Analysis of the (urban) microclimate effects on the building energy behaviour

Lucie Merlier[1,2], Loïc Frayssinet[1,2], Frédéric Kuznik[1,2], Gilles Rusaouën[2],
Kévyn Johannes[1,2], Jean-Luc Hubert[1,3], Maya Milliez[1,3]
[1]BHEE: High Energy Efficiency Buildings, joint laboratory CETHIL / EDF, France
[2]Univ Lyon, INSA de Lyon, Université Lyon 1, CNRS,
UMR 5008 CETHIL, F-69621 Villeurbanne Cedex, France
[3]EDF R.& D. – EnerBaT, F-77818 Morêt-sur-Loing Cedex, France
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Abstract

As a first but critical step toward integrated energy simulations of urban buildings, this exploratory study develops a methodology aiming at modelling the local thermo-aeraulic environment of buildings and studying the relative effects of radiative, convective, thermal and pressure conditions on their thermal behaviour. For this purpose, detailed microclimatic and building energy models are used, namely SOLENE-microclimat and BuildSysPro. This study more specifically addresses summer conditions and a thermally inefficient building given global warming challenges, urban heat island problems and the eledering building stock of European cities. As a basis for further applied studies and in order to basically highlight the effect of each above-mentioned environmental factor, this study focuses on generic tests cases: an isolated cubic building and the same building located in a theoretical urban environment.

For the considered building, results show that:

- even considering an isolated building, taking into account in details an open but mineral environment instead of outdoor conditions derived from typical weather files (except for short wave radiation fluxes) may modify results by 1.3 °C, mainly because of long-wave radiative exchanges;
- assuming no general urban heat island effect, direct effects of urban environment may decrease indoor air temperatures by 0.15 °C on average, mainly resulting from complex compensations between short and long wave radiative heat transfers as well as aeraulics.

Beside, aeraulic boundary conditions are very impacted on by surrounding buildings, which is challenging for natural ventilation issues -including free cooling- especially when further considering energy efficient buildings.

Introduction

In cities, environmental conditions can strongly deviate from regional meteorological conditions, which are often considered as input conditions for building energy models. In addition, building energy models often consider general values, empirical correlations or simple approaches to estimate e.g. convective or pressure coefficients on building outer walls (Cstola et al., 2009; Mirsadeghi et al., 2013), which can lead to substantial uncertainties when aiming to understand properly the energy behavior of a building in its actual environment. Following these observations and thanks to the development of computational capabilities, some enhanced or coupled urban climate / building energy numerical studies have been performed over the last years (e.g. Bouyer et al. (2011); Allegrini et al. (2012); Yang et al. (2012); Malys et al. (2015)), showing that the impact of the urban environment on building thermal behavior or energy consumption can be substantial.

To complement these approaches towards a comprehensive modeling of the thermal behavior of a building in / and its environment, and better understand (1) the impact of modeling assumptions as well as (2) the effect of each environmental factor on building thermal behavior, this exploratory study develops a methodology aiming at modeling in detail the local radiative, thermal and wind environment of buildings and simultaneously studying the relative effects of short and long radiation fluxes, convective heat transfer coefficients, air temperature and pressure conditions on the building thermal behavior using detailed microclimatic and building energy models. By addressing generic configurations, respective contribution of each environmental factor on building thermal loads and subsequent thermal behavior can be clearly highlighted and compared, providing thus basic material for further applied and more complex studies. This methodology also highlights uncertainties that usually underlay energy simulations of urban buildings due to the lack of knowledge about environmental conditions.

Hence, this paper is structured as follows. Sec. "Modeling" firstly presents the addressed test cases and details the implemented modeling approach. Sec. "Results analysis" synthesizes the main results in terms of building boundary conditions and compares the estimated indoor air temperature evolution. Then, Sec. “Discussion” reviews the main findings in terms of scientific contributions against work limitations and opens perspectives with respect to the thermal efficiency of building envelope and natural ventilation problems. Finally, Sec. “Conclusions and outlooks” closes the paper and specifies outlooks.

