A geoprocessing framework to compute urban indicators: The MApUCE tools chain

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Abstract

A growing demand from urban planning services and various research thematics concerns urban fabric characterization. Several projects (such as WUDAPT) are currently lead in the urban climate field to answer this demand. However there is currently a need to propose standardized methods to calculate urban indicators and to automatically classify the urban fabric for any city in the world as well as to propose platforms to share these methods and the associated results. Our contribution answers partially to this challenge. A total of 64 standardized urban morphological indicators are calculated for three scales of analysis : building, block and a reference spatial unit (RSU). A supervised classification is performed for the building and the RSU scales using a regression trees model based on these indicators and on 10 urban fabric typological classes defined by urbanists and architects. A processing chain is proposed to realize indicator calculation and urban fabric classification for any french municipality according to reference data provided by the French National Geographical Institute (IGN). Spatial reasoning and morphological indicators description are formalized with SQL language and statistical analysis is carried out with R language. Finally a geoprocessing framework based on free and open source softwares, conform to the Open Geospatial Consortium (OGC) standards and ready to serve open data is built. Indicators values and classification results for 6% of the french municipalities (corresponding to 41% of all french buildings) are available through a web cartographic portal by any person interested in such analysis.

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Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) projections, global surface temperature will increase during the XXI^{st} century. In the meantime, the world population living in cities is expected to grow (5,058 millions by 2030 against 4,250 millions in 2018 - [1]). Two factors explain this number: the population of existing cities will grow, and new cities will appear. Urbanization often implies urban temperature rise due to land cover change (pervious to impervious ground [2, 3]) and morphology change (new buildings mean more short and long-wave radiation trapping as well as wind speed decreasing [4]). Without urbanization control, this phenomenon called Urban Heat Island (UHI) may become more intense since temperature differences between an urban area and its surrounding is proportional to the logarithm of its population [5, 6]. The combination of climate change and UHI may lead to higher heat related death occurrence [7, 8] and higher energy consumption related to cooling use [9, 10]. Therefore, the reduction of the urban heat island phenomenon may contribute both to attenuate the climate change (by reducing urban greenhouse emissions) and to mitigate its impacts. Several levers have proved their efficiency to lower urban air temperature such as surface painting to modify the albedo, planting trees or covering roofs and facades with low vegetation, decreasing energy consumptions, *etc.* [11, 12]. Santamouris et al. [11] showed that their performance and surface application potential differ greatly depending on the urban environment where they are applied in. To study the influence of urban morphology and urban land-cover on urban air temperature as well as the efficiency of each UHI counter-measure, urban climate models have been developed [13] and urban classification have been proposed [14]. Urban climate models are applied to a grid of urban mesh. For each mesh, several urban parameters are needed such as mean building height, aspect ratio, etc. Concerning the urban classification, the territory is also split into elementary units which are then classified according to a Local Climate Zone (LCZ) definition based on urban parameters describing urban morphology, urban land-cover, urban land-use and material properties [15]. Research has been made to identify LCZ within urban areas from geographical data. Most of the methods are based on a process using three steps. First the territory is split according to a certain grid. Second, urban parameters are calculated within each mesh from vector database or satellite images. Third, rules are created to allocate each mesh to a LCZ. Each of these steps may be manually [16] or automatically [17, 18] performed. The limitations of those works is their lack of reproducibility. The manual classification is time-consuming and based on expert analysis. The automatic classifications proposed by Lelovics et al. [17], Zheng et al. [18] rely on local data and on their own urban indicator definition. Thus simulation and classification approaches are very sensitive to data and methodology used to calculate urban indicators (characteristic of the morphology and the land cover of the urban fabric) [19]. To obtain comparable indicators at world scale, there is a need :

- to standardize data and methodology used for urban indicators calculation [20],
- to propose collaborative and open tools to allow any user to calculate urban indicators for the city of its choice, thus allowing to share and reuse results from any calculation.

In this spirit, a collaborative project called *World Urban Database and Access Portal Tools* (WUDAPT[1]) gathers a community of researchers to classify the urban fabric by climate properties from homogeneous and available data at world scale. The objective is to identify Local Climate Zones as defined by Stewart and Oke [15]. The first step of the project have been applied. The LCZ of several urban areas have been identified according to supervised machine learning method using Landsat images (30 m resolution) as input and LCZ identified by climate expert from Google Earth software as desired output [21]. However, WUDAPT is open to improvements:

- the need to install locally several softwares (Google Earth[2], SAGA[3]) on its computer may be a break to collaborative contribution,
- it is now necessary to provide data and urban indicators at finer scale [20]. Plenty of indicators exist but they have several definitions and

[1] `http://www.wudapt.org/` accessed in July 2017
[2] `https://www.google.com/earth/` accessed in July 2017
[3] `http://www.saga-gis.org/` accessed in July 2017

they are implemented within different softwares using numerous languages and methods. Thus comparing the value of such undefined indicator throughout the world or along time is impossible [22].

Our contribution consists in the production of standardized urban morphological indicators dedicated for urban climate and useful for any other urban planning purpose. It is a component of a french research project called MApUCE[4] and is encompassed in a task of urban tissue characterization, illustrated in Figure 1.

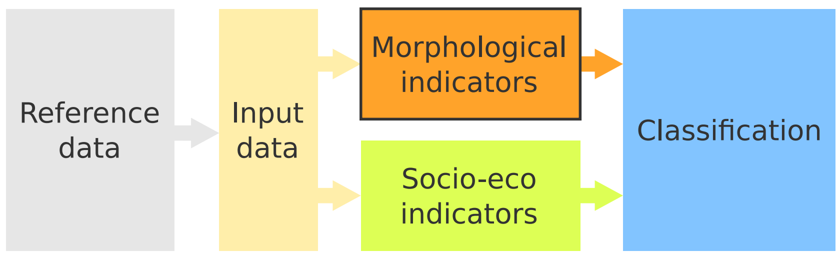


Figure 1: The main steps of the method

Input data are produced from reference data. They are used to produced both morphological and socio-economic indicators, that will be used to classify the urban fabric into typological classes. In this article, we will focus on the morphological indicators production and we will described briefly the classification step. Further details concerning the input data production and the socio-economic indicators production are available in Plumejeaud-Perreau et al. [23] whereas the classification process is further described in Faraut et al. [24], Masson et al. [25]. Because one of the objective is that the overall process be reproducible simply without any software requirement, this paper proposes an open geoprocessing framework based on free and open source softwares, conform to the Open Geospatial Consortium standards and ready to serve open data.

[4] `http://www.umr-cnrm.fr/ville.climat/spip.php?rubrique120` accessed in July 2017

1. Data

1.1. Scale definition

Whereas streets may be considered as more durable than blocks and buildings [26], building is the elementary object structuring the territory [27] and also the object of interest when focusing on urban climate application [28]. However, building scale is not appropriate when dealing with issues at city scale. For this reason, Berghauser-Pont and Haupt [29] proposed five scales to analyze urban areas : buildings, lots, island, fabric and district. The first described only building properties whereas the others described the building properties and their surrounding environment. Lots are defined by the legal boundaries specified in the cadastral map. Islands include several lots limited by road boundaries. Fabrics include several islands as well as the road network whereas districts gather several fabrics and include public parks and water surfaces. All these scales are the result of arbitrary objects aggregation, except building and lot. In this context, we define the building as the elementary scale. A second scale is chosen: the building block, defined by Berghauser-Pont and Haupt [29] as an aggregation of buildings that are in contact. This scale is particularly adapted when dealing with building energy or urban climate issues [30]. By simplification, it will be called block in this paper. To consider all the components of the urban context, the legal boundaries specified in the cadastral map are also utilized (such as the lot defined by Berghauser Pont). This scale offers the advantage to have a size close to the one usually recommended in the urban climate literature (several hundred meters wide - [28]). They are slightly modified to include public spaces such as road surfaces, public parks and water surfaces. The generic name of Reference Spatial Unit (RSU) is set for the resulting feature. Any other well defined geographical entity may be used as an RSU, such as the urban block defined by the road network [31]. Finally, three scales of analysis will be considered: building, blocks and RSU.

