Solar Analysis on Buildings of Favelas in Sao Paulo to Estimate PV Potential

Denis Giannelli

Student # 5045304

D.Giannelli@student.tudelft.nl

1st mentor: Giorgio Agugiaro

2nd mentor: Camilo Alexander León Sánchez

Date P2: 2021–06–18

1. INTRODUCTION

In the so-called Global South[1], the urbanization process throughout the past two centuries has resulted in the development of large-scale cities across the world, mainly of which have become regional economical hubs[2]. With a population of over 12 million inhabitants (2020)[3] – and 21 million across its Metropolitan Area (2018)[4] –, the city of São Paulo constitutes the financial core of Brazil and Latin-America.

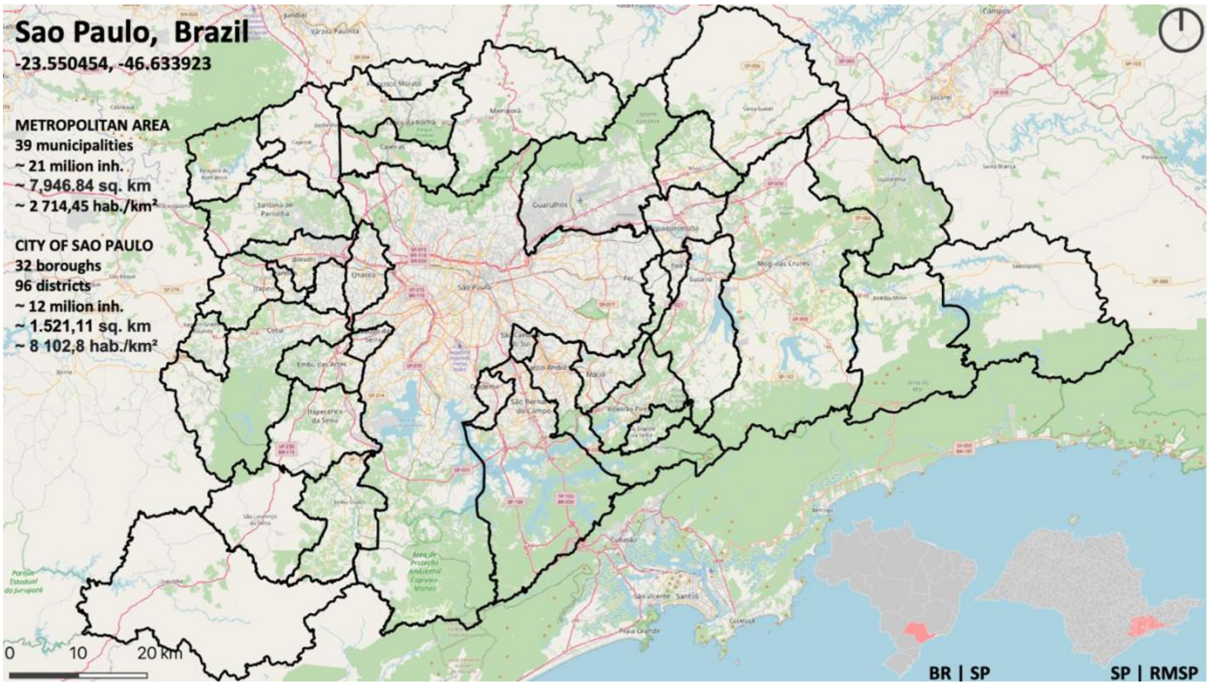


Figure 1. Municipalities of the metropolitan area of Sao Paulo, including the City of Sao Paulo in the centre of the urban core.

In spite of its wealth, this Brazilian metropolis still faces a challenge when it comes to the duality between the so-called *Formal City* and the *Informal City*[5]. A vast literature[6] discusses the socio-spatial segregation effects emerging from the way that Sao Paulo and other Brazilian cities have been planned, economically produced and designed in this dual built environment.

> "(…) unplanned settlements that have sprung up on the outskirts of Brazilian cities since the 19th century. More than 5% of the country's population lives in communities like these (…)" (DUARTE et. al, 2021, p.1)

[1] ERIKSSEN, Thomas Hylland. What's wrong with the Global South and the Global North?. In: Concepts of the Global South – Voices from around the world Global South Studies Center, University of Cologne, Germany – http://gssc.uni-koeln.de/node/452

[2] DIRLIK, Arif. Global South. In: Concepts of the Global South – Voices from around the world Global South Studies Center, University of Cologne, Germany – http://gssc.uni-koeln.de/node/452

[3] IBGE Cidades. Available at: https://cidades.ibge.gov.br/brasil/sp/sao-paulo/panorama 14 February 2021.

[4] Considering the 39 municipalities that compound the Metropolitan Area of Sao Paulo (Região Metropolitana de São Paulo), according to the Complementary Law n. 1.139 16/06/2011. Source: EMPLASA. Região Metropolitana de São Paulo. Sobre a RMSP. Available at: https://emplasa.sp.gov.br/RMSP 14 February 2021.

[5] FERREIRA (2000).

[6] BONDUKI (2011), MARQUES (2014), MEYER et. al. (2014), SOMEK (2000), VILLAÇA (2011), among others.

Figure 2 (Left). A formal neighbourhood (*Morumbi*) vs. an informal settlement (*Paraisópolis*) in Sao Paulo, Brazil. The red spot corresponds to an approximate position where the photograph on the right was taken. Source: Mapa Digital da Cidade de São Paulo.

Figure 3 (Right). The social-spatial segregation between the 'formal city' and the 'informal city'; Source: Tuca Vieira.

Nevertheless, it still remains important to address, from a geo-information perspective, the impact that the scarcity of spatial datasets has over the understanding of the urban processes that take place in these informal settlements, which are, for many application domains, a '*terra incognita*'[7].

Figure 4 (Left). *Parque Brasilândia*, Sao Paulo, Brazil. Sources: Open Street Map 2021.

Figure 5 (Right). *Parque Brasilândia*, Sao Paulo, Brazil. Sources: Orthophoto 2017 – Mapa Digital da Cidade de São Paulo.

The two images correspond to the same informal settlement in north-west Sao Paulo, but the mapping tool represent as vegetation – a greenish colour – the area that has been occupied by informal dwellings of *Parque Brasilândia*.

According to the City Hall of Sao Paulo[8], there are four main types of informal settlements in the territory of this city:

a) ***Cortiços*** (tenements) are collective and precarious housing blocks that are irregularly rented for a high amount of money per square meter. They often dispose of shared sanitary facilities among multiple rooms in a high-density environment, with precarious front door, common areas and facilities. All tenements are located in downtown.

b) **Irregular land parcelling** are informal settlements developed and/or commercialized by private entrepreneurs without previous approval by public authorities or, if such approval had been granted / was to be granted, the as-built situation is not in compliance with the specific legislation on the matter or it does not correspond to the approved project. Low-income population and poor urban design implementation are typical of these sites.

[7] The term 'Terra Incognita', derived from Latin 'Unknown Land' refers to areas that have not been mapped. https://en.wikipedia.org/wiki/Terra_incognita

[8] habitaSampa: Transparência e interação entre o cidadão e o poder público. Available at: http://www.habitasampa.inf.br/habitacao/

c) ***Favelas*** are precarious settlements resulting from spontaneous and unorganized land occupation, without pre-defined land plots or road designing. They are built on both third-party private or public property, do not rely on sufficient infrastructure and the dwellings are in their majority poorly self-constructed by low-income vulnerable families.

d) ***Núcleos*** ("urbanized nuclei") are favelas fully equipped with water, sewerage, lighting, drainage and garbage collection systems sponsored by public authorities or private investors. Nevertheless, they are still not officially regulated.

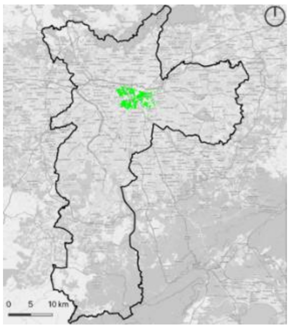


Figure 6. Location of *cortiços* (tenements) in the City of Sao Paulo. 1.478 tenements, located exclusively in city centre.

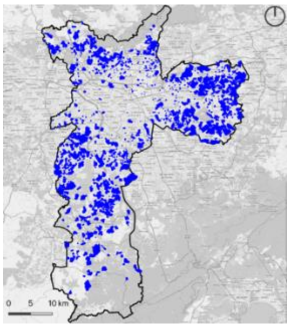


Figure 7. Location of irregular land parcelling in the City of Sao Paulo. 1.999 irregular land parcelling, 388.459 irregular land plots.

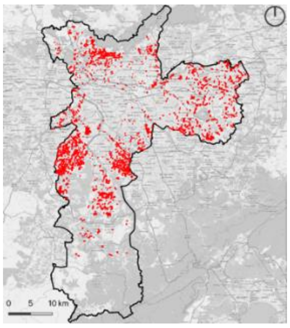


Figure 8. Location of *favelas* (slums) in the City of Sao Paulo. 1.733 favelas, 391.939 households.

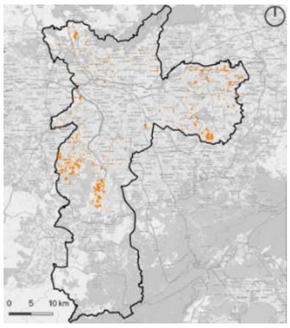


Figure 9. Location of *núcleos* (urbanized nuclei) in the City of Sao Paulo. 435 nuclei, 60.855 families.

