THE INFLUENCE OF URBAN CANYONS ON THERMAL COMFORT: THE CASE OF JUIZ DE FORA

A INFLUÊNCIA DE CÂNIONS URBANOS NO CONFORTO TÉRMICO: O CASO DE JUIZ DE FORA

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Abstract

New research regarding the comfort and liveability of modern urban areas has gained increasing attention with climate changes and the trend towards intensified urbanization in modern cities. The urbanization processes have commonly resulted in urban heat islands, dense and central spaces where the air temperature is higher when compared to peripheral areas. The increase in the temperature in these spaces causes thermal discomfort, directly impacting people's quality of life. The urban morphology impacts users' thermal perception while limiting or allowing solar and wind access, thus interfering with the thermal comfort perceived by people. That is the case of urban canyons, a morphologic phenomenon that can reduce the solar incidence and local wind speeds, altering the heat exchanges between buildings and the air and changing the thermal comfort. Thus, through parametric approaches, the present work aims to identify how the changes in the urban morphology impacted the thermal conditions of an urban canyon in the central area of Juiz de Fora, Minas Gerais, Brazil. The analyses, which compared three different moments in history (1940, 1980, and 2020), were performed using Ladybug Suite Tools / Grasshopper plugins for Rhinoceros software; and were based on the Universal Thermal Climate Index (UTCI). The maps generated indicate the changes in the local thermal comfort and its historical development. The results demonstrated that the urbanization process over the years strongly affected the thermal conditions of the urban canyon at the pedestrian level.

Keywords: *City information modeling. Urban planning. Urban management. Brazil. CIM.*

Resumo

Com as mudanças climáticas e a tendência de intensificação da urbanização nas cidades modernas, novas pesquisas sobre o conforto e a habitabilidade das áreas urbanas modernas vêm ganhando cada vez mais atenção. Os processos de urbanização geralmente resultam em ilhas de calor urbanas, espaços densos e centrais onde a temperatura do ar é mais alta quando comparada às áreas periféricas. O aumento da temperatura nesses espaços causa desconforto térmico, impactando diretamente na qualidade de vida das pessoas. A morfologia urbana impacta a percepção térmica dos usuários ao limitar ou permitir a incidência solar e ventos locais, interferindo no conforto térmico percebido pelas pessoas. É o caso dos cânions urbanos, fenômeno morfológico que pode reduzir a incidência solar e a velocidade dos ventos locais, alterando as trocas de calor entre os edifícios e o ar, alterando o conforto térmico. Assim, por meio de abordagens paramétricas, o presente trabalho visa identificar como as mudanças na morfologia urbana impactaram as condições térmicas de um cânion urbano da área central de Juiz de Fora, Minas Gerais, Brasil. As análises, que compararam três momentos diferentes da história (1940, 1980 e 2020), foram realizadas com o software Ladybug Suite Tools / Grasshopper para o software Rhinoceros; e foram baseados no Índice de Clima Térmico Universal (UTCI). Os mapas gerados indicam as mudanças no conforto térmico local durante seu desenvolvimento histórico. Os resultados demonstraram que o processo de urbanização, que ocorreu com o passar dos anos, afetou fortemente as condições térmicas do cânion ao nível do pedestre.

Palavras-chave: *Modelagem da informação da cidade. Planejamento urbano. Gestão urbana. Brasil. CIM.*

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Introduction

Studies regarding external thermal comfort have gained increased attention throughout the last decades. Due to climate change and reinless urbanization processes, urban heat islands, microclimates in which the local air temperature is higher when compared to rural areas, have been increasingly formed. Urban heat islands have caused thermal discomfort in different urban climates, being characterized as a global problem, although it manifests differently in each area and climate in the world (KIM; BROWN, 2021; BORNSTEIN, 1968; OKE, 1981; OKE, 1982; TAHA, 1997; AMORIN, 2005). In this regard, Gartland (2008) showed several studies carried out globally, demonstrating how the urban heat island phenomenon varies according to the location. For instance, measurements in 1990 in Tokyo highlighted a gradual and steady increase in air temperature from 1.0 to 1.5 °C during the summer between urban and suburban areas. On the other hand, a study in Reykjavík, Iceland, presented urban "cold" islands, in which the temperature in urban areas is lower than in rural areas during the summer. While in Phoenix, Arizona, US, the urban heat island effect results in air temperatures up to 8 °C hotter in central areas than in peripheral areas. So, it is remarkable how the urban heat island phenomenon manifests differently according to the location.

According to Oke (1981), the main factors involved in the creation and intensification of an urban heat island are: a) anthropogenic heat (heat created by human movement, cars, public street lighting, etc.); b) urban surface's properties (albedo, thermal absorptance, etc.); c) changes on the vegetative cover; d) presence or absence of bodies of water and; e) urban morphology, being the latter one of the most influential factors (OKE, 1981). In this scenario, urban canyons have become a matter of growing concern. The term urban canyon, also known as a street canyon, was described by Nunez and Oke (1977) as an area that "consists of the walls and ground (usually a street) between two adjacent buildings". The buildings located on both sides of a street create a canyon-like environment that resembles the natural formations of canyons (OKE, 1982).

The effect of this urban configuration on the environment is influenced by climatic variables such as solar incidence, wind speeds, and heat exchange between buildings and the air (OKE, 1981). Their effects, which contribute to climate changes (KIM; BROWN, 2021), may be exacerbated in the summer, resulting in outdoor thermal discomfort for pedestrians (MUNIZ-GÄAL *et al.*, 2020). In turn, tall and deep urban canyons in tropical areas can be a desirable option to maintain human comfort at acceptable levels by creating shaded spots during hot moments of the day. On the other hand, deep canyons can hinder the heat dispersion to the sky vault at the end of the day, worsening the nocturnal heat island effect (KOWALSKI, 2019). Therefore, it is important to understand the effect of urban canyons on the local thermal comfort, particularly in tropical areas, where strategies to mitigate the heat island effect may facilitate the work of architects and planners to consider urban microclimate in the early design stage (RAJAGOPALAN; LIM; JAMEI, 2014).

