Urban morphology and solar incidence in public spaces - an exploratory correlation analysis through a CIM system

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Abstract. The walkability of open spaces has been highlighted in current discussions about the production of designed environments in urban contexts (Matan, 2011). To contribute to this theme, this work selects the environmental comfort of open spaces as its element of study. The production of urban space was investigated, specifically in regard to urban morphology, understanding that city design directly influences environmental comfort (Jacobs, 1996). This work addresses the geographic context of low latitudes, specifically in hot and humid climate zones of Brazil, and, in this context, according to NBR 15220 (national performance standards), shading is one of the main comfort strategies, so solar incidence was the approached environmental phenomenon. Thus, this work presents a digital system that performs exploratory analysis on the correlations between urban form indicators and environmental performance indicators, specifically solar incidence. The method consists of three steps: urban form modeling (1), indicator measurement (2) and correlation analysis (3). In the first stage, different spatial sections of a city in Brazil were represented in the digital environment (1). This work's implementation instrument is based on a City Information Modeling framework (Beirão et al., 2012). Visual Programming Interface (VPI) and Geographic Information Systems (GIS) tools were used, in addition to a Relational Database Management System (RDBMS). Then, for each urban clipping, the values of morphological indicators and the incidence of solar radiation were measured (2). Based on the values of the indicators, an exploration of their correlation was carried out by statistical methods (3). The results of the correlation analysis and their correspondent scatter plots are presented. Finally, possible applications of the results for the creation of prescriptive urban planning systems are discussed, seeking to promote a sustainable urban environment.

Keywords: Urban Planning, Environmental Comfort, Walkability, Urban Morphology, Statistical Methods.

1 Introduction

To approach urban space is to look at the relationship between people and the natural and built environment (Matan, 2011). Public spaces are the territory of a large part of people's interactions with the city, a relationship in which walking plays an essential role (Tight, Kelly, Hodgson & Page, 2004). Thus, the quality of life in the city is directly affected by the environmental comfort provided by city design (Jacobs, 1996).

According to NBR 15220-3 (ABNT, 2005), most of Brazil's territorial extension, comprised by Bioclimatic Zone 8, of hot and humid climate and which includes almost all coastal capitals, requires shading and the possibility of natural air ventilation as corrective measures for hours of the year in thermal discomfort. Thus, it is possible to state that the analysis of solar geometry plays an important role in the development of thermal comfort strategies (Muniz-Gäal et al., 2020) and, although it is not the only dimension to be considered, it is one that allows a quick response, which proves to be very useful in early design phases, where the exploration of the range of possible solutions is essential (Wilkinson et al., 2014).

The aim of this paper is to explore possible relationships between the urban morphology and thermal comfort at road intersections in cities with hot and humid climates and low latitudes. The work was developed based on a hypothesis: the urban form, when in predominantly flat topography and described by operational variables of density that define an urban aggregation at the level of an intersection and its respective blocks, is a variable correlated to thermal comfort, when this is described by operational variables of shaded area.

In order to do that, the definitions of the main density indicators of the Spacematrix method are considered, already used in calculations of urban performance in issues similar to those explored in this research. One of the performance analyses carried out in the work of Berghauser Pont and Haupt (2009) deals exactly with a phenomenon of strong correlation with the role of solar radiation in the definition of thermal comfort used by the present research - that of performance in capturing natural light. The results suggest, specifically for open spaces, that there is a relationship between the two variables FSI and GSI and the daylight factor performance.

This paper is a development of Master's research of Passos Filho (2021).

2 Methodology

The method comprises three main steps: urban form modeling (1), indicators measurement (2), and correlation analysis (3).