Among these types of informal settlements, the scarcity of spatial datasets is typical of favelas[9], and in particular most of these lack building cadastral data in particular. When addressing favelas – but adopting the general term 'informal settlements' –, Salazar Miranda et. al. provides detailed explanation about the urban morphology of favelas:

> "Informal settlements are aggregations of homes and businesses constructed by their residents, in an initially unplanned form of urbanization. Their complex morphology is the outcome of spontaneous and competitive building without official land tenure, which results in dense and multilayered structures built up around labyrinthine street networks." (SALAZAR MIRANDA et. al., 2021, p.2)

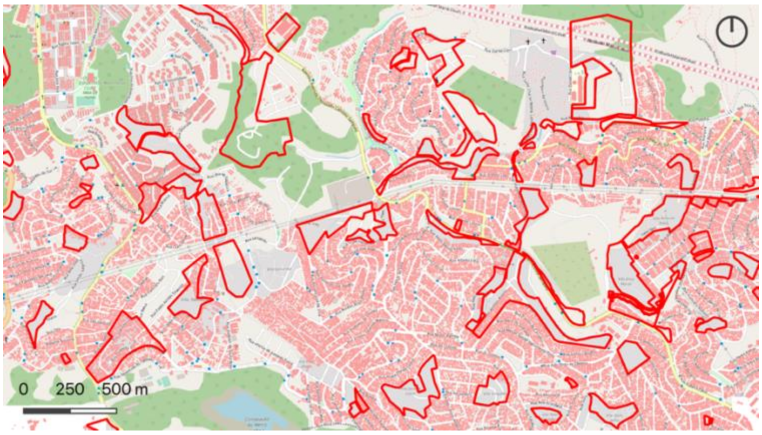


Figure 10. Official perimeters of Favelas (red edge) in the district of Brasilândia, northern west Sao Paulo. Most of these areas lack official building footprints (such as the ones represented in light pink). Sources: Open Street Map, 2021, [Mapa Digital da Cidade de São Paulo](#).

1.1. Problem Statement

[9] SOUTHWICK (2016)

As favelas are often not mapped, assessing urban phenomena becomes a technical challenge for several application domains and, as a consequence, the provision of urban infrastructure is jeopardized for these areas.

> “For informal settlements in particular, measuring morphology is an entry point to broader inquiry about the tendencies of unfettered urban development and the challenges that attend it, including lack of accessibility and cadastral mapping, crowding, environmental health, and safety.” (SALAZAR MIRANDA et. al., 2021, p.2)

> “With little formal aid or administration and scant economic opportunities, favela residents have struggled to contend with unhealthy living conditions and frequent violence. A thick wall of social segregation means that resources from the city – including electricity and clean water – must take twisting, uncertain paths to make it inside.” (DUARTE et. al, 2021, p.1)

One of these applications domains is the energy one. A recent public initiative in Rio de Janeiro, estimates solar irradiation and photovoltaic potential for buildings at city scale, but favelas are intentionally excluded from the resulting web-based solar maps.

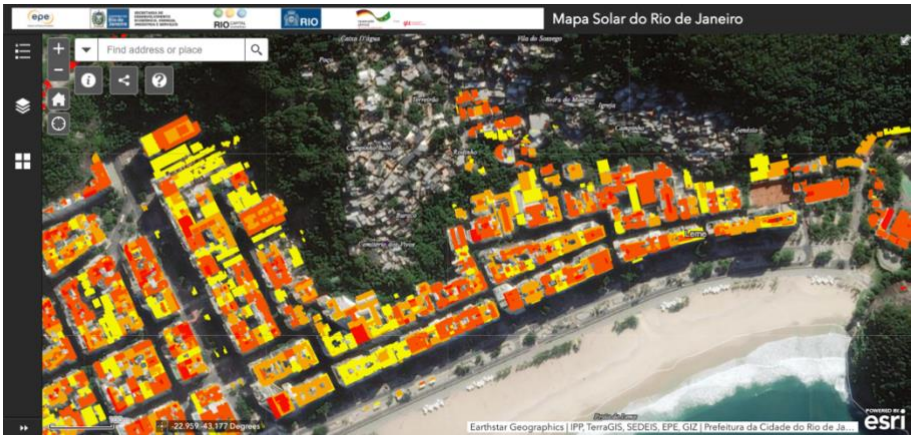


Figure 11. The formal neighbourhoods of Leme and Copacabana, in Rio de Janeiro, and their buildings modelled and classified by Solar Potential classes; The favela ‘*Morro da Babilônia*’ is excluded from such classified representation. Source: [Solar Map of Rio de Janeiro]().

FEITOSA et. al (2020) emphasise both political and technical reasons why favelas wouldn’t be present in the [Web Solar Map]() of Rio de Janeiro, another city in Brazil. When strictly addressing the technical aspects, these authors claim that the absence of a spatial pattern in favelas would call for an investigation on how to refine a roof mapping methodology:

> “The lack of information from these regions on the Solar Map suggests, therefore, that GIZ-indicated refinement studies [18] have not been carried out or that their products have not been utilized. It would bring greater methodological complexity to the construction of the Map to include such areas.” (FEITOSA et. al., 2020, p. 36)

> “Including poor areas would require more complexity from the point of view of refining the roof mapping methodology, as already mentioned regarding the possibility of developing a more inclusive methodology [18]" (FEITOSA et. al., 2020, p. 37)

In spite of this ‘greater methodological complexity’ claim, the developers of the Web Solar Map of Rio de Janeiro themselves admit the possibility of investigating a specific methodology for favelas.

> “And finally, there is unregulated residential occupation, which consists of slums. This type of occupation is not part of the roof mapping process in the present study. Its main characteristic is the absence of a spatial pattern, in addition to the impossibility of identifying

the street, lane or alley, such is the proximity between the houses." (…)" (LANGE, 2015, p. 13 – translated by the author of this document)

"Subnormal areas have characteristics that make it difficult or impossible to interpret or extract information through remote sensing techniques. This does not mean that it is not possible to use such techniques to investigate subnormal agglomerations. However, due to the limited time of this project, it was not possible to develop specific methods of remote sensing for the purposes of the study." (LANGE, 2015, p. 27 – translated by the author of this document)

In parallel with this public initiative that map solar irradiation and PV potential at an urban scale, Revolusolar – a Rio de Janeiro-based non-profit organization – has been designing and implementing PV power plants in favela settlements. In the present time, this organization is mainly focused on one community, *Morro da Babilônia e Chapéu Mangueira,* where three power plants were installed and a fourth one – in a cooperative model – is being implemented. In a meeting with technical directors, it was claimed that an expansion to other favelas in this city is foreseen by the year of 2022, but yet they do not have sufficient knowledge of these other sites in terms of solar irradiance and PV potential. This reinforces a demand for a specific roof mapping methodology for the purpose of solar analysis and PV potential in the context of scarce cadastral data regarding favelas.

Figure 12. "*Babilônia Rio Hostel*" PV power plant (2016). Source: Revolusolar.

Figure 13. "*Estrelas da Babilônia*" PV power plant (2016). Source: Revolusolar.

Figure 14. "*Escolinha Tia Percília*" PV power plant (2019). Source: Revolusolar.

In the context of the city of Sao Paulo, however, neither literature nor hands-on experience was encountered when it comes to solar analysis and PV potential for favelas at an urban scale, despite the fact that favelas in Sao Paulo similarly lack urban infrastructure as the ones in Rio do. This offers the possibility to expand the work that has been carried out in Rio de Janeiro to the city of Sao Paulo. In addition, the Spatial Data Infrastructure of the City Hall of Sao Paulo allows a much broader investigation on the matter of solar analysis in favelas, considering the presence of useful data for this research, such as the Lidar Point Cloud that covers the entire territory of the city.

2. RELATED WORK

As the present thesis lies in a cross-domain field of research, groups of relevant literature are resourceful in order to sustain the topic and strength the discussion that is carried out regarding solar energy in favelas. For pragmatical reasons, the related work if hereby presented in groups, albeit these often intertwine among themselves

2.1. Global South / 'Formal vs. Informal City'

A series of articles in the publication 'Concepts of the Global South' – including the ones written by Dinlik and Erikssen –, as well as the New Urban Agenda from the United Nations, are of particular interest when it comes to the understanding of the urbanization process in the Global South.

The discussion regarding the Formal and Informal City is brought from the academic environment of the Faculty of Architecture and Urbanism of the University of Sao Paulo – FAU USP, the institution at which the researcher has conducted his previous studies. The authors in consideration are, among others, FERREIRA et. al. (2000), BONDUKI (2011), MARQUES (2014), MEYER et. al. (2004), SOMEK (2000) and VILLAÇA (2011).

2.2. Favelas

Both PIZARRO (2014) and GUSSON (2014) address favelas from an environmental comfort perspective, discussing how the urban morphology of these settlements impact the microclimate but also offer urban design opportunities. From a personal meeting with this last researcher, it was decided to use, as a case study for this present research, one the city blocks that they had studied.

In addition, a series of web publications addressing the lack of mapping of favelas are considered, including, among others, SOUTHWICK (2016). When it comes to the energy domain in favelas, REVOLUSOLAR (2018) is the key reference, as well as the meetings that the researcher has conducted with the technicians from this institution. The educational material of *Revolusolar* was crucial to dismantle some common misconceptions that one would have of energy in favelas, as for instance the idea that all households in favelas have a clandestine connection to the official energy network of the city.

2.3. Geomatics + Energy Simulation

In AGURIARO et. al. (2012), it is proposed a data workflow in order to perform solar irradiance estimation at a city scale, and their work with GRASS GIS is one of the methodologies that will be analysed in the present research. This work is also relevant in order to cast the spatial datasets that are used in the present research.

FEITOSA et. al. (2020) and LANGE (2015) debate on solar analysis of favelas in Rio de Janeiro, and both authors address the challenges of modelling these informal settlements considering the lack of cadastral datasets. They are fundamental to justify this research.

SÁNCHEZ (2013), KADEN et. KOLBE (2014), WATE et. COORS (2015) explore the use of 3D Data Models for energy simulations. These works were important to gain theoretical experience when it comes to handle data models and data structures such as, but not limited to, CityGML.

2.4. Geomatics + 3D Modelling

DUARTE et. al. (2021) and SALAZAR MIRANDA et. al. (2021) detail the recent work that has been developed by the Senseable City Lab of the Massachusetts Institute of Technology (MIT) in Favela da Rocinha, Rio de Janeiro, where a group of experts have scanned parts of this favela with a terrestrial laser scanner. Their work is useful for three purposes:

Firstly, it demonstrates the necessity of creating digital models of informal settlements for several urban applications or, in their own words, "embracing the informal".

Secondly, it offers a recent panorama of related literature that deals with morphological studies regarding informal settlements from a spatial data perspective, which are in turn sub-divided into four categories: 1) 'Remote sensing-based studies that have refined methods of identifying informal settlements and modeling their growth'; 2) A group that 'focuses on the definition and classification of informal settlement topologies using street network maps'; 3) Another group that 'focuses on studying informal construction at the building scale'; and finally 4) 'A limited selection of LiDAR-based analyses that have been conducted in favelas at small scales.' Within this last group, TEMBA et. al. (2015) and RIBEIRO et. al. (2019) have also been analysed for the purpose of this MSc thesis.