In this work, an urban canyon in the city of Juiz de Fora, a metropolitan area in Minas Gerais, Brazil (OECD, 2022), was evaluated. The city's centre was developed without considering the effects of verticalization, and legal instruments to order urban growth were only created in 2000, with the city's Master Plan for Urban Development (JUIZ DE FORA, 2004). The work of Ferreira, Carrilho and Mendes (2015), Ribeiro, Gonçalves and Bastos (2018) and Assis (2016) identified an urban heat island in Juiz de Fora. It was found that the air temperature is 7,6°C higher in the central area compared to its surrounding neighbourhoods, which can be explained by its insipid vegetative cover and big demographic and habitational density. The authors highlighted that thermal comfort and discomfort zones vary according to the urban morphology conditions.

This study aims to identify how the changes in urban morphology over time impacted the thermal conditions of Halfeld Street, an urban canyon in the central area of Juiz de Fora. To this end, we used computational simulations to compare the area's thermal comfort in 1940, 1980, and 2020. Thus, the relevance of this study relies on addressing a historical/chronological approach to assess how the verticalization processes and built density affect outdoor comfort conditions in a dry-winter humid subtropical city (Köppen, 1900) as in the case of Juiz de Fora. Moreover, few analyses were done on this kind of climate, especially while correlating with a chronological framework.

This paper is structured through the background, case study, results, discussion, and conclusions sections. The background presents a brief literature review introducing studies on the thermal conditions of street canyons, with different climates being analyzed to identify the factors affecting the urban heat islands. The case study describes the area of analysis and the research methods. Results and discussion present the simulation and discuss the outcomes. Finally, in conclusion, reflections on the findings are presented, also indicating research limitations and further studies.

Background

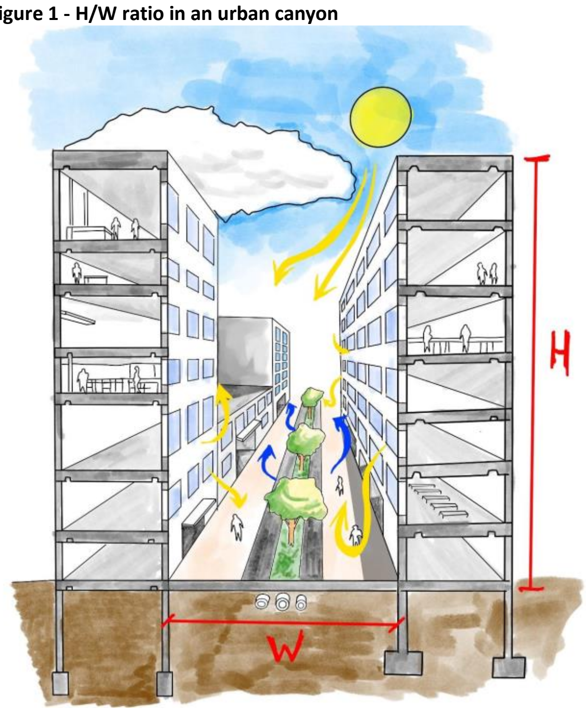
The thermal conditions in an urban canyon vary according to the local climatic conditions, such as wind speed and direction, solar trajectory, and air relative humidity. Physical parameters such as building heights, topography, green areas and water bodies, materials used on facades and floors, and surfaces albedo also play an important role. Several studies have analyzed the influence of urban morphology and other climatic and physical parameters on the thermal conditions of urban canyons.

Bourbia and Boucheriba (2010), Johansson (2006), Evola (2020), and Muniz-Gäal *et al.* (2020) carried out field measurements of air temperature in urban canyons in the Mediterranean (Algeria and Italy) and tropical (Sri Lanka and Brazil) climates. The authors analyzed the summer periods to characterize the moments of the day that the thermal discomfort happened. As a result, they identified the height-to-width (H/W) ratio as a physical parameter that influences the air and building's surface temperatures inside an urban canyon. The H/W ratio is defined by the buildings' average height (H) divided by the distance between the canyon's opposite sides (W) (Figure 1). The results indicated that as the H/W increases, the average building height also increases. Therefore, the morphology blocks the sun radiation depending on the solar angle. Hence, shade spots are created, in which the air temperature was found lower during hot moments of the day.

Rossi, Krüger, and Nikolopoulou (2011), Basso et al. (2018), and Nakata-Osaki, Souza, and Rodrigues (2016) investigated the relationships between the Sky View Factor (SVF) parameter and the comfort conditions at the pedestrian level in urban canyons in different Brazilian tropical cities. The SVF is defined as the percentage of the sky that can be seen from a particular analysis point; this factor is used to estimate how morphology limits solar incidence. The results determined that as the SVF decreased, more solar radiation was blocked by morphology. Hence, the air temperature was lower at the pedestrian level. However, in general, these studies indicated that low SVF and high H/W ratios could hinder the dispersion of the thermal energy gathered throughout the day, and, therefore, it can worsen the nocturnal heat island. This effect can be worse in tropical cities, depending on the morphological conditions.

On the other hand, Yang, Wong, and Jusuf (2013), Herrmann and Matzarakis (2012), and Abdollahzadeh and Biloria (2021) assessed urban canyons in Singapore, Freiburg, and Sidney, respectively, aiming to compare the effect of different canyon axial orientations on the radiation incidence and wind conditions. The results indicated that the street's orientation had a major influence on the outdoor comfort conditions, as it can allow solar incidence or create shaded spots during hot moments of the day and block or allow the circulation of local winds.

Figure 1 - H/W ratio in an urban canyon



Source: the authors.

The wind is another parameter that influences thermal comfort in an urban canyon. In this regard, Andreou and Axarli (2012) and Kitous, Bensalem, and Adolphe (2012) analyzed the effect of wind patterns in urban canyons in the city of Tino, Greece, and Ghardaïa, in the northern part of the Algerian Sahara. As a result, it was highlighted that local wind speed and direction were influenced by the street's axial orientation and the topography's slope, which could either slow or increase wind velocities, causing alterations in outdoor comfort conditions.

The presence of water bodies in urban spaces also greatly impacts the urban thermal environment. Syafii *et al.* (2017) evaluated the effect of the presence and proximity of water bodies on urban canyons' thermal conditions in Saitama, Japan. The results indicated that ponds closer to urban canyons could lower the air temperatures and keep the relative humidity at higher levels. However, it is important to note that it can negatively influence pedestrian comfort conditions depending on the prevailing solar radiation conditions.