Modeling

Tests cases

The considered generic test cases are 10 m high cubic constructions oriented according to the cardinal directions. Fig. 1 shows the two addressed geometric configurations: an isolated building lying on a 10×10 m large mineral area, and the same building located in a regular array of 4×4 similar constructions. Their thermal properties (Tab. 1) typically correspond to those of French multi-family houses built before 1915 as they represent the main part of the French building stock according the TABULA classification (Rochard et al., 2015). The glazing ratio is of 23 %.

Considering global and urban warming challenges in European countries, which increasingly shift the usual heating paradigm to cooling, this study focuses on the summer period (21-23 July), for the climate of Lyon (weather data based on Meteonorm - see Fig. 2).

Computational approaches

As an exploratory study, a simple external coupling was implemented between two detailed numerical tools - SOLENE-microclimat for outdoors, and BuildSysPro for the building - towards a comprehensive modeling of physical processes occurring in and around buildings. Although this approach necessarily involves some deviations between modeling assumptions, it enables:

- default and detailed approaches to be compared,
- environmental factors to be discriminated,
- and main trends to be highlighted.

SOLENE microclimat

SOLENE-microclimat is a software suite developed by the CRENAU, Nantes, France. The microclimatic simulation tool relies on a coupling between the thermo-radiative tool SOLENE, initially dedicated to compute solar fluxes in complex urban areas and imporved to account for different heat transfers, and the CFD software Code Saturne, developed by the French Electricity Company - EDF. According to Musy et al. (2015); Morille et al. (2015), applications of SOLENE-microclimat covers microclimate and building thermal behavior studies, only the first being currently used and focused on hereafter.

This study relies on a simple coupling between the thermo radiative and the CFD models. More precisely, each model is run once at each one hour time step, which means that Code Saturne considers SOLENE results of the $i-1^{th}$ time step as boundary conditions to simulate air flows and the related variables at the i^{th} time step, which values are used by SOLENE as boundary conditions to simulate surface properties at the i^{th} time step.

For simulations, geometries and meshes were carefully generated, with 1 m cell size on the obstacle edges and a global mesh size factor of 0.2. Domains were extended by 150 m following the four cardinal directions, extending usual CFD best practices guidelines (Franke, 2006; Tominaga et al., 2008) to account for the probable occurrence of any incident wind direction. These settings led to a total of 95×10^3 3D cells and 6×10^3 2D facets for the isolated cube as well as 289×10^3 3D cells and 37×10^3 2D facets for array of cubes (see Fig. 1). Fluid dynamic simulations are based on a steady RANS $k-\varepsilon$ model for turbulence and wall functions for near wall treatment. For convergence, 2000 iterations were run at each time step by the CFD code, and the evolution of normalized residuals was checked.

In line with the developed approach, no specific building energy modeling was set (every buildings are similarly modeled, with an indoor temperature of 24.2 °C corresponding to the averaged outdoor temperature over the simulated period), and clear sky conditions were considered. Building thermal properties were specified according to Tab. 1, with equivalent values resulting from the averaging of walls and windows properties. However, no wall transmitivity could be relevantly specified, which may lead to unintended increase of surface temperatures as albedo values were set according to usual wall features. In addition, buoyancy effects were neglected.

Because of computational costs of CFD, year round simulation cannot be performed. Therefore, three summer days were simulated, the first being used for initialization. For the two following days, surface averaged values of local air temperature, convective heat transfer coefficient ($CHTC = 4 + 4 \times U_{loc}$, according to the French thermal regulation), direct and diffuse short wave radiation fluxes, net long wave radiation and pressure were recorded at each time step to feed the following building model.

BuildSysPro

BuildSysPro is a building energy Modelica library focusing on the French building stock,[1] developed by EDF R&D (Plessis et al., 2014; Schumann et al., 2016). This library enables detailed dynamic building energy models to be built, by combining sub-models (windows, walls, ventilation..). Simulations were run with Dymola.

For sake of simplicity and because of the general prospect, the model is mono-zone. Walls are oriented according to the cardinal directions, and spec-

[1] An open source version is yet available https://github.com/edf-enerbat/buildsyspro/releases/tag/v2015.12b

	Wall	Window	Roof
Materials	0.4 m stone	double glazing	0.013 m plaster + 0.02 m insul. + tile
U [$\mathrm{W\,m^{-2}\,K^{-1}}$]	1.7	2.6	1.35

Table 1: Thermal properties of the generic test cases.

