the proposed design.
- Change of materials and properties in the buildings of the study case (simulation) and evaluation of the results in comparison with the base case.



**Fig. 1.** Proposed methodology for the development of the research

### 3 Case study

The study site is centered in the Casco Antiguo of Panama (coordinates  $8^{\circ} 57'09''$  N  $79^{\circ} 32'06''$  W). It has buildings of three to four floors narrow streets of at least 4.5 m to 9 m wide. This area is classified according to Stewart & Oke [9] as climate zone 3 (LCZ3), which comprises a dense area of low-rise buildings (one to three stories) with few trees and mostly covered with concrete.

Most buildings have colonial tiles, slabs, wood, and some with zinc on their roofs. The facades vary from calicanto, concrete, and clay blocks. The sidewalks and park areas are made of concrete, and the streets of basalt cobblestones.

To evaluate the nature-based strategies, parameters related to the comfort indicator were taken: air temperature, mean radiant temperature (T<sub>mr</sub>), and PET comfort index. The studied months are March with a maximum temperature of 35.6°C, a minimum of 24.9°C, a maximum relative humidity of 73 and a minimum of 36 (the hottest month) and October with a maximum temperature of 32.5°C, a minimum of 23°C, a maximum relative humidity of 96 and the minimum 62 (the rainiest month) at a critical time of 3:00 pm These values were used as input for the simulation in the ENVI-met software including the wind speed (5 m/s at 350° in March and 4.4 m/s at 90° in October).

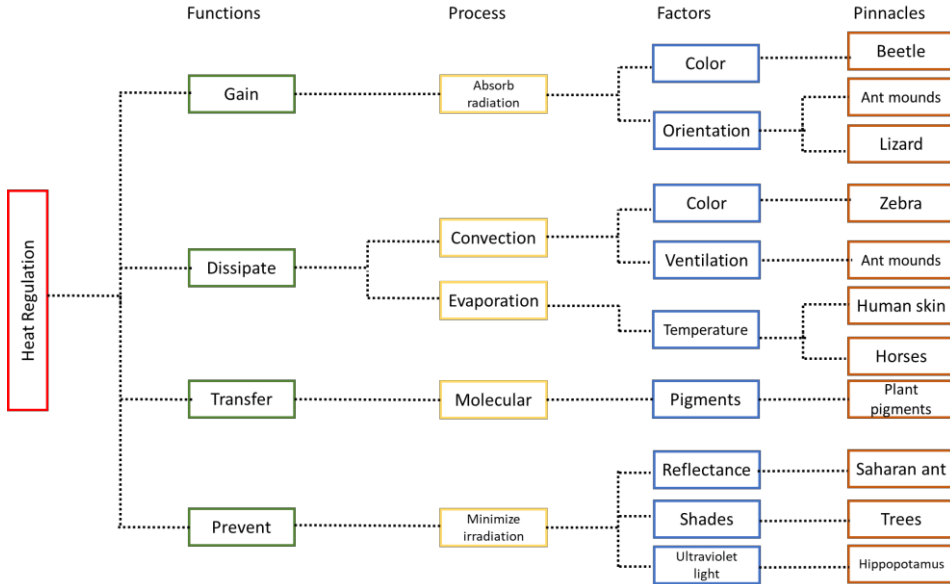
The simulation was carried out in the ENVI-met microclimate software, where the base case is initially evaluated to consider the most relevant problems within the area. This resulted in high levels of temperature and discomfort due to the urban canyons, construction materials, and shortage of green areas. Therefore, these problems are considered for the development of the design methodology.

#### 3.1 Identification and selection of biological analogies

The exploration model is the first step for identifying biological analogies where heat regulation is considered a primary problem as described in the methodology proposed in [10]. Thus, the biomimetic design is based on four initial functions: gain, dissipate, transfer, and prevent (Figure 2). The exploration model for heat regulation is structured in four levels. The first level describes the functions (for example, heat prevention). The second level highlights how each of the functions is performed (e.g., minimizing irradiation). The factors exhibited

by the highlighted processes are at the third level (e.g., reflectance). The fourth level represents the pinnacle or biological analogy with a particular function, such as the ant of the Sahara.