1.2. Reference data

The reference data sets of the MApUCE tool chain are provided from the french national databases which are freely available for research and academic purpose. They have been produced following identical rules since many years and they offer a complete spatial coverage of the French territory. It concerns two types of data: spatial (Table 1) and statistical (Table 2).

data set	Description
BD Topo®	Topographic data, in vector format, provided by the French National Geographical Institute (IGN) (see `http://professionnels.ign.fr/bdtopo`). The data are classified in ten topics. Each topic contains a set of layers distributed in a GIS file format. *e.g* "*BUILDING*" theme includes undefined, industrial or remarkable building layers, ...
Parcels	Cadastral parcels, in vector format, provided by IGN (see `http://professionnels.ign.fr/bdparcellaire`)
Gridded population	This data set depicts the distribution of human population across the french territory. The data is distributed by the French National Institute for Statistics and Economic Studies (INSEE) (see `https://www.insee.fr/en/accueil`)
IRIS contouring	The IRIS contouring contains a set of polygons that represents an area of 2,000 grouping inhabitants. The median area is about 740 ha, and maximal size is of 36,700 ha. This data set is provided by IGN.

Table 1: Input spatial data sets used by the MApUCE tool chain

data set	Description
Households survey	The french households survey is provided by the National Institute of Statistics and Economics and Studies (INSEE). This survey is linked to the IRIS contouring thanks to a key index.

Table 2: Input statistical data set used by MApUCE tool chain

1.3. Data pre-processing

The above data sets were used to derive 3 spatial layers computed in 3 main steps [23].

1.3.1. Step 1: Data cleaning and structuring

The quality aspects of the spatial data sets are inspected using quality control metrics and assessment procedures. They are implemented using the Structured Query Language (SQL) extended with spatial functions. The PostGreSQL-PostGIS database has been selected for this purpose. Five types of geometry inconsistencies are checked : redundancy (same geometry, same geometry with different attributes), overlapping (geometries having a surface in common), invalid, null, size (geometry area or length greater than a threshold). They are corrected using a rules based system. The following pseudo code illustrates the principle (Table 3)

```
if the geometry is null
   then delete
else if the geometry is invalid
   then correct
if the geometry overlaps another geometry
   then remove the part of  the geometry that have
      lowest overlapping area
...
```

Table 3: Pseudo code to control and fix the geometry quality

The data quality processes are chained with a data structuring task used to organize the input data sets into main tables. This is especially the case for the BD Topo® data set that are grouped in two layers : *BUILDING* and *ROADS*. *e.g* the *BUILDING* table contains all features from the three vector layers undefined, industrial or remarkable building theme.

1.3.2. Step 2: RSU computing

A new partitioning of the urban territory is computed. Based on the dual of a Delaunay triangulation, its boundaries correspond to the medial axis of negative area of the union of the cadastral parcels. We call it "Reference Spatial Unit" (RSU).

The properties of the Voronoï tessellation are used to create the RSU (Figure 2). First, contiguous parcels are unified (1). Then the seeding points of the Voronoi tesselation are prepared. Those points are used to compute the Voronoi polygons (3). Finally, RSU are generated (4) and smoothed (5).

The RSU geometries are stored into one table. They are computed municipality by municipality. Each RSU is related to one and only one municipality using a national index named in the data.

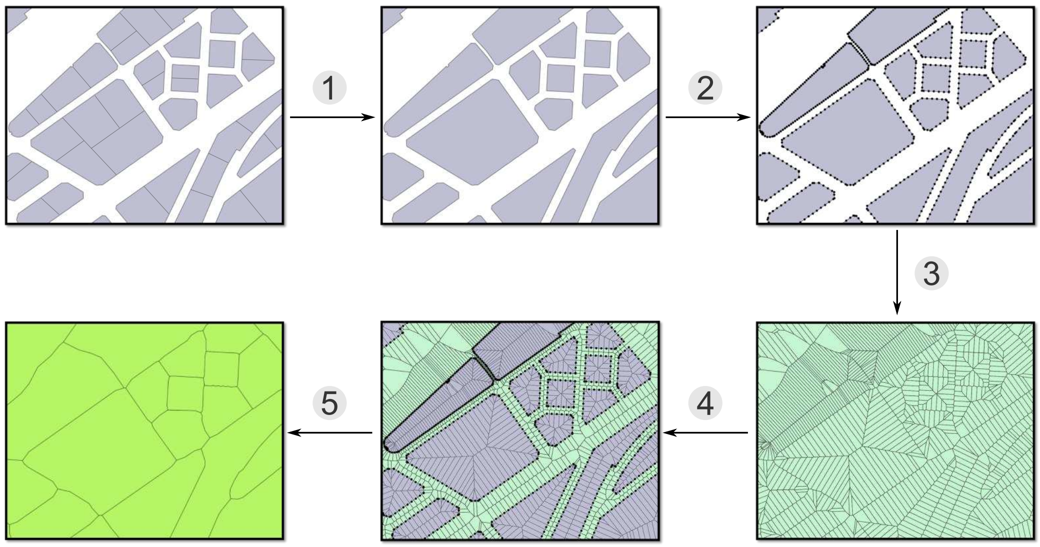


Figure 2: The RSU generation process *(adapted from Plumejeaud-Perreau et al. [23])*

1.3.3. Step 3: Data enriching

Data enriching is the final step of the data preprocessing stage. It involves to integrate new variables on the two tables *BUILDING* and *RSU*. The integration is solved by chaining spatial analysis methods and aggregating processes. The tables 4 and 5 list the final variables computed. Note that these variables include the socio-economic indicators computed by [23].

The final result of this data pre-processing task is a set of 4 tables stored in a PostGIS database. They are the main entries for the MApUCE tool chain (implying the computation of the required urban indicators). The Table 6 gives some statistics about the number of features yet processed.

2. Method

2.1. Morphological indicators

The calculation method of a wide range of indicators is presented in this section. The list of indicators has been established based on the results of a literature review (mixing urban climate and geography issues but also geographical issues only), discussions with architects and urban planners and needed indicators as input in urban climate models. Some of them are specific to the calculation scale: they are called "primary indicators". The others are

Variable	Description	Method	Step
pk_build	Building unique identifier	Incremental value (Primary Key)	1
the_geom	Building geometry	Geometry of the building	1
insee_code	Id of the commune that contains the building	Unique key value that refers to a municipality	3
pk_rsu	Id of the RSU that contains the building	Unique key value that refers to a RSU geometry. A spatial join process is used with a constrained area. e.g. If a building overlaps two RSU, the affected pk_rsu is the one corresponding to the maximal intersected area	3
h	Building height available in the BD Topo	-	1
h_fixed	Corrected height *(calculated from an iterative process using indicators computed in the section 2)*	If $h = 0$ *or Null* then {if $\frac{h\_std_{rsu}}{h\_mean_{rsu}} < 0.5$ then $h\_fixed = \lvert round(h\_std_{rsu} - h\_mean_{rsu}) \rvert$ else $h\_fixed = \lvert round(h\_mean_{rsu}) \rvert$} else $\{h\_fixed = h\}$	3
nb_level	Number of level deduced from *h_correct*	For building with the *indifferencie* theme, if $h\_fixed \geq 3$ $nb\_level = round((h\_fixed - \frac{4}{3}) + 1$ else $nb\_level = 1$	3
insee_inhab	Number of inhabitants	Derived from INSEE 200m gridded cells	3
theme	Name of BDTopo theme	Building theme from BD Topo : *industriel* (industrial), *remarquable* (remarkable) or *indifferencie* (undistinguished)	3

Table 4: List of variables in the BUILDING table

Variable	Description	Method	Step
pk_rsu	RSU unique identifier	Incremental value (Primary Key)	1
the_geom	RSUs geometry	Geometry of the RSU	2
veget_surface	Total vegetation surface	Area of vegetation intersecting the RSU	3
road_surface	Total road surface	Area of roads intersecting the RSU. This area is determined thanks to a width attribute included in the road layer. Spatial processes, using buffer and intersection are done to compute this area.	3
road_length	Total road length	Length of roads intersecting the RSU	3
sidewalk_length	Total length of sidewalk	Perimeter of the geometry resulting from the union of contiguous parcels	3
hydro_surface	Total hydrographic surface	Area of hydrological objects (based on *RESERVOIR_EAU* and *SURFACE_EAU* layers from BD Topo) intersecting the RSU	3
hydro_length	Total hydrographic length	Length of hydrological objects (based on *TRONCONCOURS_EAU* layer from BD Topo) intersecting the RSU	3
insee_inhabit	Number of inhabitants	*	3
insee_hh	Number of household	Number of households having a principal residence. *	3
insee_hh_coll	Number of households in collective dwellings	Number of households living in collective housing. *	3
insee_men_surf	Cumulative Surfaces of Main Residences in square meters	Cumulated area of housings for households having a principal residence computed in square meter. *	3
insee_surf_col	Estimation of the area of collective housing	Estimation of collective housing from INSEE indicators. *	3
insee_code	French municipality unique identifier	Transferring the municipality identifier from the municipality layer to the RSU geometry using a spatial join.	3

* Derived from INSEE 200m gridded cells

Table 5: List of variables in the RSU table

Data set	**Description**	**Number of features**
BUILDINGS	French buildings	8 942 135
ROADS	French road network	17 043 575
RSU	Reference Spatial Units	454 308
MUNICIPALITIES	French municipalities	36 553

Table 6: Number of features available after the pre-processing task

aggregated from primary indicators calculated at lower level: they are called "derived indicators".

