"MultipliCities": multi-scale energy modelling of urbain archetype buildings, case-study in Toulouse

Tathiane Agra de Lemos Martins, Serge Faraut, Luc Adolphe, Nathalie Tornay, Marion Bonhomme, Geneviève Bretagne, Patrice Contart, Géraldine Casaux-Ginestet

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Design to Thrive

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Tathiane A.L. Martins[1], Serge Faraut[1] Luc Adolphe[2] Nathalie Tornay[1] Marion Bonhomme[1] Genevieve Bretagne[3] Patrice Contart[3] and Geraldine Casaux-Ginestet[2]

[1] LRA, Ecole Nationale Supérieure d'Architecture de Toulouse, Université Fédérale de Toulouse, Toulouse, France, email : tathiane.martins@toulouse.archi.fr;

[2] LMDC, Institut National des Sciences Appliquées de Toulouse, Université Fédérale de Toulouse, Toulouse, France, email : ladolphe@insa-toulouse.fr

[3] AuaT, Agence d'Urbanisme et de l'Aménagement Toulouse aire métropolitaine, Toulouse, France, email : genevieve.bretagne@aua-toulouse.org

Abstract: Given the complexity of urban systems, it becomes essential to integrate different disciplines as well as to fit the different spatial and temporal scales of the urban planning in order to produce useful knowledge for planners. To face this challenge, the national French research project, called "multiplicities", proposes a prospective contribution to support energy-based urban renewal for European cities focused on the built urban forms and their materiality at three nested spatial scales: the urban district, the building and the building envelope. In this context, this paper focus on the methodology proposed for identifying urban typology representative cases in the city of Toulouse and for evaluating the energy demand of buildings based at three nested spatial scales simultaneously: the urban district, the building and the building envelope. This methodology allows treating with various levels of details of urban typologies: from a very detailed approach for building materials to a simplified approach for the urban neighbourhood "horizon". From a set of energy-related indicators of the urban morphology and of its materiality, three French representatives urban archetypes have provided the basis to this analytical study. A multi-scale modelling strategy is developed and integrated in an energy simulation tool. A comparative analysis of the buildings energy performance between a single scale and a multi-scale approach is drawn.

Keywords: Urban archetypes, multi-scale modelling, energy, temperate climate.

Introduction

Building is the largest energy-consuming sector in urban areas today. In France, buildings are responsible for a fraction of 46% of all final energy demand, and far more pollutant than transportation and industry (ADEME 2011). Even if civil engineering construction is a very dynamic economic sector in France (INSEE 2010), it has suffered for many years from structural weaknesses, particularly in terms of energy and environmental impacts. Over the last thirty years, the final energy consumption of urban buildings has increased by more than 20% (ADEME 2011). In this context, evaluating the potential energy demand and production of buildings at the urban scale is a crucial starting point for optimizing cities energy.

In the sustainable urban development perspective, the built morphology plays crucial role on the global energy demand of cities (Owens, 1986) (Williams, Burton, Jenks, 2000) By urban morphology, we refer here to the complex shape, dimensions and materiality of buildings. At this scale, city configurations directly affect the indoor and outdoor climates of inhabited areas and have a direct impact on embodied energy of buildings and on their use and occupancy (Ratti, Raydan, & Steemers, 2003).

Many efforts have been made in recent decades in order to promote the energy efficiency of the built environment in many cities, but most of them have been mainly applied to the building scale. An increasing number of researches have recently tried to measure and demonstrate the impact of urban densities and different urban forms on the energy performance of buildings individually (Martins, Bonhomme, & Adolphe, 2013) (Boyeur, Inard, & Musy, 2011), and also on the local renewable energy production such solar energy (Compagnon, 2004) (Montavon, 2010) (Kampf, Montavon, Bunyesc, & Robinson, 2010). Nevertheless, an analysis of the urban morphology integrity, based on a reasoned evaluation of its different scales and levels of details on the reduction of energy demand of buildings and also the maximization of the local production of energy has not yet been further developed.

Today, the energy impact of urban configurations has been well stated in various ways. Many studies have proceeded to evaluate and compare the energy performance of different urban typologies at many different urban and climate environments (Arantes, Bucchianeri, Quenard, & Baverel, 2014) (Rode, Burdett, Robazza, & Schofield, 2014) (Martins, Adolphe, & Bastos, 2014). To do so, for instance, researchers have developed methodologies aiming at extracting homogenous representative urban typologies from different urban fabrics at the urban block or at neighbourhood scales (Rode, Burdett, Robazza, & Schofield, 2014) (Martins, Adolphe, & Bastos, 2014). Others have simplified and studied archetypal generic urban forms out of real urban landscape context (Ratti, Raydan, & Steemers, 2003) (Arantes, Bucchianeri, Quenard, & Baverel, 2014).