For the modeling of the analyzed spaces and calculations of density and quantification of the urban form in quantities compatible with the studies to be carried out, the system developed by Moreira et al. (2022) was adopted. It is a City Information Model (CIM) structure, based on the connection between a Database Management System (DBMS), a Geographic Information System (GIS) and a set formed by a Visual Programming Interface (VPI) and a Computer-aided Design (CAD) tool, which is called the Algorithmic Modeler. PostgreSQL was the free software used for the DBMS, and QGIS was the adopted GIS solution, while Rhinoceros 3D and its parametric environment Grasshopper 3D set the Algorithmic Modeler. A plugin for Grasshopper 3D called Carcará was used to establish the connection between the VPI and the database, and was also responsible for translating the georeferenced geometry into Cartesian coordinates, manageable by the VPI and representable by the CAD environment (Moreira et al., 2022).

The result is an LOD 1 model of neighborhoods in the city of Fortaleza, the capital of Ceará state, Brazil, within a parametric platform capable of extracting all the operational variables. The aggregation level used for the analysis was that of the road intersections. This decision is due to a better interpolation between performance indicators of neighbouring nodes of the road network, so that any calculated intermediary value will necessarily be contained in extralot space. The delimited area comprises the point of intersection between streets and a radius that takes this point as its center and extends to the middle of the side of the block. From this circumference, the area of the surrounding lots is subtracted, leaving only the area of the circumference that belongs to public space. This area is then discretized, as a grid, into small cells that will be used as an analysis position for the calculations involving solar geometry (Figure 1).

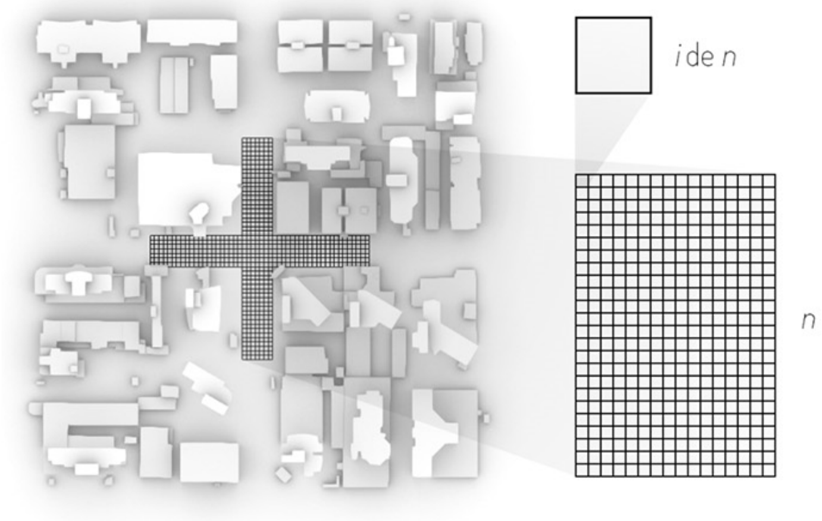

Figure 1. Aggregation level and its grid of analysis. Source: Authors, 2023.

In the next step, morphological indicators and solar incidence were measured for each road intersection. As a morphological indicator, the density measures developed by Pont & Haupt (2009) were used. Tables 1 contain the primary indicators for the different levels of urban aggregation contained in the surroundings of a road intersection. Features with variants "(min)", "(max)" and "(mean)" refer to the lowest, highest and average values present at the intersection surroundings, respectively.

Table 1. Primary indicators for the different levels of urban aggregation.

Features	Descriptions	Units
F(min); F(max); F(mean)	Total built area (by lot)	(m²)
A_b(min); A_b(max); A_b(mean)	Building's projection area	(m²)
A_l(min); A_l(max); A_l(mean)	Lot area	(m²)
t_l(min); t_l(max); t_l(mean)	Building-lot tare	(m²)
A_i(min); A_i(max); A_i(mean)	Block (island) area	(m²)
t_i(min); t_i(max); t_i(mean)	Lots-block tare	(m²)
A_is	Intersection area	(m²)
t_is	Blocks-intersection tare (network area)	(m²)
l_i	Network's internal segments summation	(m)
l_e	Network's external segments summation	(m)

Source: Authors, 2023.