In turn, the effect of vegetation on the air temperature was verified by Coutts *et al.* (2016), Wang and Akbari (2016), and Gong *et al.* (2018). The authors highlighted the climatic mitigator role of green areas in canyons. In Montreal, Canada, they reduced thermal stress by up to 4 to 6 °C, lowering temperatures even at a higher level (2 °C at 60m from the ground). The effect of green areas varies according to canopy cover, geometry, and prevailing weather conditions. Results also indicated an increase in the cooling effect according to the height and size of the treetops, which reduces the radiation that reaches the ground level and provides an evaporative cooling effect from leaf surfaces. Still, trees managed to absorb air pollution from road traffic emissions, improving the local air quality in a study of urban canyons in densely built areas of Hong Kong, China (Gong *et al.*, 2018).

Finally, it should be noted that many of the studies on urban canyons were carried out in cities located mainly in the northern hemisphere and in areas close to the sea. The literature also indicated that although some of the studies were carried out in Brazil, few of them used computational simulations (ENVI-Met being the most used software). Nevertheless, we did not find studies that used a chronological approach to understand the impact of urban canyons on outdoor thermal conditions of a dry-winter humid subtropical climate.

Case study

Area of analysis

The central area of Juiz de Fora has an orthogonal urban layout (Figure 2) due to the first city's development plan, created in 1855. The streets in the central area were designed rectilinearly and perpendicularly to each other, sheltering the city's main commercial buildings and being the densest and most populous part of the city (SAMPAIO, 2010). Thus, some streets are conformed as corridors with buildings on both sides, configuring urban canyons, as in the case of Halfeld Street (highlighted in red in Figure 2), one of the leading commercial streets in Juiz de Fora.

Figure 2 - Urban layout of Juiz de 'Fora's central area

Source: adapted from (JUIZ DE FORA, 2004).

Methods

The methods used in this study were adapted from works by Evola et al. (2020) and Naboni et al. (2017, 2019). They performed analyses using the Ladybug Suite Tools software to assess the thermal conditions of urban environments. This methodology is structured in 4 parts: a) data collection, b) modelling of the area analyzed in the three periods considered, c) conduction and analysis of parametric simulations, and d) data analysis. Table 1 summarizes our methodological procedures.

Table 1- Methodological procedures used

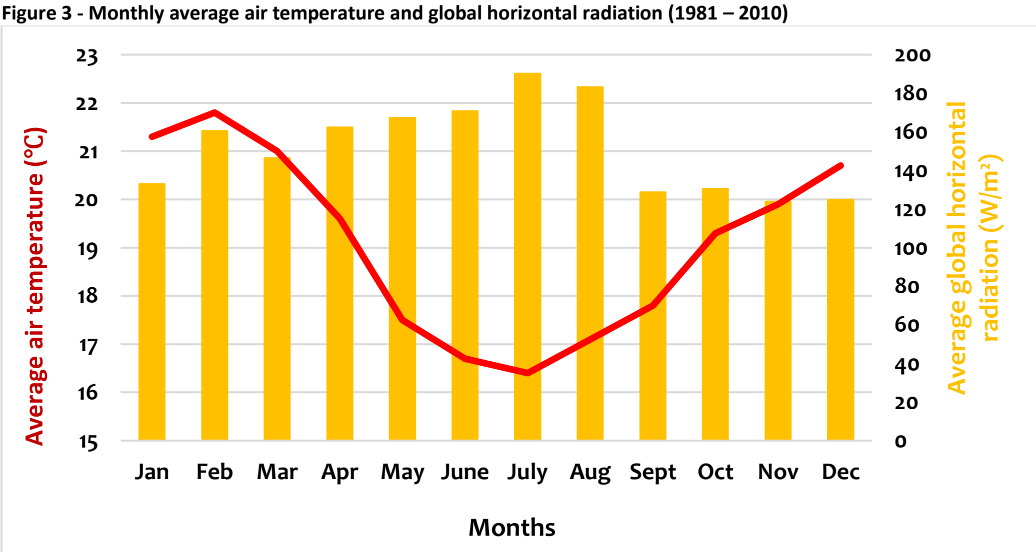
part 1 DATA COLLECTION	part 2 MODELING	part 3 SIMULATIONS	part 4 DATA ANALYSIS
PHYSICAL DATA (analysis of photos and historical documents)	BUILDING HEIGHT AND FOOTPRINT	1940, 1980, and 2020 (summer and winter solstices)	STATISTICAL SIGNIFICANCE ANALYSIS
CLIMATIC DATA (.epw)	CLIMATIC DATA (UWG)	8am, 12pm, 4pm and 8pm	VARIANCE ANALYSIS (Friedman's Two Way Analysis)

Source: the authors.

Part 1 – Data collection

The data collection was based on two types of information: physical and climatic. For the physical data, the building footprints and heights of Halfeld street were collected from the cadastral plans and photos from the city's historical archives (1940 and 1980). For the current period (2020), loco observations and the Google Street View tool were used. For the climatic data, the climatic file used in the simulations was collected from the Energyplus energy website database. Juiz de Fora is located at latitude 21° '41' "20" south and longitude 43° '20' "40" west, with humid and hot summer and dry and cold winter, as shown in Figure 3. During cold seasons, the radiation levels are higher from May to August, reaching up to 190 W/m² and air temperature levels are as low as 16,4°C. The humidity and precipitation levels are lowest in July and August, reaching a minimum of 60%. On the other hand, during the warmer seasons, humidity reaches up to 86% and accumulated precipitation of up to 300mm, approximately. The city's prevailing wind direction is north-south, with an average of 3,09m/s.

Figure 3 - Monthly average air temperature and global horizontal radiation (1981 – 2010)



Source: data from the National Institute of Meteorology.