However, cities are complex systems composed of mixed heterogeneous geometries and textures, which induce complex climatic phenomena at various scale levels simultaneously. Though, multi-scale modelling of urban form and its wide effect in climate variables and energy demand in building is still a complex task to achieve.

To study the impact of urban form on buildings' energy and to optimise their performance, we have developed a methodological approach aiming at reasonably integrate the different levels of details in the energy modelling process of built environments. Although great progress has been made on building simulation in urban scale, energy multi-scale analysis remains a challenge (Nouvel, Kaden, Bahu, & Kampf, 2015).

Many studies have presented different methodologies out to define physical properties of spaces at different scales, but not much work can be found to date on an urban multi-scale integrated approach.

In the urban scale, we should deal with the modelling of multiple and complex urban forms. Today, 3D modelling offers an enormous technical potential but is still constrained by computational cost limits. The number of calculations increases with the number of objects to model or with more precisely facets involved. The level of details should then follow with the relevance of geographical scale.

"multipliCities" is a French national research project that searches to optimise urban built environments in the European urban landscape context in terms of potentially consumed and produced energy of buildings. The challenge of this project lies essentially in composing the optimisation problem from a multi-actor, multi-criteria and multi-scale point of view.

Objective

This paper presents a methodological approach for multi-scale modelling of urban buildings in regards to energy demand and solar potential optimisation of cities. It draws a comparison between current single-scale procedures against the proposed multi-scale modelling.

Development

To do so, three main methodological steps were taken and are thoroughly described as follows:

a. Definition of urban building archetypes for the study city area of Toulouse, France.
b. Characterization of the three main scales and levels of details applied to a case study in the city of Toulouse.
c. Multi-scale evaluation of buildings energy demand through a comparison analysis.

Urban archetypes for Toulouse

There are many different ways of describing an urban archetype. Number of authors has used this concept to model and assess energy and other environment impacts as well as to predict future energy of cities at a regional scale (Lechtenböhmer & Schüring, 2010) and at the urban scale (Firth, Lomas, & Wright, 2009) (Shimoda, Fujii, & Mizuno, 2004).

At the urban block scale, Ratti, Raydan & Steemer (2003) examine environmental performance of a few generic urban archetypes, such as pavilions, slabs, terraces and courts. Arantes et al. (2013) applied six different generic urban blocks based on a density definition (number of habitat/ha) to analyse energy performance of built urban forms. Cheng et al. (2006) studied the impact of randomness in the plot layout and height of buildings at high urban densities forms. Rode et al. (2014) created five idealised samples, based on the most generic features of the building configurations of the four biggest cities in Europe. Although the foremost interest of comparing energy performance of different geometries for a given climate, most of the cited research works does not take into account the real urban immediate and near context-related characteristics that mostly coexist with the assessed urban form or archetype of interest and that should interfere the energy analysis.

Together with the Urban Association of the Toulouse Area (auaT), an interdisciplinary methodological approach has been carried out. Urban archetypes have been defined based on four main principles: historical diversity of urban form and construction; national representativeness (so that the study could be easily transposed), local urban regulation limits and geographical situation (e.g. varied types of urban fabric). The different levels of this methodological approach allowed a better integration of the multi-scale modelling.

Eight urban archetypes have been carefully identified from different architectural periods as well as different centralities (e.g. downtown, inner suburbs, ZAC, etc.) for the city of Toulouse and that could be easily applied for the other French traditional cities (Table 1). The extension of each archetype is determined individually according to its local urban regulation limits.

Working precisely on these archetypes using various key parameters defined by our research team as well as professional urban designers will allow to link theses results with other urban projects with similar parameter values.

Table 1: urban archetypes methodological approach for French cities.