Three scales are considered for the morphological indicators production: building, blocks and RSU (Figure 3). A block is an aggregation of buildings that have at least one point in common when intersected.

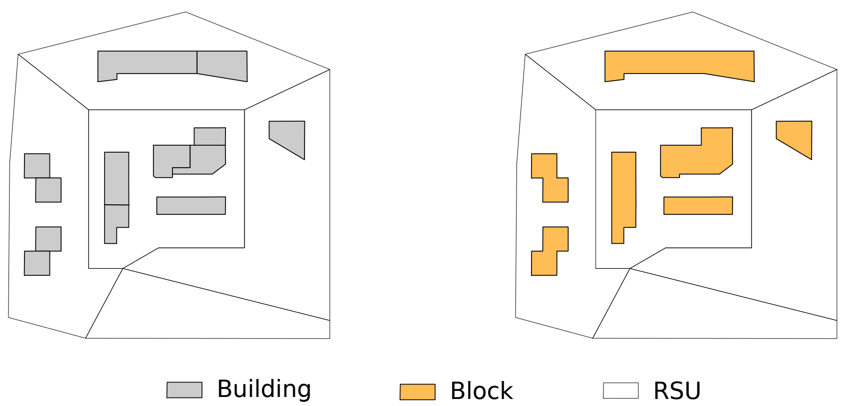


Figure 3: The three scales of analysis

2.1.1. For buildings

27 indicators are computed at the building scale (Table 7).

Name	Description	Method	Biblio
area	Building area	Area of the building geometry (footprint)	[27]
floor_area	Building floor area	$area \cdot nb\_level$	
vol	Building volume	$area \cdot h\_fixed$	

Table 7: List of primary building indicators

Name	Description	Method	Biblio
perimeter	Building perimeter	Perimeter of the building geometry	
perimeter_cvx	Building convexhull perimeter	-	
form_factor	Building form factor	$\frac{area}{perimeter^2}$	[32]
nb_neighbor	Building number of neighbor	Number of buildings that are in contact (at least one point) with the building of interest	[27]
b_wall_area	Total area of building walls (including holes)	Sum of the linear of facades multiplied by the building height	
p_wall_long	Total length of common (party) walls	Sum of the linear of facades that are in contact with other buildings	
p_wall_area	Total area of common (party) walls	When the building has a common linear of facade with another one, the common wall area is the linear of facades multiplied by the height of the smallest building. Then the sum of these areas is realized for each neighbors in contact with the building.	
free_ext_area	Area of free external facades, that are in contact with the air	$\sum b\_wall\_area - \sum p\_wall\_area + \sum area$	
concavity	Building concavity	Building area divided by its convex hulls area	[33, 34]
contiguity	Building contiguity	$\frac{p\_wall\_area}{b\_wall\_area}$	[35]
compacity_r	Building raw compacity	$\frac{b\_wall\_area+area}{volume^{\frac{2}{3}}}$	[29]
compacity_n	Building net compacity	$\frac{free\_ext\_area}{volume^{\frac{2}{3}}}$	
compactness	Building compactness	Ratio between the building perimeter and the perimeter of a circle having the same area	[36, 37]

Table 7: List of primary building indicators

Name	Description	Method	Biblio
main_dir	Building main direction (in degree)	The main direction is defined as the direction given by the longest side of the building Smallest Minimum Bounding Rectangle (SMBR)	[38, 39]
p_vol_ratio	Building passive volume ratio. This ratio can be expressed as the building portion that can be naturally lit and ventilated.	Area taken up to 6 m from a free facade inside the building, then divided by the building area	[40, 41, 36]
fractal_dim	Building fractal dimension	$2 \cdot \frac{log(perimeter)}{log(area)}$	[42, 43]
min_dist	Distance between the building of interest and the closest building which is in the same RSU	Minimum distance between the building of interest and the other ones in the same RSU	
max_dist	Distance between the building of interest and the furthest building which is in the same RSU	Maximum distance between the building of interest and the other ones in the same RSU	
mean_dist	Mean distance between the building of interest and the other buildings which are in the same RSU	-	[44]
std_dist	Population standard deviation distance between the building of interest and the other buildings which are in the same RSU	-	

Table 7: List of primary building indicators

Name	Description	Method	Biblio
num_points	Building number of points	Count the building number of points after removing duplicate (e.g startpoint and endpoint are counted once)	[27]
l_3m	Linear of building walls next to road	For each building, total length of walls that are less than 3m far from the road	
l_ratio	Part of building walls next to road	$\frac{l\_3m}{perimeter}$	
l_ratio_cvx	Ratio between linear of building walls next to road and the building convex-hull perimeter	$\frac{l\_3m}{perimeter\_cvx}$	

Table 7: List of primary building indicators

2.1.2. For blocks

A total of 9 indicators are computed at the block scale (tables 8 and 9).

Name	**Description**	**Method**	**Biblio**
area	Building area composing the block	Footprint area	
compacity	Block net compacity	$\frac{\sum free\_ext\_area^{\frac{2}{3}}}{Sumvol}$	
main_dir	Block main direction	The main direction is defined as the direction given by the longest side of the blocks Smallest Minimum Bounding Rectangle (SMBR)	
holes_area	Area of holes in a block	-	[27]
holes_ratio	Ratio between the holes area and the blocks area	$\frac{holes\_area}{area+holes\_area}$	

Table 8: List of primary block indicators

Name	Description	Aggregation method	Biblio
floor_area	Block floor area	$\sum floor\_area$	
vol	Block volume	$\sum vol$	
h_mean	Block mean height	$\frac{\sum area \cdot h\_fixed}{\sum area}$	[35]
h_std	Block standard deviation height	Block population standard deviation building height	

Table 9: List of derived block indicators

2.1.3. For RSU

A total of 9 indicators are computed at RSU scale (tables 10 and 11).

Name	Description	Formula	Biblio
build_numb	Number of buildings in the RSU	-	
dist_to_center	Distance to the city center	Distance between RSU centroid and the city center	

Table 10: List of primary RSU indicators

Name	Description	Aggregation method	Biblio
area	Building area in the RSU	$\sum area_{build}$	
floor_area	Building floor area in the RSU	$\sum floor\_area_{build}$	
floor_ratio	Building floor area ratio	$\frac{\sum floor\_area_{build}}{rsu\_area}$	[29, 35, 45, 46, 47]
vol	Building volume	$\sum vol_{build}$	
vol_m	Building mean volume	$\frac{\sum vol_{build}}{build\_numb}$	
ext_env_area	Building external area	$\sum free\_ext\_area_{build}$	
compac_m_w	Building weighted mean compacity	$\frac{\sum compacity\_n_{build} \cdot area_{build}}{\sum area_{build}}$	

Table 11: List of derived RSU indicators

Name	Description	Aggregation method	Biblio
compac_m	Building non-weighted mean compacity	$\frac{\sum compacity\_n_{build}}{build\_numb}$	
contig_m	Building mean contiguity	$\frac{\sum contiguity_{build}}{build\_numb}$	
contig_std	Building standard deviation contiguity	Population standard deviation contiguity of buildings	
main_dir_std	Main direction of buildings standard deviation	Population standard deviation main direction of buildings	
h_mean	Building mean height	$\frac{\sum area_{build} \cdot h\_fixed_{build}}{\sum area_{build}}$	
h_std	Building standard deviation height	Population standard deviation height of buildings	
p_vol_ratio_m	Building mean passive volume ratios	$\frac{\sum floor\_area_{build} \cdot p\_vol\_ratio_{build}}{\sum floor\_area_{build}}$	
min_m_dist	Mean of the minimum distance between buildings that are in the same RSU	$\frac{\sum min\_dist_{build}}{build\_numb}$	
mean_m_dist	Mean of the mean distance between buildings that are in the same RSU	$\frac{\sum mean\_dist_{build}}{build\_numb}$	
mean_std_dist	Standard deviation of the mean distance between buildings that are in the same RSU	Population standard deviation of the mean distance between buildings that are in the same RSU	
bl_hole_area_m	Mean courtyard ratio of blocks within an RSU	$\frac{\sum holes\_ratio_{block} \cdot area_{block}}{\sum area_{block}}$	