Table 2 presents the secondary features, calculated from the values in the previous table. For feature groups, calculations are made with values referring to the specific aggregation level, that is: lot (l), block (i) and intersection (is). Therefore, F_l will be the sum of all F of the respective lot, A_l will be the area of the lot; F_i will be the sum of all the F of the respective block, A_i will be the area of the block; F_is will be the sum of all the F of the respective intersection, A_i will be the area of the intersection and its surroundings; A_b_l will be the sum of all projection areas of the buildings on the respective lot; A_b_i will be the sum of all the projection areas of the buildings in the respective block; and A_b_is will be the sum of all the projection areas of the buildings of the respective intersection. Again, for variants "(min)", "(max)" and "(mean)", it refers to the lowest, highest and average values present in the intersection.

Table 2. Secondary indicators for the different levels of urban aggregation.

Feature group	Features	Formula	Units
Network Density	N	(l_i + (l_e/2)) / A_is	m/m²
Floor Space Index	FSI_l(min); SI_l(max); FSI_l(mean)	F_l / A_l	-
	FSI_i(min); SI_i(max); FSI_i(mean)	F_i / A_i	-
	FSI_is	F_is / A_is	-
Floor Space Index	GSI_l(min); GSI_l(max); GSI_l(mean)	A_b_l / A_l	-
	GSI_i(min); SI_i(max); GSI_i(mean)	A_b_i / A_i	-
	GSI_is	A_b_is / A_is	-

Source: Authors, 2023.

Figure 2 illustrates each feature for the calculation of the morphology indicator.

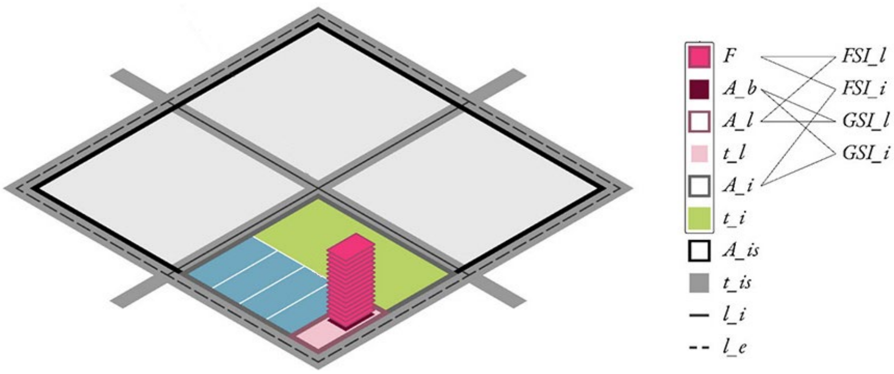

Figure 2. Aggregation level and its grid of analysis. Source: Authors, 2023.

For the solar incidence measurements, the bioclimatic chart of Olgyay (1963) was adopted as the tool for the conceptualization of comfort based on dry bulb temperature, given a certain value of relative humidity, if the space is in shade, with the possibility of corrections by wind speed. The Olgyay model stands out for its simplicity and objectivity in the application of climate variables that are easily accessible through climate files widely used in computer simulations, in addition to establishing a clear relationship between comfort and built space.

In order to obtain the necessary data for the analysis according to the Olgyay chart, simulation engines are used together with climate files obtained for the city of Fortaleza, within the parametric modeling environment of VPI. The Ladybug Tools plugin for Grasshopper 3D is used for solar geometry calculations (Figure 3). The performance indicator for each intersection is then calculated as the arithmetic average of the percentages of the total amount of daytime hours of a year in which there is a shadow cast on each cell of the grid of analysis of that intersection and its corresponding combination of temperature and humidity is comfortable (Formulas 1 and 2).

$$C_i = HS_i/H_y \quad (1)$$

$$C = (C_1 + C_2 + C_3 + \ldots + C_n)/n \quad (2)$$

Where:

- n is the total amount of cells in the analysis grid;
- i is the index of each individual cell in the grid;
- HS_i is the amount of daytime hours, in a year, when there is a shadow cast on the cell of index i and there is a comfortable setting of temperature and humidity;
- H_y is the total amount of daytime hours, in a year;
- C_i is the performance indicator of the cell of index i;
- C is the performance indicator of the intersection, as the arithmetic average between all C_i.

