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GENIUS: A methodology to define a detailed description of buildings for urban climate and building energy consumption simulations

Nathalie Tornay [a,*], Robert Schoetter [b], Marion Bonhomme [a], Serge Faraut [a], Valéry Masson [b]

[a] *LRA–Laboratoire de Recherche en Architecture, ENSA–École Nationale Supérieure d'Architecture de Toulouse, 83 rue Aristide Maillol, 31106 Toulouse CEDEX 1, France*
[b] *CNRM UMR 3589, Météo-France/CNRS, 42 avenue Gaspard Coriolis, 31057 Toulouse CEDEX 1, France*

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ABSTRACT

Urban canopy parametrisations like the Town Energy Balance TEB solve the urban surface energy balance for a simplified urban morphology in order to provide the lower boundary conditions for atmospheric models in urban areas. The urban surface energy balance is influenced in various ways by physical parameters related to building architecture. The albedo of the covering materials of roofs and walls is crucial for the radiation balance, the thermal conductivity and thermal capacity of the construction materials influence the heat storage inside the urban fabric. In this study we introduce a methodology to define the characteristics of building architecture with the precision required by state of the art urban canopy parametrisations. The geographical scope of our analysis is France. We assume that the building architecture depends mainly on the urban typology, the building use, the construction period, and the geographical location. Based on a literature survey on architectural practices and building regulation standards in France we define one to three building archetypes for each combination of these four parameters. For each building archetype, information on the construction type of walls and roofs (main materials, insulation, internal and external cover), the glazing ratio, type of windows, presence of shading elements, the airtightness and presence of a mechanical ventilation system is provided. We perform idealised simulations with TEB to determine the sensitivity of the urban surface energy balance on building architecture. We find

* Corresponding author at: Laboratoire de Recherche en Architecture, Ecole Nationale Supérieure d'Architecture de Toulouse, 83 rue Aristide Maillol, 31106 Toulouse CEDEX 1, France.
E-mail address: nathalie.tornay@toulouse.archi.fr (N. Tornay)

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that the albedo of the roof and the presence of insulation materials in wall and roof as well as their position with respect to the main wall and roof material are crucial for an accurate simulation of the urban energy balance. Future developments of the architectural database will therefore focus on these parameters.

1. Introduction

The surface energy balance in urban areas (Eq. (1); Christen and Vogt, 2004) is the sum of the solar and infrared radiation balance (R_{net}), the turbulent fluxes of sensible (Q_{sen}) and latent heat (Q_{lat}), the storage (Q_{sto}) and the anthropogenic heat flux (Q_{ant}).

$$R_{net} = Q_{sen} + Q_{lat} + Q_{sto} + Q_{ant} \tag{1}$$

The surface energy balance in urban areas can differ considerably to rural areas (Shepherd, 2005). These differences are mainly responsible for the development of a specific urban climate (Arnfield, 2003). Simulations with atmospheric models aiming to include or investigate urban climate effects require an accurate representation of the specifics of the urban energy balance. Due to computational constraints, such models operate at horizontal resolutions between 100 m and several kilometres. The buildings can therefore not be explicitly resolved but their effect on the urban energy, water and momentum balance needs to be parametrised. An overview of urban energy balance parametrisations of different complexities is given in Grimmond et al. (2010). The so-called Urban Canopy Parametrisations (UCP) assume a simplified homogeneous urban morphology (e.g. buildings oriented along street-canyons) and solve the surface energy balance separately for roof, wall, road, and sometimes also for urban vegetation. A simple Building Energy Model (BEM) solving the energy budget for a representative building can be included in the UCP (e.g. Kikegawa et al., 2003).

Various input data are required when simulations with an UCP-BEM shall be conducted for a given urban agglomeration. They can be grouped into data describing the urban morphology (e.g. building height, building surface cover fraction), data on building architecture (e.g. construction materials, presence of insulation materials, glazing ratio) and data on building use and occupant behaviour (e.g. design temperature for heating and air conditioning). Parameters related to building architecture influence the urban energy balance in various ways. The albedo and emissivity of the external coating of roofs and walls, the glazing ratio and the window characteristics directly influence the urban radiation balance (R_{net}) and can indirectly influence Q_{ant} since they affect the building energy budget and thus the energy demand for heating and air conditioning. The thermal conductivity and thermal capacity of the roof and wall materials directly influences Q_{sto} and indirectly Q_{ant} and R_{net}. The airtightness of the buildings and the presence of mechanical ventilation systems are relevant for the air and moisture exchange between indoor and outdoor and therefore directly influence Q_{sen} and Q_{lat} and indirectly Q_{ant}. Detailed knowledge on building architecture is therefore crucial for urban climate simulations.

In this study we describe how we define building archetypes providing the parameters on building architecture required for the initialisation of an UCP-BEM. The main issue in integrating this type of information to urban scale simulations is the lack of precision of the existing data for buildings (Ching et al., 2009). If a limited number of buildings can be very precisely described, (through architectural inventories for instance), the data available at the city scale remain poorly detailed. The World Urban Database and Access Portal Tools project (WUDAPT; Ching, 2012) aims to define a worldwide building database usable for urban climate and building energy simulations based on the Local Climate Zone (LCZ) classification of urban forms developed by Stewart and Oke (2012). We contribute to this aim by defining building archetypes for France.

Previous work on the existing building stock has been performed for 19 European countries in the context of the TABULA (Ballarini et al., 2014) and EPISCOPE (IWU, 2016) projects. These have focussed mainly on residential buildings and assumed that building types can be defined as a function of building size and shape, construction period and the prevailing climatic conditions. The focus of these projects has been mainly on building energy consumption. Therefore the building types are described by the U-values of the roof, wall, floor and windows, the airtightness and ventilation rate (Protopapadaki et al., 2014). Not so much emphasis has been on the construction materials. In this study we focus also on non-residential buildings by distinguishing 12 different building uses and provide more details on the construction materials prevailing on the French territory.

We use the Urban Canopy Parametrisation Town Energy Balance (TEB; Masson, 2000) coupled with a simple Building Energy Model (BEM; Bueno et al., 2012; Pigeon et al., 2014) in order to simulate the urban energy balance for different building archetypes. We determine to which degree the building characteristics influence the different components of the urban energy balance. The results show which architectural parameters are most relevant for an accurate simulation of the urban energy balance.

This article is structured as follows. A general overview of the methodology for identifying building archetypes is given in Section 2. Section 3 describes which input data are used for classification of building archetypes. The characteristics of the reference buildings are described in Section 4. The sensitivity of the Town Energy Balance on different building characteristics is determined in Section 5. Conclusions are drawn in Section 6.

2. Methodology for defining building archetypes

We make the assumption that the architectural practices on the French territory are mainly dependent on the urban typology (e.g. “low-rise”, “high-rise”, …), the building use, the construction period, and the geographical location of the building due to the use of local construction materials. The database will therefore be structured as to provide detailed information on the building archetypes for a given combination of urban typology, building use, construction period and geographical location within France. The general structure of the database is therefore similar to what has been done during the TABULA and EPISCOPE projects, but we enlarge the database by the dimension of building use and we distinguish regions with different construction materials for historical buildings.

Our methodology for defining the building archetypes consists of three steps and is depicted in Fig. 1.