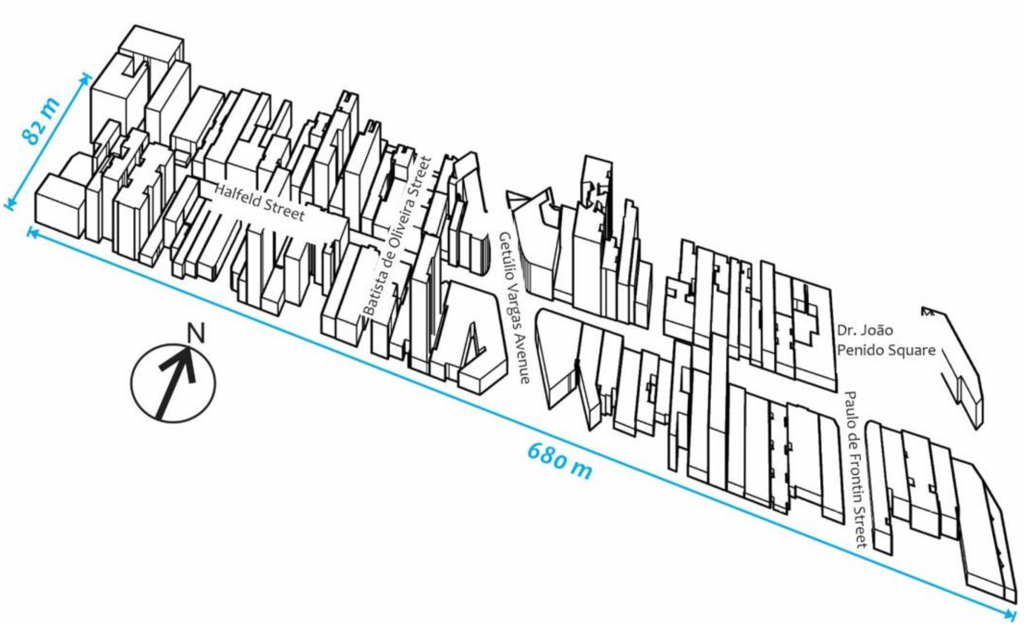
Part 2 - Modeling

The three considered moments were modelled in the Rhinoceros 3d software. Halfeld street is 11.5m wide and has 680m in length. For the simulations, an area of 82m x 680m was developed considering the whole urban canyon and its building geometries (Figure

4). The detailing considered for modelling the building's geometries was based on Level of Detail (LOD) standards proposed by CityGML[1]. According to Gimenez et al. (2015), the LOD-1 is appropriate for thermal analysis. Therefore, only the basic shapes of the buildings were considered. Thus, balconies, roofs, openings, and other architectural elements were not considered. In addition, a height of 3 meters was stipulated for each floor of the buildings.

The .epw file was modified for each period of analysis using the tool Dragonfly through the Urban Weather Generator – UWG. This algorithm allows making macroclimate files compatible with a microclimate scale, given the fact that it is a component created for urban heat island studies (MACKEY *et al.*, 2017). The component allows the user to assign parameters such as car traffic, public lighting, pedestrian activity (sensible heat or anthropogenic heat), and physical attributes of buildings (albedo). The parameters were configured according to Table 2.

Figure 4 - Snippet delimited for the analysis



Source: the authors.

Table 2 - Main parameters assigned to the UWG algorithm according to the year of analysis

YEAR OF ANALYSIS	ALBEDO (SOIL)	ALBEDO (WALLS)	SENSIBLE HEAT – W/m²
1940	0.1	0.35	4
1980	0.2	0.50	10
2020	0.2	0.50	10

Source: the authors.

Finally, the soil and walls' albedo values were based on the Pomerantz *et al.* (2000) study, which delimited typical albedo values for different surfaces based on field measurements. The sensible heat values were based on the work of Sailor (2011), which presented standard values for sensible heat. The study did not consider green areas as Ladybug does not consider vegetative masses (evapotranspiration) in its simulations, and there are no green areas along the canyon of Halfeld Street.

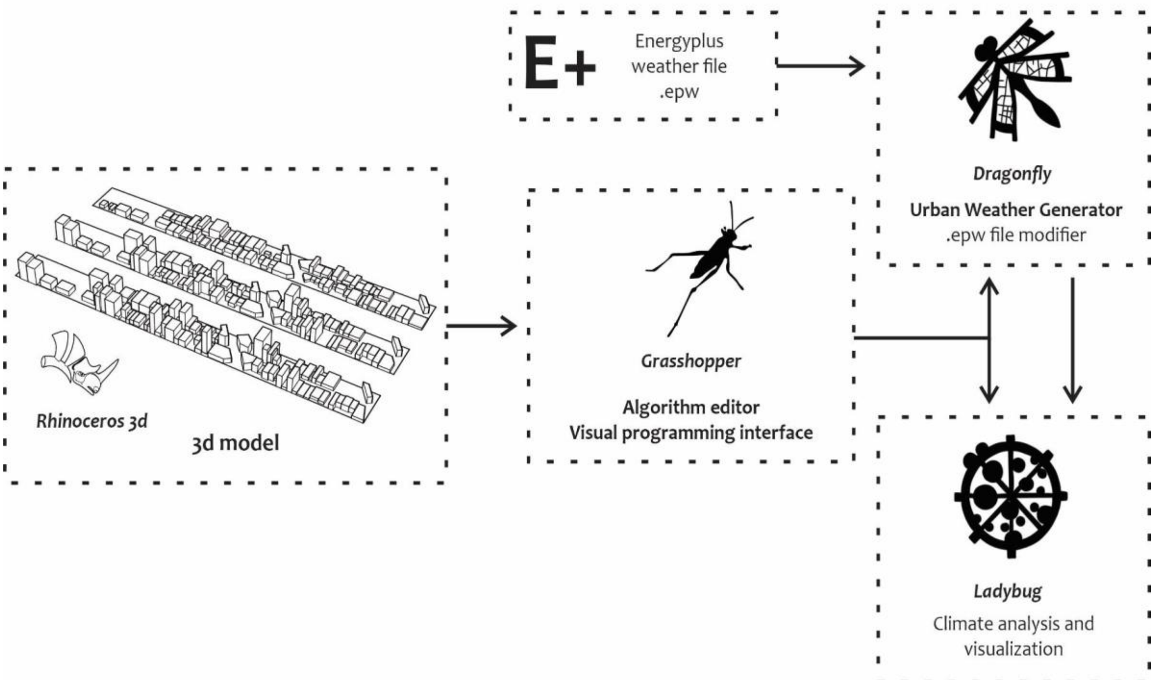
[1] CityGML is an open data model and XML-based format for storing and exchanging virtual 3d city models. Available on: https://www.ogc.org/standards/citygml

Part 3 – Simulations and data analysis

Although ENVI-Met has been extensively used for urban comfort evaluations (NABONI, 2017), it has some drawbacks for complex geometries and accounting for heat storage of walls, which can, therefore, underestimate air temperature values at night. Furthermore, although a student license is freely available, the analysis grid is limited to a 50 x 50m size, limiting the simulation environment to a smaller scale (EVOLA et al., 2020). Ladybug Suite Tools, created in 2012, on the other hand, was firstly developed for parametric analysis of design options at a building scale. With the addition of tools embedded in Grasshopper, the software then allowed the prediction of outdoor comfort conditions. Ladybug is freely available, has a user-friendly interface, and is more accessible to urban planners, architects, and designers within the Rhinoceros 3d CAD background. In addition, 'Ladybug's workflow presents good and valid data compared to measured data (ROUDSARI et al., 2013). Hence, this was used for the analyses.