The chosen design challenges (or functions) to solve the problem of heat regulation are preventing solar heat gains in the studied area by reducing irradiation and increasing heat dissipation to avoid heat build-up in buildings and streets (Figure 2).



**Fig. 2.** Scanning model for the temperature regulation.

The challenge of "Preventing heat" to avoid heating are skills of some species that can be developed through their morphology, physiology, or behavior. Here, the minimization of solar radiation includes important factors such as reflectance and shadows. Thus, the representative pinnacles selected for this design challenge are the Saharan ant (reflectance) and the trees (shadows).

The ant is considered the pinnacle that best complies with the reflectance process and presents values among the highest reflectivities. From the exploratory model, trees minimize solar radiation by increasing the shadow area and are considered applicable in simulation software.

In addition, "increasing heat dissipation" to eliminate excess heat from surfaces is a common characteristic of species, called thermoregulation, performed either by morphology, physiology, or behavior. Therefore, for this design challenge, the selected process improves convection due to coloration in the zebra, one of the chosen pinnacles.

Moreover, Figure 3 shows the imaginary pinnacles marked in blue and green for the two challenges, dissipation, and prevention, respectively. The concept of an imaginary pinnacle is introduced to represent a pinnacle that possesses all the dominant characteristics of both pinnacles chosen for each design challenge in the seven categories (process, flow, adaptation, scale, environmental context, morphological characteristics, and material characteristics). The most relevant aspects of each pinnacle in each category are marked with an "X"; the imaginary pinnacle will then inherit the overlapping aspects of both pinnacles. For each category, the dominant characteristics determine the aspects to be considered: implemented process (e.g., Improve irradiation), flow strategy (passive or active), type of adaptation (e.g., morphological), performance scale (e.g., Macro), environmental context (e.g., tropical),

morphological characteristics (e.g., adjacent), and material characteristics (e.g., elastic).

After identifying the imaginary pinnacles for each design challenge, a design path matrix is drawn (not presented here) to help visualize the dominant characteristics of the imaginary pinnacles combined. From this, the following characteristics and relevant properties to the design concept resulted in:

- Process: Improve convection and minimize irradiation.
- Flow: Passive flow for dissipation and radiation prevention.
- Scale: Macro.
- Environmental context: Arid
- Morphological characteristics: Adjacent (or grouped) and pigment.
- Material characteristics: Low conductivity, high reflectivity, and emissivity.

Challenge	Pinnacle	Process -Improve convection -Minimize Irradiation	Flow -Active -Passive	Adaptation -Physiological -Morphological -Behavior	Scale -Nano -Micro -Meso -Macro	Environmental Context -Arid -Tropical -Moderate -Continental -Polar	Morphological characteristics -Pigments -Adjacent -Branch -Ducts -Hairs	Material characteristics -Conductive -Reflective -Emissive -Elastic
<b>Dissipation</b>								
	Zebra	X X	X	X	X	X X X	X X	X X X
	Imaginary pinnacle	X X	X	X	X	X X X	X X	X X X
<b>Prevention</b>								
	Saharan ant		X	X X	X X	X	X X	X X
	Trees	X X	X	X X	X X	X X X X	X X X	X X
	Imaginary pinnacle	X X	X	X	X	X	X	X X

Fig. 3. Pinnacles analysis matrix.

### 3.2 Proposed designs and simulation: Numerical Model

According to the design methodology implemented, a design case is proposed, based on applying a super reflective and emissive coating on the roofs, emulating similar characteristics of the Saharan ant with an adjacent behavior variation, that is, in the ceilings. Half of the ceiling surfaces are covered with cladding, and the other half is not. This aims to create a temperature difference between high and low reflectivity, generating convective currents that obtain dissipation and evaporation as occurs morphologically in the Zebra.