Level 0 **Historical period**	**Level 1** **Major Types**	**Level 2** **Architectural Typology**	**Level 3** **Urban Archetypes**
Housing of the 50s/60s	Individual houses	Detached houses	Discontinuous pavilions
Housing of the 30s /40s		Semi-detached houses	Semi-continuous pavilions
Market gardening (“Maraîchère”)			Continuous pavilions into open city block
Ancient / medieval downtown	Semi-collective houses	Terraced houses	Continuous pavilions into closed
Haussmann inner suburbs		Townhouses	Continuous building into closed city block
Housing complexes of the 60s/70s	Collective houses	Tall buildings	Vertical city blocks
		Mixed buildings	Grouped city blocks

Multi-scale modelling

In order to take into account the energy impact related to the urban form complexity of a large scale without diminishing the building archetype resolution, a reasoned multi-level multi-scale modelling is proposed. For modelling purposes, only one archetype of Toulouse will be used here: the semi-continuous pavilions into open city block “Cité Castors” (Figure 2).

Figure 2: The studied city block “cité castors” in Toulouse.

From a set of georeferrenced urban data (SIG) available for most of the French cities in a 2.5D format (BD-TOPO), the urban archetype at its neighbourhood scale is extracted in a dxf format and the block scale complemented with 3D data obtained with the city administration of Toulouse (Toulouse Métropole).

Three nested scales are then determined:

a. *The urban archetype city block* – This urban zone consists of a set of buildings presenting a remarkable homogeneity in its morphological treats. This scale should be studied in a detailed three dimensions, the building resolution. The actual dimensions of this scale can vary according to this homogeneity characterisation. At this scale, the architectural type is very important (form, period, materiality). In the case of the “Cité Castors”, few detailed parameters should be modelled: the roof slope, the openings displacement, the wall and roof composition and its users profile.

b. *The surrounding neighbourhood* – Beyond the archetype block perimeter, a ‘buffer’ area corresponding to the nearby urban zone is created. This intermediate zone comprises varied built typologies and characterizes the neighbourhood scale. At this scale, the urban form can be sufficiently modelled in 2.5D (buildings footprint and height). The definition of the building compositions is way less detailed. The modelling hypothesis consists of asserting that most of the surrounding urban blocks impact is defined by the major obstructions and solar reflexions to the main urban scene. In the case, of the “Cité Castors”, the varied large and tall buildings are well pronounced.

c. *City skyline* – If we zoom out of the neighbourhood of the “Cité Castors”, one may observe numerous obstacles that might as well impose a non-negligible influence to the urban scene of interest. A third and larger scale is then modelled. A second "buffer" from the centre of our archetype is defined. To obtain a good trade-off between modelling a larger urban scale and keep a low computational cost on the energy calculation, we have reasonably simplified the urban form considering its relative influence. For this, an urban horizon line has been defined. This skyline is determined by both an azimuthal angle (Φ), and the maximum height angle of far field buildings (ϑ) inside each angular step, as shown in Figure 3.

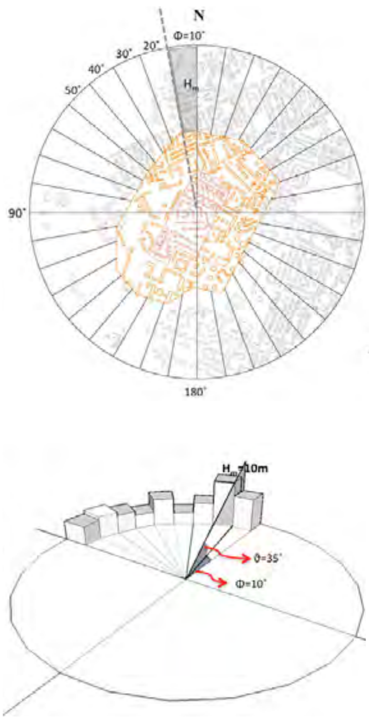
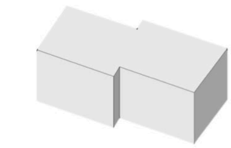
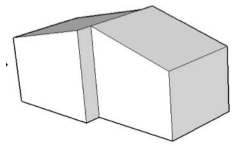
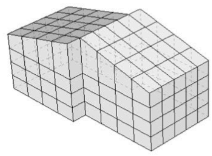
Urban scales : urban horizon, neighbourhood and urban block		**Levels of details**
		 **2D ½**
		 **3D**
		 **Decomposed facades**

Figure 3: The three scales and levels of detail.

This multi-scale approach allows evolving the most representative urban forms reasonably and simply regarding their belonging to a particular urban fabric and their capacity to renew themselves in the future.