Thirdly, the work from MIT also deals with plane extraction algorithms from point clouds, which will be useful for understanding to what extend it is possible to create a specific roof mapping methodology for favelas without building footprints.

2.5. Other

Other complementary literature is analysed, such as: the Municipal Master Plan of the City Hall of Sao Paulo (2014), the National Demographic Census (2010), the Atlas of Energy Efficiency Brazil (2020) from the national Energy Research Office (EPE in Portuguese), among others.

3. RESEARCH QUESTION(S)

Considering the aforementioned context and problem statement, the research topics that this thesis is going to address are:

R.Q. 1 – How far is it possible to perform solar analysis in buildings of favelas in Sao Paulo with the goal of estimating PV potential?

R.Q. 2 – What are the minimum requirements in terms of geodata to map buildings (and more specifically, roofs) in a favela, and can a specific methodology be set up?

R.Q. 3 – What are the requirements, the level of applicability and the type of results (e.g., in terms of accuracy) delivered by different existing irradiation models?

It is important to emphasise that the present research will not model PV panels for a specific favela, but rather understand what the necessary geodata and workflow are order to compute solar analysis with the goal of estimating PV potential. In other words, there will not be a concrete project for a power plant.

This MSc thesis will focus on solar analysis rather than thermal balance or energy demand of buildings. Some simulation methods offer a complete package of solutions, and only in this case the thermal balance / energy demand results may be presented for the sake of reporting purposes. The focus will nevertheless remain on solar irradiation modelling.

4. METHODOLOGY

From GUSSON (2014), it is possible to select a first study case for the present MSc thesis. One of the sites that had been chosen by this researcher is a small-scale city block located in the district of *Brasilândia*, Sao Paulo. The area is bounded by four local streets, totalizing 21.794 square meters with a moderate terrain slope, and it contains 168 buildings.

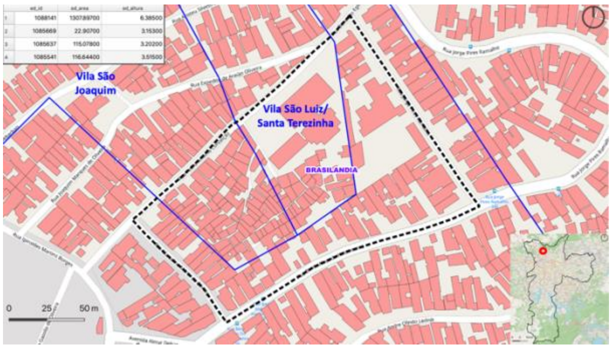


Figure 15. *Brasilândia* City Block (dashed black) in Sao Paulo, Brazil. 2D Footprints with height information (light pink) and irregular land parceling perimeter (blue). Source: Geosampa, Open Street Map.

Figure 16. *Brasilândia* City Block (dashed black) in Sao Paulo, Brazil. Ortophoto RGB (2017) Source: Geosampa, Open Street Map.

On the one hand, this settlement is not classified as a favela from a legal perspective[10], but rather as an irregular / clandestine parcelling for most of its extension (Figure 15, blue perimeter). Even so, from an urban planning point of view, it presents characteristics that are typical of favelas, including aggregated buildings, different and irregular building heights, small building sizes, simplicity in the shape of roofs, narrow streets/pathways, etc.

On the other hand, the 2D building footprint dataset containing height information is available for this particular site. Therefore, it is possible not only to start gaining hands-on experience with solar

[10] SÃO PAULO, Prefeitura do Município de São Paulo. LEI Nº 16.050, DE 31 DE JULHO DE 2014. Aprova a Política de Desenvolvimento Urbano e o Plano Diretor Estratégico do Município de São Paulo e revoga a Lei nº 13.430/2002. Available at: https://gestaourbana.prefeitura.sp.gov.br/arquivos/PDE-Suplemento-DOC/PDE_SUPLEMENTO-DOC.pdf 14 February 2021.

analysis while the roof mapping is not tested, but also to establish a geometrical 'ground truth' for the reconstruction phase when this is carried out.

Apart from the geometrical data that are used in order to create city models, weather information is also necessary to perform solar analysis. The benefit of choosing this area relies also on the fact that a meteorological station lies only nine kilometres away from this site, and its historical dataset is available with all necessary parameters in order to perform solar analysis.

Therefore, in order to establish ground truth also in terms of solar irradiance, the area around the meteorological station *Mirante de Santana* is also modelled, and the values computed in the position of this station determine how accurate different existing solar models are with respect to this ground truth.

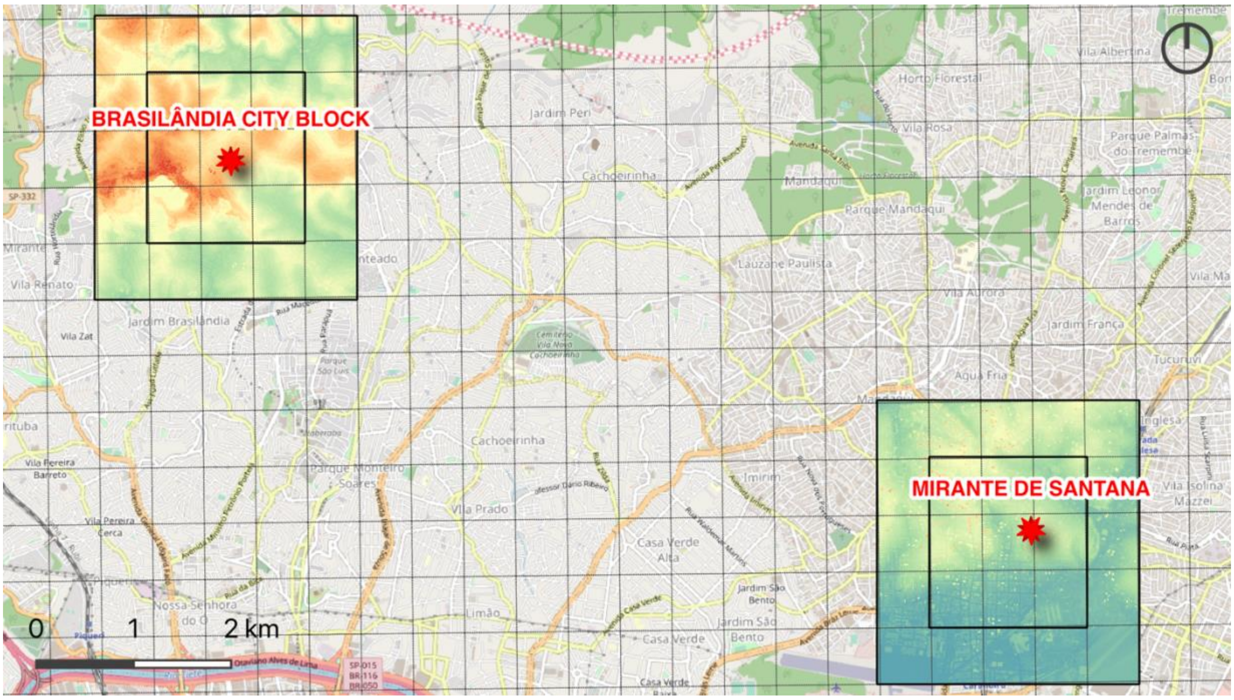


Figure 17. Surroundings of the city block in *Brasilândia* (left dot) represented by an approx. 2900 x 2700 m Digital Surface Model (DSM), which was computed from the Lidar point cloud dataset and whose tiles are represented in squares with transparent background. The same modelling was also performed for the surroundings of *Mirante de Santana* (right dot) where the meteorological station lies. Both sites are located in the northern district of Sao Paulo, in between the Tietê river basin (to the south) and the Cantareira hills (to the north).

The technical procedures for the present MSc thesis are therefore divided into two main workflows:

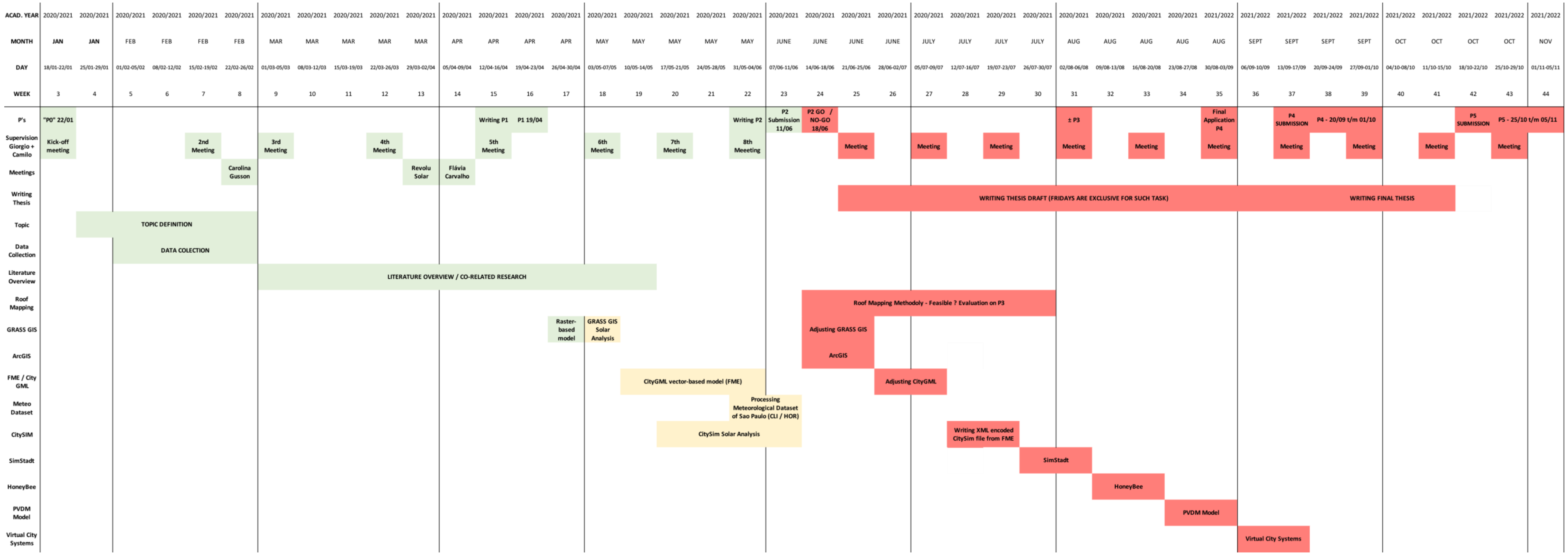
- With the available Lidar point cloud dataset, it will be evaluated if plane detection algorithms are efficient and effective methods for mapping building roofs in the site of *Brasilândia*, considering the hypothetical absence of the 2D footprints.
    - It is worth highlighting that one of the research questions is: "What are the minimum requirements in terms of geodata to map buildings (and more specifically, roofs) in a favela, and can a specific methodology be set up" In other words: if this research reveals that this technical procedure is too complex, the outcomes will be

systematically reported, and the challenge could be still investigated in further research.

