Tool for Heat Island Simulation (THIS) and simulation of different urban scenarios

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Abstract

This paper presents the development of a simulation model, which was incorporated into a GIS in order to calculate the maximum intensity of urban heat islands based on urban geometry data. The methodology of this study is based on a theoretical-numerical basis (Oke's model), followed by the development of a calculation algorithm incorporated into the GIS platform, which is then submitted to an adjustment and used as exemplification. The results show that for the same value of H/W ratio, urban canyons with greater roughness result in lower heat island intensity values in relation to the less rough canyons.

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1. Introduction

Computational tools have been increasingly used in urban planning research, simulations predicting future scenarios and the inclusion of mathematical models. Concerning urban planning, the topic of urban heat islands has been the focus of much research and urban geometry is one of the main factors that influence its development.

The urban heat island phenomenon is defined by the temperature rise in dense city centres compared to the surrounding countryside. Air temperatures and surfaces in urban areas tend to be higher than in surrounding rural areas due to their properties, characterising the formation of heat islands. The heat island phenomenon has been observed in various cities around the world, occurring predominantly at night, being able to reverse the difference between rural and urban temperatures during the day.

Cities and urban areas change the climate creating various urban microclimates. This is due to a number of complex factors, such as the loss of cooling on vegetated surfaces, increased human activity and heat storage built in urban environments, as well as the effect of the canyon (Levermore and Cheung, 2012).

In order to characterise the various forms of surface arrangement on a scale of the urban cover layer, it is usual to adopt a unit of active surfaces, the urban canyon, which consists of walls and floor (usually a street) between two adjacent buildings. This arrangement recognizes the three-dimensional nature of urban coverage and allows for interactions between buildings, rather than treating them as isolated objects, and is called the H/W ratio (a relationship between the height and the width of a street), a concept adopted in a numerical model by Oke (1981).

The H/W ratio application is also found in a study by Schrijvers et al. (2015), in which an analysis to identify the dominant factors involved in the energy balance of the nocturnal heat island at the level of the buildings for an idealized 2D urban geometry was carried out. The authors analysed the radiative transfer, conductive heat flux and ventilation (in the CFD model) considering a range of H/W ratios (0.0, 0.5, 1.0, 2.0 and 4.0) in order to study the importance of the geometry of the building. The experiments carried out by these authors demonstrated that the air temperature for the H/W ratios of 2.0 and 4.0, due to the very stable stratification in the lower part of the canyon, was much lower than in the H/W ratios of 0.5 and 1.0.

However, the H/W ratio is a parameter that can greatly simplify the interpretation of urban geometry in cities, considering the urban canyon as a two-dimensional, homogeneous and infinite profile. Another parameter of urban geometry, the roughness length (Z0), considers, as well as the height, the façade area and the area occupied by the buildings. Its application in urban climate studies often aims to compare urban geometry with changes in the wind flow (Zaki et al., 2011, Millward-Hopkins et al, 2011, Kanda and Moriizumi, 2009, Sugawara and Narita, 2009). The roughness was also one of the twelve morphological parameters used in the study by Martins et al. (2013) as indicators of the impact of the urban form on the energy demand of the buildings.

This paper presents the development of a simulation model, which was incorporated into a Geographic Information System (GIS) in order to calculate the maximum intensity of urban heat islands (UHImax) based on urban geometry data. This tool is called THIS – Tool for Heat Island Simulation, and it was developed as a calculation subroutine built into the ArcGIS 10.2 GIS.

The GIS was selected for the development of this tool because of its ability to store topological relationships between geographic objects (represented in the vector model by points, lines or areas) and these objects to tabular data (alphanumeric) containing the most diverse characteristics. In addition to having numerous analysis tools incorporated into their own commercial packages, the GIS consists of a platform on which to develop and incorporate new techniques and methods of territorial planning (Silva et al., 2004).

There are many possibilities of using GIS to develop models: allowing urban form recognition or prediction of air temperature and heat islands (Quant et al., 2015; Peeters and Etzion, 2012; Jusuf and Hien, 2009; Balázs et al., 2009; Unger Savic and Gál, 2011).