In a first step, the input data used for construction of the database need to be determined. The French Geographical Institute “Institut national de l'information géographique et forestière” (IGN) has compiled a digital cadaster dataset (the IGN-BDTOPO) providing information on building footprint, height, use and date of construction. However, no information concerning the construction materials is provided. Our typological approach, called GENIUS (GENerator of Interactive Urban blockS), is meant to enrich those data and provide a detailed description of a limited number of building archetypes in terms of materials (supporting structure, thermal insulation, types of windows, roof and floors) but also the glazing ratio, airtightness and so on. The building use and geographical location are directly taken from the IGN-BDTOPO dataset, the construction date is available from census data gathered by the French Institute on Economics and Statistics “Institut national de la statistique et des études économiques” (INSEE). The information on prevailing urban typology is not available from national datasets and has been gathered by performing a literature review combined with interviews of urban planners.

In a second step, we define detailed characteristics of the building archetypes. It is supported by a literature survey on the use of building materials and constructive systems, architectural practices and building cultures, conservation of historical buildings, and so on.

The third step consists of simulating all building archetypes with the Town Energy Balance TEB and to determine the sensitivity of the urban surface energy balance on the building architecture. The results help to determine how precise the building archetypes need to be described.

3. Input data for building characterisation

In order to characterise the buildings we need to combine four input data: urban typology, building use, construction date and geographical location. In order to obtain a complete building characterisation we need to determine the variety of urban typologies, and building uses on the French territory. The construction dates need to be classified into periods suitable for distinguishing key changes in architectural practices (e.g. due to changing thermal regulations).

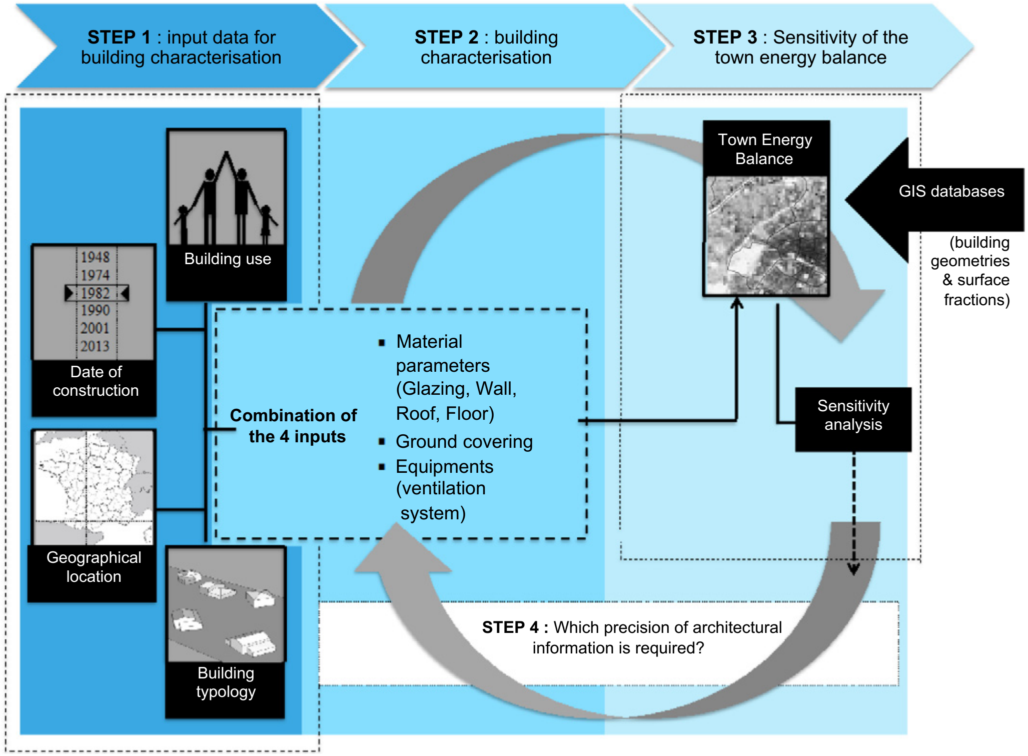


Fig. 1. Methodology for defining building archetypes for urban climate and building energy consumption simulations.

3.1. Urban typology

Previous studies on urban typologies have developed methods for classification of urban forms at the scale of a given city of investigation (e.g. Marseille; Long and Kergomard, 2005), or they identified the urban forms of the built heritage (e.g. AUAT, 2004 for Toulouse). Other studies aimed at the identification of archetypal buildings. Christen et al. (2012) defined a typology with twelve archetypal buildings combined with five building sizes for Vancouver. The Local Climate Zone (LCZ) classification of Stewart and Oke (2012) aims to classify the urban forms in order to discriminate their impact on the local climate. It has been used in various studies on urban climate and energy (Alexander and Mills, 2012; Bechtel and Daneke, 2012; Kotharkar, 2012; Perera et al., 2012).

Based on these previous studies, Bonhomme (2012, 2013) proposed seven typical urban typologies that can be found in most European cities: detached low-rise, continuous low-rise, detached mid-rise, continuous mid-rise, high-rise, old centre, and industrial building. To improve this classification, we consulted urban planners through a survey. The survey was broadcast by the French Association of urban planning agencies (Fédération Nationale des Agences d'Urbanisme; FNAU) to 52 public organisations dealing with development and management of urban agglomerations in France. The survey has received 18 answers covering a variety of regions in France with different climatic background. The results have suggested an expansion to 10 urban typologies (Fig. 2). These can be matched to the "built series" of the LCZ classification. This shows that the LCZ classification used in the framework of the WUDAPT project is applicable for France.

3.2. Building use

To be able to define detailed architectural characteristics of a building, it is necessary to know what the building is used for. For instance, a high-rise building in France can be used as residential or office building.

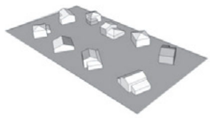
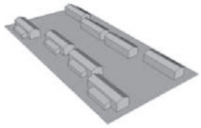
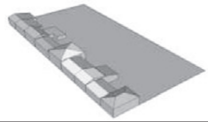
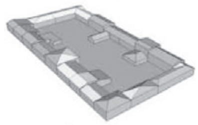
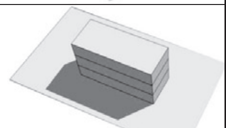
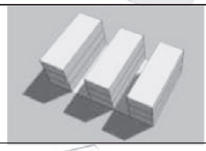
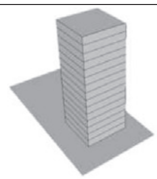
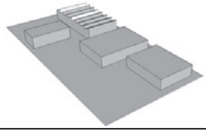
GENIUS typology	Illustration	Corresponding LCZ
Detached low-rise One or two-storey houses of at least four façades often located in the centre of plot of land.		Sparsely built
Semi-detached low-rise Town houses, terraced houses or houses detached on one side, with façades aligning the street.		Open low-rise
Discontinuous row of low-rise Street aligning terraced houses with gardens in the back.		Open low-rise
Continuous row of low-rise Typical intermediary housing, terraced houses with patios, constructions typical for historical centres.		Compact low-rise
Detached mid-rise One or more buildings built in the centre of the block.		Open mid-rise
Discontinuous row of mid-rise A building complex in the centre of the urban block.		Open mid-rise
Continuous row of mid-rise Perimeter block development: Connected buildings with street front elevations. This typology is often present in historic centres, urban fabric of the industrial revolution (Haussmannian buildings) or, more recently, neighbourhood seeking moderate density (ecological districts).		Compact mid-rise
High-rise building A building of more than 12 storeys such as an apartment tower or office tower		Open high-rise Compact high-rise
Extended low-rise Industrial, commercial or agricultural buildings. They are characterised by their simple morphology and their large footprint		Large low-rise Heavy industry
Informal building Ephemeral constructions, non-traced on registers (caravans, temporary prefabricated buildings, ...).		Lightweight low-rise

Fig. 2. The urban typologies distinguished in the architectural classification, with their corresponding Local Climate Zone.