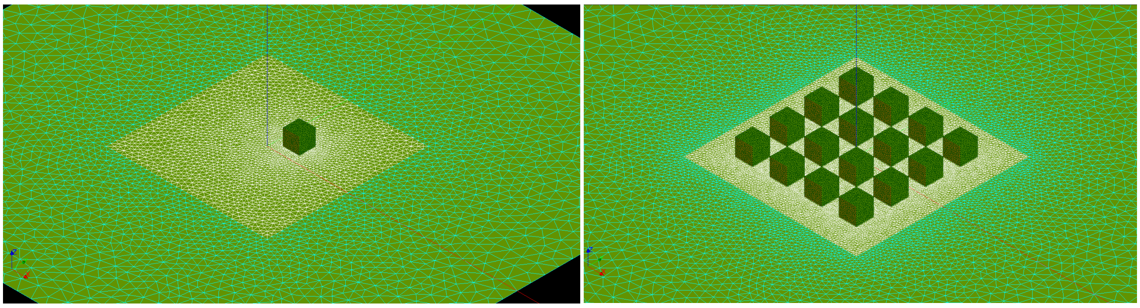

Figure 1: Geometric configurations: isolated and array of cubes.

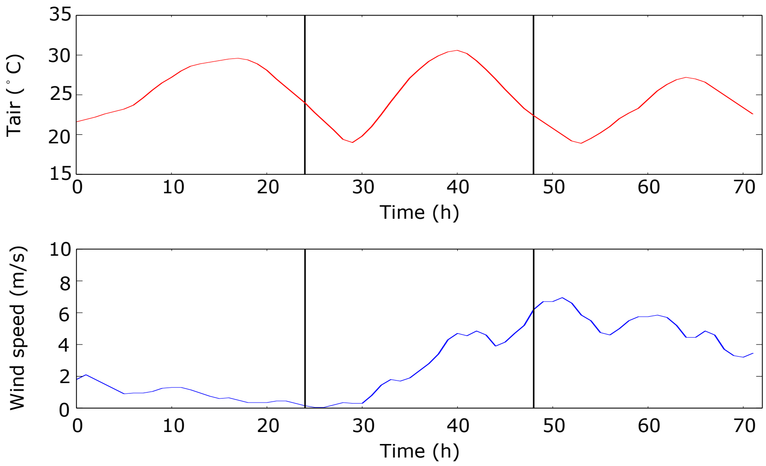

Figure 2: Air temperature and wind velocity during the period of interest.

ified with $\epsilon = 0,9$ (emissivity) and $\rho = 0.4$ (albedo). Double glazed windows properties include $\tau = 0.75$, $U = 2.6\,\mathrm{W\,m^{-2}\,K^{-1}}$, and $g = 0.76$. The ventilation flow rate was scheduled according to the French thermal regulation recommendations (1.5 vol/h during occupancy, 1 vol/h otherwise), and no model for humidity was considered as air moisture impact is low in temperate climates.

Fig. 3 shows the implemented coupling strategy between SOLENE-microclimat and BuildSysPro, which relies on a modification of the building boundary conditions. Corresponding values either directly came from the Metenorm weather file ("Default" - isolated building configuration), or from the outputs of SOLENE-microclimat simulations ("Isolated" or "Array"). On the one hand, short wave radiation fluxes computed by the microclimatic model for the isolated configuration were specified as input for the default BuildSysPro model for sake of comparability. On the other hand, although being actually similar, the external air temperatures next to walls were differentiated in the building model depending on the modeled phenomenon (the convective heat transfer (T_{air}) or air renewal flow rate, including infiltrations, (T_{vent})) in order to further distinguish their effects. More precisely, if the outdoor air temperature is uniform in the default configuration and equals the weather dry bulb temperature, temperatures were spatially differentiated when based on SOLENE-microclimat outputs and these values could be or not considered when studying convection or air renewal effects. In addition, detailed external heat transfer modelings were used in order to account for specific environmental factors. In particular:

- Net long wave radiation fluxes were estimated using the Stephan-Boltzmann law, based on the sky and air temperatures (approximation for the ground and the urban environment) and an assumed 0.5 view factor in the default configuration while values were directly specified to the wall surface thermal nodes when based on SOLENE-microclimat outputs. Note that in this case and because of the implemented microclimatic model, the same value was assigned for both opaque walls and windows.