2. Methodology

For this research development, the study of the theoretical-numerical basis (Oke's model) was applied by proposing a calculation subroutine. This was based on the parameter of H/W ratio, as in Equation 1 (where: $\Delta T_{u-r(max)}$ is the maximum urban heat island, H is the height of buildings in the urban canyon, W is the width of the street in the urban canyon).

$$\Delta T_{u-r(\max)} = 7.45 + 3.97 \ln(H / W) \quad (1)$$

The subroutine was then created to identify the potential of urban geometries in developing urban heat islands. Thus, comparing the simulated data to an actual condition of a tropical city, adjustments were made to the algorithm, so that the subroutine could be applied to hypothetical urban scenarios.

In order to carry out the data collection for the comparison stage using the simulated data, 21 study points were selected in two Brazilian cities. Six points are located in the city of São José do Rio Preto (data obtained in collaboration with Masiero, 2014) and fifteen points in the city of Bauru (Leme, 2005).

Urban air temperatures were registered using data-loggers. For the city of São José do Rio Preto, the data-loggers applied were the HOBO Pro v2, U23-001 model, Onset brand, using temperature sensors (measurement range of -40 to 70ºC) and humidity (0-100%), both with an error of 1%. For the city of Bauru, the data-loggers applied were the HOBO H8 Pro Series Temp/External Temp H08-031-08, Onset brand, using air temperature sensors (-30º to 50ºC) and external/superficial (-40º to 100ºC) with a resolution of 0.02ºC in high resolution mode and 0.04ºC in normal resolution.

Only stable days without rain or fog, clear sky (low cloud cover, less than 50%) and low average wind speed (less than 2.0 m/s) were selected. The UHImax values of the measurement days were selected at night in the hours after sunset (between 18h and 22h). All measurements, in both cities, were made to 3 meters high (in power supply poles) facing the south to avoid direct solar radiation.

After comparing the simulated data with the measured data, a relationship with the maximum intensity of the heat islands was observed, not only with the urban geometry unit - the H/W ratio - but also with the roughness (Z_0). Therefore, it was necessary to include the roughness equation (Equation 2). This equation allowed for the calculation of spatial relationships between the represented objects in the GIS, as well as the inclusion of the correction equations (found specifically for these Brazilian cities in which the data measurements were taken).

$$Z_0 = 0.5H(A^*/A') \tag{2}$$

For the roughness equation (Eq. 2), Z_0 is the roughness length (m); H is the average height of buildings in the urban block (m); A* is the vertical surface average area facing the canyon (m²); and A' is the average area occupied by each building of urban blocks, the horizontal projection (m²).

The entire process for calculating the H/W, Z_0 and the heat island intensities using the Oke model and adapted model was programmed using a subroutine incorporated into the ArcGIS 10. The result of calculating the first three output data enabled us to observe the relationships between urban geometry and the night heat island, and consequently, obtain the adapted model, resulting in the development of the tool THIS (Tool for Heat Island Simulation). The organization of these steps taken to develop the THIS can be observed in Figure 1.

To develop the subroutine, the coding environment of ArcGIS 10 was used. Firstly, the process is based on a logical sequence of tools that meet the spatial and numerical relationships needed for the urban geometry calculation. Subsequently, the value of the H/W ratio is determined and the UHImax is calculated by incorporating Oke's equation into the algorithm. The computational code was written in Visual Basic language and incorporated into ArcGIS 10 as a new extension.

The subroutine runs by recognizing inputs such as street axes (lines), buildings (polygons), the buildings´ heights (attributes of the polygons) and a distance radius of the building-axis (determined by the user). Then, it identifies the average height of the canyon (H) and the average width of the canyon (W) in order to determine the H/W ratio. By applying the equation from Oke's model, the output generated in the first phase of the development process was the UHImax related to each block. This was the first raw result without any adjustment.

The second part is the result of the calculation of the Z_0 and the maximum UHI by the adapted model. Thus, the output data of the THIS is the maximum heat island intensities (UHImax) by the original Oke model and the adapted model.