Similarly to the description of 3D environment engines used in video games, this multi- scale multi-level approach, allows reducing the amount of input information in simulation software, thus reducing the power required and the computation cost. This will reduce the time needed to assess urban fabrics, and their morphological-technical variants.

Multi-level energy modelling

The recent developments of computer modelling has profoundly impacted the field of urban morphology research, especially at the neighbourhood scale where significant macro scale data can be difficult to obtain and sufficient micro scale data (defining building form) becomes too compute-intensive to analyse when scaled beyond the plots of one or two buildings (Rode, Burdett, Robazza, & Schofield, 2014). With computer automation, more complex geometries could be explored and calculations could be rapidly repeated for many buildings in order to expand the analysis to the neighbourhood scale. For this to be useful, new data to feed such models is required. Many developments have also been done notably in the satellite imagery and GIS field that can be used to automatically generate extruded or “2.5D” massing models of whole cities such as the one used in this research. However, when working with urban block scale, we need to simultaneously integrate some important level of building information (e.g. envelope shape, roof slope, openings displacement, etc.) and nearby and surrounding buildings at the neighbourhood scale that interfere with the assessed urban form but need way less detailed data.

To predict the energy demand and the solar irradiation availability on building surfaces, at a large urban scale, a simplified energy model was applied. The Citysim software (Robinson, 2011) couples together models predicting radiant energy flux reaching and emitted by any shape of building, accounting for the effects of urban obstructions in reducing direct and diffuse radiation, and contributing to reflected radiation. A nodal thermal model based on analogy with an electrical circuit (resistor-capacitor network) is considered (Robinson, 2011). Citysim is currently one of the few models that allows, on one hand, robustness on modeling the complex solar behavior in the urban district scale of hundred of buildings and, on the other, fast computer simulation.

In order to model the 2.5D and 3D geometry, Citysim allowed importing it in a regular 3DFACE dxf file. The software offers a plugin to SketchUp to create it. To enhance the 3D geometry, a new plugin that allows creating automatically decomposed facades to our 3D model is proposed here.

For the city horizon, a skyline tool support by ArcMap (ArcGIS) has been applied and the results were transposed to the far field obstruction input file of CitySim.

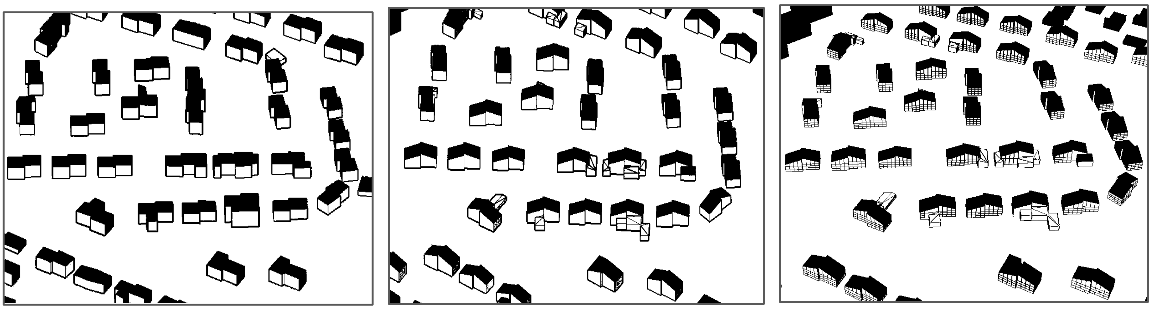


Figure 4: Three different geometry models for the urban block of “Castors City” in Toulouse.

Results

The results of various simulations using Citysim are presented below, according to three criteria: irradiation availability on building surfaces, cooling and heating demand.