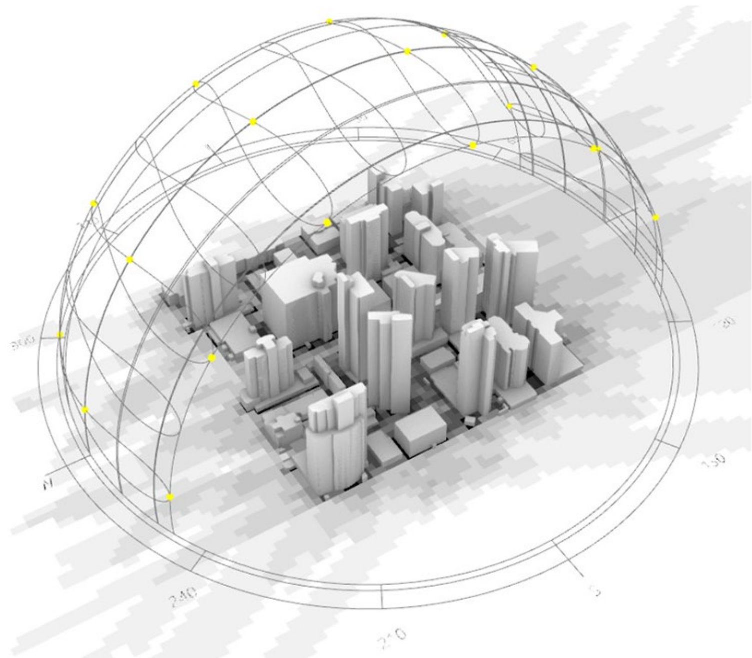

Figure 3. Cumulative shadows cast on the grid of analysis. Source: Authors, 2023.

The third step (correlation analysis) involved statistical methods to explore the correlation between the indicator values obtained in Step 2. The study introduced a digital system designed for exploratory analysis, with a specific focus on investigating the connections between urban form indicators and environmental performance indicators, particularly solar incidence.

Figure 4. Total urban environment that was segmented into minor urban aggregations (road intersections) for the simulations. Source: Authors, 2023.

Therefore, the produced database correlates the thermal comfort indicator of each crossing with its variables, or features, of urban form. The technique used for correlation analysis consisted of the product-moment correlation coefficient, also known as Pearson's correlation coefficient. It functions as a linear correlation measure between two sets of data. It is the covariance of two variables, divided by the product of their standard deviations, and is therefore essentially a normalized measure of covariance (Kent State University, 2020). The data used were extracted from the CIM model, characterizing each intersection with the morphological features and the result of the shading simulation.

3 Results

As a result of the previously detailed method, the analysis provided a general profile of correlation in regard to all morphological variables assessed. Figure 4 shows a bar chart with the value of the Pearson’s correlation coefficient for each density dimension.