- CHTC were modeled as described above, considering either the meteorological wind velocity roughly corrected as a function of the wall azimuth; or directly specified according to SOLENE-microclimat outputs.
- Infiltrations were modeled assuming an homogeneous wall permeability (K) and a power law for infiltrated air flow rates: $Q_{\Delta P} = K \times \Delta P^n$, the external pressure being either computed using default pressure coefficient (Cp) values and the meteorological wind velocity at the building height; or specified according to SOLENE-microclimat outputs.

The building model was initialized by running 4 times the 2 days studied.

Result analysis

Boundary conditions

To highlight differences in building thermal and aeraulic solicitations, Fig. 4 compares the specified boundary conditions depending on the considered configuration.

Results clearly show direct solar masks effects in the morning and afternoon on the East and West faces of the non isolated building. As the sun is high, their is no shade on the South face at midday. Masks affect diffuse solar radiation as well, as surrounding buildings reduce the received fluxes from the atmosphere on all faces except the roof but they also reflect incoming short wave radiation towards facing facades. Therefore, incoming diffuse radiation on vertical faces generally decrease because of surrounding buildings except on the North face.

Differences induced by the modeling approach (Default / Isolated), as well as the modeled environment (Isolated / Array), are observed both for the net long wave radiative fluxes, CHTC, air temperatures and relative pressure. In particular, BuildSysPro-based results predict that all faces release heat by radiation to their environment, including windows with an almost constant $\approx -20\,\mathrm{W\,m^{-2}}$ (not shown) during the simulated period, while SOLENE-microclimat results indicate that some faces are positively balanced, especially when they do not directly face the sun.

Compared to the default values, increased air temperatures are generally observed next to building faces according to SOLENE-microclimat results, especially next to sunlit surfaces undergoing low wind speeds.[2] Regarding convection, a minimal CHTC value of $4\,\mathrm{W\,m^{-2}\,K^{-1}}$ for leeward faces, which corresponds to a zero wind speed, and maximum values for the roof for windward faces are computed by BuildSysPro, while SOLENE-microclimat-based values show more homogeneous CHTC. Their intensities are reduced when surrounding obstacles are present as wind speed is reduced in the array because of wind masks and the development of recirculation flows. According to SOLENE-microclimat results, these aerodynamic masks also reduce pressure intensities on building outer walls, and only negative relative pressures are estimated in this case. On the contrary, positive and relatively high pressure values are also derived from the CFD computation for the isolated configuration, with higher intensities occurring for high incident wind speeds. With the exception of the roof, which is assumed similar as the South face in BuildSysPro model, comparable Cp values (not shown) are estimated for the isolated configuration by both computational approaches.[3]

Hence, these intermediate results stress differences due to the modeling approach in case of an isolated building, especially regarding assumptions impacting long wave radiative exchanges as well as the deviation induced by considering no, or relatively simple, aeraulic models for outdoors. Beside, results highlight that by constituting solar and wind masks, surrounding constructions substantially impact on building boundary conditions, which may consequently affect its external thermal and aeraulic balance.

Indoor air temperatures

To study building response to the modified boundary conditions described above, Tab. 2 reports the computed (averaged) day and night indoor air temperatures for the three studied configurations. More precisely, the effect of the modeling approach is highlighted by comparing BuildSysPro and SOLENE-microclimat -based predictions for the isolated configuration (Default / Isolated) and the effect of the urban environment is addressed by comparing the two SOLENE-microclimat model results (Isolated / Array). To further understand consequences of modeling assumptions or environmental effects, Tab. 2 also indicates the specific contribution of short wave, long wave, aeraulic and convective boundary conditions on the building thermal behavior. To complete these results and stress dynamic effects due to the building physical properties, Fig. 5 compares the evolution of the indoor air temperature for the three tested configurations.

Regarding the isolated building, major effects (+2.05 °C compared to the mean indoor air temperature estimated in the default case) of the modeling approach is due to the difference in the long wave radiative transfer modeling. This is not only ex-

[2]Note that the outlier value computed in the beginning of the first day in the array configuration is certainly explained by numerical problems due to the very low wind speed occurring at this time step. However, the consequence of this unrealistic value on the computed dynamic behavior of the building is negligible, as no singularity is observable in any building simulation result.