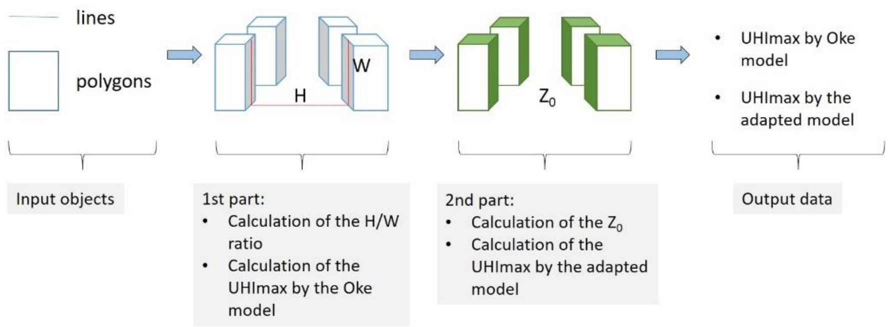


Figure 1. Sequence of processes involved in the THIS subroutine

The tool was adjusted based on comparing the simulated data from Oke's model with the heat island data obtained from the field measurements. The measured data was obtained from 21 study points in two Brazilian cities (São José do Rio Preto and Bauru), both located in the state of São Paulo – Brazil.

Comparing the field data to that simulated by Oke's model, two different trends for two groups were observed:

- Group 1 – H/W ratio = 0.16 to 0.28 and Z_0 = 0.39 to 1.23: the measured data can be found above the simulation of Oke's model, with differences ranging from 1.25ºC to 2.25ºC (simulated data underestimated UHI intensity);
- Group 2 – H/W ratio = 0.28 to 1.25 and Z_0 = 2.39 to 15.98: measured data is below the simulation of Oke's model, with differences ranging from 0.53ºC to 3.63ºC as values of the H/W ratio increase (simulated data overestimated UHI intensity).

The parameter Z_0 was included in the subroutine, after verifying the testing phase of Oke's model. This adjustment phase identified different trends of UHImax for different groups of Z_0. Through this classification, carried out in this first adjustment phase, correction equations (called adapted model here) could be included. Thus, the Z_0 calculation was incorporated into the code, so that the GIS could classify the blocks and apply the correction equation (the result obtained using the Oke's model) corresponding to each Z_0 range calculation. Thus, the correction equations are also included in the model, according to the deviation indicated by the equation of Z_0.

After the subroutine has been completed, a simulation of twelve hypothetical urban scenarios was performed. These scenarios correspond to different configurations of urban blocks, both in the value of H/W and in the roughness length (Z_0) as both parameters are calculated by the subroutine itself.

In order to cover a wide range of scenarios, for the verification of the influence of urban geometry on maximum heat island intensity (UHImax), the following H/W ratio values were determined for the simulation: 0.25, 0.5, 1, 2, 3 and 4. This H/W ratio scale was simulated for both $Z_0>2.0$ and $Z_0<2.0$, extrapolating the two groups of values for which different growth trends were found of the UHImax.

Table 1 presents a classification of the simulated scenario (hypothetical urban blocks) based on the predefined criteria for the simulation and Figure 2 illustrates the geometries of these scenarios in a simplified and three-dimensional way.

Table 1. Determination of the criteria for simulations of urban scenarios

Range of Z_0	Block	H/W avg.	H avg.	W avg.	L avg.	C avg.	A*	A'	Z_0
< 2.0	A1	0.25	4	16	8	8	32	64	1.00
	A2	0.5	8	16	8	20	64	160	1.60
	A3	1	16	16	30	70	480	2.100	1.83
	A4	2	20	10	30	110	600	3.300	1.82
	A5	3	30	10	100	250	3.000	25.000	1.80
	A6	4	40	10	200	420	8.000	84.000	1.90
≥ 2.0	B1	0.25	4	16	10	3	30	30	2.67
	B2	0.5	8	16	25	12	300	300	2.67
	B3	1	16	16	20	40	800	800	3.20
	B4	2	20	10	20	40	800	800	5.00
	B5	3	30	10	20	40	800	800	11.25
	B6	4	40	10	30	60	1800	1.800	13.33

. Legend: H avg.: average height of buildings (m); W avg.: average width of the roadway measured form the face to face of buildings (m); L avg.: average width of buildings (m); C avg.: average length of buildings (m); A*: average area of the facade facing the axis (m²); A': average occupied area of the buildings (m²); and Z_0: roughness length (m).

