UWG -TRNSYS Simulation Coupling for Urban Building Energy Modelling

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Abstract

This paper presents a new methodology to carry out building performance simulation at the district scale integrating the building thermal model TRNSYS with the climate model 'Urban Weather Generator' (UWG). The integrated methodology is designed to include the microclimatic modifications induced by urban environments on buildings' cooling load calculation. The impact of shadows, air temperature increase and urban radiant environment on building cooling performance has been highlighted for hot arid climates (Antofagasta, Chile). Results indicate that the impact of urban context on energy performance of buildings at the neighbourhood scale varies significantly with building typology and urban tissue density.

Introduction

Building simulation science has recently shifted the focus from the building scale to the district/city scale, responding to the growing need of modelling the interactions between built environment and urban microclimate and its consequences on buildings energy performance, especially on cooling loads (Reinhart and Davila, 2016; Barnaby and Crawley, 2011; Crawley, 2008; Sailor, 2014; Santamouris et al. 2015, Salvati et al. 2017). The inherent complexity of urban environments makes urban building energy simulation much more challenging than building performance simulation. For this reason, most of the research in this field is focused on the identification of appropriate methods of approximations capable of catching the fundamental properties of urban context that influence building energy performance.

Two kinds of approaches have been proposed for urban energy modelling, known as top-down and bottom-up models (Li et al. 2017; Kavgic et al. 2010). The top-down models are statistically based and start from energy consumption data of a region to estimate the energy use of groups of buildings, considered as a single energy entity (Howard et al. 2012). The bottom-up models calculate the energy consumptions starting from the individual properties of buildings, or using representative features for defined building typologies, and estimate residential energy use at a district scale (Reinhart and Davila, 2016). Bottom-up models can be either statistical or physical based.

In both cases, several parameters are involved in the simulation process, being the most important: the anthropogenic heat generated in the streets, the materials of surfaces that conform the urban radiant environment, the morphology of urban tissue that determines the shadow range and modifies wind speed. The selection of representative values for the aforementioned variables is thus the first challenge of urban building energy simulations. Then, the simulation procedure itself entails a number of further challenges, which arise from the conflict between the complexity of urban physical phenomena and the need to reduce time and computation power necessary to run the simulation. Some of the questions in this regard are: is computational fluid dynamics necessary or also simplified urban energy balance model could be suitable for the purpose of urban building energy simulations? And what should be the output?

Some microclimate tools, such as Envi-met, are able to provide very high spatial resolution of data for a short simulation time period. Other tools, like the Urban Weather Generator (UWG) model (Bueno et al. 2013), provides annual hourly urban weather data (altering typical meteorological year files) but with low spatial resolution. Therefore, the choice of the most suitable climate model depends on the objective of the analysis. As regarding the calculation of the input values of the urban parameters involved in urban microclimate generation, two strategies can be applied.

One option is to calculate the exact value of all the necessary parameters on the specific urban area to be simulated.

One other possibility, much more effective for studies at the city level, is to divide the city into homogeneous urban environments in terms of microclimate, such as the 'local climate zones' classification proposed for urban heat island studies (Steward & Oke, 2012), and to use the microclimate data of the corresponding zone for the urban building energy simulations. Both strategies require adequate techniques of urban data gathering and analysis such as extrapolation of data from geographic information system (GIS), statistical data processing (e.g. principal component analysis) or neural network development. Many studies have been developed in this way in the last years (Li et al. 2015; Palme et al. 2017a and 2017b; Salvati et al. 2016; Van Der Heijden 2013).

This paper introduces a new methodology for integrating the building thermal model TRNSYS with the climate model UWG so as to include the effect of urban environment on building energy simulation at the district scale.

Methodology

The simulation methodology consists of three consecutive steps aimed at including three microclimate modifications induced by urban environments in building thermal simulation: urban heat island intensity,

- Urban heat island intensity
- Shadows from surrounding buildings
- Urban surface temperature and fictive sky temperature for infrared radiation exchange

The proposed approach can be applied to calculate the energy demand of a specific building in the urban context but also to estimate the energy demand of buildings at the district scale.