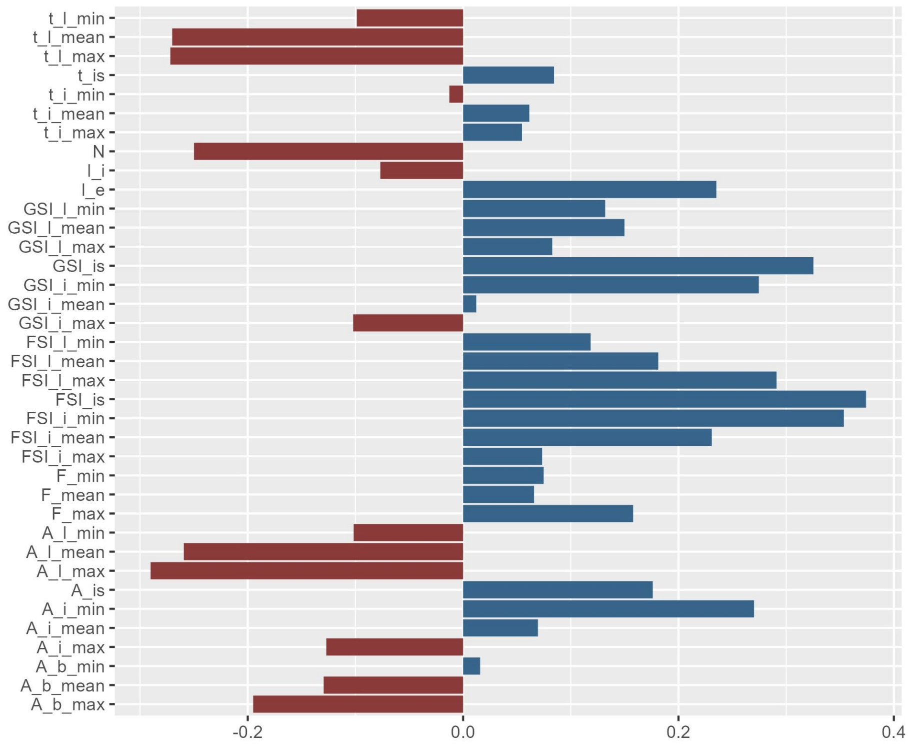

Figure 5. Pearson's coefficient for all density dimensions. Source: Authors, 2023.

Positive correlation values were obtained for lots-block tare, Ground Space Index, Floor Space Index, total built area, area of blocks and area of intersection features, while negative values were found for building-lot tare, Network, area of lot and area of building's projection features.

The most correlated features in each set of positive and negative correlation coefficients are Floor Space Index of the intersection (0.37) and maximum lot area (-0.29), respectively. Correlation details between both features and target variable are shown in Figure 4 as scatter plots and distribution charts.