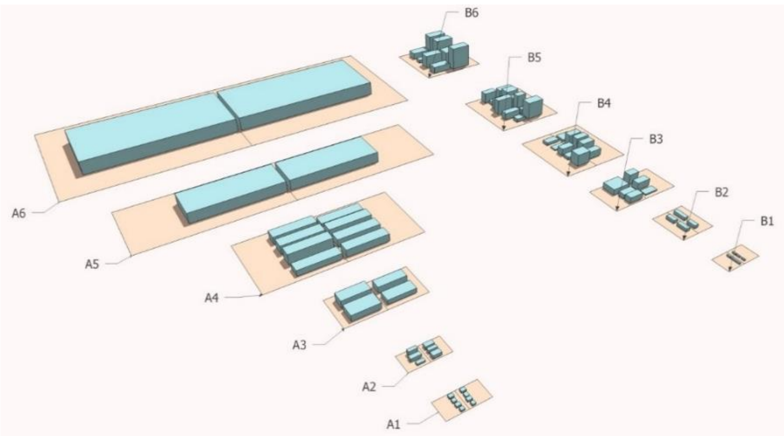


Figure 2. Representation of the geometry of the twelve simulated hypothetical scenarios

3. Results

The comparison between real and simulated data using the Oke model for the same points showed an increasing tendency of UHImax compared to the value of H/W. However, the correlation between these data was low; the coefficient of determination (R^2) was 0.63 and the standard deviation was 2.20.

It was found that this low correlation is due to the differentiated behaviors for two Z_0 ranges. When the analysis was performed by Z_0 ranges, the correlation of the data (R^2 of 0.80 and 0.97 for the two different Z_0 ranges) was obtained.

The range of 'Z_0 = 0.39 to 1.23' shows the relationship between UHImax values for a range of H/W between 0.16 and 0.28. The measured values are above those simulated by the Oke model, with differences of 1.25ºC to 2.25ºC. The coefficient of determination of this relation is R^2 = 0.80 with a standard deviation of 1.15.

The range of 'Z_0 = 2.39 to 1.98' presents results for the range of H/W of 0.28 to 1.25. There is a greater correlation between the curves of the simulated values by the Oke model and the actual data, which also presents a relation directly proportional to the H/W, but less strongly than the Oke model. The curve of the real data, however, was below the curve of the Oke model, with differences varying from 0.53ºC to 3.63ºC. This relationship showed a coefficient of determination of R^2 = 0.97, with a standard deviation of 2.13.

The difference in trend noted between the two ranges of Z_0 presented served as an additional parameter for the calibration of the Oke model for the cities analysed in this study. As the real data of the studied cities presented a gap of values of Z_0 between 1.23 and 2.39, this gap could cause a problem of a lack of values in the simulation. For this problem to be avoided, the possible values of Z_0 when inserting the equations in the tool code were extrapolated. This extrapolation considers Z_0 values smaller than 2.0 for the first group, and greater or equal to 2.0 for the second group (Figure 3).

The adapted model provided results of higher correlation with measured data than those calculated by the Oke model. Data simulated by the adapted model result in a R^2 of 0.92 with a standard deviation of 1.01. The adjustment of this simulated data curve can be seen in the graph in Figure 3, where the UHImax curve by the adapted model significantly approximates the measured UHImax curve.