Table 11: List of derived RSU indicators

Name	Description	Aggregation method	Biblio
bl_std_h_mean	Mean of the standard deviation height of buildings, computed at the blocks scale within a RSU.	$\frac{\sum h\_std_{block} \cdot area_{block}}{\sum area_{block}}$	
bl_m_nw_comp	Block non weighted mean compacity	$\frac{\sum compacity\_n_{block}}{block_n umb}$	
bl_m_w_comp	Block weighted mean compacity	$\frac{\sum compacity\_n_{block} \cdot area_{block}}{\sum area_{block}}$	
bl_std_comp	Blocks standard deviation compacity	Population standard deviation of block compacities	
build_density	Building density in the RSU *(based on the RSU area called "rsu_area", computed on the fly)*	$\frac{\sum area_{build}}{rsu\_area}$	[29, 27, 46, 45, 47, 35]
hydro_density	Hydrographic areas density in the RSU	$\frac{hydro\_surface}{rsu\_area}$	[48, 49, 50]
veget_denstity	Vegetation areas density in the RSU	$\frac{veget\_surface}{rsu\_area}$	[48, 49, 50]
road_density	Road areas density in the RSU	$\frac{road\_surface}{rsu\_area}$	[48, 49, 50]

Table 11: List of derived RSU indicators

2.2. Urban fabric typology

Energy consumption and urban climate issues differ greatly throughout a city depending on the urban structure, the building use and the socio-economic profile of the inhabitants. Ten french types of urban fabric have been identified using a review of technical literature combined with the result of a survey addressed to urbanists [51] (Figure 4).

It is important to note that a simplified typology has been recently proposed by Tornay et al. [52] to make these classes fit with the LCZ classes (Table 12).

Figure 4: Typological classes used to classify the urban fabric

These classes have been used to automatically classify the urban fabric of any french municipality into each of this urban type. For this purpose, a supervised classification method has been used. First, a sample of 27,096 buildings from 7 french conurbations have been manually classified from satellite images according to a predefined typological identification procedure (Figure 5). Second, a classification algorithm is established to automatically allocate a building to one of these typological classes from its 78 morphological and 6 socioeconomic indicators values. For this purpose, 6 supervised classification methods are tested, based on 70 % of the buildings total sample. Finally, each of these methods are evaluated from the last third of the building sample (30% of the total sample). The classification obtained using the regression tree analysis is finally selected since it has the lowest prediction error (11.06%). Any building from any French municipality may then be classified according to the corresponding algorithm as well as the morphological and socioeconomic indicators. The dominant building typological class within a RSU is finally selected to characterize the RSU scale. Further details regarding the methodology is available in Faraut et al. [24], Masson et al. [25].

Proposed urban typology	Simplified typology	Corresponding LCZ
Detached house	Low-rise	Sparsely built
Semi-detached house		Open low-rise
Row house on open island		Compact low-rise
Row house on closed island		
Detached building	Mid-rise	Open mid-rise
Linear building on open urban island		Compact mid-rise
Linear building on closed urban island		
High-rise building	High-rise building	Open high-rise
		Compact high-rise
Industrial building	Extended low-rise	Large low-rise
Informal building		Heavy industry
		Lightweight low-rise

Table 12: Link between the proposed urban typology and the LCZ typology through a simplified typology used for defining the architectural parameters in the simulation tool Town Energy Balance (TEB). Adapted from Tornay et al. [52]

3. Implementation

The development of standards for data description and data exchange (interoperability) as well as the arrival of the concept of Spatial Data Infrastructure (SDI) facilitate the interconnection of systems and the implementation of systemic approaches [53, 54]. Several issues have been solved by the Geographical Information Sciences (GIS) community in order to unify systems and tools and to organize the knowledge in the fields of spatial analysis and cartography. The MApUCE geoprocessing framework takes advantage of these trends. Based on open source tools, open standards and ready for open data, it relies on full transparency and explicit references to both methods and data to target: verifiability, cross-disciplinary studies, re-use, compatibility [55, 56].

3.1. Languages

To develop an open processing framework, two languages have been selected: SQL and R. The first one has been used to formalize spatial reasoning and to describe the morphological indicators. The second one has been chosen to carry out statistical analysis.

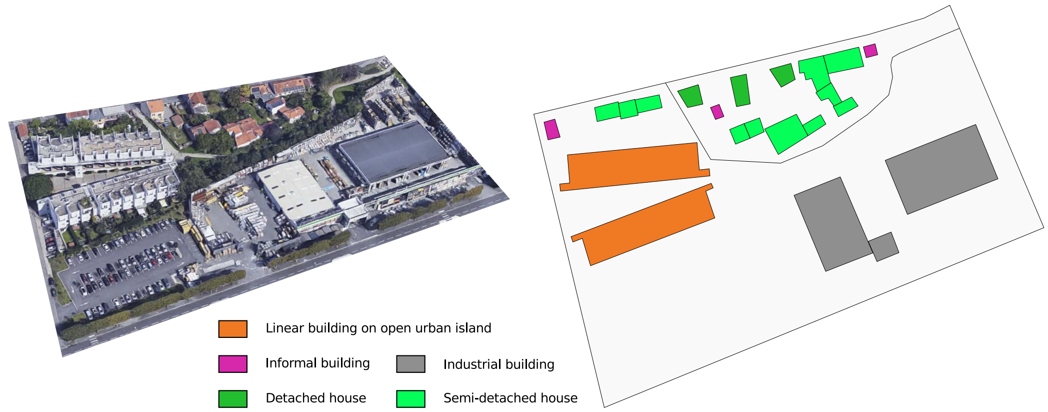


Figure 5: Production of the sample data set

3.1.1. From indicators to SQL scripts

Various approaches have been proposed to manipulate spatial data and formalize spatial analysis [57, 58]. From the Map Algebra language [59] to GeoScript[5] or GeoSPARQL [60], developers and scientists have shown great imagination and originality to propose extensions or new syntaxes and operators to query geographical informations, including 3D, temporal, topological features, *etc.* Nevertheless, the Structured Query Language (SQL) extended with spatial capabilities remains the heart of many GIS applications. SQL spatial offers several advantages :

- the preservation of SQL concepts such as the ability to *Create* a new entry, as well as *Read*, *Update* and *Delete* existing entries in a data set containing geometries (CRUD),
- the incorporation of spatial operations and relationships normalized by the Open Geospatial Consortium specified in the OpenGIS Simple Features Specification for SQL [61, 62],
- a comprehensible and human readable language.

The developments of the open-source relational database PostgreSQL[6] with the spatial extender PostGIS[7] are a key of this success. PostGIS offers

[5] `http://geoscript.org/` accessed July 2017
[6] `https://www.postgresql.org/` accessed in july 2017
[7] `http://postgis.net/` accessed in july 2017

a flexible analytical tool to organize spatial analysis allowing overlay, spatial joining and spatial summaries. Despite the NOSQL trend, the use of SQL spatial grows in the last years due to the development of new spatial databases like SpatialLite[8] or H2GIS[9] [63]. Therefore, to facilitate the reuse of the morphological indicators available in the MApUCE processing chain, each indicator has been described in SQL spatial.

An illustration with the form factor indicator (FF_{build}), calculated at the building level is given below.

$$FF_{build} = \frac{S_{build}}{L_{build}^2} \tag{1}$$

Where
- S_{build} is the building area
- L_{build} is the building length (perimeter)

Translated into a SQL script, the form factor is computed using two spatial operators "ST_Area" and "ST_Length" and one mathematical function ("Power") (Table 13).

```
-- Drop the table if it already exists
DROP TABLE IF EXISTS BUILD_FORM_FACTOR;
-- Create the table and compute the form factor value
CREATE TABLE BUILD_FORM_FACTOR (PK integer primary key,
    FORM_FACTOR double)
  AS SELECT PK, ST_AREA(THE_GEOM) / POWER(ST_LENGTH(
      THE_GEOM),2) AS FORM_FACTOR
FROM BUILDINGS;
```

Table 13: SQL script to compute the building form factor

This kind of approach allows to describe in a generic way a set of indicators that will be applied in any Relational DataBase Management System (RDBMS) that supports the SQL spatial standard.