- Different existing solar irradiation models will be tested for both city models under analysis, i.e. Brasilândia and Santana.
  - For each one of these methods, the present research will evaluate:
    - The data requirements – e.g., input – in terms of city model and weather info.
    - The level of applicability, potentials and limitations.
    - The results – output – in terms of data model, data structure and accuracy with respect to the ground truth offered by the meteorological station data.
  - These solar irradiation models may be subdivided into two data structure groups, each one with some specific tools making use of that data structure:
    - Raster-based approach: **GRASS GIS** and **ArcGIS**
    - Vector-based approach: **CitySim**, **SimStadt**, **Honeybee**, the model developed by the **PVMD group at TU Delft** and the one developed by **Virtual City System**.

5. TIME PLANNING

The activities already conducted in the past months of thesis preparation, as well as the upcoming tasks are presented in the following Gantt Chart.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P5 SUBMISSION
P5 - 25/10 t/m 05/11
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Kick-off meeting
2nd Meeting
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4th Meeting
5th Meeting
6th Meeting
7th Meeting
8th Meeeting
Meeting
Meetings
Carolina Gusson
Revolu Solar
Flávia Carvalho
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WRITING FINAL THESIS
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TOPIC DEFINITION
Data Collection
DATA COLECTION
Literature Overview
LITERATURE OVERVIEW / CO-RELATED RESEARCH
Roof Mapping
Roof Mapping Methodoly - Feasible ? Evaluation on P3
GRASS GIS
Raster-based model
GRASS GIS Solar Analysis
Adjusting GRASS GIS
ArcGIS
ArcGIS
FME / City GML
CityGML vector-based model (FME)
Adjusting CityGML
Meteo Dataset
Processing Meteorological Dataset of Sao Paulo (CLI / HOR)
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CitySim Solar Analysis
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SimStadt
HoneyBee
HoneyBee
PVDM Model
PVDM Model
Virtual City Systems
Virtual City Systems

6. TOOLS AND DATASETS

6.1. DATASETS

The main source of data is Geosampa, the geo-portal of the City Hall of Sao Paulo. Apart from the auxiliary datasets meant for data visualisation, the following ones are the most used datasets so far.

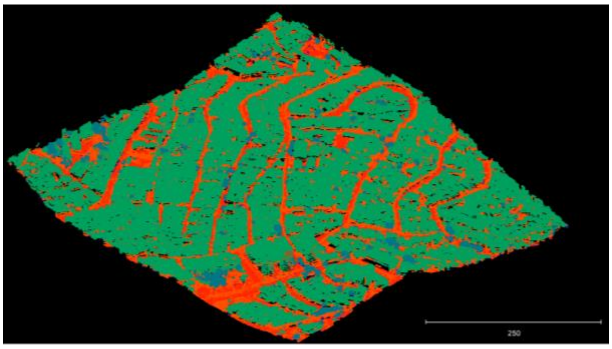


Figure 18. The RGB Lidar Point Cloud. Colours in the picture represent classes according to the ASPRS. This is just one tile.

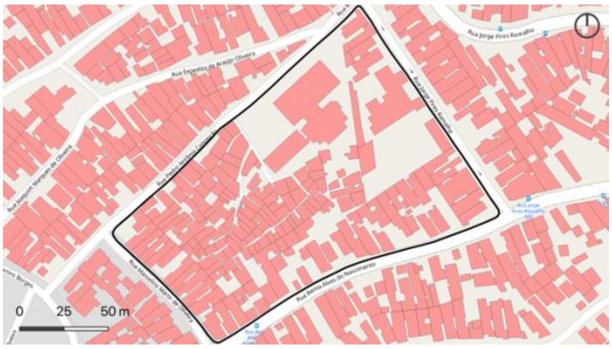
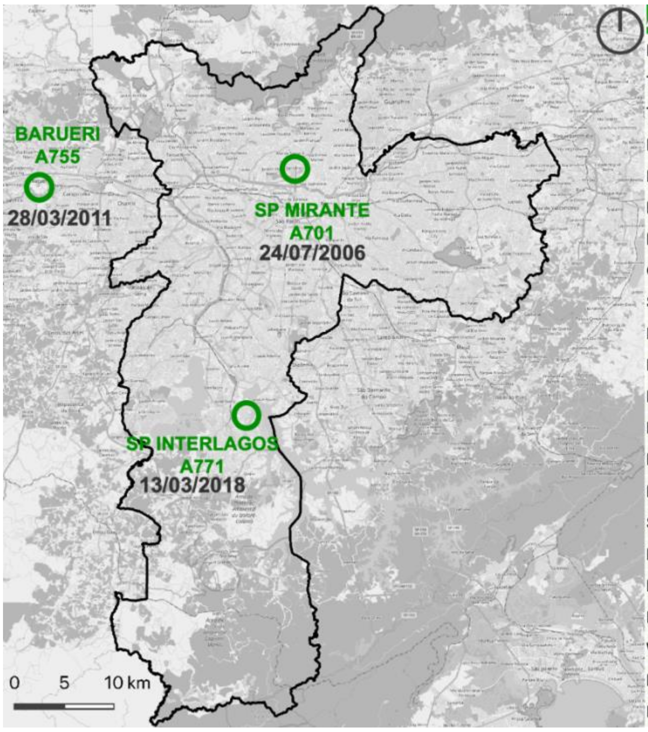


Figure 19. The 2D building footprints (light pink) with height information, area and unique building IDs (no building parts).

In addition, there are also the two meteorological datasets coming from the database of National Institute of Meteorology – INMET.



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MINIMAL ATMOSPHERIC PRESSURE OF THE PREVIOUS HOUR (AUT)(mB);
GLOBAL RADIATION (KJ/m²);
STATION CPU TEMPERATURE (ºC)
HOURLY DRY-BULB TEMPERATURE (ºC)
DEW POINT TEMPERATURE (ºC)
MAXIMUM AIR TEMPERATURE OF THE PREVIOUS HOUR (AUT)(ºC)
MINIMUM AIR TEMPERATURE OF THE PREVIOUS HOUR (AUT)(ºC)
MAXIMUM DEW POINT TEMPERATURE OF THE PREVIOUS HOUR (AUT)(ºC)
MINIMUM DEW POINT TEMPERATURE OF THE PREVIOUS HOUR (AUT)(ºC)
STATION'S BATTERY VOLTAGE (V)
MAXIMUM RELATIVE HUMIDITY OF THE PREVIOUS HOUR. (AUT)(%)
MINIMUM RELATIVE HUMIDITY OF THE PREVIOUS HOUR. (AUT)(%)
HOURLY RELATIVE HUMIDITY (%)
WIND DIRECTION (AZIMUTH º)
MAXIMUM WIND BLOW (m/s)
HOURLY WIND SPEED (m/s)

Figure 20. Automatic meteorological stations in the city of Sao Paulo and surroundings. Values are available at every hour, and the dates in the map represent the start of the records. Timestamps must consider the local time in Eastern Brazil, and therefore a reduction of three hours must be performed (UTC-3). The chosen one is SP Mirante A701. Sources: Geosampa, Open Street Map, INMET.

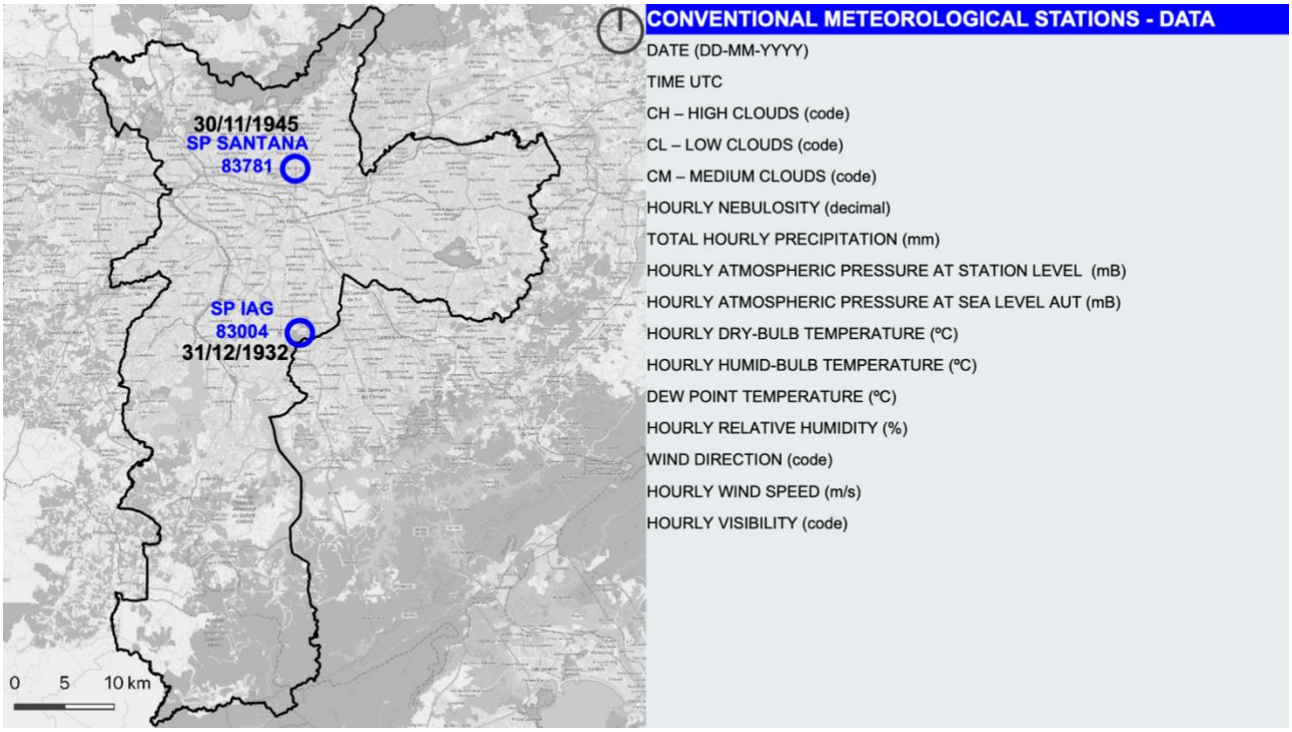


Figure 21. Conventional meteorological stations in the city of Sao Paulo and surroundings. Values are available three times per day, and the dates in the map represent the start of the records. Hourly nebulosity is a value that is important for simulations in CitySim, and therefore both datasets are joined, and null values are interpolated. The chosen one is SP Santana 83781, which lies in the same site as SP Mirante A701. Sources: Geosampa, Open Street Map, INMET.