The simulations were carried out considering the winter and summer solstices (21 of June and December, respectively) at 8 am, 12 pm, 4 pm, and 8 pm, resulting in eight different analysis moments of thermal spatial conditions. The procedures for the simulations followed the scheme shown in Figure 5. Seven analysis points were strategically placed along the canyon according to Figure 6. The points were located in different spots to obtain a wider variety of results. Some points were allocated in the middle of the canyon. In contrast, others were placed on open spaces which received more radiation (street crossings and urban squares) and were closer to buildings (possibly shaded areas).

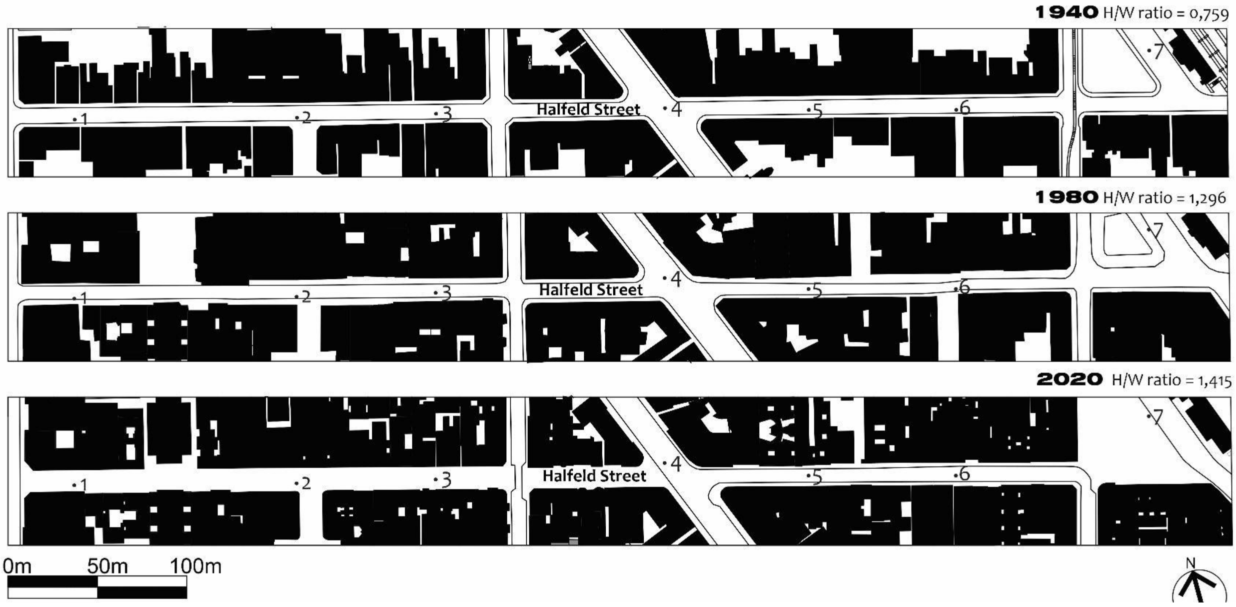
Figure 5 - Scheme of simulation construction based on the software and plugins used



Source: Adapted from Evola *et al.* (2020).

The workflow of the simulations started by modelling the geometries within Rhinoceros 3d. The geometries were inserted into Grasshopper as Breps (Boundary Representations) and linked to Ladybug. The .epw file from Energyplus was morphed using the Urban Weather Generator component from Dragonfly, as mentioned in the previous step. Finally, the morphed .epw file was connected to Ladybug, which performs the simulations.

Figure 6 - Maps showing the location of the seven analysis points (1940, 1980, 2020)



Source: adapted from (JUIZ DE FORA, 2004).

The thermal comfort metric used for the analysis is the Universal Thermal Climate Index (UTCI), which was created to apply to all climates. The UTCI index is a standard for the "feels like" temperature sensation. The index is defined as the air temperature of a reference environment of 50% relative humidity and having the air temperature equaling the radiant temperature, which produces the same strain index value as in the real, more complex real environment. The index is based on a single equation and accounts for human variables such as activity and clothing insulation (MATZARAKIS; NASTOS, 2011). The UTCI has been already considered in canyon studies (Couts *et al.*, 2016; Park, Tuller, and Jo, 2014) as an acceptable and easy way to determine thermal comfort. The results can be used as a human bioclimatic map for analyzing the outdoor thermal effects, contributing to urban and landscape planning and design. The index is calculated based on four main climatic variables: mean radiant temperature, air temperature, relative humidity, and local wind speeds. The temperature scale is categorized in stress levels, as shown in Table 3.

Table 3 - Thermal discomfort categories

UTCI scale (ºC)	Stress category
Above +46ºC	Extreme heat stress
+38 to +46 ºC	Very Strong heat stress
+32 to +38ºC	Strong heat stress
+26 to +32ºC	Moderate heat stress
+9 to +26ºC	No stress (comfort zone)

Source: adapted from (MATZARAKIS; NASTOS, 2011).

The UTCI index calculation was based on the Urban Microclimate_-_Simple Spatial UTCI component, embedded within the 'Ladybug's tools. The calculation process accounts for the presence or absence of direct sunlight on people, but it does not account for spatial thermal differences driven by the local wind speeds. It is important to highlight that the mentioned component does not account for tree evapotranspiration processes; however, it was not considered in the analysis. The climatic file used for the simulations does not account for local climate specificities. Its climatic data is usually obtained in urban places away from the central area, free from obstacles (MACKEY *et al.* 2017).

Statistical analysis was performed comparing the UTCI values obtained to assess the modification of the thermal comfort conditions over the years. For this, the R software (version 4.0.3) was used. Datasets (UTCI values for winter and summer solstices at 8 am, 12 pm, 4 pm, and 8 pm) were first tested for normality using the Kolmogorov-Smirnoff and Shapiro-Wilk tests, and it was found that data followed a non-parametric distribution. Hence, variance analysis was carried out using Friedman's Two Way Analysis of Variance by Ranks for each solstice day and hours of analysis, grouped by years, which resulted in 8 different tests ($n = 68$, $k = 3$). Multiple comparisons between the groups (years) were made to assess which ones were significantly different from the others.