[8] http://www.gaia-gis.it/gaia-sins/ accessed in july 2017
[9] http://www.h2gis.org/ accessed in july 2017

3.1.2. R language to build the urban fabric classification

R[10] is one of the most famous statistical analysis tool. Using R provides a broad range of advantages. It incorporates a great number of the standard statistical methods and it is a comprehensive language for managing and manipulating data. The R interpreted language permits to easily and quickly create new computational methods. Moreover, R is driven by an important community that provides an impressive list of packages that do everything: data loading, manipulation, visualization and modelling as well as results reporting in various application fields such as finance, biology or any time series or spatial application, *etc.*

To compute the typology of the urban fabric, two R scripts are written. The first one is used to elaborate the decision trees model (Table A.15) and the second one is executed to predict the typology classes of each buildings (Table A.16). The scripts take advantage of the two packages called *randomForest* [64] and *RPostgreSQL* [65].

To extract the first and second main type of urban fabric, the result of the typology prediction at building scale is aggregated at RSU level based on the percentage of the floor area.

3.2. The MApUCE tools chain

The MApUCE tools chain implements the methodology and algorithms described previously to compute indicators and urban fabric classification. It is established around the concept of SDI in order to overcome inconsistencies in data structure as well as in data querying and to break the barriers to share and re-use spatial processing or results. The SDI includes several components (Figure 6):

- a "Web Processing Service[11]" system to execute treatments in a documented and standardized way, available as a service using H2GIS, Renjin[12] and managed from the OrbisGIS[13] GIS platform [66],
- a spatial database management system to store all data (reference, input and results), using the PostGreSQL and PostGIS applications,

[10] `https://www.r-project.org/` accessed in july 2017
[11] `http://www.opengeospatial.org/standards/wps` accessed in july 2017
[12] `http://www.renjin.org/` accessed in july 2017
[13] `http://orbisgis.org/` accessed in july 2017

- a cartographic server, named GeoServer[14], to publish maps within a standardized image stream, based on the "Web Map Service[15]" specification,

- a web cartographic portal to restitute in a user friendly way the results of the geoprocessing tools chain.

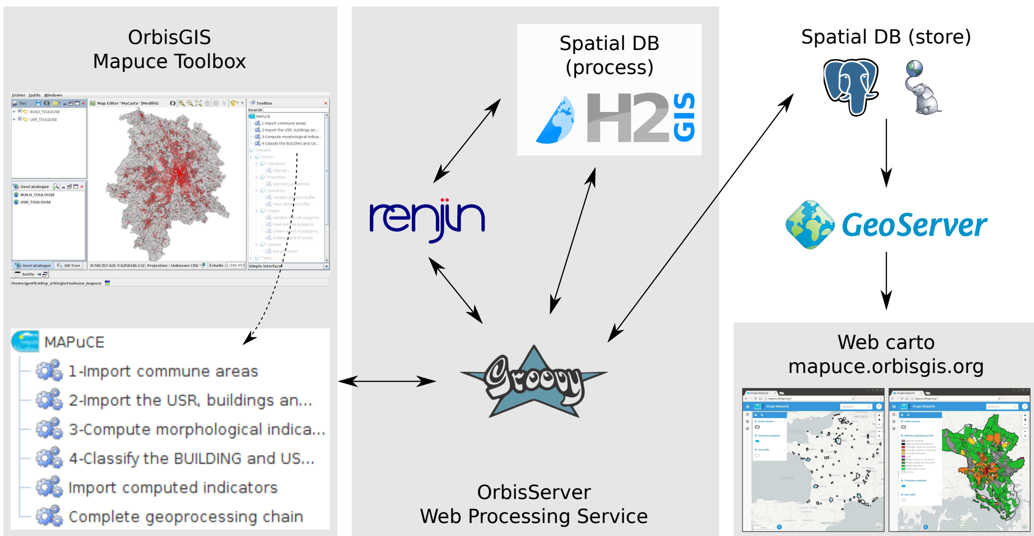


Figure 6: Components of the MApUCE SDI tools chain

3.2.1. The Web Processing Service

The OrbisServer is the main piece of the SDI. It has been developed on top of the H2GIS database [63] and the Apache Groovy[16] programming language. OrbisServer implements the version 2.0 of the Web Processing Service standard approved by the Open Geospatial Consortium. The WPS defines a standardized interface to facilitate the publishing of geospatial processes and to discover and execute those processes by a client. A WPS implementation allows to establish geospatial service chains in a distributed way.

[14] `http://geoserver.org/` accessed in july 2017
[15] `http://www.opengeospatial.org/standards/wms` accessed in july 2017
[16] `http://groovy-lang.org/` accessed in july 2017

In practice, the SQL and the R scripts used to process the data in the MApUCE framework are exposed as web processes. A web process is described from a groovy script that contains: a list of input data, a run method to execute the process and a list of output data. The Table B.17 gives an example for the building form factor indicator. The script is defined with one input data corresponding to the buildings table (in the database) and one output data being a message warning the user that the processing method has been run.

To execute the R scripts, OrbisServer integrates the Renjin engine. Renjin is a JVM-based interpreter dedicated to the R language (for statistical computing [67]). Aside its capabilities, the biggest advantage of Renjin is that the R interpreter itself is a Java module which can be seamlessly integrated into any Java application (this is the case for the MApUCE SDI).

The WPS scripts are managed from the OrbisGIS user interface. A toolbox plugin lists the 6 processes offered by the OrbisServer application (described in section 4).

3.2.2. The spatial database

As explained previously, the input data, the morphological indicators and the urban fabric classification results are stored in a PostGreSQL-PostGIS database. The database communicates with the OrbisServer to serve data to the scripts. The results are stored in 6 tables (Figure 7). These tables are suffixed with the name "METROPOLE" to isolate the geographical data that cover the french metropolitan territory. Each feature is linked to a municipality area using a key index.

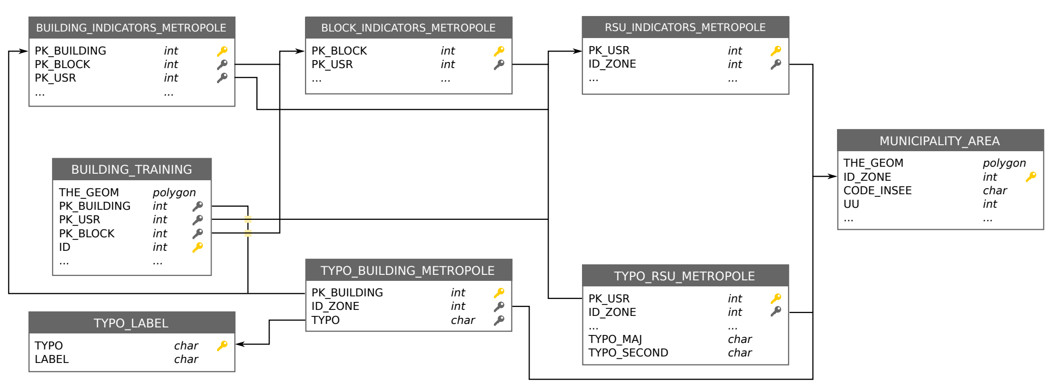


Figure 7: Data model of tables finally produced

3.2.3. The Cartographic server

The Geoserver application is used to publish the data available in the spatial database. Geoserver is advantageous because it is open source and conform to the main OGC standards such as Web Map Service (WMS) or Web Feature Service (WFS). It is stable since few years and it offers a well suited user interface to control spatial data access. From GeoServer, the MApUCE SDI delivers a set of WMS layers styled with the Style Layer Descriptor[17] (SLD) standard. These layers represent the morphological indicators at RSU scale. Their rendering is automatically updated after each change in the database.

3.2.4. The web cartographic portal

The web cartographic portal is based on the javascript framework mviewer[18]. mviewer is a responsive template to build simple and elegant web mapping applications organized around one configuration file. The configuration file contains informations:

- to customize the *look and feel* of the portal,
- to build a thematic sidebar that lists a set of layers (WMS or geojson file),
- to add tools on the map such as zooming and distance measurement, map sharing from a permalink, ...

4. Results

Three types of results have been obtained. The first concerns the indicators and the classification produced from the MApUCE data. The second and the third are the description of respectively the MApUCE toolbox and the MApUCE web cartographic portal.

4.1. MApUCE data

Currently, 80 of the main french urban areas have been processed, representing 2,238 municipalities (6% of the total number in France), 3,726,108 buildings (41%) and 181,752 RSU (40%). Those computed areas are represented in Figure 8.