Depending on the use, the construction materials for the façade as well as the glazing ratio will differ considerably. Based on the IGN-BDTOPO database we identified 12 different prevailing building uses: residential, office, commercial, school, hospital, industrial, agricultural, greenhouse, religious, sport facility, castle, and non-heated buildings (e.g. garage, cellar).

3.3. Building construction period

The building materials are dependent on the construction period. The main drivers for changes in the construction materials are evolutions in construction technology, successive building regulations, and historical fashions and doctrines in architecture. They influence mainly the supporting structure, thermal insulation and types of windows. To take into account the impact of various construction periods in France, this work anchors itself on the successive thermal regulations, which is one of the main drivers of the evolution of the building architecture (choice of the insulation, the bioclimatic design, and so on). Consequently, seven construction periods are distinguished (Table 1). The buildings constructed before 1948 consist of the built heritage (P1). P1 is followed by the reconstruction period after World War II (P2). After the 1st oil crisis in 1973, the first thermal regulation was adopted in France and thus the construction periods after 1974 are defined by the dates of the successive thermal regulations.

3.4. Building location

To take into account French regional architectural heritage, the first step is a large literature review taking into account local inventories of built heritage constructed by the French energy provider Electricité de France (EDF) and a wide national inventory provided by the RAGE report (RAGE, 2012) which has been commissioned by a French government program on good practices in environmental regulation "Règles de l'Art Grenelle Environnement". The report is the result of a collection of available studies on the existing housing stock crossed with interviews of building professionals. This first step allows us to identify local specifics in construction techniques.

A second step is to cross this information with the use of local materials. As a matter of fact, the built heritage is deeply influenced by the availability of raw materials in a region. We locate regions corresponding to the use of local materials based on publications by EDF and the RAGE report. These results are formalised by the creation of GIS maps that mark out regions where a raw material (e.g. bricks, sandstone, …) will influence the type of constructive device for wall or roof for the built heritage. The minimum extent of the construction material regions is one French department. A first series of maps allows to identify the local materials for historical buildings (P1). The construction materials are more homogeneous for P2 to P7. However, some regional differences remain. These concern the material covering the roof for which historical preferences (slate or tile-brick) also influence the more recent constructions. There are also differences between regions dominated by brick-based construction materials and stone-based construction materials. For this reason, a second series of maps is constructed for the construction periods after 1948. The regions identified in a given period may overlap.

The third step is to define the dominant construction material for each department. For this purpose, the RAGE (2012) report is crossed with surveys on stone quarries conducted by trade unions (SNROC; National union of ornamental industries and construction) and the association of French slate extractors. For the construction period P1 we distinguish the dominant local materials for the wall which are pebble, sandstone, earth, limestone, meuliere stone, schist, gneiss, granite, volcanic, brick and wood. Their geographical distribution is displayed in Fig. 3. For the construction periods P2 to P7, we distinguish only between the regions

Table 1
Definition of the building construction periods.

Name	Date of construction	Period characterisation
P1	Before 1948	Built heritage
P2	1949 to 1973	Reconstruction period after World War II
P3	1974 to 1981	1st thermal regulation
P4	1982 to 1989	2nd thermal regulation
P5	1990 to 2000	3th thermal regulation
P6	2001 to 2012	4rd thermal regulation
P7	after 2013	5th thermal regulation

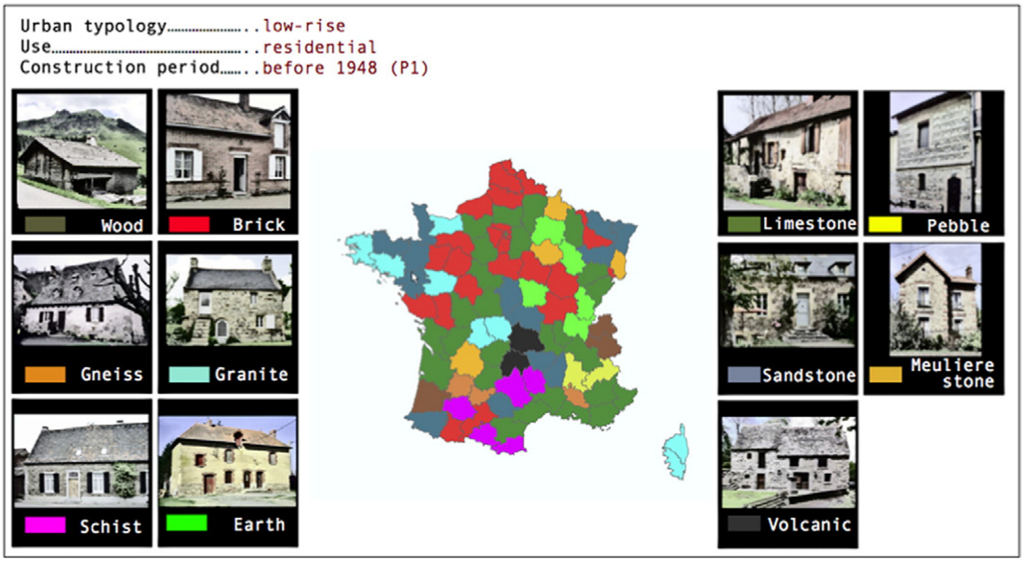


Fig. 3. Geographical distribution of the dominant wall construction material for residential buildings of the French built heritage (P1). The information is available at the scale of a French department.

where architecture is influenced by brick materials, stone materials and none of them. The geographical distribution of these regions is displayed in Fig. 5. For the roofs we distinguish between the covering materials tile-brick, slate and zinc (only in the centre of Paris).

4. Characterisation of reference buildings in France

4.1. Literature review

Taking into account the four inputs urban typology, building use, construction period and location, it is possible to define representative building archetypes on the French territory. To establish this connection, we went through an extended literature review. Information on historical building characteristics are taken from a series of reports constructed by EDF for the different French regions (EDF, 1980a, 1980b, 1980c, 1980d, 1981a, 1981b, 1981c, 1981d, 1981e, 1981f, 1982a, 1982b, 1982c, 1982d, 1982e, 1983a, 1983b, 1983c, 1983d, 1983e, 1983f, 1983g, 1984a, 1984b, 1984c, 1984d, 1984e, 1984f, 1984g, 1985a, 1985b, 1985c, 1985d, 1985e, 1985f, 1985g, 1985h, 1985i, 1988). Information on the more recent buildings is taken from national inventories, like the RAGE (2012) report, which collect data on "reference buildings" in France and more technical works on building practices and the choice of materials (Deplazes, 2008; Hegger et al., 2009; Vittone, 2010), studies specific to building use (Morancé, 1930; Brigode, 1966; Pélegrin-Genel, 2006 and 2007; Maillard, 2007) and two studies focusing on airtightness (Litvak, 2001, 2005).

Various studies on the architectural characteristics of residential buildings exist. Based on RAGE (2012) it is possible to identify the constructive systems for wall and roof. RAGE (2012) further identifies regions (French territory or local material regions) with specific main materials for the walls (one to three possibilities) and the roofs (one to two possibilities). The study does not indicate the thickness of different materials. However, the date of construction allows to know the thermal requirement of the envelope and therefore, it is possible to estimate the thickness of the materials by assuming that they are conform to applicable thermal regulations (Dal Zotto et al., 2014).