- The modelling workflow is reported in figure 1, and consists in the following steps:The portion of urban area to be modelled (urban context) is identified
- A simplified model of urban morphology is created based on significant parametrization
- Urban heat island intensity (UWG) and obstruction angles are calculated on the simplified urban textures
- Building energy demand is modelled (TRNSYS) using outputs from the simplified urban models

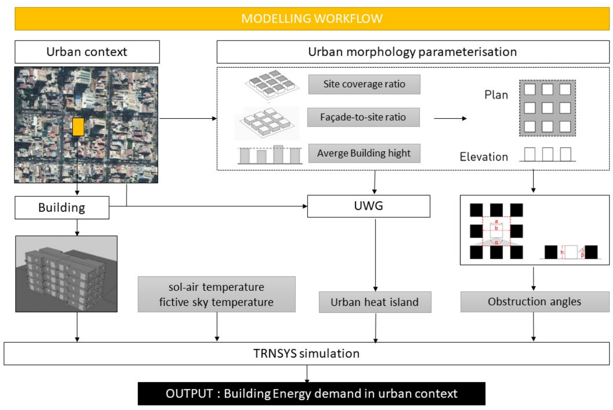

Figure 1: workflow of the simulation process

The urban context corresponds to an area of about 250/500m around the reference building – or an homogeneous urban area of the same dimension – which is the distance within which local climate phenomenon take place according to previous studies (Steward and Oke, 2012; Salvati, 2016).

Urban weather generation

The increase of air temperature in urban environments is included in the simulation using urban weather files obtained with the urban weather generator (UWG). UWG generates urban weather files from hourly weather data measured at operational weather stations, modifying the values of air temperature and humidity to capture the heat island effect in urban areas. The model needs several input parameters (Bueno et al. 2013), of which urban morphology resulted one of the most important (Salvati et al. 2017). Urban morphology is described by three parameters:.

- *Site coverage ratio* (ρ): ratio of the building footprints to the urban site area
- *Façade-to-site ratio* (VH): ratio of the building facades to the urban site area
- *Average building height* (H): average height of building normalised by building footprint

These are among the most sensitive parameters of the urban weather generator model (Nakano, 2015; Palme et al., 2016), which can be calculated from data normally available in GIS tools (Palme at al. 2017a and 2017b), following the equations:

$$\rho = \frac{Built\text{-}up\ Area}{A_{site}} \qquad (1)$$

$$VH = \frac{\sum P \times H}{A_{site}} \qquad (2)$$

Where the built-up area is the sum of building footprints, A_{site} is the urban site area, P is the perimeter of buildings and H is the average building height weighted by footprints. Other important parameters of UWG simulation are specifications of materials, building operation settings (e.g. heating and cooling set points) and anthropogenic heat released to the urban environment from traffic.

Solar radiation and shadows

Considering the real values of the three morphology parameters, a simplified urban model is built to calculate the average horizontal (α) and vertical (β) obstruction angles of building facades. The simplified model consists of square-plan buildings arranged on a regular orthogonal street network. The size of the building and the distance between adjacent buildings (a and b in Figure 2) are calculated based on the following equations (Bueno et al., 2013; Bueno et al., 2014; Masson 2000):

$$\rho = \frac{a^2}{\left(\frac{a}{2}+\frac{b}{2}\right)^2} \qquad (3)$$

$$VH = \frac{4a \times H}{\left(\frac{a}{2}+\frac{b}{2}\right)^2} \qquad (4)$$

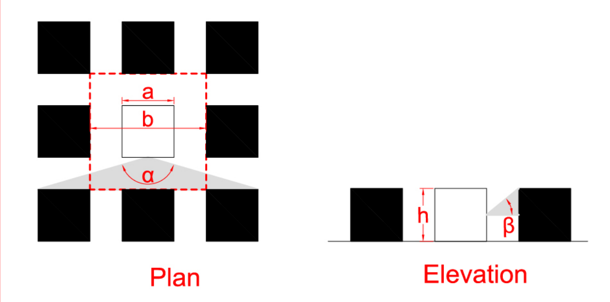

Figure 2: representative shadow environment generation

Each urban context is thus transformed in a representative morphological environment whose values of a, b, and H give the same *site coverage ratio* and *façade-to-site ratio* of the real one.

The obstruction angles α and β, calculated in the middle of the façade of the central building (Figure 2), are used to define the shadow masks in TRNSYS v. 17. For each representative environment, the same shadow mask is used to calculate the average incident solar radiation on buildings facades i . Shadow masks can be defined in TRNSYS with a desired angular step of description, which was set to 15° in this case.