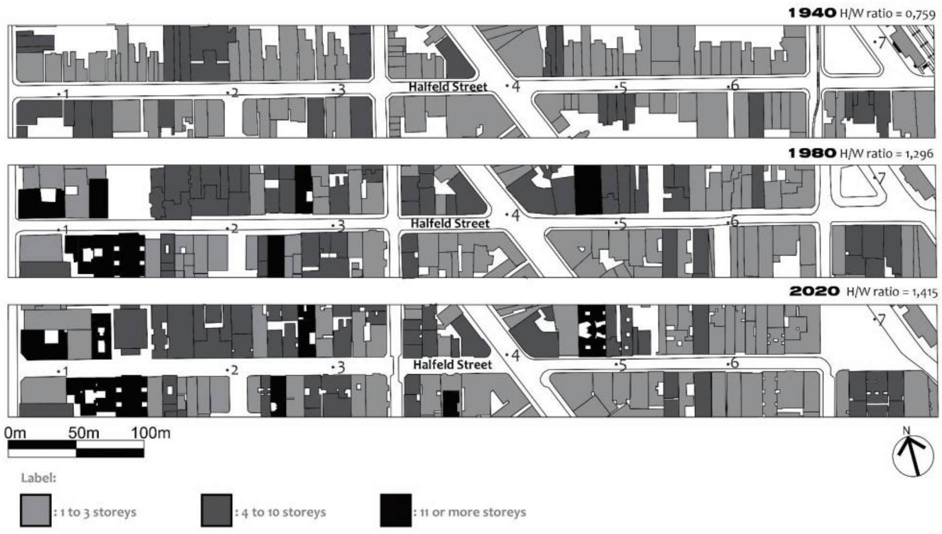
Results and discussions

This section presents and discusses the obtained results. It includes the building heights and urban density evaluations of each year analyzed, followed by the sky view factors of the canyon. For the last, the analysis grid was positioned at 1.7m from the ground to obtain the SVF values from an average person's standing viewpoint. Then, the UTCI analyses on the winter and summer solstices are presented, comparing the three studied moments: 1940, 1980, and 2020. The impact of the morphological changes on the 'canyon's thermal comfort is identified.

Urban Parameters analysis

From the photos and analysis of the historical archives, it was possible to identify the morphological changes in the space evaluated. Figure 7 depicts how the H/W ratio has changed over time. In 80 years, it went from an average of 0,759 to 1,415, increasing about 86%. However, it is important to note that according to Evola (2020), Halfeld Street is not consolidated as a deep canyon, as its ratio is lower than 1.5.

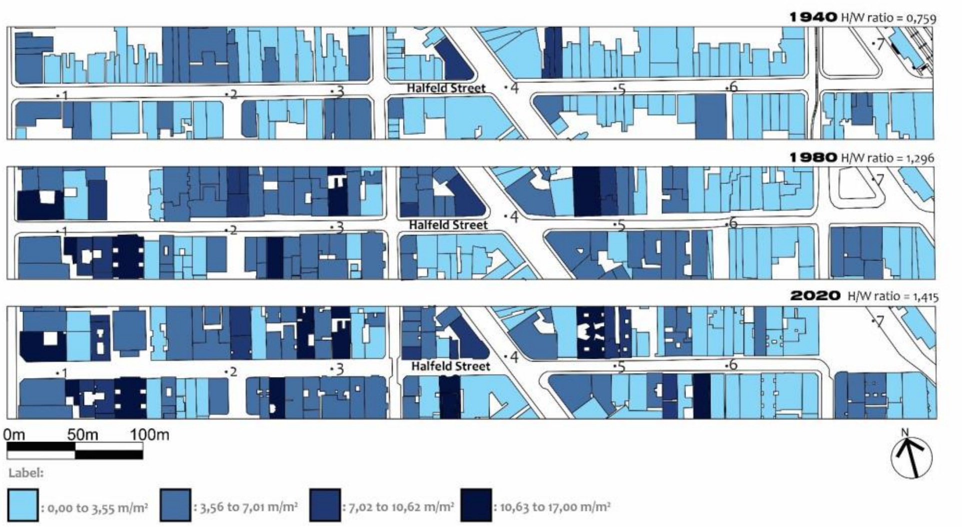
Figure 7 - Building height maps for the three analysis periods (1940, 1980, 2020)



Source: adapted from (JUIZ DE FORA, 2004).

The Ground Space Index (GSI) and Floor Space Index (FSI) (PONT; HAUPT, 2021) of the analyzed area are presented in Figures 8 and 9. The FSI consists of the ratio between the building's footprint area and the land area. On the other hand, the GSI is the sum of all gross floor area of buildings, divided by the area of the building's land. From Figure 7, it was possible to identify areas within the canyon that became denser throughout the years. The changes were more expressive from 1940 to 1980, when, on average, the FSI and the GSI increased by about 222% and 74%, respectively.

Figure 8 - Floor Space Index maps for the three analysis periods (1940, 1980, 2020)



Source: the authors.

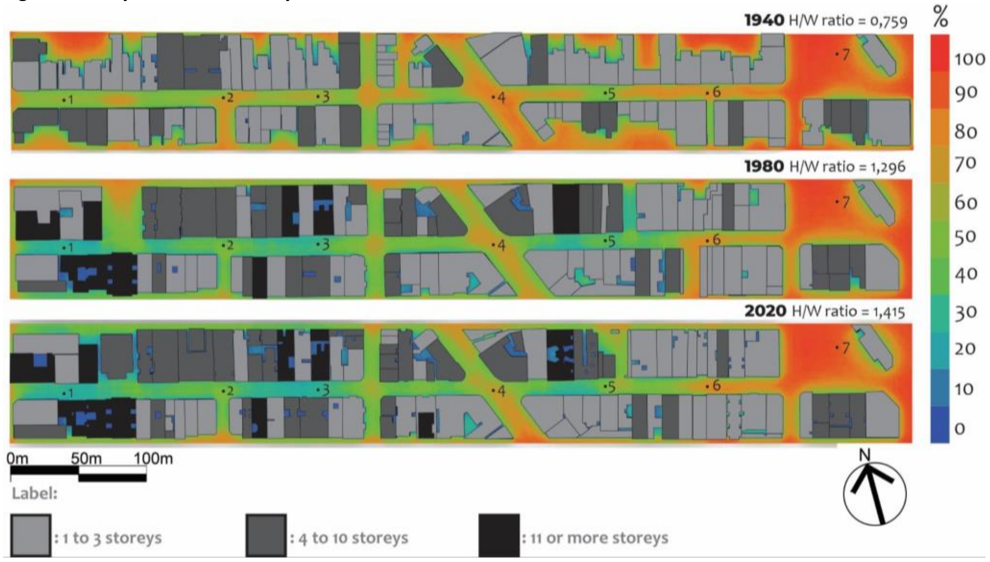
Figure 9 - Ground Space Index maps for the three analysis periods (1940, 1980, 2020)

Source: the authors.