6.2. TOOLS

The tools and software packages that will be used may be divided into three groups:

- Pre-processing: Python 3, QGIS, Cloud Compare, Safe Software FME.
- Processing: GRASS GIS, CitySim PRO, SimStadt, HoneyBee (via Grasshopper), the PVMD model developed at TU Delft, the model developed by Virtual City System.
- Post-processing / Visualisation: Safe Software FME, Azul, QGIS, and others to be defined in needed..

7. PRELIMINARY RESULTS

In order to start gaining hands-on experience with the solar analysis simulation tools, some experiments have already been conducted with GRASS GIS and CitySim.

Initially, four pre-processing activities were conducted in order to start with the first simulations.

- Rasterization of the Lidar Point Cloud into a Digital Terrain Model (DTM) and a Digital Surface Model (DSM), both with a spatial resolution of 1 m. Due to computation efficiency, the extent of these models was firstly set as 5x5 tiles of the lidar dataset, but they may be enlarged if necessary. The algorithm was implemented in an FME workbench.

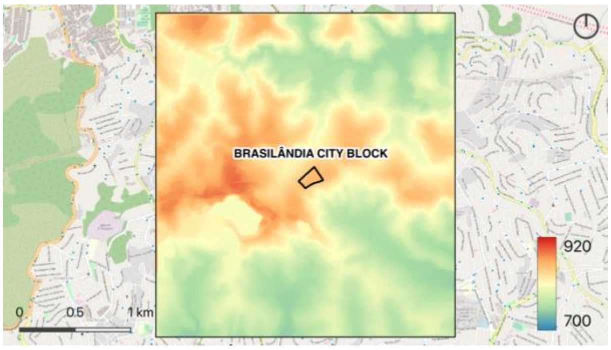


Figure 22. Brasilândia DTM 5x5 1m resolution.

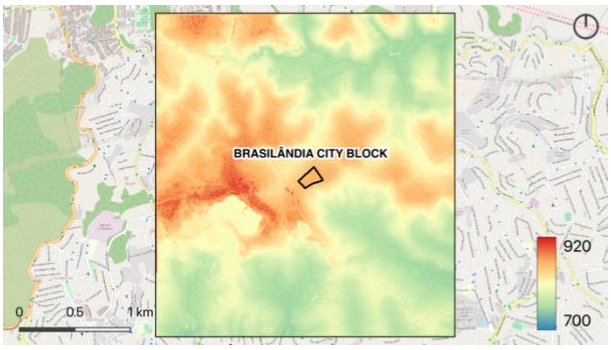


Figure 23. Brasilândia DSM 5x5 1m resolution.

Figure 24. Santana DTM 5x5 1m resolution.

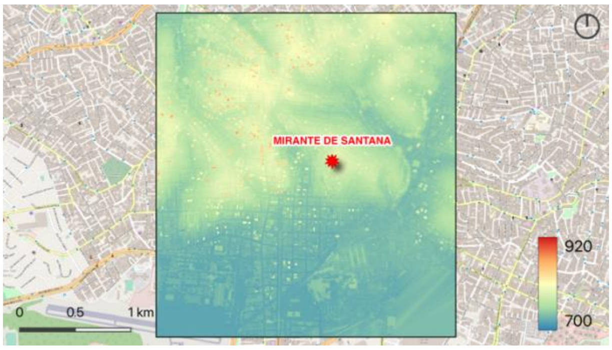


Figure 25. Santana DSM 5x5 1m resolution.

- Vectorization of the Lidar Point Cloud into a CityGML model with buildings in LoD2 and a TIN terrain in LoD1, appearances included. Due to computation efficiency, the extent of these models was firstly set as 1x1 tiles of the lidar dataset, but they may be enlarged if necessary. Some adjustments are still needed, but the models are already in compliance with the CityGML standard. The ETL (Extract, Transformation and Load procedure) was implemented in an FME workbench.

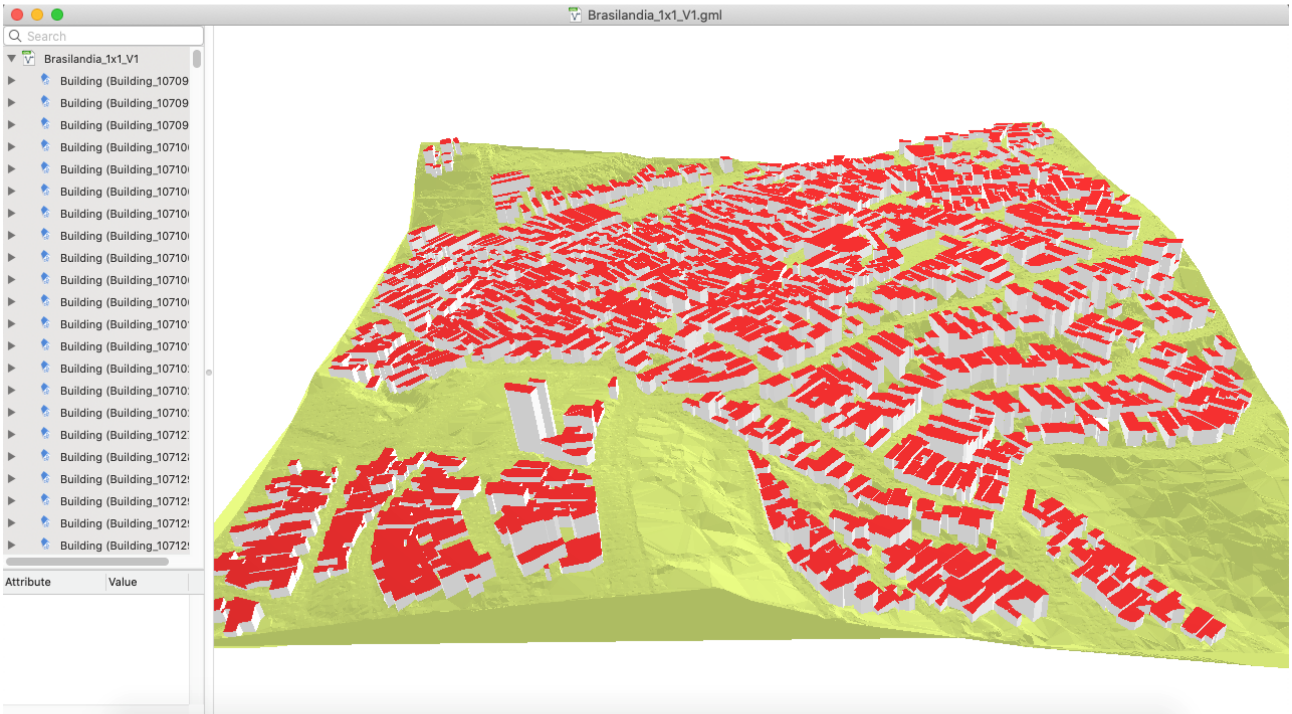


Figure 26. Brasilândia CityGML 1x1 – Buildings LoD2, Terrain LoD1.