Infrared radiant environment

The infrared radiation exchanges between surfaces is calculated in TRNSYS 17 considering the temperature of roofs and walls and two fictive temperatures, namely the *fictive sky temperature* (obtained as a function of sky cloudiness) and another temperature for the opposite surface with respect to the sky, referred to as *ground temperature* (T_{ground}) from here on. As a first approximation, the *ground temperature* is calculated as the sol-air temperature according to ASHRAE (2017), considering two main assumptions for urban environments: no wind and same sky view factors for ground and vertical surfaces. So, *ground temperatures* are calculated with the following equations for urban (5) and rural (6) environments:

$$T_{ground} = T_{urban\ environment + 0.2 \times \alpha \times I_H \times svf} \quad (5)$$

$$T_{ground} = T_{environemnt} + \frac{\alpha \times I_H - 100 \times \varepsilon \times (1-C)}{9.42 + 3.68 \times v} \quad (6)$$

Where:

- v is the wind speed (m/s)
- α is the solar absorption of the ground (0-1)
- I_H is the total incoming radiation on the horizontal (W/m^2)
- ε is the emissivity of the ground (0-1)
- C is the cloudiness factor (0-1)
- svf is the sky-view factor of the ground

Building performance simulation (BPS)

The integrated methodology has been tested on the calculation of cooling loads of two housing types: terraced houses and medium size block of apartments. Table 1 (building envelope) and 2 (building use) report the model set-up for the main parameters of building performance simulation.

Table 1: values of building envelope parameters in BPS

	Wall	**Floor**	**Roof**	**Window**
U (W/m^{2}K)	2.15	1.79	0.48	5.81
h_e (W/m^{2}K)	25	0	25	25
h_i (W/m^{2}K)	8	6	10	8
M (kJ/m^3)	1400	1400	950	80
α (solar)	0.6	0.6	0.4	/
ε (infra-red)	0.9	0.9	0.9	/
g-value	/	/	/	0.85
	Detached house		**Block of apartment**	
window ratio	16%		32%	

Table 2: values of building use -related parameters in BPS

Solar protection	**Cooling set-point**	**Lighting**	**Gains**
70%	26 ºC	10 W/m^2	5 W/m^2
People	**Lighting schedule**	**Activity**	**Occupancy schedule**
25 m^2/person	18-24	1 Met	0-24

The BPS has been performed four times for each housing type as follow:

1. using rural weather files (from the city airport weather station)
2. using urban weather files calculated with UWG
3. using urban weather files and shadow masks
4. using urban weather files, shadow masks and urban radiant temperatures

32 energy simulations were performed in total.

Case study

Four samples of urban fabric of the city of Antofagasta, Chile have been used as case study to test the simulation methodology. The morphological parameters characterising the 4 samples (u1, U2, U3 and U4) are reported in Table 3. Other sensitive parameters of UWG simulation, like the anthropogenic heat from traffic and building conditioning systems, were set to fixed values. The heat from traffic was set to 25 W/m^2 and the building internal gains were set to 5 W/m^2, in agreement with previous studies (Palme et al. 2017a and 2017b) The heat released to the urban canyon by air-conditioning systems was set to 80% of total waste heat. The cooling demand temperature was set to 26 ºC for both day and night.

Table 3: morphological parameters used in UWG

Urban morphology	Site coverage ratio	Façade to site ratio	Average height
U1	0.76	1.65	11.3
U2	0.69	0.81	6.6
U3	0.42	2.06	15.4
U4	0.23	0.32	6.0

The four morphologies used as case study are representative of typical urban tissues categories (UTC) of the city. They have been obtained applying advanced statistical analysis (principal component analysis) to a wider set of GIS data of urban fabric of Antofagasta, as explained in detail in Palme et al. (2017a and b). The variability of the shadows range is very intuitive looking at figures 3 to 6. U1 is a compact urban tissue (built-up area is 76% of total site area), where buildings are close and relatively high, so the effect of shadows is expected to be significant.U1 is also the case with the highest UHI intensity according to UWG calculations. U2 is also compact urban tissue, but buildings height is half than in U1.

This means that the shadows effect in this urban context is expected to significantly influence the energy performance of detached houses (6 m height) but not that of blocks (15 m height). U3 is less dense in terms of built-up area, but it has the highest average building heights, so the impact of shadows is still expected to be high. The influence of the infra-red exchanges is also expected to be higher than in other cases, due to the high value of the façade-to-site ratio. U4 is less dense than the previous ones and it also has the lowest value of façade-to-site ratio. In this context, the effect of shadows is expected to be low, but the infra-red environment plays a very important in modifying building energy performance compared to rural environments.