For more specific uses, such as offices, health care facilities or educational buildings, the construction journal "Le Moniteur" has edited books dedicated to each of these buildings uses (Pélegrin-Genel, 2006, 2007; Maillard, 2007). These books are composed of two parts. The first is a theoretical approach that describes the development of buildings in shape and structure. The second part presents case studies of recent construction projects. Based on these works, it is possible to analyse the main constructive choices and to cross that information with regulatory issues. It is then possible to deduct the composition of walls, roofs, floors and thickness of each item.

4.2. Architectural information provided by the database

The literature review led to the conclusion that only four urban typologies are necessary to discriminate the building materials. However, the ten typologies previously defined are useful for other purposes such as the characterisation of urban morphology. Table 2 shows the correspondence between the ten and the four typologies as well as the Corresponding Local Climate Zone (LCZ). We assume that, from the architectural point of view (especially construction materials), informal buildings/light low-rise LCZ, (e.g. shanty towns) are built in a similar way than large low-rise buildings (e.g. storehouses).

The use of the simplified typology with four classes renders the architectural database much more transferable to other contexts, and in particular within the WUDAPT approach. In the framework of WUDAPT, urban agglomerations are characterised by maps of the LCZ. These can be linked to the 4 simplified urban typologies (Table 2). In France, the architectural characteristics of buildings could therefore be assigned based on LCZ maps. This approach, as discussed in Section 6 can be extended worldwide.

For a given combination of simplified urban typology, building use, date of construction and geographical location, there is not one single constructive system for wall and roof but several might coexist. As a consequence, the database provides one to three options for the wall constructive system and one to two options for the roof constructive system. The options are ranked from the most to the less frequent.

For every building archetype included in the database the constructive system of wall, roof, floor and ground cover is described in detail. The constructive system can consist of one to four layers. These include the main material (e.g. concrete, brick, stone, and so on), internal and external coating and insulation. For the insulation the additional information on the position with respect to the main material (internal or external insulation) is provided. As an example, in Fig. 4, we display the temporal evolution of French building archetypes for mid-rise residential and office buildings, and in Fig. 5 the geographical distribution of the wall constructive system for low-rise residential buildings. This shows the temporal and spatial variability of French building architecture covered by our database.

Every layer is described via its material and its thickness. For each material the density (kg/m^3), thermal conductivity (W/mK) and thermal capacity (J/kgK) are provided. Reflectivity of solar radiation (albedo) and emissivity of infrared radiation are also given for the external coating of roofs and walls. For each archetype the glazing ratio and the type of windows (single, double or triple glazing) is provided. There is further an information whether shading elements are present (yes or no). The physical characteristics of the windows are described via their U-Value (W/m^{2}K), solar heat gain coefficient (1) and solar heat gain coefficient when shades are closed (1). The information on the ventilation system indicates the presence of mechanical ventilation (yes or no) and its air exchange rate (vol./h). For each building archetype the airtightness is provided (vol./h at 50 Pa pressure difference).

Table 2
Link between the full GENIUS urban typology, the simplified typology used for the defining the architectural parameters and the corresponding Local Climate Zone (LCZ).

GENIUS typology	Simplified typology	Corresponding LCZ
Detached low-rise Semi-detached low-rise Discontinuous row of low-rise Continuous row of low-rise	Low-rise	Sparsely built Open low-rise Compact low-rise
Detached mid-rise Discontinuous row of mid-rise Continuous row of mid-rise	Mid-rise	Open mid-rise Compact mid-rise
High-rise building	High-rise building	Open high-rise Compact high-rise
Extended low-rise Informal building	Extended low-rise	Large low-rise Heavy industry Lightweight low-rise

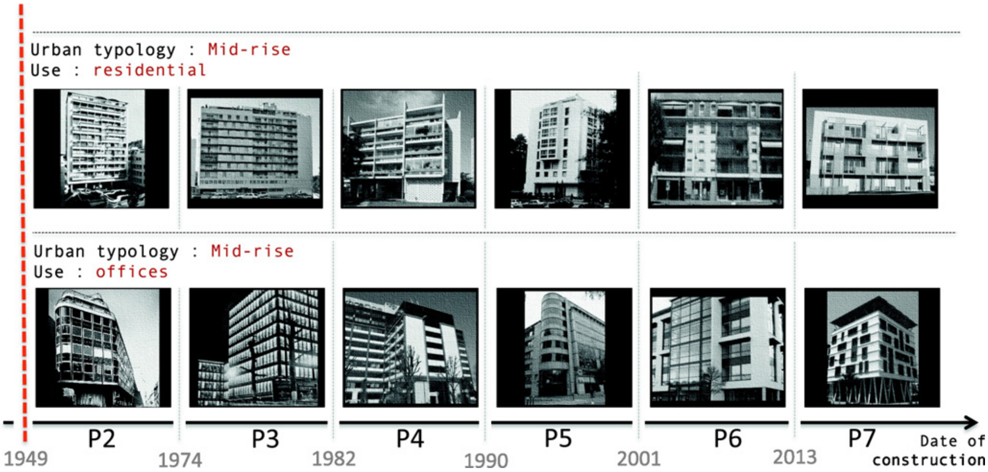


Fig. 4. Temporal evolution of French building archetypes for mid-rise residential and office buildings.

5. Sensitivity of the Town Energy Balance on building architectural characteristics

5.1. Link between the architectural database and the Town Energy Balance

In order to initialise the TEB variables related to building architecture for a given French city, maps of the input data for building characterisation (urban typology, use, construction period, construction materials) need to be available. For the construction materials, the maps for construction period P1 (Fig. 3) and for P2 to P7 (Fig. 5) are directly read by TEB. Amossé (2015) developed a statistical model to predict the urban typology at building scale based on the IGN-BDTOPO data. The building use at building scale is directly available from the IGN-BDTOPO. The construction periods of residential buildings are included in the INSEE census data. The building-scale-data are aggregated to raster maps with $100 \times 100\ m^2$ horizontal resolution containing information on the dominant urban typology, use, and construction period at grid-point-scale. These rasters are used for initialisation of TEB. For each combination of these input parameters, there are up to three building archetypes available in the architectural database. In order to reduce the computational cost, only the most frequent building archetype at grid-point-scale is simulated with TEB.

Several uncertainties are associated with the described approach.

- The combination of dominant urban typology-use-construction period and most frequent building archetype might represent only a small percentage of the actual buildings prevailing at grid-point-scale in a very heterogeneous urban area. For such areas a tile-approach could be made. It consists of performing several simulations of TEB for different building archetypes prevailing at grid-point-scale and then aggregate the resulting fluxes.
- The cadastral information on the building use is complete for public buildings (administration, schools, and so on) but does not contain much information on mixed office/commercial/residential use in formerly purely residential buildings that is quite frequent in French city centres. An estimation of the commercial and office fraction in the city centres could be made by using the population density and the total floor area.
- The construction period is only known for residential buildings. Non-residential buildings are assumed to have been constructed during the same period than the residential buildings in this area. This might introduce uncertainties especially in areas with few residential and many non-residential buildings.
- Renovation of old buildings in order to reduce the heating energy demand is only partly considered by assuming that office and commercial buildings constructed before 1974 (construction periods P1 and P2) have been renovated. No renovation is taken into account for residential buildings.