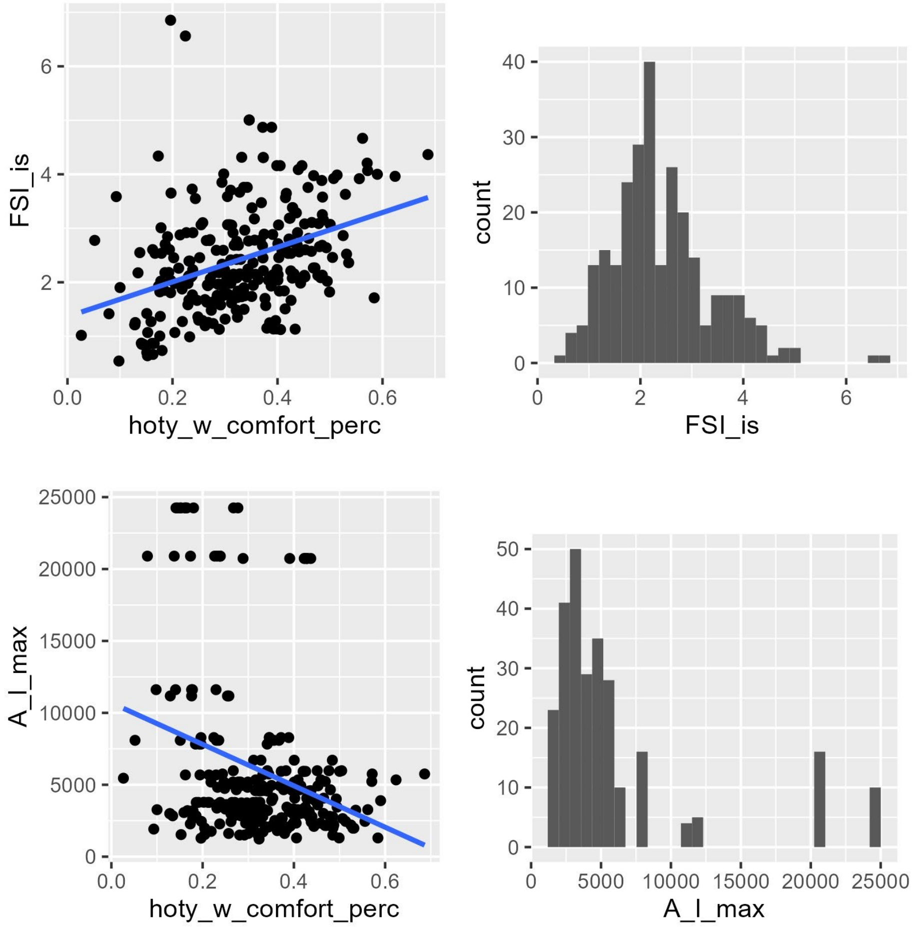

Figure 4. Scatter plots and distribution charts for most correlated density dimensions. Source: Authors, 2023.

Some minor contradictions were also found in regards to specific lots-block tare features. Minimum values were negatively correlated (-0.01), although maximum and mean values were positively correlated (0.05 and 0.06, respectively). However, all values are low enough to safely disregard these features as poor predictive variables, when analysed independently. Something similar happens to the maximum area of blocks, which is negatively correlated (-0.12), while minimum and mean values of this feature are positively correlated (0.27 and 0.06, respectively).

4 Discussion

This study seeks to investigate potential correlations between urban morphology and thermal comfort at road intersections within cities situated in low-latitude regions with hot and humid climates, as long as their topography is predominantly flat. It is also guided by the underlying hypothesis that the urban configuration, quantified by operational density variables defining the spatial arrangement of intersections and their adjacent blocks, exhibits a significant correlation with thermal comfort, as characterized by operational variables related to shaded areas.

However, analyses carried out in the course of this research have led to some noteworthy both expected and unexpected findings:

1. Positive correlation values were found for morphological features regarding both horizontal and vertical dimensions of built spaces. This is perfectly in line with previously intuited reasonings. The more is built, the more is shaded.

2. Negative correlation values were found for morphological features mostly related to how empty is the intersection space, further contributing to intuited reasonable predictions. The less is built, the less is shaded.

3. Certain negatively correlated features, however, are related to how large is a space dedicated to the built environment but not necessarily built to its full capacity. In this case, then, the larger the lots, the less is shaded.

4. None of the studied morphological features reached a significant level of correlation to the target variable when considered individually, staying close, but still under, the 0.4 value for the Pearson's coefficient.

These findings collectively underscore the importance of density in the better understanding of certain aspects of urban performance, especially those features that more closely resemble urban parameters contained in city regulations. In this case, shading was also analysed and proven to be, to some degree, an aspect correlated to the specific measurements of urban morphology taken into consideration by the investigations that took course during this research.

It is necessary, though, to highlight how still imprecise these measurements are on their own, when used as individual predictive factors. Further improvements on their descriptive capabilities will be sought in future investigations regarding different scales for urban aggreggations to be simulated, revisions on the calculations of density for these new proposed aggregations, and the use of more advanced techniques, such as machine learning, to use these features collectively as a model to serve as a predictive tool.

Counterintuitive findings also state much more about the specific characteristics of our chosen urban cut. The fact that large lots implicate on less shaded areas means that most large lots are usually internally less occupied with buildings, which is a statement that is not possible to generalize.

We can also infer that due to the poor capability of these morphological features more closely related to current legislative urbanistic parameters in individually controlling thermal comfort performance at the extralot level, other urban features should also be taken into consideration, such as green infrastructure.

Nonetheless, it is clear, for this relatively small sampling of 267 road intersections, that some urban density features have the potential of, when more intricately associated and analysed in larger sets of more diverse urban configurations, being useful in more than just understanding correlations, but also as a predictive tool to help in early stages of planning and design.

In summary, the research followed a structured approach involving urban form modeling, indicator measurement, and correlation analysis to investigate the relationship between urban form indicators and environmental performance indicators, presenting new insights on how to improve legislative prescriptive parameters in order to guarantee better tools for urban planning.

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