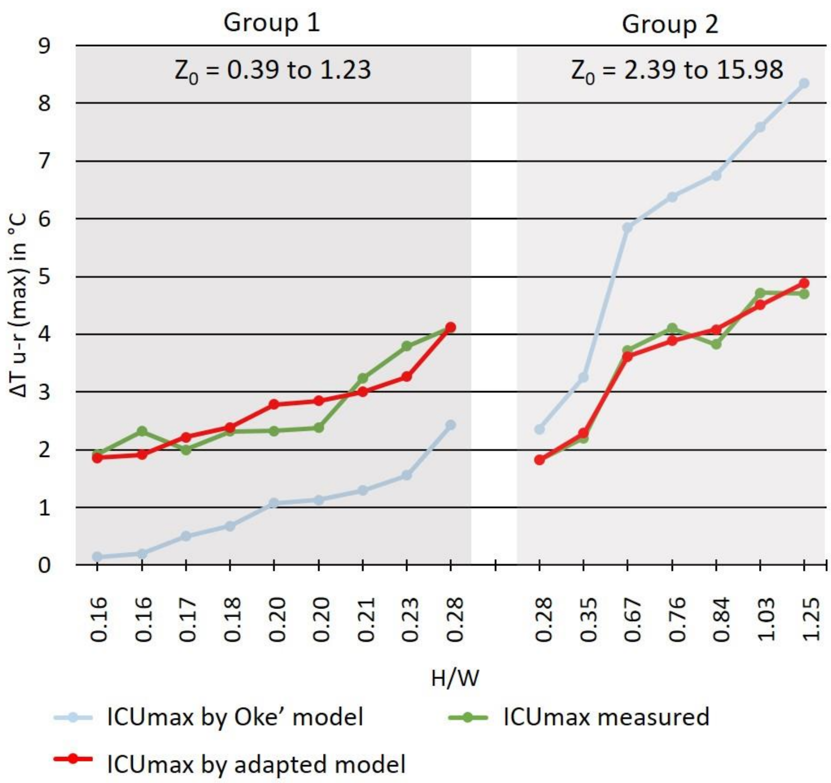


Figure 3. Two groups of trends validate the model.

The simulation using the THIS of the hypothetical scenarios (Figure 4) made it possible to compare the two roughness ranges that presented different tendencies to predict the UHImax during the validation process.

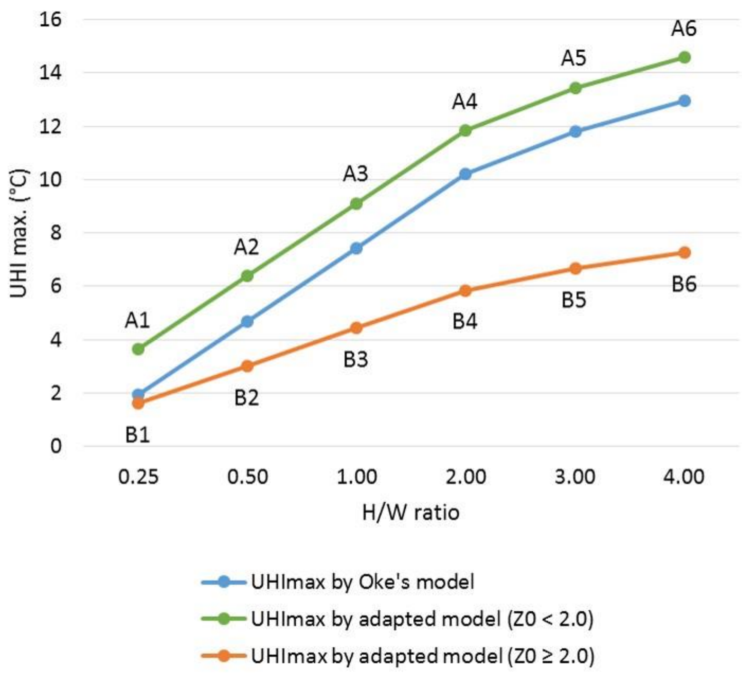


Figure 4. Graph of results showing the simulation of urban scenarios

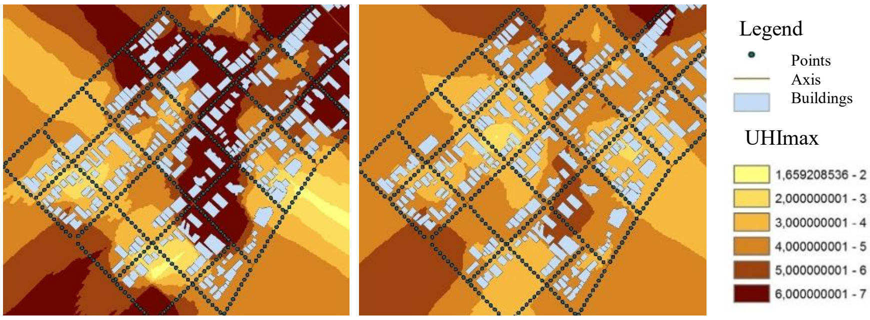
Observing the graph shown in Figure 4, it can be seen that the trend curve of the Oke model is similar to the predicted UHImax adapted model curve for roughness values less than 2.00. This leads us to reflect on the fact that the 31 study points in cities in Australia, Europe and North America measured by Oke (1981) would have bigger occupied areas of buildings compared to the façade area and height of these buildings. However, in that study it is not possible to confirm this assumption, as the author presents the measurements of urban geometry only by the Sky View Factor (SVF).