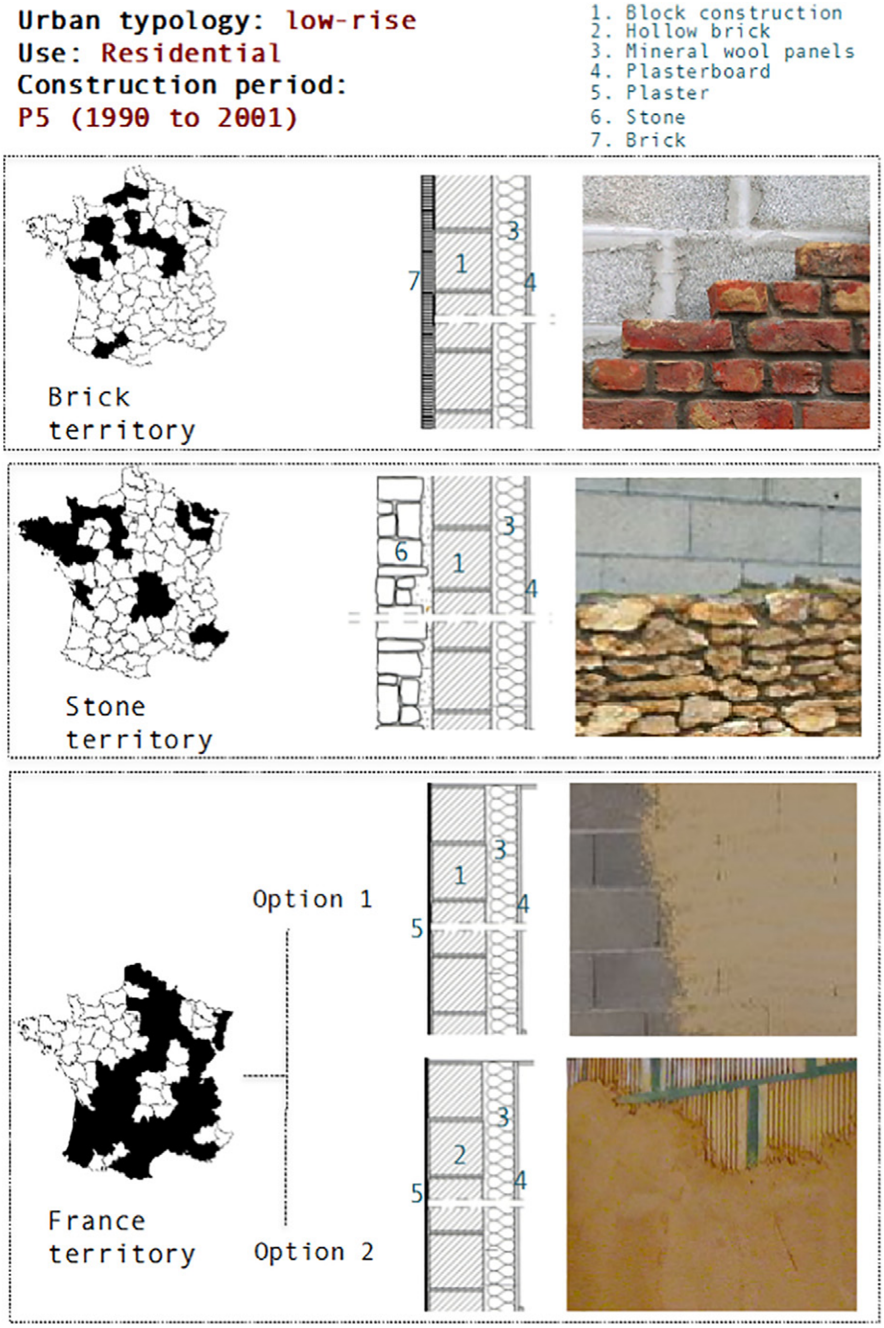


Fig. 5. Constructive system for the walls for the example of low-rise residential buildings of construction period P5. Information is provided on the main material, the internal and external coating as well as the insulation material.

- The same physical parameters are attributed to one type of construction material. However, there might be disparities depending on region and age. For example, bricks are different between northern and southern France, the emissivity of metals like steel or zinc might evolve with time due to ageing.

The described uncertainties need to be kept in mind during applications of TEB for real cities. In this section, the focus will be on an idealised sensitivity study with only one urban typology-use-construction period per grid point.

5.2. Model configuration for the idealised sensitivity study

We quantify the sensitivity of the TEB results on the building architectural characteristics for an idealised model configuration. We perform one-dimensional simulations (one grid point) for each combination of urban typology, use, construction period and construction material included in the database. The TEB simulations are forced by observations at a meteorological tower performed during the CAPITOUL campaign (Masson et al., 2008) in the centre of Toulouse, southern France (~43.6°N, ~1.4°E). The tower observations have been made in about 30 m above the average roof height. The observation period extends from March 2004 to February 2005. The meteorological forcing consists of half-hourly values of air temperature, specific humidity, wind speed, direct and diffuse solar radiation, infrared radiation, as well the rainfall and snowfall rate. The wind direction is not relevant for this one-dimensional application of TEB. The climate of Toulouse is characterised by mild and wet winters and dry and hot summers (Pigeon et al., 2007). Heating is necessary during the cold season, whereas air conditioning is not made in most residential buildings during the warm season.

The components of the urban energy balance R_{net}, Q_{sen}, and Q_{lat} have been observed at the same meteorological tower which provides the forcing data. This allows for an evaluation of the simulated fluxes for the combination of urban typology (mid-rise), use (residential), construction period (P1), and construction material (brick walls, tile-brick-covered roofs) prevailing in the centre of Toulouse.

Not all input parameters of TEB are initialised based on the building archetypes. The surface cover fractions (buildings, urban vegetation, roads), the urban morphology (e.g. building height, wall surface density) as well as parameters related to human behaviour (e.g. design temperature for heating, internal heat release) also need to be prescribed. These non-architectural parameters can have a large influence on the urban surface energy balance (Best and Grimmond, 2015). However, the scope of this study is to determine the sensitivity towards the architectural parameters represented by the building archetypes. The values for the surface cover fractions and the morphological parameters are therefore prescribed as a function of the urban typology (Table 3). For the Mid-Rise buildings we additionally explore the sensitivity on the building density by performing simulations for Compact Mid-rise and Open Mid-rise. The street orientations are assumed to be uniform. The morphological parameters for Compact Mid-rise are set to similar values than in a 500 m radius around the meteorological tower in the centre of Toulouse (Pigeon et al., 2007). The simulated fluxes for this urban typology can then be evaluated against the tower observations.

The parameters related to human behaviour are attributed depending on the building use. For the sake of simplicity we limit the discussion to residential buildings. For these, we assume that people heat to 20 °C when the building is occupied (7 h to 9 h and 18 h to 24 h) and to 19 °C when the building is vacant (9 h to 18 h) and during night (0 h to 7 h). The internal heat release is 4 W/m^2 during the day and 2 W/m^2 during the night. During the cold season, it is assumed that people keep their shading elements open during the day in order to allow for solar heat gains. Ventilation during the cold season is neglected. No air conditioning is considered in summer. However, it is assumed that people close the shades during the day to reduce solar heat gains and open their windows in the evening and during the night to cool their homes. The assumed human behaviour is only a very simple approximation of the varieties of human behaviour inside residential

Table 3
Values of the surface cover fractions and urban morphology parameters attributed as a function of the building typology for the model sensitivity experiments.

Urban typology	Low-rise	Mid-rise, compact	Mid-rise, open	High-rise
Building fraction	0.2	0.65	0.2	0.3
Urban vegetation fraction	0.6	0.1	0.5	0.5
Road fraction	0.2	0.25	0.3	0.2
Building height [m]	3	15	15	50
Aspect ratio of street canyons	0.2	1.5	0.4	2.5
Wall surface density [m^2 (wall)/m^2]	0.32	1.05	0.64	3.5

buildings. More detailed description of behaviours is beyond the scope of this study dealing with building architectural characteristics.