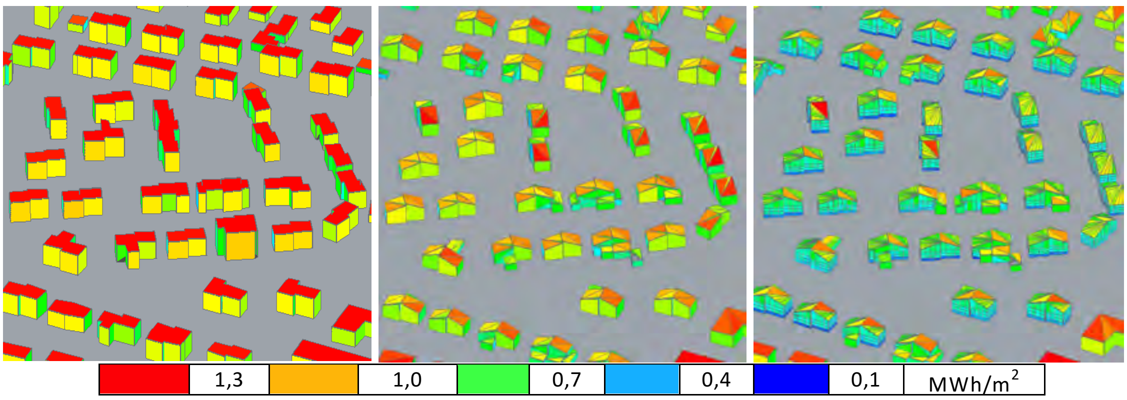


Figure 5: solar irradiation on the surfaces of the three modelled urban geometries.

For all the geometries studied, an important variation of the solar irradiation levels over facades was found, due at the same time to their orientation and to the multiple inter-reflexions between buildings. Facades with the same orientation can also have very different levels of irradiation.

By considering the proposed multi-scale multi-level approach, an improved assessment of the direct and reflected solar radiation is consequently obtained. The solar irradiation is calculated for the roof slope and for a larger number of facade patches. In addition, the shadow effects due to near and far-field obstructions of the district is also decisive. Only by adding surrounding buildings and 3D features to our city block, such as the roof slope, less 25% can be found in the irradiation levels of roofs compared to the single 2.5D scale geometry.

As one can observe in Figure 5, a single 2.5D scale of an urban environment overestimates solar potential over building surfaces compared to the multi-scale urban geometries proposed. For the third mode complex input geometry proposed, a gradient of solar potential is precisely calculated to the city block envelope of interest, which allows better sizing and allocating solar panels.

Consequently, the heating and cooling loads of these buildings in this particular city block are also largely affected. A single scale geometry evaluation underestimates in 18% the heating load and overestimate in 40% the cooling demand compared to a reasoned multi-scale configuration. This can be easily explained by two major factors: the changes observed on the incident solar radiation (reduced solar heat gain of buildings) and the displacement of windows glazing. For the 2.5D and 3D urban geometry, a glazing ratio is considered for each façade, while in the proposed approach, the multi-patched facade allows placing more precisely the glazing fraction of the wall.

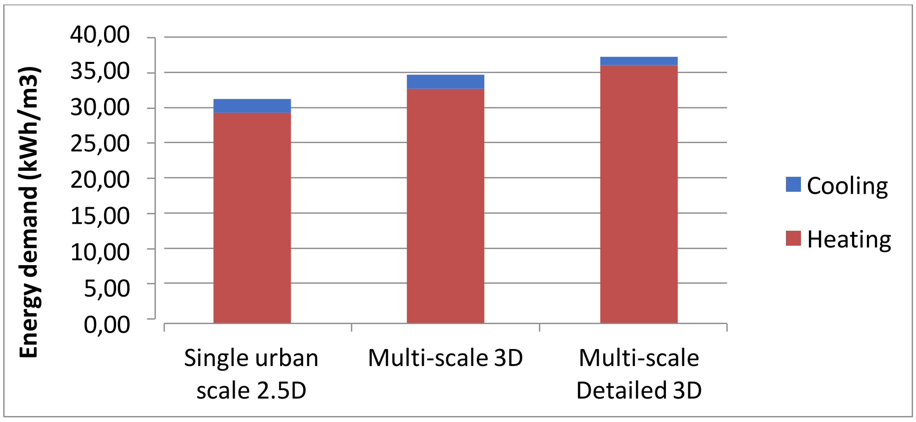


Figure 6: heating and cooling loads both the three urban geometries input.

Conclusions

Most of the urban energy analysis is based on morphological and technical simplification allowing a simplified assessment of a complex reality. In this context, this work aims to automate geometrical data entry for urban energy modelling, adapting the level of detail to the relevance of the urban scale of analysis. This allows finding a reasonable trade-off between accuracy and computational cost.

Between the single 2.5D and the multi-scale 3D model approach, we have obtained on a specific district of Toulouse, France, differences of about 20% and 40% for the heating and cooling loads, respectively, and important variations in the distribution of solar irradiation over facades.

This multi-scale multi-level approach can be of great interest for consideration in the energy balance analyses can support early and late urban design stage (feasibility analysis).

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