Figure 4 shows the changes made for the proposed case, where trees are added in Cathedral Square and Herrera Square. These two areas presented, according to the base case study, some higher temperatures. These trees have an albedo 0.1 greater, chosen from the 'software library, and the height was varied according to the area. The reflective coating has a reflectivity of 0.92 and emissivity of 0.9.

To evaluate all the parameters, the results are presented using a distribution of streets, organized as shown in Figure 5. This before to help the better interpretation of the results obtained for both cases and to be able to determine a more accurate description. In Figure 5, the vertical lines (A, B, C, D, E) represent the streets between the buildings, where the comfort of pedestrians at 1.5 m height is investigated. The horizontal lines (F, G, H, I) indicate the lanes, and the numbers (1, 2, 3, 4) represent the blocks. Finally, the shaded areas represent the squares

(Cathedral and Herrera square) with the same purpose mentioned above. In addition, the input values are considered earlier in section 3.

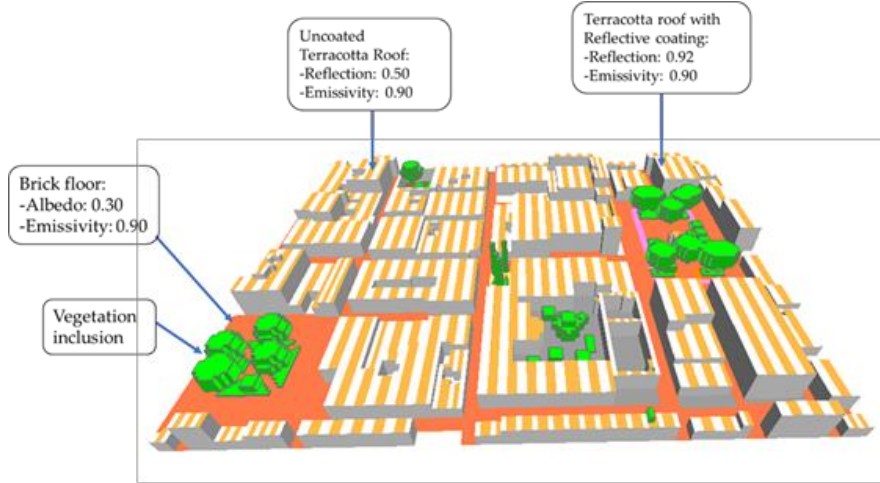


Fig. 4. Schematic of the case proposed developed in Envi- Met.

#### 4 Results analysis and discussion

In this section the results will be shown according to the simulation carried out in ENVI-met with the applied strategies and their comparison with the base case.

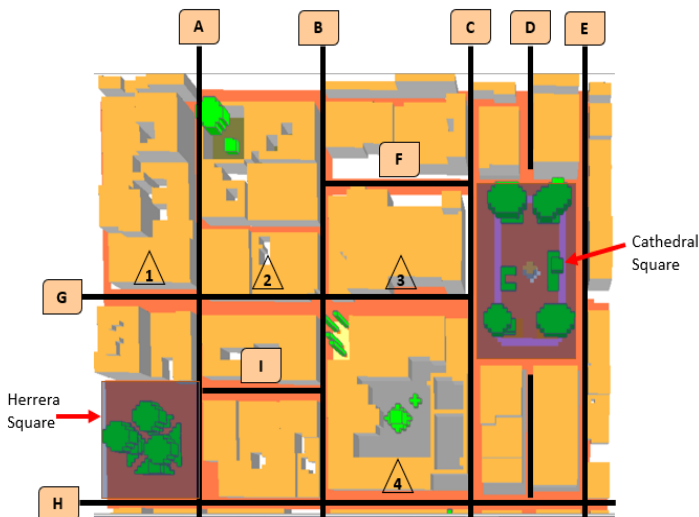


Fig. 5. Distribution and arrangement of zones.

##### 4.1 Air Temperature

Table 1 shows the comparison of the results at 1.5 m height of the base case concerning the proposed case in terms of average reductions. In March, the most significant reduction is found in Herrera Square and streets G1-G3, F, due to the incidence of the sun and the existence of greater shadow projection and the added vegetation. In October, the reductions are smaller, which indicates that the applied strategies have less effect in the rainiest month..