5.3. Results

We explore the sensitivities of the Town Energy Balance on the construction materials and the construction period for one given combination of urban typology and building use. We discuss the results in detail for Compact Mid-rise residential buildings and briefly summarise the results for the other typologies.

The sensitivity of the diurnal cycle of the urban surface energy balance to the historical construction material averaged over June, July, August (JJA) is displayed in Fig. 6. For R_{net} (Fig. 6a), the results are grouped into 3 clusters: the buildings with roofs covered by slate (albedo 0.1; emissivity 0.8), by tiles (albedo 0.25; emissivity 0.8) and by zinc (albedo 0.45, emissivity 0.3). The roofs covered by slate absorb more radiation during the day than the roofs covered by tiles. The roofs covered by zinc are quite similar to the roofs covered by tiles during the day, because the effects of higher albedo and lower emissivity compensate. However, during the night, the roofs covered by zinc emit less infrared radiation and therefore their R_{net} is less negative than for the other roof cover materials. During the day, Q_{sen} (Fig. 6b) is higher for the roofs covered by slate which shows that one part of the excess of R_{net} is immediately converted into Q_{sen}. However, the buildings covered by slate also store more energy during the day (Fig. 6c) and heat up by ~1 K more (Fig. 6d) than the buildings

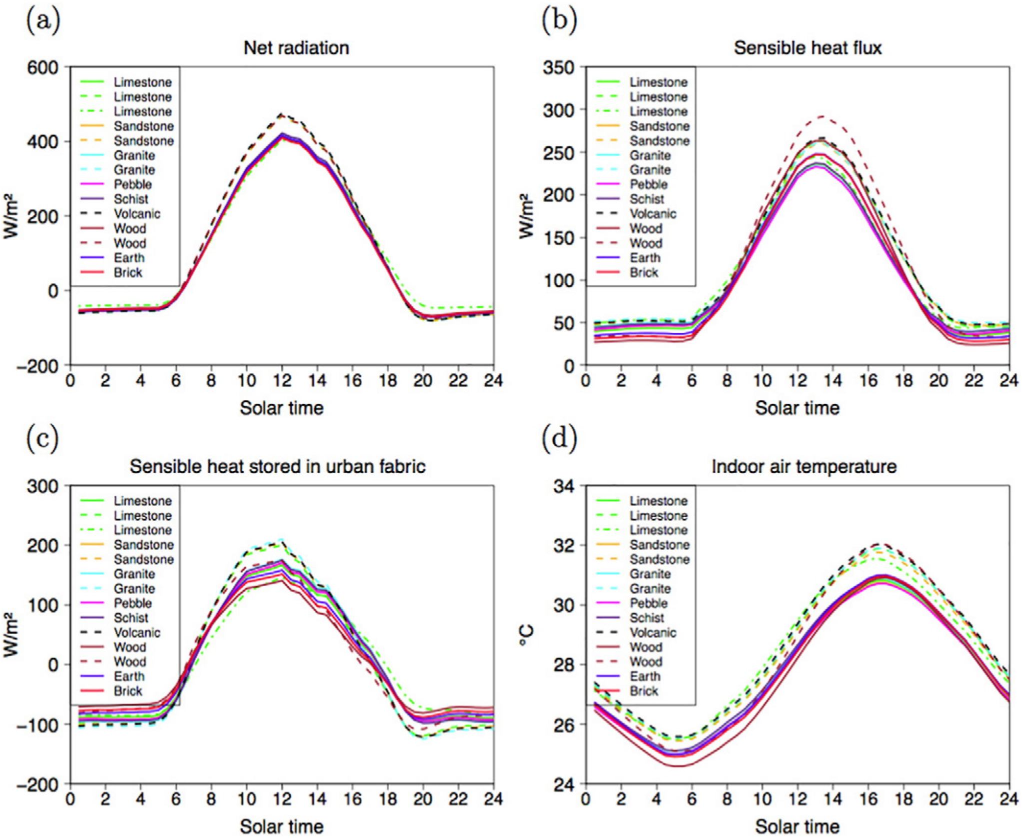


Fig. 6. Sensitivity of the diurnal cycle of the urban surface energy balance on the main wall material and the roof covering material. (a): net radiation, (b): sensible heat flux, (c): storage heat flux and (d): indoor air temperature. The results are averaged over June, July, August (JJA). The continuous lines depict the buildings with a roof covered by tile-brick, the dashed (dash-dotted) lines the buildings with a roof covered by slate (Zinc).

covered by tiles and, as a consequence release more heat during the night. The difference in R_{net} during the day therefore, by the means of the storage of heat in the urban fabric, impacts Q_{sen} during the evening and night which is relevant for the formation of a nocturnal urban heat island. The buildings with a roof covered by zinc are characterised by a smaller value of Q_{sen} during the day (less absorption of radiation) and a higher value during the night since they emit less infrared radiation.

For the Compact Mid-rise buildings, the albedo of the wall material is not very important, which is due to the low values of solar radiation captured by the walls due to the combination of high solar elevation angle at mid-day and narrow street canyons, which limits the solar radiation received by the walls. The indoor air temperature decreases more during the night for the buildings made of wood, because we assume a higher value for the air exchange due to infiltration for these buildings. However, the impact on the fluxes over the urban area is low.

For the Open Mid-rise buildings (not shown), the relative importance of the wall material increases compared to the roof covering material. Due to the low building fraction, the net radiation averaged over the urban area differs only slightly between the slate and tile-brick roofs. For the wall materials with a relatively low thermal conductivity (e.g. wood and brick) there is less (more) Q_{sto} (Q_{sen}) than for the materials with relatively high heat conductivity (e.g. limestone, granite).

During the winter season (not shown) the type of historical construction material only modulates the heating energy demand by about 10%. The reason is that for the construction materials with relatively high thermal conductivity (stones) the thickness of the wall (80 cm) is larger than for the construction materials with lower thermal conductivity (bricks and wood with 60 cm and 50 cm respectively). There is thus a compensation between the larger values of heat conductivity and the larger thickness of the main wall material.

The sensitivity of the diurnal cycle of the urban surface energy balance on the building construction period averaged over December, January, February (DJF) is displayed in Fig. 7. For P1, the walls consist of 60 cm thick brick walls, the roofs consist of tiles as covering material and some plaster and wood below. For P2, the main wall is made out of 20 cm thick concrete blocks and the roof consists of a concrete slab covered by gravel. Insulation of walls (roofs) interior to the main wall (roof) appears for P3 (P4), double glazing of windows has been applied for the first time in P5. The thickness of the insulation material increases until P7. The more recent buildings gradually become more airtight. For P7, contrary to P3–P6, the insulation materials are placed exterior to the main roof and wall (external insulation).

For P1 and P7, R_{net} (Fig. 7a) is slightly reduced during the day since for these buildings less energy is stored in the roof materials, the roof surface temperature is higher and therefore more energy is lost by emission of infrared radiation compared to P2–P6. During the night, R_{net} is generally increasing for the more recent buildings, since the better insulation leads to a reduction of the roof and wall surface temperature and therefore smaller heat loss by infrared radiation. The energy demand for heating (Fig. 7d) is a major component of the urban energy balance during the cold season. It decreases by a factor of ~4 between the non-insulated historical and post war buildings and the modern buildings respecting very rigourous thermal regulation standards. This relative decrease corresponds quite well to the values reported by Rochard et al. (2015) for representative French residential buildings determined during the EPISCOPE project. The storage heat flux (Fig. 7c) is not very different for P2–P6, despite the changes in roof and wall insulation. The reason is that the insulation is placed interior to the main material of the roof and wall and therefore does not reduce the storage of heat in this material. For P1 and P7, the magnitude of the heat storage term is reduced by about 40% compared with P2–P6. For P1, this is due to the lack of a concrete slab below the tiles covering the roof. This considerably reduces the storage of heat in the roof. For P7 it is due to the placement of the insulation material exterior to the main roof and wall material which markedly reduces the heat storage inside the construction materials.