Sky View Factor analysis

Figure 10 shows the sky view factor of the three moments evaluated. Considering the 7 points of analysis, the SVF dropped 21% from 1940 to 2020. Points 1 and 3 had the most expressive reductions in the visible sky, going from 67% to 26% and from 61% to 32% over the 80 years. From Figure 7, it can be seen that those were the spots with a verticalization of the buildings nearby. On the other hand, points 6 and 7 suffered the lower changes over the years, as they are located by the edge of the street and in an open area. It is also important to note that points 3 and 5 had their SVF slightly increased after 1980, showing that a change in one of a few buildings' heights may implicate changes in the SVF. Lastly, it is interesting to notice that in point 4, the sky visibility reduced by 23% from 1940 to 2020, even though it is located at the street crossing. Basso *et al.* (2018) found similar results on analysis with canyons of H/W > 3. The SVF was higher (90-100%) in open areas, allowing higher sky visibility. A bigger part of the sky was blocked; hence, the SVF dropped approximately 60%.

Figure 10 - Sky View Factor analysis



Source: the authors.

UTCI analysis

For the UTCI values, the grid of results was positioned at 1.1m above the ground to get the findings considering the pedestrian's height. Figure 11 shows the comfort map for the three periods analyzed at 8 am on the winter solstice. It can be seen that the UTCI values are lower on the spots shaded by the buildings. In this case, the range of temperatures did not vary much over the years, going from 11.2°C to 19.6°C, which is considered thermally comfortable. It is important to highlight point 5, which is in an area of the canyon that used to receive sunlight in 1940 but was shaded at this time by 1980. There was a difference of 14% in the comfort temperature in this spot. As the sun is at a lower position at 8 am, the shade promoted at the pedestrian level remained similar over the years even with the buildings' rise.

Figure 11 - UTCI map at 21 of June, 8 am

Source: the authors.

In Figure 12, which shows the comfort temperatures for the summer solstice, it can be seen that, as the sun is at a higher position, there are more sunlit areas within the canyon. Thus, sunshades are more expressive in the areas close to the highest buildings, and therefore, there is a clear difference in the UTCI values between the years. In the summer, points 1, 2, and 5 decreased the UTCI value by about 93% from 1940 to 1980 due to the verticalization of buildings nearby.

Figure 12 - UTCI map at 21 of December, 8 am

Source: the authors.

By comparing the UTCI values for winter and summer solstices at noon, the difference in temperatures on the spots is higher for the case in June, as the sun is at a lower position. This shows that the shade promoted by the buildings during the morning period induces a considerable decrease in the temperature within the street canyon.

At noon, the sun is higher than at 8 am, and therefore more sunny areas promote higher temperatures, as shown in Figure 13. Consequently, the UTCI range is higher than at 8 am along the street. For instance, points 2 and 6 present a difference of UTCI of about 7°C between 8 am and 12 pm in 2020, as the buildings close to analysis points are taller. However, as in wintertime, the sun is low, and there are still several shaded parts of the canyon. This causes a similar range of temperatures at the same spots over the years. An expressive difference in comfort temperature was observed in Point 4, located at the street crossing. While the UTCI was 29.4°C in 1940, it dropped to 20.4°C in 1980, remaining with the same value in 2020.

Figure 13 - UTCI map at 21 of June, 12pm

Source: the authors.

In the summer solstice (Figure 14), the 1940s morphology indicates higher temperatures within the canyon, varying between 23.4°C and 25.1°C on all points of analysis. By this time, as the sun is higher and the shades less substantial, the differences in the UTCI values over the years are less expressive.

Figure 14 - UTCI map at 21 of December, 12 pm

Source: the authors.

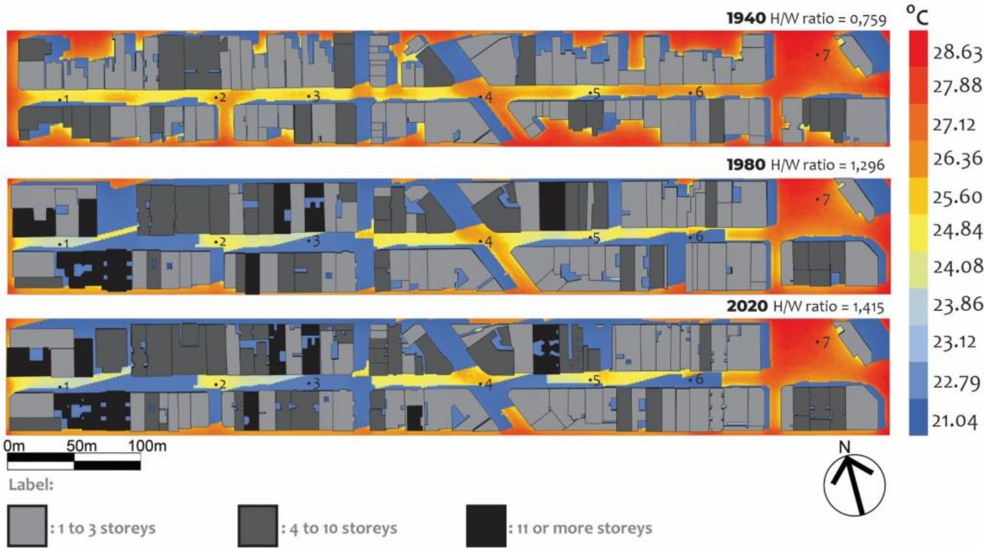
By 4 pm in the solstices (Figure 15 and 16), all analysis points are shaded in all analysis periods, except point 7, which is completely exposed to the sun. However, the general values are within the comfortable range. Unlike the cases above, there was a slight increase in the UTCI values over the years by this time in winter. Although an intense shading marks this time in the canyon, this phenomenon can be explained by the release of heat stored on the building fabric over the day. As the air temperature drops, convective heat gain is discharged into the air. This does not happen in the summer due to the higher air temperature. In this case, the heat loss may still not be enough to increase UTCI values. Park, Tuller, and Jo (2014) found that the period from 2 pm to 4 pm had the strongest heat stress level, so shaded areas that previously had no thermal stress during the mid-afternoon presented moderate heat stress according to the UTCI scale. Areas shaded by buildings presented a 1 °C lower, and sunlit areas had 1 to 2 °C higher. As in the case of the present work, the difference between sunlit and shaded areas was more expressive, with almost 7 °C of difference in the summer and 3 °C in the winter. Therefore, this shows how expressive the urban heat island effect can be in tropical climates.