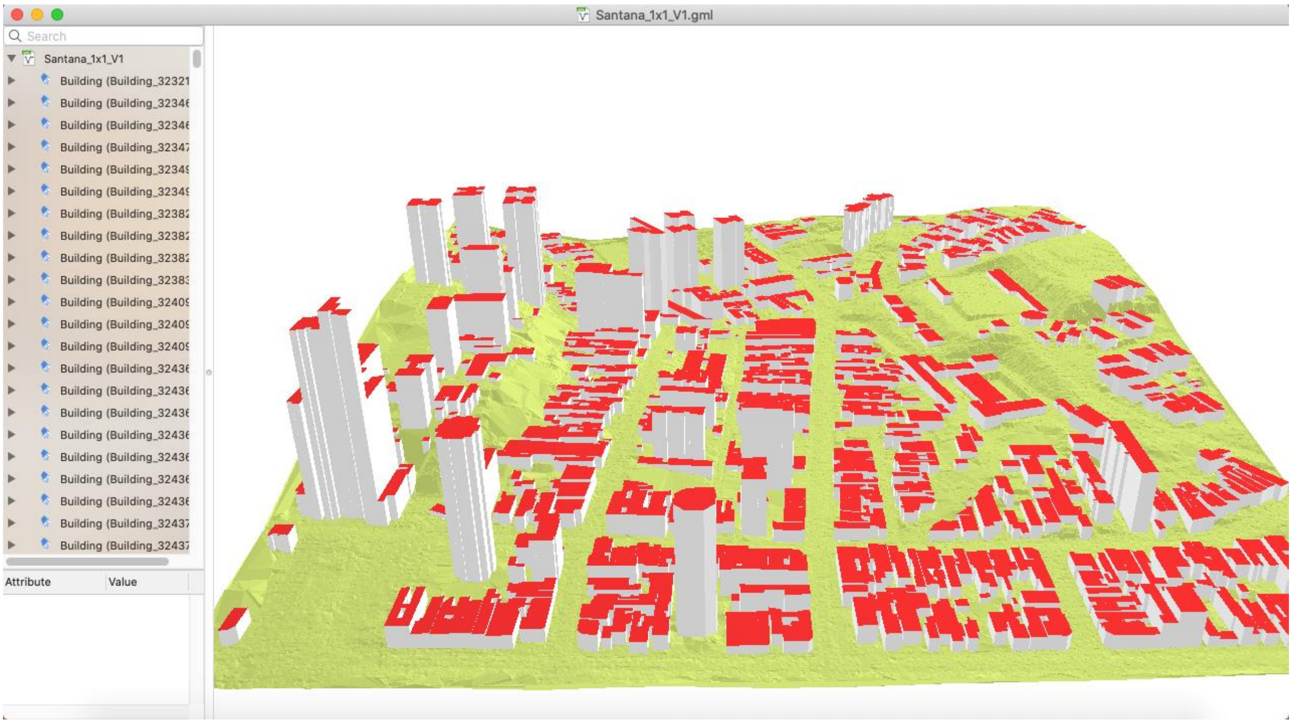
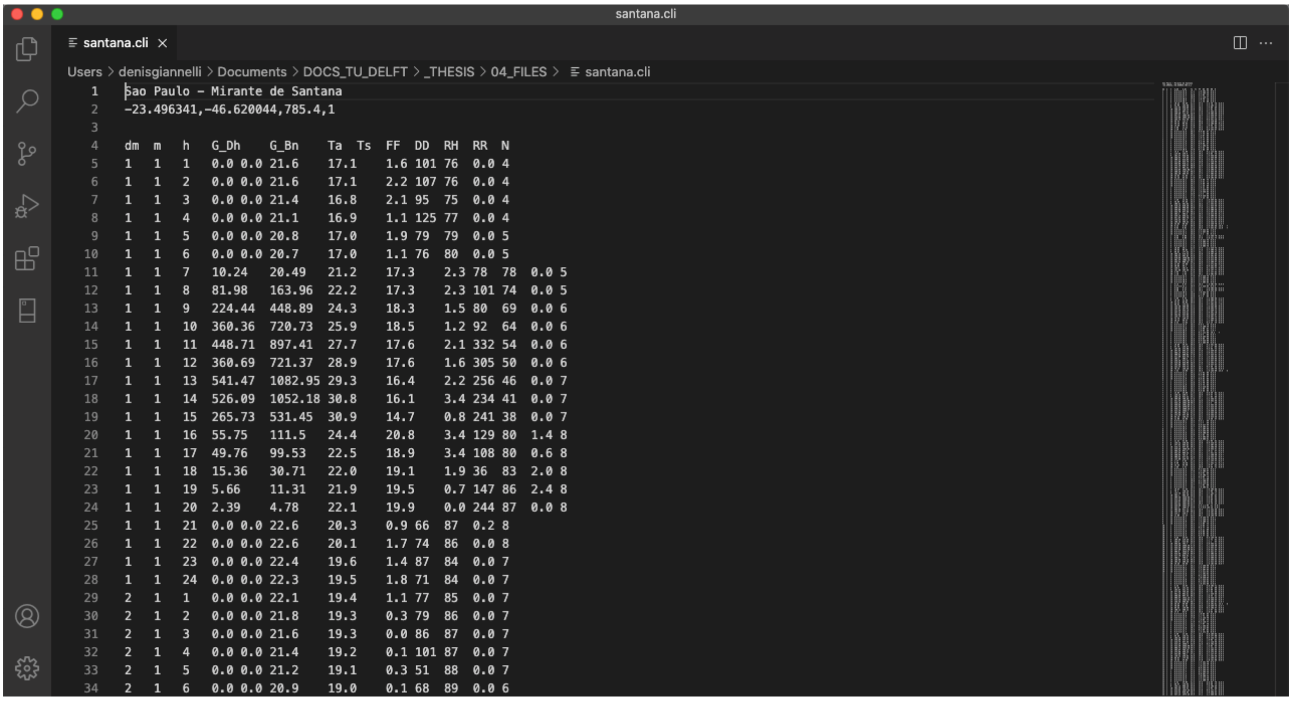


Figure 27. Santana CityGML 1x1 – Buildings LoD2, Terrain LoD1.

- Pre-processing of the meteorological dataset in order to establish ground truth and compute solar analysis on CitySim. The two aforementioned datasets (automatic and conventional) were joined, and a local interpolation was carried out for all null values found in between known values along the time series. This data preparation was conducted with Python. The output of this step is a .CSV file containing all necessary meteorological data, as well as the climate (.CLI) file necessary for CitySim.




```
Sao Paulo - Mirante de Santana
-23.496341,-46.620044,785.4,1

dm  m   h   G_Dh    G_Bn    Ta  Ts  FF  DD  RH  RR  N
1   1   1   0.0 0.0 21.6    17.1    1.6 101 76  0.0 4
1   1   2   0.0 0.0 21.6    17.1    2.2 107 76  0.0 4
1   1   3   0.0 0.0 21.4    16.8    2.1 95  75  0.0 4
1   1   4   0.0 0.0 21.1    16.9    1.1 125 77  0.0 4
1   1   5   0.0 0.0 20.8    17.0    1.9 79  79  0.0 5
1   1   6   0.0 0.0 20.7    17.0    1.1 76  80  0.0 5
1   1   7   10.24   20.49   21.2    17.3    2.3 78  78  0.0 5
1   1   8   81.98   163.96  22.2    17.3    2.3 101 74  0.0 5
1   1   9   224.44  448.89  24.3    18.3    1.5 80  69  0.0 6
1   1   10  360.36  720.73  25.9    18.5    1.2 92  64  0.0 6
1   1   11  448.71  897.41  27.7    17.6    2.1 332 54  0.0 6
1   1   12  360.69  721.37  28.9    17.6    1.6 305 50  0.0 6
1   1   13  541.47  1082.95 29.3    16.4    2.2 256 46  0.0 7
1   1   14  526.09  1052.18 30.8    16.1    3.4 234 41  0.0 7
1   1   15  265.73  531.45  30.9    14.7    0.8 241 38  0.0 7
1   1   16  55.75   111.5   24.4    20.8    3.4 129 80  1.4 8
1   1   17  49.76   99.53   22.5    18.9    3.4 108 80  0.6 8
1   1   18  15.36   30.71   22.0    19.1    1.9 36  83  2.0 8
1   1   19  5.66    11.31   21.9    19.5    0.7 147 86  2.4 8
1   1   20  2.39    4.78    22.1    19.9    0.0 244 87  0.0 8
1   1   21  0.0 0.0 22.6    20.3    0.9 66  87  0.2 8
1   1   22  0.0 0.0 22.6    20.1    1.7 74  86  0.0 8
1   1   23  0.0 0.0 22.4    19.6    1.4 87  84  0.0 7
1   1   24  0.0 0.0 22.3    19.5    1.8 71  84  0.0 7
2   1   1   0.0 0.0 22.1    19.4    1.1 77  85  0.0 7
2   1   2   0.0 0.0 21.8    19.3    0.3 79  86  0.0 7
2   1   3   0.0 0.0 21.6    19.3    0.0 86  87  0.0 7
2   1   4   0.0 0.0 21.4    19.2    0.1 101 87  0.0 7
2   1   5   0.0 0.0 21.2    19.1    0.3 51  88  0.0 7
2   1   6   0.0 0.0 20.9    19.0    0.1 68  89  0.0 6
```

Figure 28. Santana climate file (.CLI).

- From the previously computed 5x5 Digital Terrain Models, two horizon files (.HOR) were generated for the sites under analysis. This step is also required for the solar analysis simulation in CitySim. It was generated in GRASS GIS with the r.horizon command (point module), and later processed in Python in order to establish Phi values (orientation considered here as horizontal angle from the South) and Theta values (elevation from the horizontal plane, in degrees), as requested in the .HOR data structure.

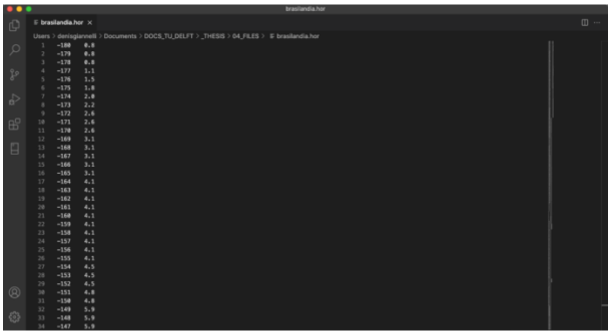


Figure 29. Brasilândia horizon file (.HOR).

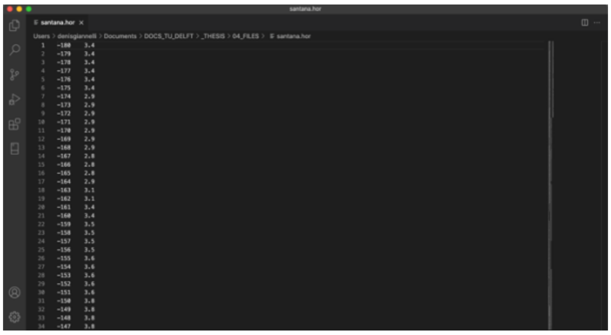


Figure 30. Santana horizon file (.HOR).

Finally, it was possible to obtain some preliminary results when it comes to the solar analysis simulations. Until now, a raster-based model was achieved with GRASS GIS, with solar irradiance values per pixel, and another vector-based CityGML model was exported from CitySim, including Energy ADE 1.0. Some adjustments still need to be taken care of, namely:

- Running the simulations on GRASS GIS once more, with the newly respective 5x5 DSM, and computing intermediate horizon maps at every 1 degree, instead of the original 15-degree step.
- Running the simulations on CitySim once more but this time opening an XML encoded CitySim file instead of importing a CityGML data structure. The necessity of this step will be validated with a meeting with the developer of CitySim PRO. The current importing process ignores the terrain, which must be present in the analysis.

The following images contain some screenshots from simulations that were conducted both in GRASS GIS and in CitySim PRO.

GRASS GIS Solar Irradiation Brasilândia – Min. value: 377.37, **Max. value: 9557.05 (Wh/m²)**

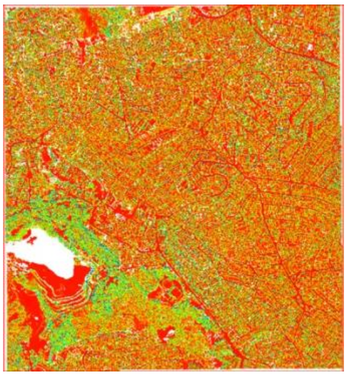


Figure 31. GRASS GIS – Brasilândia Solar irradiance – January.