Due to the combined effects of heating energy demand and heat storage, Q_{sen} (Fig. 7b) strongly decreases between P1 and P7. In addition, due to the large modification of the storage term, the shape of the diurnal cycle of Q_{sen} is modified a lot between P6 and P7. Based on the large differences in the simulated Q_{sen} one can conclude that the knowledge of the presence and placement of the insulation materials is highly important for an accurate simulation of the urban surface energy balance.

For JJA (not shown), the sensitivity on the building construction period is lower, because there is no heating and we assume that no air conditioning is made. However, the differences of the storage heat flux between P1/P7 and P2–P6 described for DJF are also present in JJA. The placement of insulation materials with respect to the main material might therefore influence the urban heat island during both the warm and the cold season.

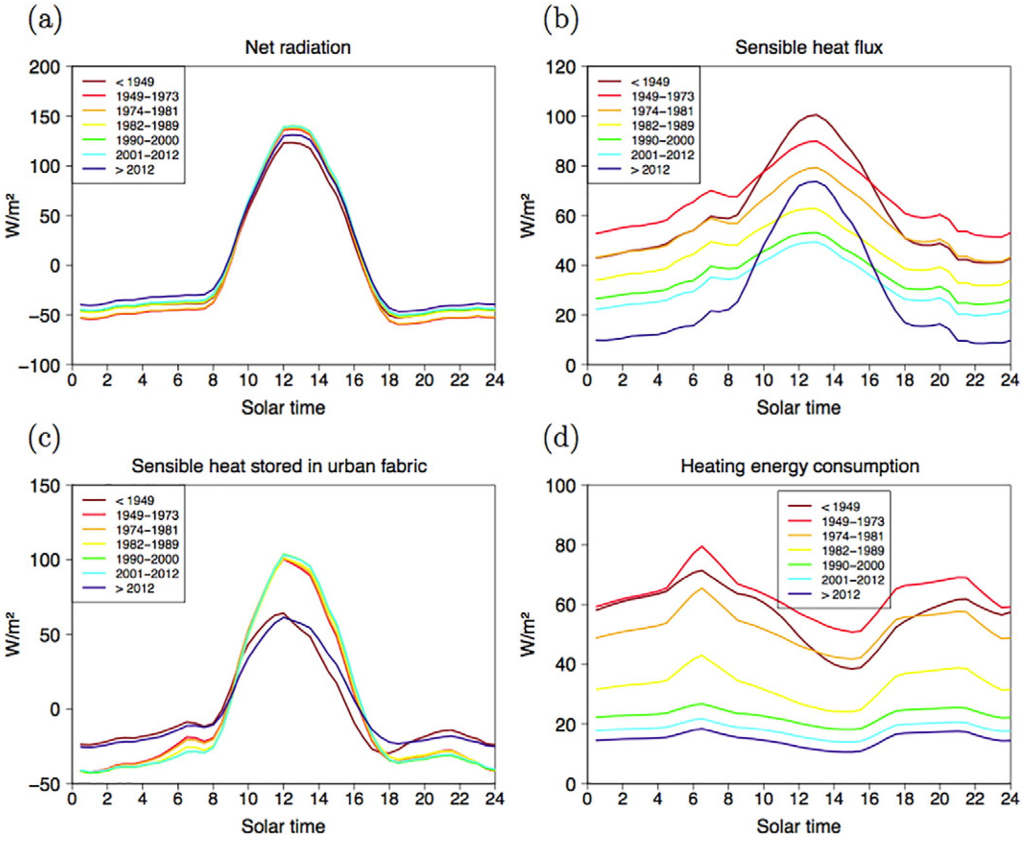


Fig. 7. Sensitivity of the diurnal cycle of (a): net radiation, (b): sensible heat flux, (c): storage heat flux and (d): heating energy consumption on the building construction period. The results are averaged over December, January, February (DJF).

We discussed the sensitivities of the urban energy balance exemplary for mid-rise buildings. The main outcomes are also found for low-rise buildings (not shown). However, the albedo and insulation of the roof are even more important than for the mid-rise buildings. For high-rise buildings, the characteristics of the wall are more important which is plausible since the wall surface area dominates over the roof surface area for these buildings.

In summary, our sensitivity study for the French building archetypes indicates that there are 3 highly influential architectural characteristics that need to be known for an accurate simulation of the urban energy balance.

- The albedo of the material that covers the roof
- The presence and thickness of insulation materials in wall and roof
- The position of the insulation material relative to the main wall and roof

The type of material used for the main wall has relatively low importance in urban environments with compact buildings. It becomes more important in more open urban environments (e.g. Open mid-rise) since then the walls receive more solar radiation and the ratio of wall to roof surface increases.

Our results are consistent with previous findings. Porson et al. (2009) found that the highest priority when designing an urban canopy parametrisation should be given to separately treat the roof energy balance compared to the wall and surface energy balance. Loridan et al. (2010) report for the city of Marseille that the albedo and thermal characteristics of the roof are the most important parameters for the simulation of the urban energy balance. Best and Grimmond (2015) found that the town albedo is one of the most relevant parameters.

For the interpretation of this sensitivity study it has to be kept in mind, that the results have been obtained for a mid-latitude climate with relatively mild winters and warm, but not hot summers. Different results for the sensitivities might appear for other climatic regions. For example, the albedo and thermal conductivity of the wall might become more important in more northern regions with colder winters, a lower solar elevation angle and wider street canyons.

We compare the simulated R_{net} and Q_{sen} for Compact mid-rise residential buildings of the P1 period to the CAPITOUL tower observations. The tower was placed on top of a building with very dark roof which is not representative for the centre of Toulouse. The simulated and observed fluxes are displayed exemplary for DJF and JJA in Fig. 8. The daytime values of R_{net} are overestimated for all seasons (Fig. 8a, c). This is plausible since R_{net} is representative for the roof on which the tower has been placed which has a systematically lower albedo than the typical building in this area. We therefore do not change the physical parameters of the roof in order to better represent the observed net radiation during the day. Q_{sen} is well simulated for all seasons, except for DJF (Fig. 8b). For this season, the overestimation of Q_{sen} during the early morning might be due to an overestimation of the heating energy consumption since a considerable part of the buildings close to the centre of Toulouse is not residential, but consists of little stores, restaurants or offices. These are not occupied in the early morning.

In summary, the fluxes over the urban area are simulated reasonably well and the biases that have been revealed can be explained by factors not related to the building archetypes.