Results and discussion

The variation in cooling loads for the two housing types in the four urban configurations are reported in Figures 7 to 10, comparing the simulation results obtained using: a) rural weather file; b) urban weather file; c) urban weather file and shadow masks; d) urban weather file, shadow masks and urban radiant temperatures. As expected, each urban context affects the results in different ways In U1 and U3, the increase in cooling demand caused by UHI intensity is compensated by a beneficial impact of shadows. When the infra-red environment is also modelled, the positive effect of shadows is reduced and the final urban cooling demand results higher compared to a rural environment in most of the cases (only the detached house in U1 shows a reduction in cooling demand with respect to the rural case).

Results for U2 show a different impact of the urban context on the two building types (terraced house and block of apartments). This happens because the urban texture is dense but the average height of buildings is less than in U1 and U3.

Therefore, of the impact of shadows= is significant on the terraced houses (6 m height) but it is not in on the blocks (15 m height). In U4, the impact of shadows is instead almost negligible on both housing types, due to the low density of the urban tissue.

In this kind of texture, the overlapping effects of UHI intensity and infra-red environment without the beneficial effect of shadows determine the highest increase of cooling loads compared to a rural environment. However, this result is influenced by the assumptions made in the estimation of ground temperature, namely that no breeze is present in an urban environment compared to a rural one.

This is certainly true in very compact urban environments (Oke, 1988; Allegrini et al., 2015; Di Bernardino et al., 2015), but it is much more unlikely in a low density urban texture such as U4, where it wind most probably beneficially affects cooling loads of buildings, depending also on the city size and on the location of the neighbourhood within the city. Urban wind simulations should be addressed in such cases, so as to estimate the influence of horizontal air movement on surface temperature of ground and buildings facades.

Conclusion and future work

This paper presented a simulation methodology to include urban microclimate effects in building energy performance simulations. The results showed that if only the UHI intensity is taken into account, cooling loads are likely to be largely overestimated. The beneficial effect of shadows compensates the detrimental impact of air temperature increase on cooling loads in many cases. This means that the urban sectors with the highest UHI intensity are not necessarily also the ones with the highest cooling demands.

On the other hand, the results showed that also the infra-red environment pays an important role in increasing the cooling loads in urban context. In most of the cases, the cooling loads are overestimated considering only the UHI effect and neglecting the impact of radiant environment and shadows determined by urban texture morphology. However, in less dense urban tissues, where the effect of shadows is not strong, the infra-red environment determines a further increase in cooling load than the one caused by UHI.

One of the limitations of the study, which will be addressed in future works, regards the calculation of the shadow range on building façades. In this first approach, the obstruction angles have been computed only on the middle point of the façade. A better approximation could be obtained calculating the vertical obstruction angles on each floor, which would provide a better assessment of the shadow range on the lower floors. This approximation led in fact to an underestimation of shadows on the facades of the block of apartments in U2.