[3]Differences in pressures intensities are explained by coefficient applied to the wind speed in the default configuration.

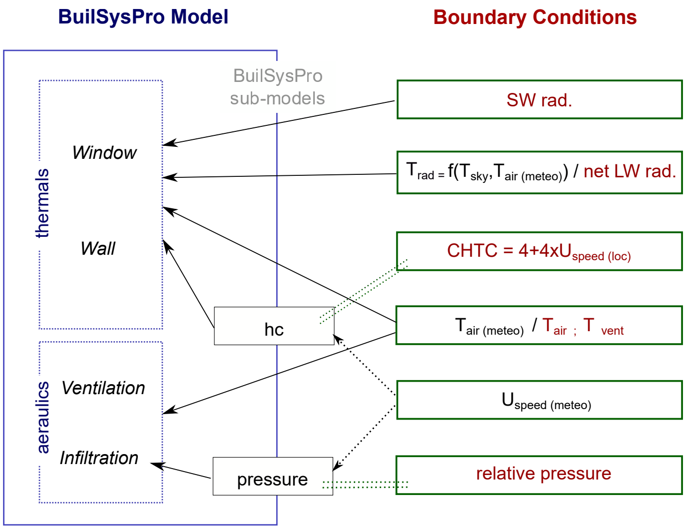

Figure 3: Coupling strategy: red: SOLENE-microclimat- based boundary condition (differentiated by face), dark: default approach.

Indoor air temperature [°C]					
Case	Day	Night	Case	Day	Night
Default	32.2	30.3	Isolated	33.6	31.5
Isolated	33.6	31.5	Array	33.5	31.4

Boundary condition effect [°C]			
Isolated - Default		Array - Isolated	
SW rad.	0	SW rad.	-1.22
LW rad.	$+2.05$	LW rad.	$+0.55$
Aero.	-0.12	Aero.	$+0.36$
Conv.	$+0.07$	Conv.	$+0.23$
Total	$+1.30$	Total	-0.15

Table 2: Comparison of the simulated mean indoor air temperatures and boundary conditions effects. Day: 10 h - 22 h, Night: 22 h - 10 h according to the indoor temperature distribution
- SW rad.: Short wave radiation (direct + diffuse), *- LW rad.: Long wave radiation,*
- Aero.: Infiltration + ventilation (pressure + T_{vent}), *- Conv.: Convection (CHTC + T_{air}),*
- Total: Combined effects (all boundary conditions)

plained by the assumptions made for windows and indoor air temperatures, but also because SOLENE-microclimat models a mineral ground, whose temperature is generally higher than that of the surrounding air. Regarding the effects of the urban environment, changes in solar radiation due to surrounding constructions is the main factor affecting the building thermal behavior (-1.22 °C compared to the mean indoor air temperature estimated in the isolated case). Effects of the long wave radiation balance are also substantial. Convection and aeraulics show lower impact on indoor air temperatures, although not negligible especially when considering their potential accumulated effects. However, it is worth mentioning that the combined effect of boundary conditions does not equal the sum of individual contributions due to interactions.

Hence, regarding the simulated building configurations, predictions based on SOLENE-microclimat data for the isolated building (simultaneous modification of all boundary conditions) show 1.3 °C higher indoor air temperature than estimated in the default configuration on average. This effect is rather constant during the period of interest, but show maximum differences during the day. On the contrary, for the considered cases, the presence of surrounding buildings tends to decrease indoor air temperatures up to 0.15 °C on average, especially due to solar masks with a characteristic dynamic pattern. However, solar reflections and modifications of the other boundary conditions modulate this effect. This observation may further be related to the urban heat island effect, although current simulations do not show increased outdoor air temperatures during the night.