[17] `http://www.opengeospatial.org/standards/sld` accessed in july 2017

[18] `https://github.com/geobretagne/mviewer` accessed in july 2017

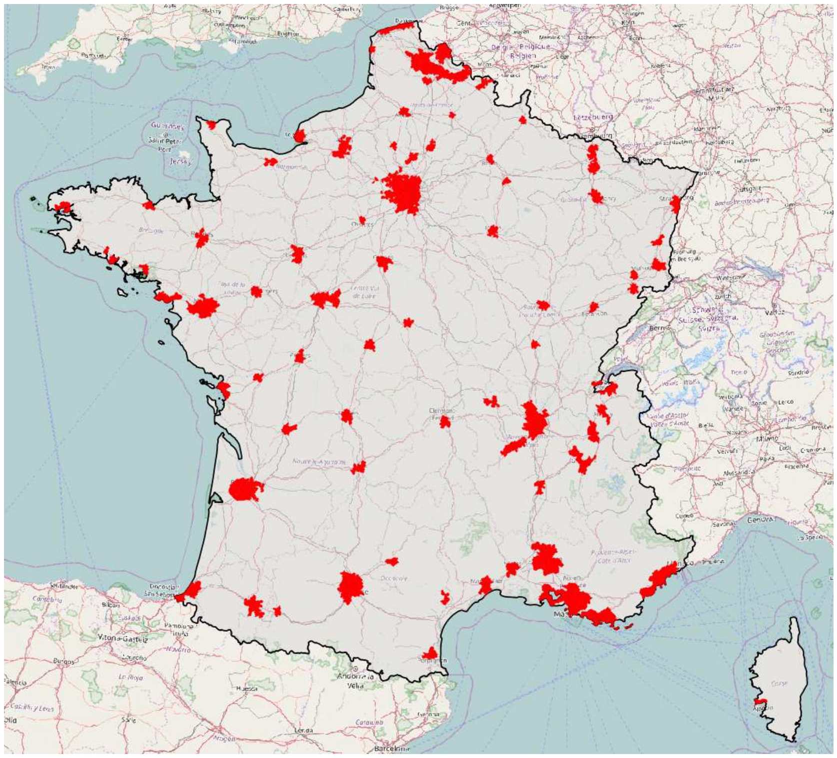


Figure 8: Cartography of the processed french urban areas (red polygons) on top of the OpenStreetMap layer

An overview of the results obtained for the three scales is presented Table 14. Two types of maps are provided. The first one uses a *unique symbol representation* to display the raw geometries. The second one shows the distribution of two variables using a *choropleth technique* : the building height and the compacity.

The result of the classification at both building and RSU scales is illustrated in Figure 9 : the distribution of urban tissue is shown using a *unique values classification.*

The distribution of building height and compacity (Figure 14) as well as building typology (Figure 9) is not homogeneous. The building scale is interesting when we focus on a very restricted area but it is inappropriate for a larger scale analysis. Depending on the scale of interest (neighborhood, city, conurbation,etc.), the information should be aggregated. The block

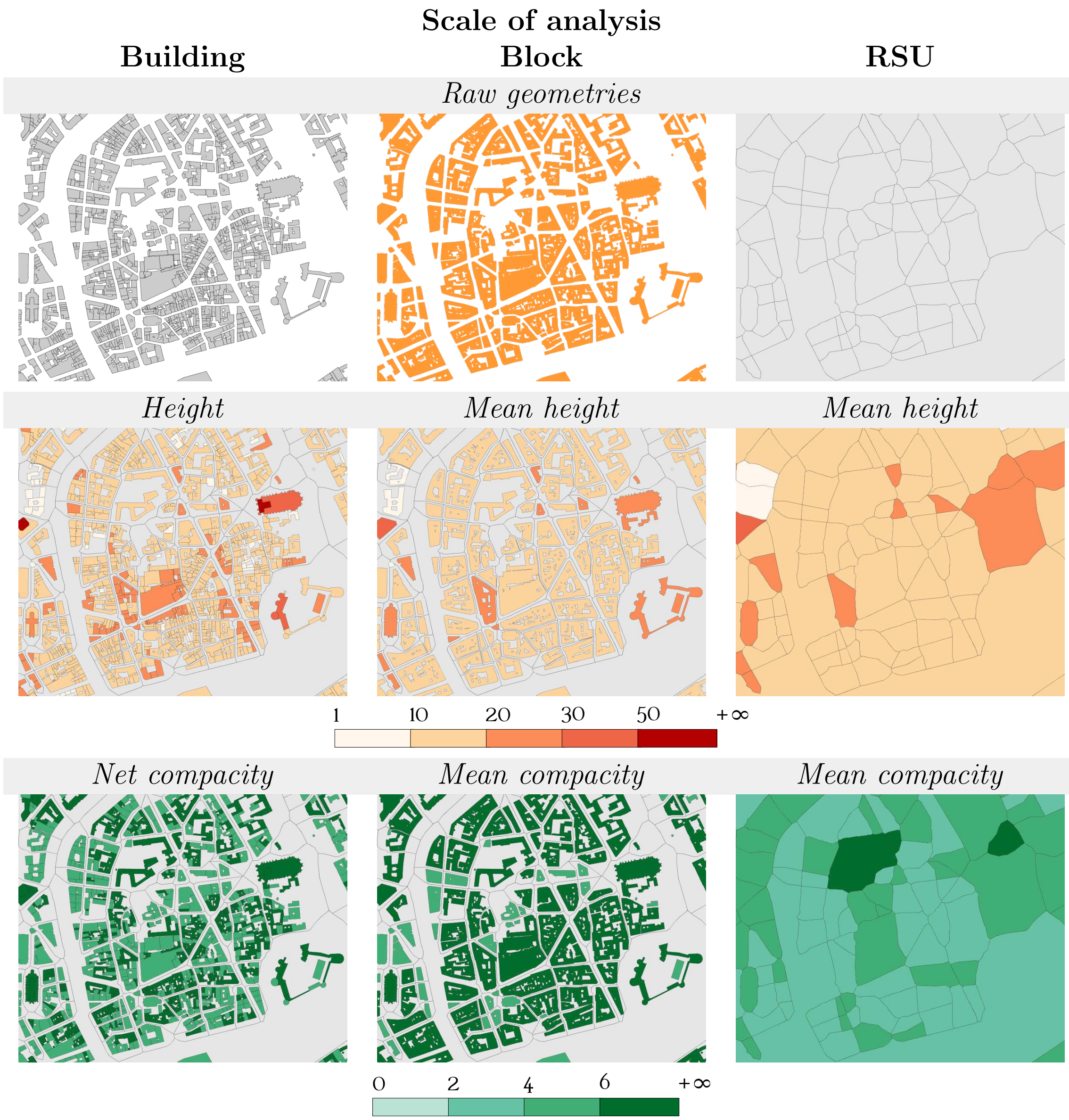


Table 14: Maps for the three scales, zoomed in the city center of Nantes

and RSU scales are more suited for such scales (Table 14) : some clusters can be observed at Blocks and RSU scales, which reinforces the interest of geographic aggregation of data to classify a territory.

Figure 9: Comparison between the satellite image (top left) and the urban fabric typology classification at the building level (top right) and RSU level (bottom right) in the French municipality of Toulouse

4.2. The MApUCE toolbox: An interface to execute the complete chain

As described in the section 3 ("Implementation"), a dedicated user interface called MAPuCE toolbox has been developed to execute the complete chain (Figure 1) through the open-source GIS software OrbisGIS (Figure 10). It takes advantage of the GIS capabilities to navigate, represent and query the data. This MAPuCE interface allows non-expert users to execute processes and to obtain data depending on their study area (defined by at least one municipality).

This dedicated interface is provided as a free plugin, making available a set of 6 scripts in the OrbisGIS Toolbox panel (top right red rectangle in Figure 10 and zoomed in Figure 11). For each script, a user interface is generated on the fly, offering to the user to choose some options and to set parameter values for the computation.

Two needs are answered by the plugin: either to get the final and the intermediate results using the step-by-step processing scripts, either to obtain only the final results (indicators and classification).