The above phenomenon is more expressive at 8 pm (Figures 17 and 18). On both days evaluated, the comfort temperatures increased over the years as the buildings radiate the heat absorbed throughout the day during nighttime. Nakata-Osaki, Souza and Rodrigues (2016) found an increase of approximately 2 °C in air temperature on nocturnal heat islands in canyons (with H/W ratio = 2) in the city of Passo Fundo. The increase in temperature occurred as the H/W ratio also increased in the simulated scenarios. This is similar to the results found in this work, as the temperatures in the canyon were higher in areas with taller buildings (with higher H/W and lower SVF). However, the H/W assessed is lower than the one in the study analyzed, so the temperature range was lower than 1 °C. It is also important to notice the rise in the temperature on the building's courtyards and near the facades. Although the studies do not always consider night analysis, it can impact the urban thermal environment and the indoor thermal conditions of naturally ventilated buildings.

Figure 15 - UTCI map at 21 of June, 4 pm

Source: the authors.

Figure 16 - UTCI map at 21 of December, 4 pm

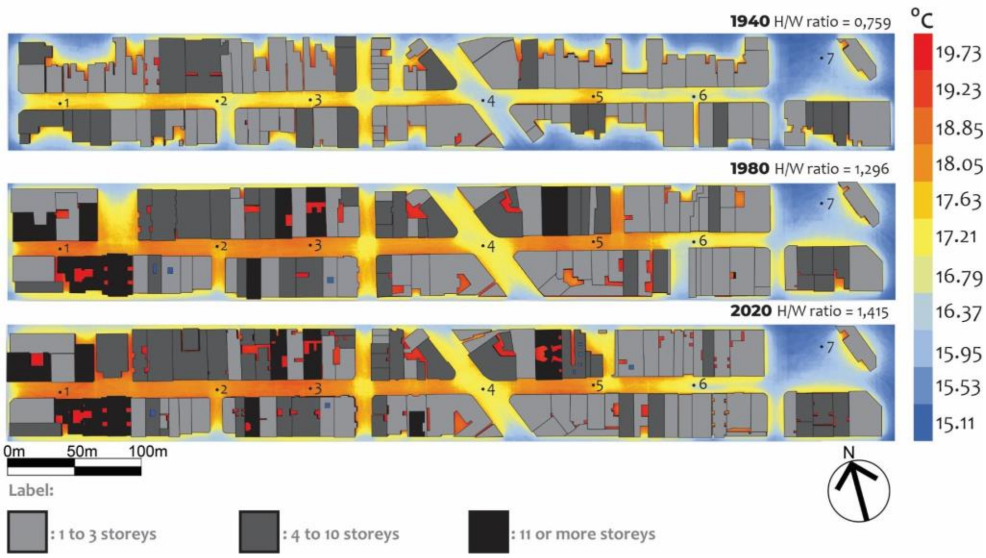


Source: the authors.

Figure 17 - UTCI map at 21 of June, 8 pm

Source: the authors.

Figure 18 - UTCI map at 21 of December, 8 pm



Source: the authors.

In general, the values of UTCI obtained for Juiz de Fora in the winter and summer solstices are within the comfort zone in shaded areas. It is also important to highlight that in all times analyzed, the differences in the temperatures were higher from 1940 to 1980, following changes in the heights of the buildings. During hot moments of the day (from 12 am to 4 pm), urban morphology managed to lower the UTCI in about 2 stress categories, going from 'strong heat stress' to 'comfort zone' between sunlit and shaded areas, when the index varied in average from 31°C to 20°C.

The results from statistical analysis indicated that in 20 out of the 24 analyses, the UTCI values presented significant differences over the years. The exceptions were found for the UTCI measured during the winter solstice at 12 pm, and 8 am between 1980 and 2020. This indicates that the changes in the urban canyon through the urbanization process significantly modified the comfort conditions of Halfeld Street in Juiz de Fora.

Conclusion

The present work aimed to identify how the changes in the urban morphology impacted the thermal conditions of an urban canyon in the central area of Juiz de Fora, Minas Gerais, Brazil. This study evaluated the thermal comfort in the street with computational simulations over 80 years, considering three moments of analysis (1940, 1980, and 2020).

The results indicated that the changes in the urban street canyons strongly affect the thermal comfort at the pedestrian level. The temperatures varied significantly over the years, especially from 1940 to 1980. Looking at the changes during the day, the shaded areas have lower temperatures than the sunny spots in the morning periods. By the end of the day and night, this phenomenon changes, and the temperature increases, especially close to the highest buildings, due to the heat released by the building fabrics, which was similar to previous findings. It is important to note that the verticalization in the street evaluated is not expressive; therefore, the comfort temperatures are generally similar over the day. As the studied city has two defined seasons, with hot summer and cold winter, it was noticed that, while the canyon raised the thermal conditions during summer, it worsened comfort in winter. Thus, understanding the influence of shading (related to the street orientation) on the thermal comfort of the urban areas is important to planners when defining urban layouts and limits to building heights.

Wind computation was a limitation of the study. As the software uses the wind conditions written in the .epw file, accurate local wind distribution in an urban canyon was not considered. This implies inaccuracies in the thermal analysis since the heat exchanges by convection on the surfaces can be underestimated. Therefore, future research may consider coupling Computer Fluid Dynamics (CFD) simulation results to Ladybug to obtain more accurate wind distribution. In addition, the effects of vegetation interactions were also not considered. Another limitation of the study was the difficulty of simulating the thermal properties of materials. This involves different construction materials and window reflexivity, which can significantly increase the simulation's computational time. Nevertheless, the methodology and the index used in the study may be useful to other cities to evaluate current local thermal conditions of urban canyons and estimate the magnitude and intensity of thermal conditions variations over time, projecting the future, particularly in tropical areas.

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