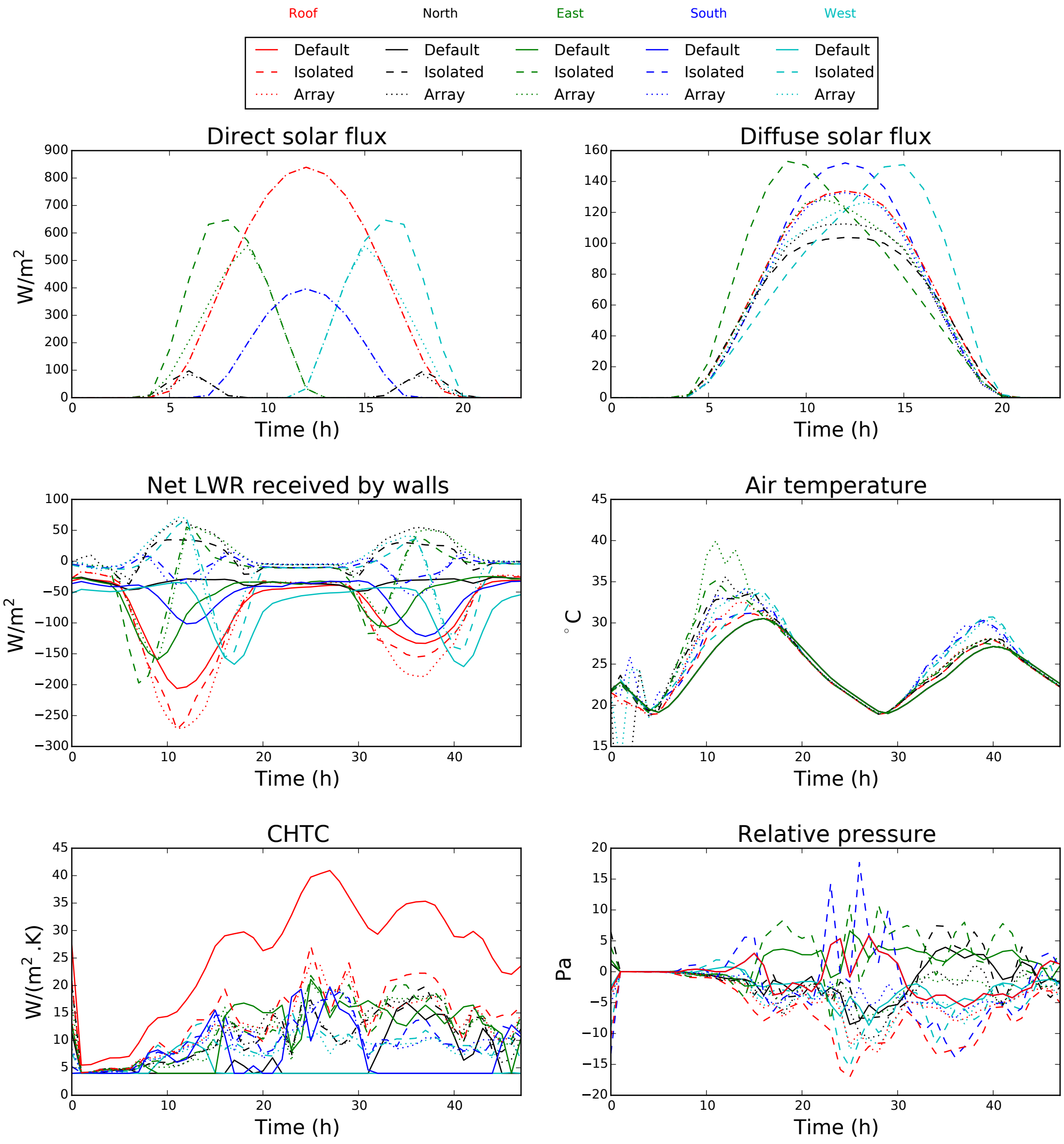

Figure 4: Comparison of the boundary conditions for the different configurations.

Discussion

Main contribution of the work

By developing two modeling approaches based on the same building thermal model, and an external coupling with a detail microclimatic model, this study (1) stresses uncertainties related to the use of default boundary conditions in usual dynamic building energy studies and (2) highlights potential effects of urban environments on the building thermal behavior. Besides, the methodology enables specific contribution of radiative (short wave and long wave) and convective heat transfers as well as aeraulics to be distinguished. In addition, dynamic behaviors are highlighted for summer days in the context of global and urban warming.

For the case studies reported in this paper, results show major effects of short wave radiative heat transfers: masks tend to reduce indoor air temperatures, with a clear dynamic temporality. However, non negligible effects of long wave radiative and wind induced exchanges on the building thermal balance, including changes due to aeraulics are also highlighted. These factors tend to constantly increase indoor air temperatures, while being less straightforward to manage during building operation compared to direct solar loads (shading), and whose effects on the building thermal behavior may be amplify by a larger scale urban heat island phenomenon.