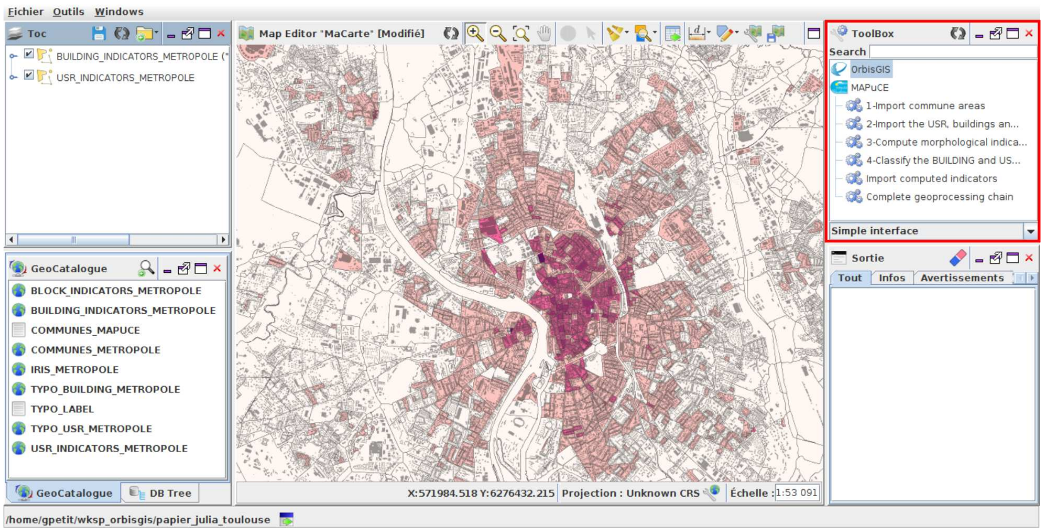


Figure 10: OrbisGIS UI

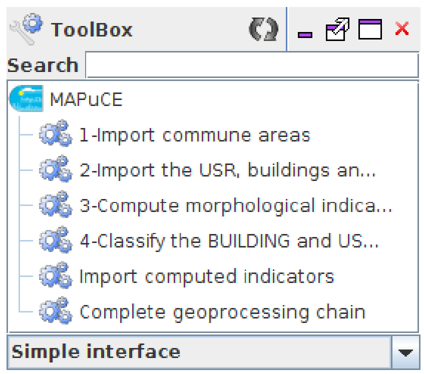


Figure 11: Zoom on the OrbisGISs Toolbox and the MAPuCE plugin

The performance of the algorithms have been evaluated for a middle size French city called Vannes. Its overall footprint is 32,30 km^2, it includes 16'448 buildings, 775 RSU and 7'043 roads. To compute all the indicators, the hardware[19] and software[20] used needed 130s whereas it tooked 40 s for the classification. The entire process is then run in less than three minutes.

[19] Processor : Intel W3520 - Cores/Threads : 4c/8t - Frequency : 2.66GHz / 2.93GHz - RAM : 32GB DDR3 1333 MHz - Disks : SoftRaid 2x2TB SATA

[20] OS : Ubuntu server 14.10 - JAVA 8

4.2.1. Step-by-step processing

1- Import commune areas

This script has to be executed at first to return the list of available municipalities which are ready to be processed. The user is invited to enter his login and password[21] and then to press the green arrow icon to execute the script (Figure 12).

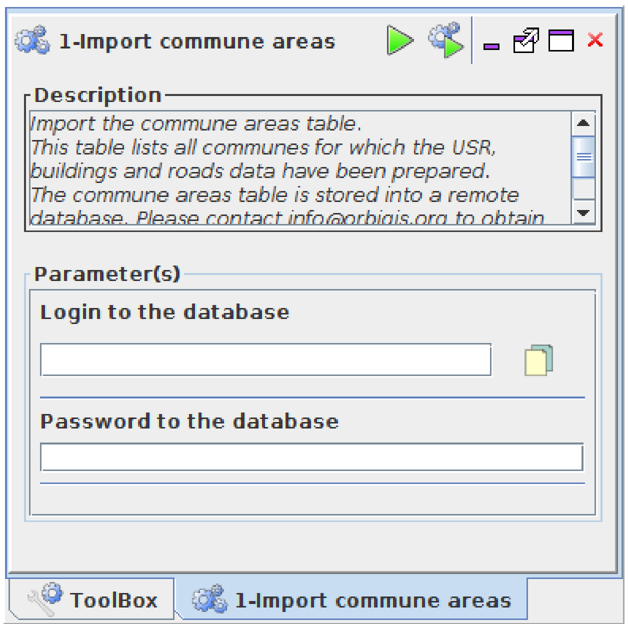


Figure 12: User Interface of the script called "1-Import commune areas"

2- Import the USR (french translation for RSU), buildings and roads

The script number 2 will import all required data, related to the municipalities that users are invited to select in a dropdown list. The selection is made through the "INSEE Code" which is the french unique identifier for municipalities (Figure 13).

[21]For security reasons the remote database can only be accessed through personal accounts.

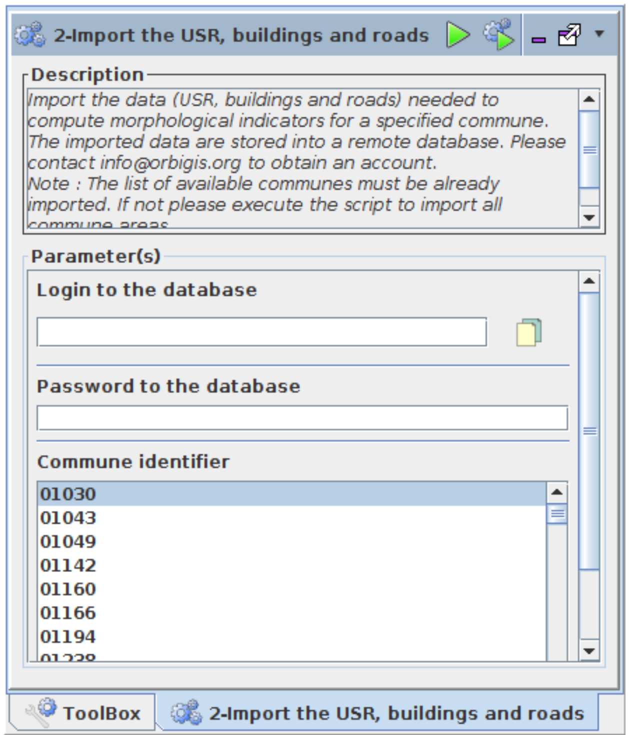


Figure 13: User Interface of the script called "2-Import the USR, buildings and roads"

3- Compute morphological indicators

Once data are imported, this script will automatically compute all the indicators. The user has nothing to do except pressing the "execute" button.

4- Classify the BUILDING and USR (RSU) features

Based on computed indicators, this script will perform the random forest classification. The user has nothing to do except pressing the "execute" button.

4.2.2. Direct final results obtention

It is possible to obtain directly the final tables (indicators and classification) using the two following scripts.

Import computed indicators

This script is used to download data that have already been computed on the server side and are thus available in the spatial database. The user must fill his login and password, choose the spatial unit scale (*commune* (CODE_INSEE) or *urban area*) and select the corresponding identifiers.

Complete geoprocessing chain

This script is used to run the complete geoprocessing chain in a single step (*i.e.* import the data, process the indicators and classify the urban fabric) in the case where the municipalities have not been yet processed on the server side. The user must fill his login and password, choose the spatial unit scale (”*municipality*” (CODE_INSEE) or ”*urban area*” (UNITE_URBAINE)) and select the corresponding identifiers (Figure 14).

4.3. The MApUCE web cartographic portal

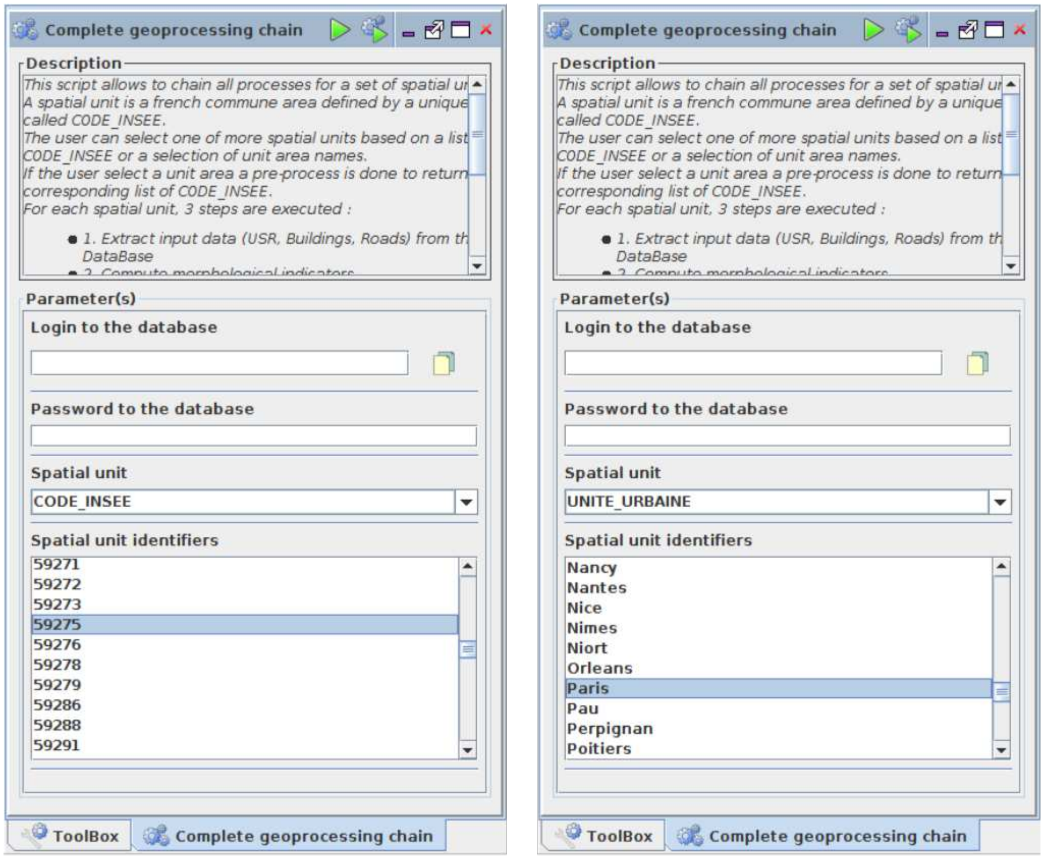
The result are available accessing the mapuce.orbisgis.org web cartographic portal. People can navigate into the map and choose to display a set of layers, grouped into three categories:

- spatial units : urban area, already computed municipalities and RSU boundaries,
- RSU indicators : thematic analysis based on several morphological indicators,
- typology : building classification at the RSU scale.

To comply with data licences, only RSU results are presented. Two screenshots are presented in Figure 15 to illustrate the type of maps that can be consulted by users.

Conclusion & Prospect

We have proposed an open geoprocessing framework to calculate standardized urban indicators useful for urban climate application and also for planning purpose in some other fields.



Choose one (or many) municipality(ies) Choose one (or many) urban area(s)

Figure 14: User interface for the script "Complete geoprocessing chain"

Morphological indicators have been computed at three different scales : building, block and the Reference Spatial Unit (RSU). The boundaries of the RSU are generated by a Voronoï tessellation from the legal boundaries specified in the cadastral map. This scale is appropriate to analyze the climate property heterogeneity of the urban fabric within an urban area. Such map can be used directly by the urban planners for planification purpose, by researchers to simulate the urban climate or by researchers to highlight the differences of development typology between several cities. However, geometric issues have been observed in certain RSU: some of them are too small (Figure 16 left), have weird shape (Figure 16 right) or they separate buildings in two parts. Investigations should be realized to overcome this

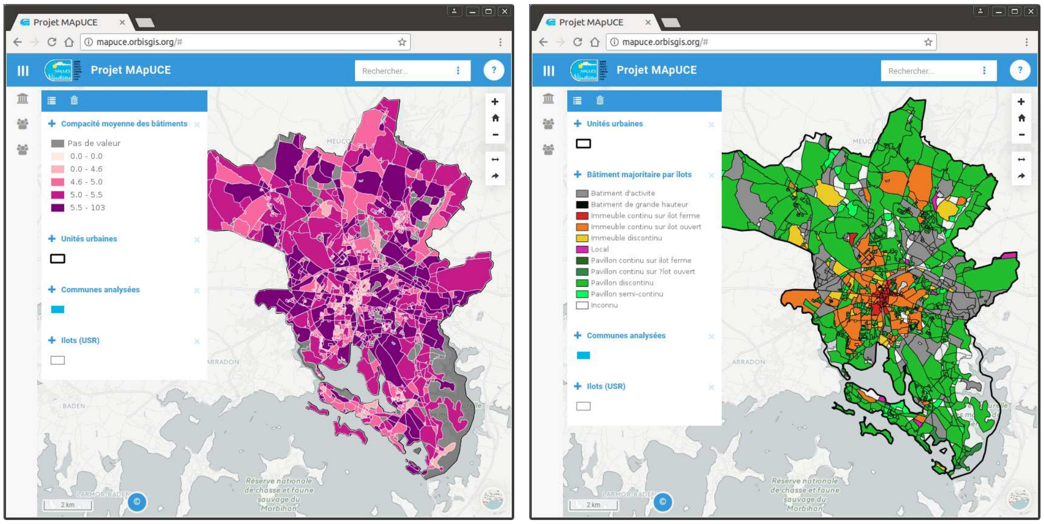


Figure 15: Screenshots of the mapuce.orbisgis.org portal, zoomed on the french city of Vannes (left: thematic analysis of the building mean compacity at the RSU scale / right: building classification by RSU)

issue, for example using the road network to slice the territory.

Figure 16: Two examples of geometric issues on RSU: too small (left), weird shape (right)

Indicator calculations are based on geographical databases which are available and homogeneous for the french territory. Preprocessing tasks have been performed by [23] to clean and structure those data, to create the RSU and to enrich building and RSU tables by database cross-feeding. Because the french databases used are updated every year, the preprocessing task as well as the indicators calculation may be applied on annual data in order to make diachronic analysis. The use of open data such as OpenStreetMap[22] may also be investigated to generate worldwide homogeneous information.

27 morphological indicators have been calculated at building scale, 9 at block scale and 28 for the RSU. These 64 indicators are finally affected to each building and are used (together with socioeconomic indicators calculated by Plumejeaud-Perreau et al. [23]) to classify buildings according to 10 typological classes defined by urbanists, architects and using technical literature. The supervised classification method used has a prediction error of about 11% [24]. The dominant building typological class within a RSU is selected to characterize the RSU scale. Indicator calculation and classification application may now be extended to the entire french territory. However, the list of the calculated indicators is not irrevocable. An overall reflection may be performed to both identify existing indicators that are redundant or not relevant and new indicators to improve the classification process.

The overall processing chain is uniquely composed of open-source tools and close to open standards: the OrbisGIS platform is used for morphological indicator calculation and Renjin is used for building and RSU classification. A free OrbisGIS plug-in called MAPuCE is available for any user interested in applying the processing chain or to analyze the results obtained for the municipality of its choice. It is also possible to access the results directly on the internet from a web portal dedicated to this work. Future work implies to give the opportunity to any user to produce the indicators through a full distributed service.

Finally, the results of this paper offers new opportunities to extend the WUDAPT database at a finest scale. Indeed, one idea would be to reuse the entire processing chain (territory segmentation, indicator calculation, classification model creation and application) but using as training data the LCZ typologies instead of the one presented in this article.

[22]`https://www.openstreetmap.org/` accessed in july 2017

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Appendix A. R scripts

```
## Load packages
library(randomForest)
library(RPostgreSQL)
## Import the training data from the database
## con object is the connection to the database
training_data= dbGetQuery(con, "SELECT␣*␣FROM␣building_training")
## Build model
treesModel=randomForest(i_typo~.,data=training_data,ntree=500,mtry=7,replace=TRUE)
## Save the model
save(treesModel,file="mapuce_model.RData")
```

Table A.15: Pseudo-R script to create the decision trees model

```
## Load packages
library(randomForest)
library(RPostgreSQL)
### Load the model based on the morphological train data
treesModel=get(load(model_path))
## Get the data to predict from the database
## The buildings_to_predict is a temporary table created on the fly with a SQL command. It contains all the indicators at building, block and RSU scales
data_to_predict = dbGetQuery(con, "SELECT␣*␣FROM␣buildings_to_predict")
## Apply the predict function to compute the typological class for each building
typology=predict(treesModel,data_to_predict,type="class")
```

Table A.16: Pseudo-R script to predict the urban fabric typological class

```
/** String input of the process */
@LiteralDataInput(
        title="Buildings table",
        description="Name of the buildings table")
String buildingsTable

/** SQL code to execute with some metadata */
@Process(title = "Building form factor",
        description = "Compute the building form factor")
def processing() {
-- Drop the table if it already exists
DROP TABLE IF EXISTS BUILD_FORM_FACTOR;
-- Create the table and compute the form factor value
CREATE TABLE BUILD_FORM_FACTOR (PK integer primary key, FORM_FACTOR double)
  AS SELECT PK, ST_AREA(THE_GEOM) / POWER(ST_LENGTH(THE_GEOM), 2) AS FORM_FACTOR)
FROM $buildingsTable; //The input table name

literalOutput =   The form factor indicator has been computed }

/** String output of the process */
@LiteralDataOutput(
        title="Output message",
        description="The output message")
String literalOutput
```

Table B.17: Example of a WPS script