In all simulated H/W values, the UHImax intensity for lower roughness scenarios ($Z_0 < 2.0$) was higher than for the higher roughness scenarios ($Z_0 \geq 2.0$) with differences ranging from 2.04ºC to 7.31ºC as the H/W increased. Considering the roughness length calculation equation (Eq. 2) for the same H/W values, urban scenarios in which buildings with a larger occupied area in relation to the façade area predominate tend to have higher UHImax values.

For urban scenarios where the building facades are predominantly larger than the areas occupied by them for the same H/W values, UHImax values tend to be lower. The simulated results for scenarios with $Z_0 < 2.0$ present UHImax values twice as large as the $Z_0 \geq 2.0$ scenarios for the same H/W value.

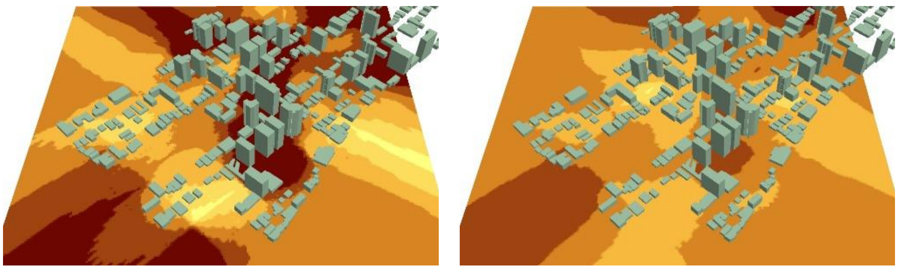
It is important to emphasize here that the calibration of the model, however, was based on data from urban canyons of H/W from 0.15 to 1.25. Therefore, the values obtained from the simulation for the H/W ratio 2.00, 3.00 and 4.00 are predictions based on the extrapolation of the calibration of the model performed for the measured urban geometry data.

As a result of the comparison of part of a neighborhood surveyed in the city of São José do Rio Preto (SP-Brazil), Figure 5 shows the simulation using the THIS of a map of the maximum heat island intensity simulated by the Oke model (Figure 5a) and the adapted model (Figure 5b). Correspondingly, Figure 6 shows the same map result, viewed using the ArcScene extension.



(a) (b)

Figure 5. Map of the UHImax simulated by the Oke model (a) and the adapted model (b) using the THIS



(a) (b)

Figure 6. Map of the UHImax simulated by the Oke model (a) and the adapted model (b) using the THIS and viewed by using the ArcScene extension

4. Conclusion

The importance of the Oke model to develop climate studies is clear and serves as the basis for the development of many other studies. However, due to its simplifications and limitations, the Oke model underestimated maximum urban heat island values for urban canyons of roughness less than 2.00 and overestimated for scenarios of roughness higher and equal than 2.00 in comparison between measured and simulated data. The tool was validated by analysing the relationship between the measured and simulated data using the Oke model, and incorporating correction equations into the calculation subroutine. Thus, the adapted model was obtained and the THIS was completed.

The results obtained by the comparison between the simulation and the Oke model and the data obtained from the survey in the two Brazilian cities showed a coefficient of determination R^2 of 0.63 and standard deviation of 2.20. The data simulated by the adapted model of THIS presented good correlation with the measurement data, with R^2 of 0.92 and a standard deviation of 1.01, showing the importance of the tool validation process for scenario simulations in different cities. Including the additional roughness length parameter (Z_0) was fundamental for this increase in the calculation performance by the tool.

In addition, the results show that for some Brazilian cities, not only can the value of the H/W ratio influence the intensities of the nocturnal heat island, but also the variation of the façade and occupation areas of the buildings that form the urban canyon. Thus, greater roughness represents attenuation of heat island intensity values for the same value of the H/W ratio. However, a more in-depth study of the impact of this configuration on other factors influencing the urban microclimate, such as changes in wind speed and direction, is suggested.

The development of this tool intends to help researchers and planners in heat island formation trends in different urban scenarios and suggests a more in-depth discussion concerning the influence of different configurations of urban geometry on the formation of heat islands.

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