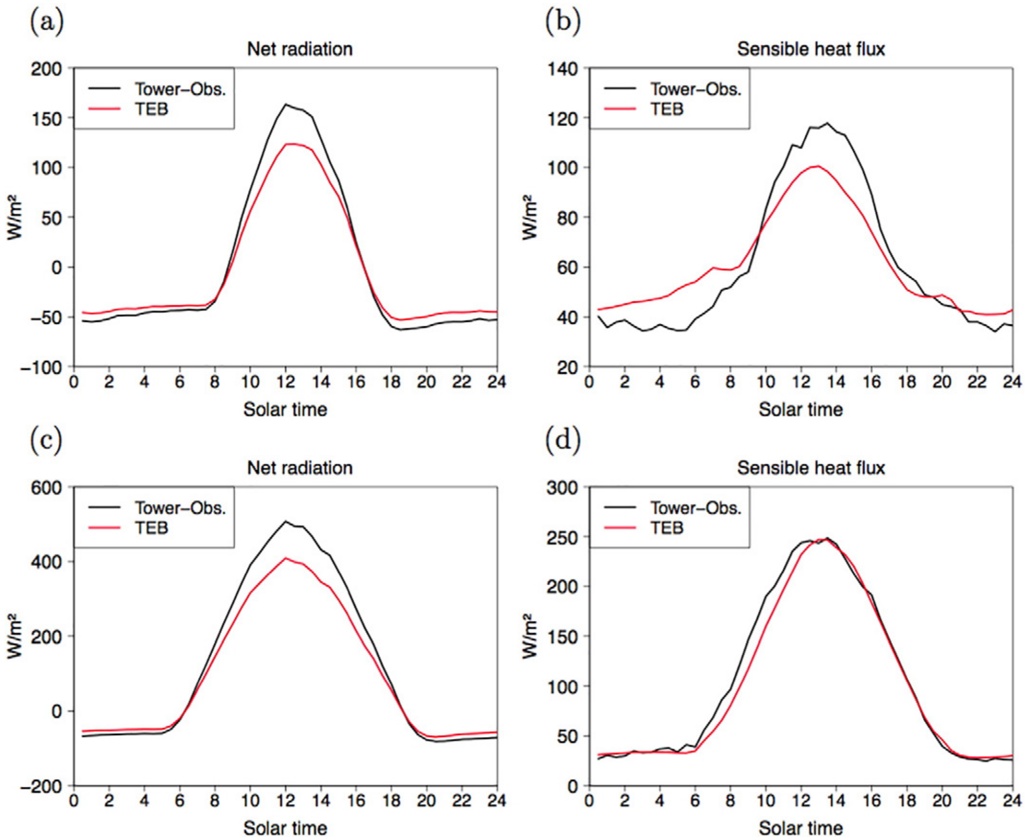


Fig. 8. Comparison between simulated and observed values of (a): net radiation averaged over DJF, (b): sensible heat flux averaged over DJF, (c) and (d): same as (a) and (b), but for JJA. The observed values correspond to the tower observations made during the CAPITOUL intensive observation campaign in the centre of Toulouse, France.

6. Conclusions and considerations concerning a worldwide application of our methodology

The GENIUS database structures the information on building architecture according to four main themes: type of urban form (e.g. low-rise, mid-rise), building use (e.g. residential, office), date of construction and geographical location. For each combination, our database provides detailed information on building materials (envelope materials for walls, roofs, floors and windows) and the ventilation system. Such data is crucial for modelling the urban energy balance.

In the future, the GENIUS database on French building archetypes will evolve to more precisely describe the built environment. More emphasis will be on how buildings are renovated and on what kind of foundations there are built. Those improvements of the database will come from deeper literature review, surveys and newer versions of cadastral and census data. Future evolutions of the database will also enable life-cycle assessments of the buildings.

These evolutions of the GENIUS database will be guided by the conclusions of the sensitivity study which showed that a lot of attention needs to be paid to the characteristics of the roof, the presence of insulation materials and their position relative to the main material. Detailed knowledge on building renovation practices is required in order to determine at which rate buildings are renovated and how this renovation is made (changes of the airtightness, external or internal insulation of walls, …). The high importance of the roof albedo hints at using satellite data in order to obtain spatial maps of this parameter. These maps could be used complementary to the building archetypes which contain many parameters that cannot be determined via satellites.

While our work allows to describe building architecture rather precisely for the whole French territory, the proposed methodology is general and can serve to enrich other databases worldwide (e.g. Jackson et al., 2010) in the follow-up of the WUDAPT project.

The use of four simplified building typologies (Low-rise, Mid-Rise, High-Rise, Extended Low-Rise; Table 2) reduces the requirements for morphological input data and could allow to identify easily building characteristics based on the LCZ classification. This facilitates a worldwide application of the proposed methodology. For a study over a given geographic area, an architectural analysis of the typical construction materials of each of these four building typologies allows to estimate the building materials mostly used, and the associated physical parameters required by the models. Given the scale at which this analysis is done (country, region, city, neighbourhood), the detail of representation of the spatial variability of building architecture would vary. For example, our study is done at the scale of approximately 100 administrative regions within France (Fig. 3). This is a fine scale, but still implies that all buildings of same use and built during the same construction period within a city are characterised by the same architecture, which is only a simplified representation of the reality.

For the building construction period, the GENIUS approach is mainly driven by thermal regulations. That method could be applicable in Europe and other industrialised regions. For instance, the TABULA project that involved thirteen European countries has based the definition of construction periods on each country's thermal regulation and historical context (Ballarini et al., 2014). However, a local expertise is always required to identify if this approach is relevant and, if so, which periods are the most representative of national or regional thermal regulations. Other drivers than thermal regulations might have influenced the evolution of building architecture and construction materials. For instance, massive economic or demographic changes can lead to a fast densification of a city with very specific architectures (that phenomenon can be observed in Vietnam or China). Political factors can also influence architecture and construction regulations. For old buildings, an influential factor could be the beginning and the end of a colonisation period. Another vivid example of political factors is the evolution of East Berlin buildings after the fall of the Berlin Wall in 1989.

As described above, the building use is also an important driver for the building architecture. While a building can shift from one use to another during its lifetime (for example from residential to offices for some old city centres), more recent constructions are likely to display an architecture specific to a given use (Fig. 4). The twelve categories of building use identified in Section 3.2 are a direct result of the availability of data in the French administrative datasets. In a broader context, as in WUDAPT, a reduced set of building uses should be considered. The uses agricultural, greenhouse, religious, sport facility, castle, and non-heated should normally only contribute to a small amount to the total floor area in the centre of a city and should mostly be characterised by a small degree of heating or air conditioning. They could therefore be omitted or grouped into one category. For residential buildings it might be necessary to distinguish between different socio-economic classes (e.g. slum, middle class, rich) in countries with a large spread in income. Given their different architecture, the uses office, commercial and industrial should be treated separately.

However, in the absence of specific data on the actual building use, a first-order-approximation could be to distinguish five uses: residential, commercial, industrial, office and other. These could be directly linked to the LCZ classification: industrial for LCZ10 (Heavy industry), commercial for LCZ8 (Large low-rise), offices for LCZ1 and LCZ4 (Compact and Open high-rise), and residential for all other LCZ. However, this first-order-approximation will have to be critically evaluated given that it will not be valid for all cities. For example in Hong Kong, high rise buildings can be both of residential and office use.

Therefore, we recommend to define building archetypes for a region or city of investigation for at least the combinations of simplified urban typologies (low rise, mid rise, high rise, extended low rise) and the simplified uses (residential, industrial, commercial, offices, other). A dependency on the date of construction or other factors should also be considered. With this approach, the architectural classification could become relevant when maps on building use or age become available in addition to the LCZ maps.

While the way to acquire the architectural information may be challenging, the completion of such a database globally, in many countries, regions or even cities, would render the use of urban climate models more precise than the usual general, worldwide uniform, look-up table parameters. This would allow to describe the geographic variability of the architecture and building materials of the urban fabric.

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