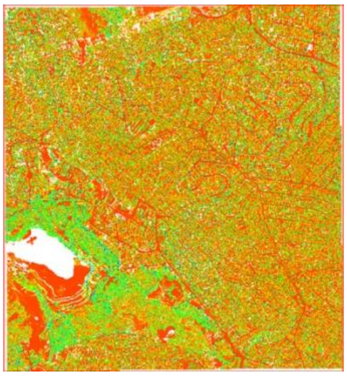


Figure 32. GRASS GIS – Brasilândia Solar irradiance – February.

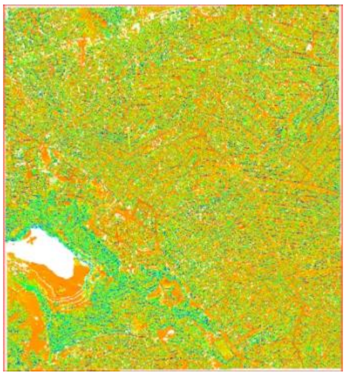


Figure 33. GRASS GIS – Brasilândia Solar irradiance – March.

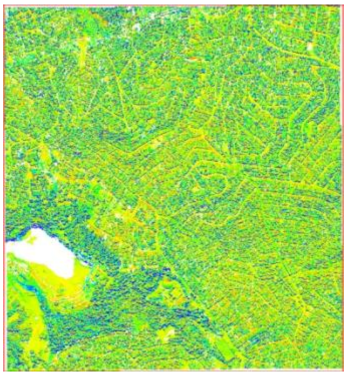


Figure 34. GRASS GIS – Brasilândia Solar irradiance – April.

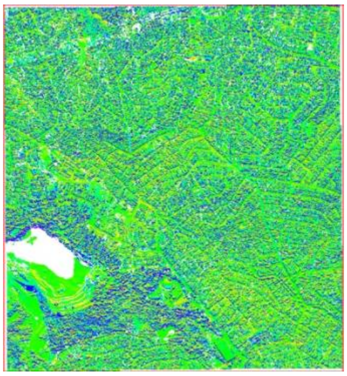


Figure 35. GRASS GIS – Brasilândia Solar irradiance – May.

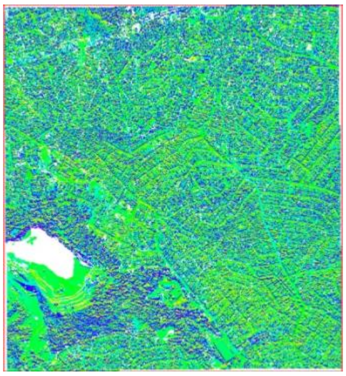


Figure 36. GRASS GIS – Brasilândia Solar irradiance – June.

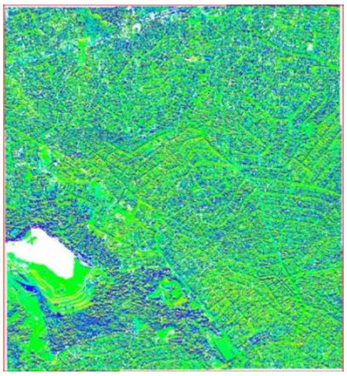


Figure 37. GRASS GIS – Brasilândia Solar irradiance – July.

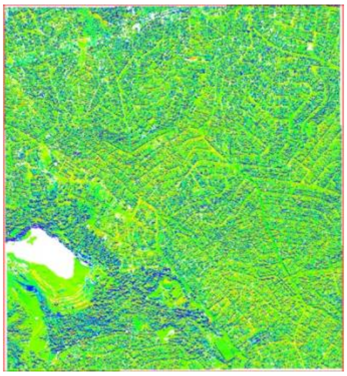


Figure 38. GRASS GIS – Brasilândia Solar irradiance – August.

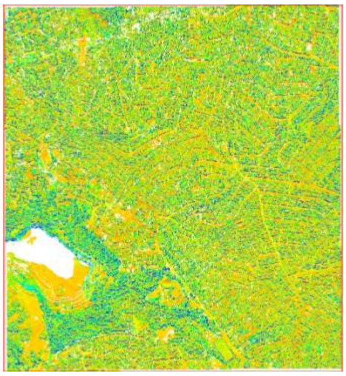


Figure 39. GRASS GIS – Brasilândia Solar irradiance – September

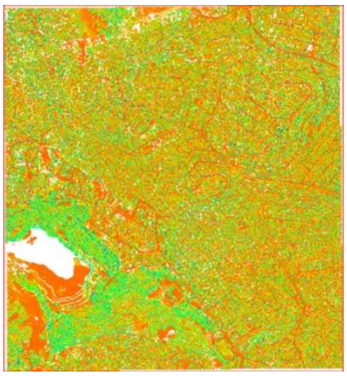


Figure 40. GRASS GIS – Brasilândia Solar irradiance – October.

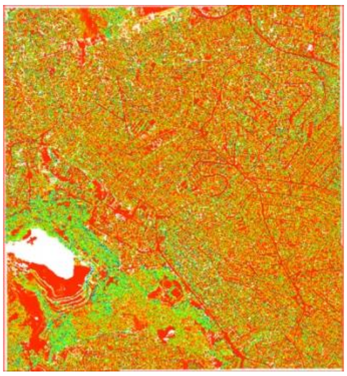


Figure 41. GRASS GIS – Brasilândia Solar irradiance – November.

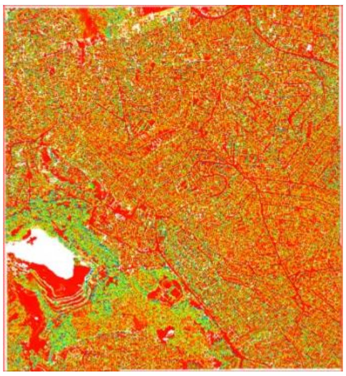


Figure 42. GRASS GIS – Brasilândia Solar irradiance – December.

GRASS GIS Solar Irradiation Santana – Min. value: 373.43, **Max. value: 9544.04 (Wh/m²)**

Figure 43. GRASS GIS – Santana Solar irradiance – January.

Figure 44. GRASS GIS – Santana Solar irradiance – February.

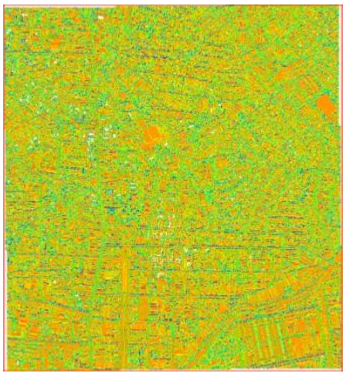


Figure 45. GRASS GIS – Santana Solar irradiance – March.

Figure 46. GRASS GIS – Santana Solar irradiance – April.

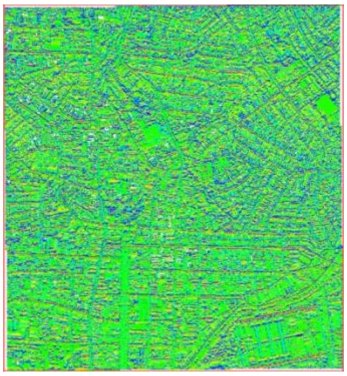


Figure 47. GRASS GIS – Santana Solar irradiance – May.

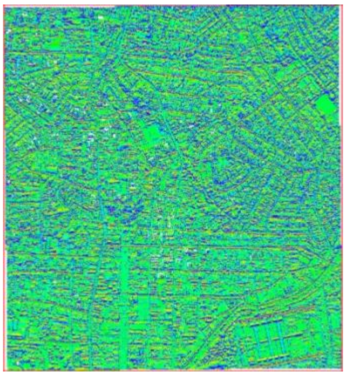


Figure 48. GRASS GIS – Santana Solar irradiance – June.

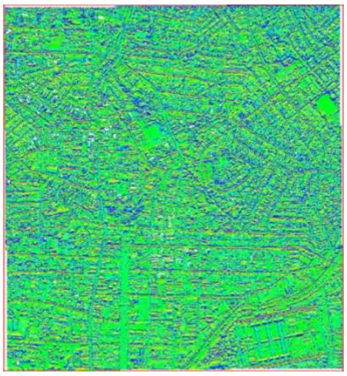


Figure 49 GRASS GIS – Santana Solar irradiance – July.

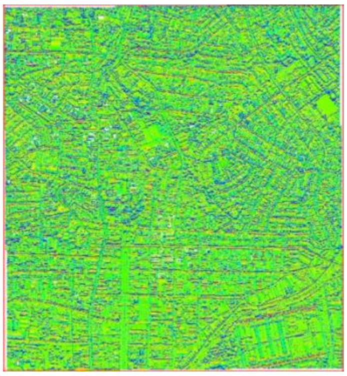


Figure 50 GRASS GIS – Santana Solar irradiance – August.

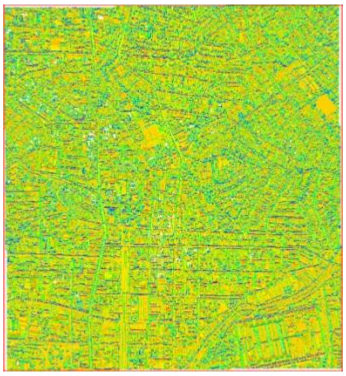


Figure 51. GRASS GIS – Santana Solar irradiance – September

Figure 52. GRASS GIS – Santana Solar irradiance – October.

Figure 53. GRASS GIS – Santana Solar irradiance – November.

Figure 54. GRASS GIS – Santana Solar irradiance – December.

CitySim Short-Wave Irradiation Santana – Min. value: 0.0, **Max. value: 2500.0 (Wh/m²)**

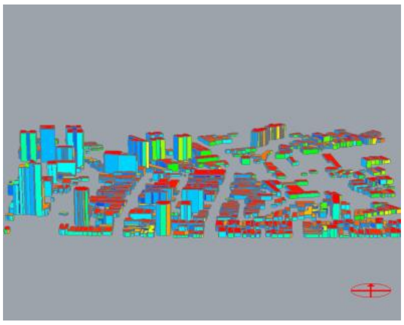


Figure 55. CitySim – Santana
Short-wave irradiance – January.

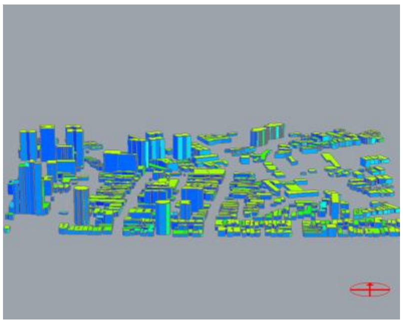


Figure 56. CitySim – Santana
Short-wave irradiance – February.