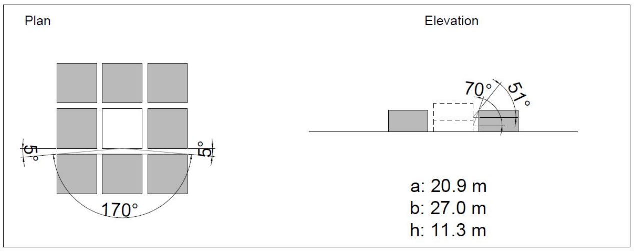

Figure 3: representative model and obstruction angles for U1

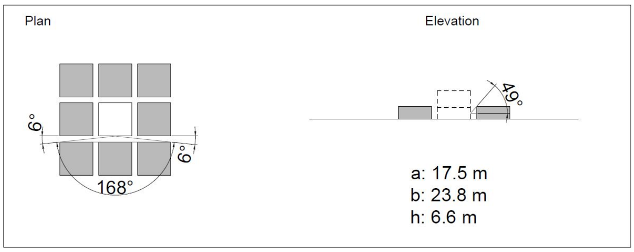

Figure 4: representative model and obstruction angles for U2

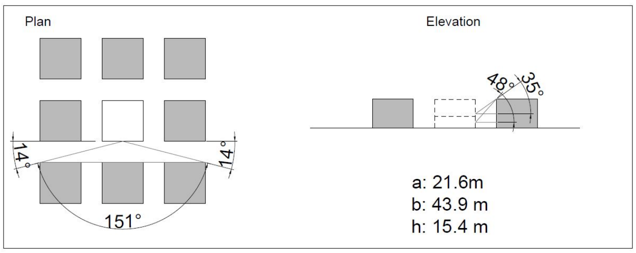

Figure 5: representative model and obstruction angles for U3

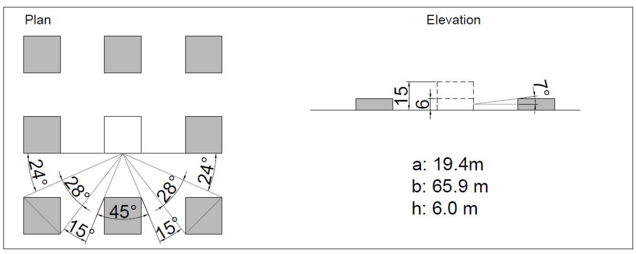

Figure 6: representative model and obstruction angles for U4

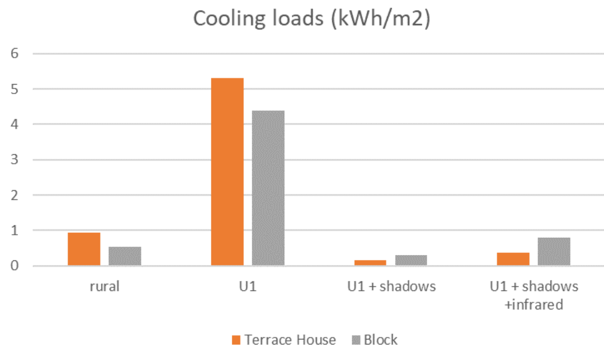

Figure 7: cooling demand in U1

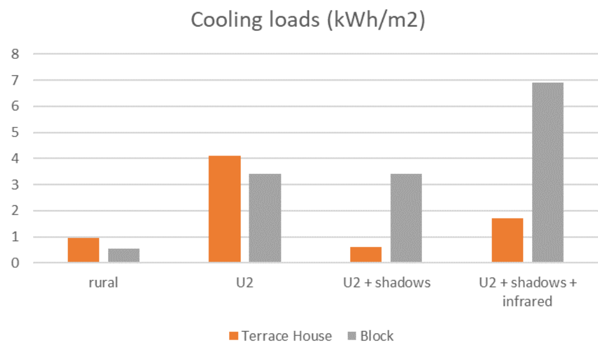

Figure 8: cooling demand in U2

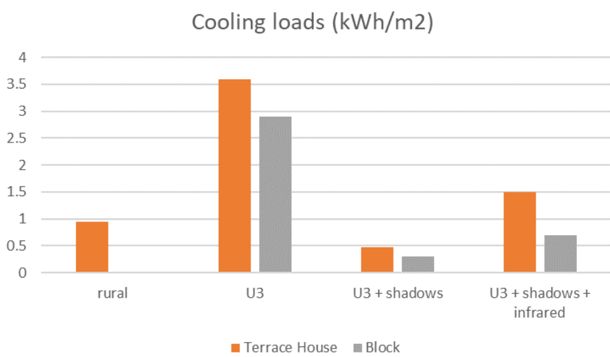

Figure 9: cooling demand in U3

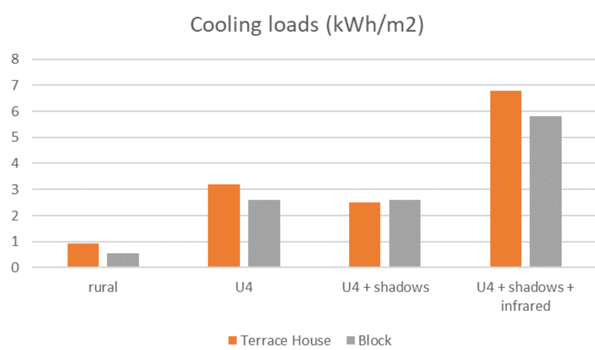

Figure 10: cooling demand in U4

Another limitation regards the use of ground temperature as representative of the urban infra-red environment. A better approximation would consider the average temperature, weighted by view factor, of all the surfaces surrounding each building facade. However, if no special materials are present (for example, solar absorbers or low-emissivity materials), the approximation is valid with an error of about 10% that entails an error of less than 5% on energy consumption calculations.

A final limitation, already discussed in the text, is the fact that urban breeze is assumed to be negligible in this study, which is acceptable for compact urban textures but not for low-density urban sectors, for which microclimate simulations would be necessary to estimate the urban breeze. In spite of these limitations, that will be addressed in future works, the proposed simulation methodology showed to be an effective and novel approach to urban building energy modelling considering the complex energy relationship between buildings and surroundings in urban environments.

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