Model limitations

Although this exploratory study already points out phenomena to be necessarily accounted for in urban building energy studies, some limitations should now be overcome towards more integrated and accurate building comfort studies and energy / power, predictions in the context of urban densification and climate change. In particular, the simple coupling between

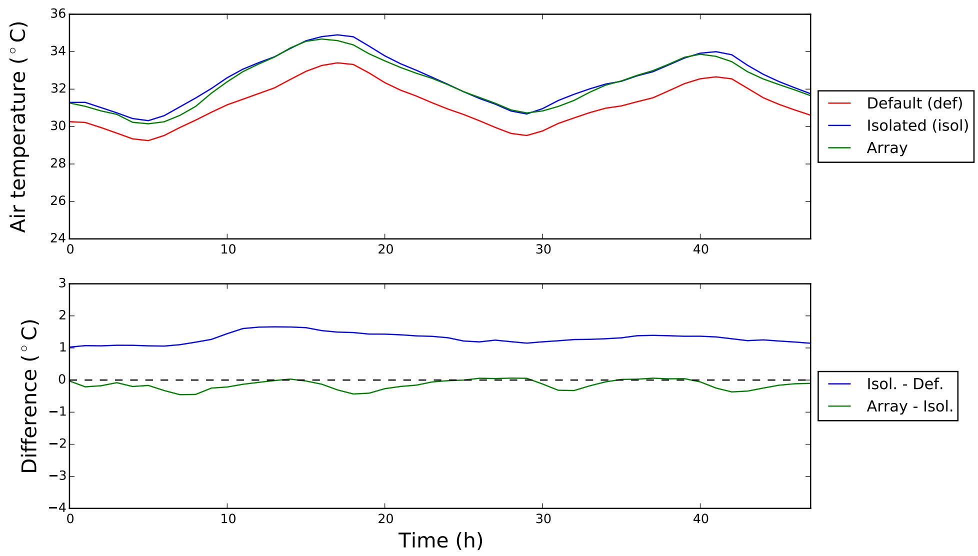

Figure 5: Evolution of the indoor air temperature during the two simulated days and differences between configurations.

the two models considered is particularly detrimental for long wave radiation exchanges, and some (assumed minor) inconsistencies between the microclimatic and the building energy models could not have been avoided, especially equivalent wall properties *vs.* wall and windows differentiation, and fixed *vs.* free indoor temperature. In addition, although microclimatic results are currently assumed more accurate than default values, or at least relevant enough to highlight uncertainties involved in usual building energy studies, the microclimatic model involves some shortcomings, especially with respect to the coupling strategy and some simplifications in both models (buoyancy, transmittivity). Further sensitivity analysis to these assumptions as well as a general validation should now ideally be performed, which would estimate the accuracy of results. However, this exercise is made difficult by the computational costs involved, the complexity of the modeled interacting / coupled phenomena and the lack of comprehensive validation data.

Regarding applications, only one thermal efficiency of envelope was tested as the aim of the study was primarily methodological. However, considering a renovated building further highlights very high indoor air temperatures, which would be unbearable in real building operation conditions. Therefore, due to the strong dependence of the thermal behaviour of such buildings to solar loads, shading devices should be modeled, and natural ventilation should also be considered. Indeed, according to simulation results, the modeled urban environment decreases infiltrated air flow rate due to wind-induced pressure differences by a factor of 0.4 on average, which may be critical for free cooling. Therefore, modeling accurately solar masks and the building wind environment appear even more important further considering passive strategies and low energy buildings.

Conclusion and outlooks

This study develops an exploratory approach aiming at highlighting uncertainties linked with the use of usual building energy model assumptions, and the impact of urban environment on the building thermal behavior by differentiating radiative, convective and aeraulic factors. Despite some model limitations, results show that relevantly modeling radiative heat exchanges and the building aeraulic environment in terms of wind effects on convective heat transfers and pressure difference-induced indoor air flows is advisable when addressing urban problems. This seems to be even more important when addressing energy conservation in (highly energy efficient) buildings with a dynamic approach, but a dedicated study, potentially involving a multizone approach and a more complex urban environment, would be necessary to support this conclusion.

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