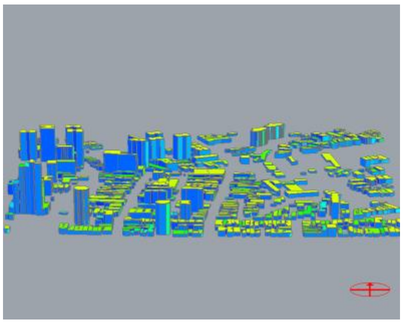


Figure 57. CitySim – Santana
Short-wave irradiance – March.

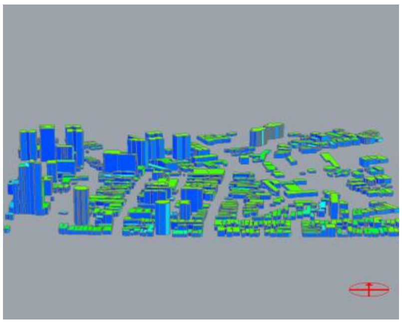


Figure 58. CitySim – Santana
Short-wave irradiance – April.

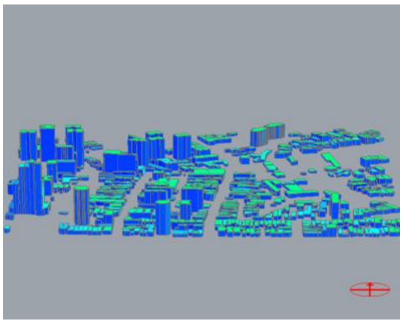


Figure 59. CitySim – Santana
Short-wave irradiance – May.

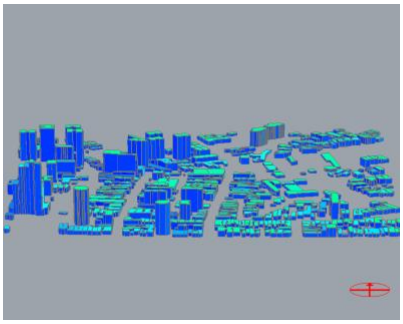


Figure 60. CitySim – Santana
Short-wave irradiance – June.

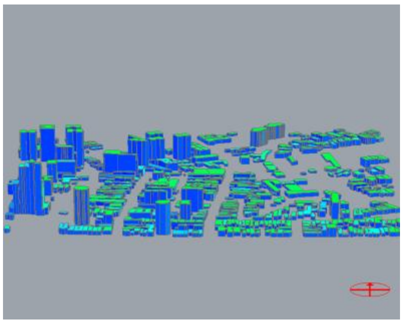


Figure 61. CitySim – Santana
Short-wave irradiance – July.

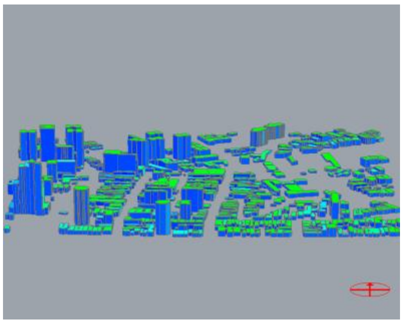


Figure 62. CitySim – Santana
Short-wave irradiance – August.

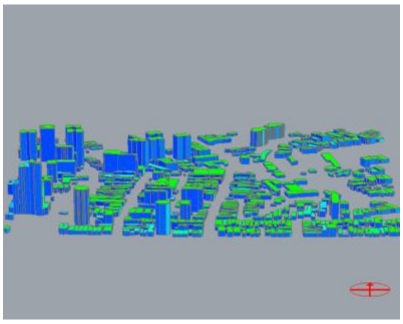


Figure 63. CitySim – Santana
Short-wave irradiance – September

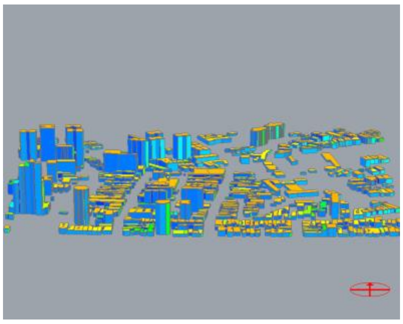


Figure 64. CitySim – Santana
Short-wave irradiance – October.

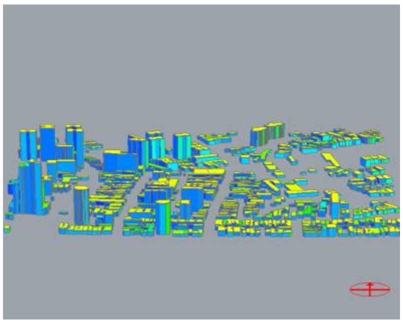


Figure 65. CitySim – Santana
Short-wave irradiance – November.

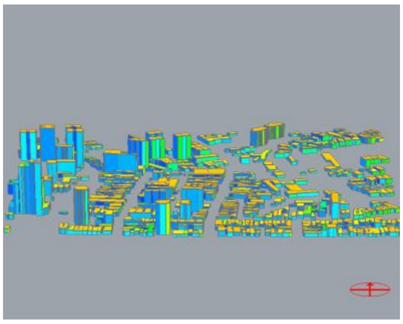


Figure 66. CitySim – Santana
Short-wave irradiance – December.

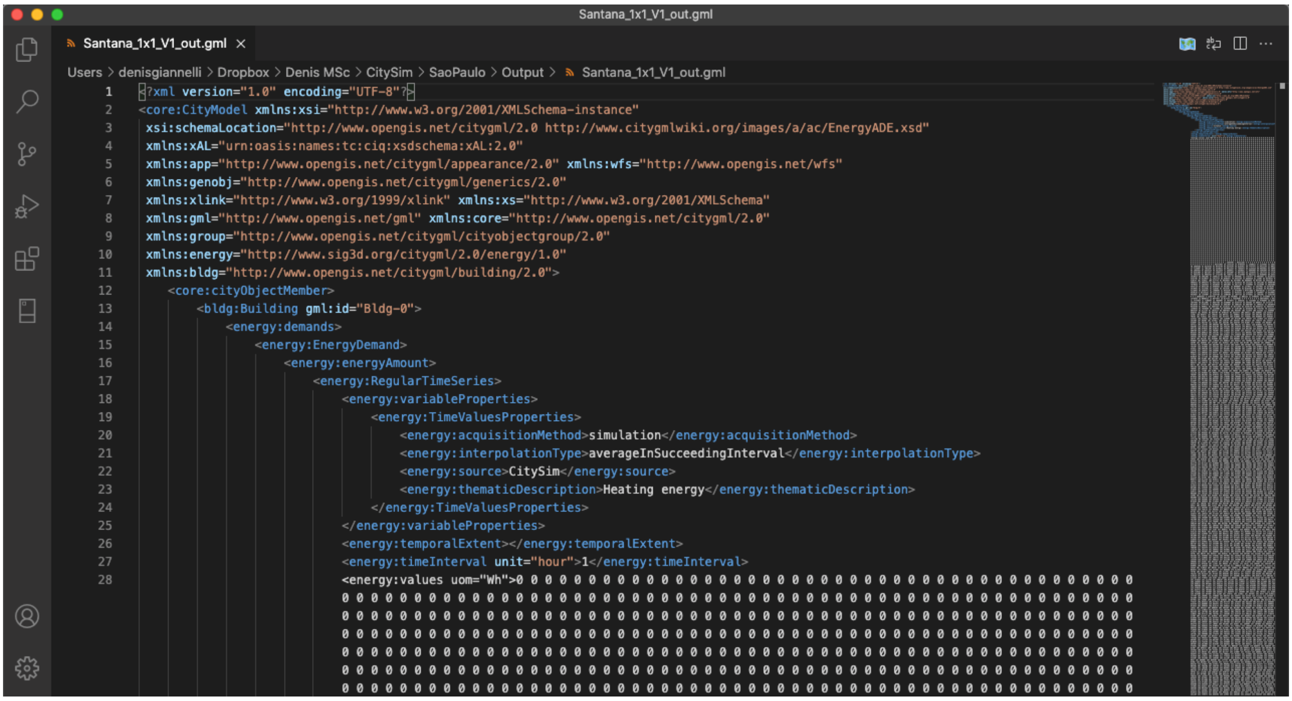


Figure 68. Santana CityGML 1x1 – Buildings LoD2 and Energy ADE 1.0

Until now, it was not possible to conclude the simulation of Brasilândia CityGML 1x1 in CitySim Pro. There are errors when importing the CityGML file in CitySim – one building is pointed out as having no volume and is therefore imported as a shading surface – but, most important, the simulation process crashes. The pictures illustrate the encountered errors:

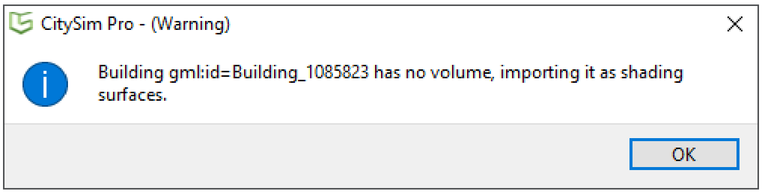


Figure 69. Error when importing Brasilandia_1x1_V1.gml to CitySim PRO.

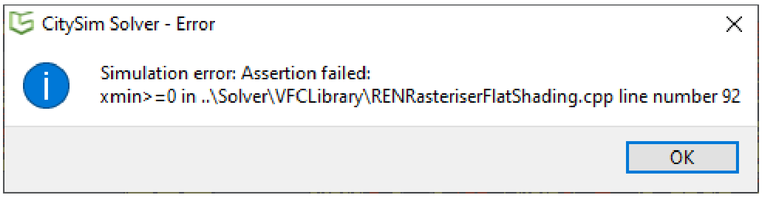


Figure 69. Error when simulating Brasilandia_1x1_V1.gml with CitySim PRO.

These initial tests show that – despite some issues that need further investigation – it is possible to run some solar irradiation simulation using the test data of Sao Paulo. In the next weeks, attention will be paid to solving these issues, possibly contacting the developers of CitySim to get a deeper insight in the data requirements of the software.

8. LITERATURE

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