**Table 1** Comparison of air temperature for base case and proposed case by streets for critical months.

Air temperature		Area / Street	Reduction (° C)
March	15:00	Herrera Square	0.32
		Cathedral Square	0.12
		G1-G3, F	0.32
		H, I	0.13
October		Herrera Square	0.18
		Cathedral Square	0.17
		A, B	0.18
		G3	0.10
	H	0.17	

### 4.2 Mean radiant temperature (T<sub>mr</sub>)

Table 2 shows the reduction of the proposed case against the base case in terms of the average radiant temperature where it was reached in a range of 0.48 °C to 0.5 °C for specific areas in March, and for October, it ranged between 0.41 °C to 0.43 °C. This reduction might be due to the hour of solar exposure in the urban area since the materials are thermally loaded, resulting in weak reductions. In addition, the T<sub>mr</sub> is mainly influenced by the urban canyon. In the more clustered buildings, the adjacent vegetation also generates shade and its canopy by having a greater albedo, obtaining less absorption of solar radiation, but other alternatives are required to mitigate this effect further.

**Table 2.** Comparison of the mean radiant temperature for base case and proposed case by streets for critical months.

Mean radiant temperature		Area / Street	Reduction (°C)
March	15:00	Herrera Square	0.5
		G1-G3, H, I	0.48
		Catedral Square	0.48
		A, B, C, D, E	0.5
October		Herrera Square	0.42
		Catedral Square	0.41
		A, B, C, D, E	0.43
		G1-G3, H, I, F	0.41

### 4.3. Comfort index PET

Table 3 shows the comparison between the proposed case concerning the base case of the PET thermal comfort index. It can be clearly observed that only one category change in the index was achieved in Herrera Square in October (it was reduced from extreme heat to high heat). In streets A, B, C, D, and E in October, the index indicates moderate thermal stress, but there were no significant changes, and thus, thermal stress persists at a high level.

**Table 3.** Comparison for PET for base case and case proposed by streets for critical months.

	PET		Thermal stress		Reduction (°C)
	Time	Zone	Base Case	Proposed Case	
March	15:00	Herrera square	Extreme	Extreme	0.46



<b>October</b>	Cathedral square	Extreme	Extreme	0.47
	G1, G2,G3,H,I	Extreme	Extreme	0.23
	A, B, C, D, E	Extreme	Extreme	0.49
	Herrera square	Extreme	High Heat	0.44
	Cathedral square	Extreme	Extreme	1.9
	G1, G2,G3,H,I	Extreme	Extreme	0.43
	A, B, C, D, E	Moderate	Moderate	0.45

There is another indicator called UTCI (Universal Thermal Climate Index) also used to evaluate human thermal comfort in various microclimates, although the evaluation criteria and input parameters are very similar to PET (weight, metabolic rate, clo, etc.) and the Indicators for the PET are stricter unlike the ICU, therefore it was decided to continue evaluating only the PET.

## Conclusions

The main objective of this research was to conceptualize and evaluate heat mitigation through biomimetic strategies at an urban scale in the Casco Antiguo. The biomimicry-based strategies were developed using the problem-based approach. Finally, although considerable reductions in temperature and thermal stress indexes were achieved, high levels of discomfort persist, so it is recommended for future research to use the design methodology based on the same or other biomimetic strategies in building envelopes to consider cloudiness, rain, and the evaluation of the behavior of green walls and roofs versus reflective materials in this case study. In addition, future work should consider evaluating how the use of these strategies affects energy efficiency in buildings and the reduction of electricity consumption by air conditioners.

## Acknowledgements

This publication is part of the project FID18-056, which has received funding from Secretaria Nacional de Ciencia, Tecnología e Innovación (SENACYT). The authors would like to thank the Faculty of Mechanical Engineering, as part of the research group in Energy and Comfort in Bioclimatic Buildings (ECEB in Spanish), within the Universidad Tecnológica de Panama for their collaboration on this work. Extended gratitude to the Sistema Nacional de Investigación (SNI).

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