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A new building thermal model to a better evaluation of the thermal comfort during heat waves

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Abstract

This paper is about urban building thermal simulation during summer and heat waves conditions. Summer building thermal behavior are already well performed by popular building simulation software such as TRNsys and EnergyPlus. The effect of the urban fabric could be simulated by an Urban Canopy Models (UCMs) or a District Scale Models (DSMs) but the coupling between these models and a building simulation software requires a high expertise and is not computer efficient. This paper focuses on the construction of a simulation chain of tools that is computer efficient and do not require high expertise to run simulation. The methodology is based on in-situ measurements.

The paper describes how the in-situ measurements setup was designed to provide sufficient information to enhance the model settings. It also shows the good accuracy of the model based on the measured data.

Key Innovations

- Urban building thermal simulation

Practical Implications

This paper builds an urban building thermal simulation chain of tools that is easy to use and make fast long-term calculation in summer conditions. It is compared to in-situ measurements to assess its accuracy. It will be used to evaluate the thermal comfort of inhabitants during heat waves.

Introduction

With global warming, climatic events such as heatwaves will be longer, more frequent and more intense. This issue will be more critical in cities since the heat waves are accentuated by the phenomenon of urban heat islands (UHI). Air temperatures in cities are likely to be increasingly unbearable. Extreme urban temperatures will impact a fair majority of the worldwide population since, according to (The World Bank, 2018), nearly 56 percent of the worldwide population lives in urban areas, with a net increasing trend over the past decades. The extreme temperature will cause discomfort and diseases in the urban outdoor environments and within the urban buildings. This is especially true in buildings which are not equipped with cooling systems.

Appropriate building thermal models are needed to predict accurately the comfort of inhabitants in urban

buildings under heat waves events, and more generally under hot summer conditions. The purpose of this paper is to propose such an appropriate model. The model is described in the first section of the paper. Its main specificity lies in the fact that it takes into account the impacts of the urban fabric on the thermal loads on the buildings, in a summer weather context.

A measurement campaign was conducted in two apartments located in the city of Lyon (France) during the summer of 2020. Those measurements produced reference data to assess the accuracy of the proposed model. Details about the measurements are given in the second section of the present paper. The confrontation between the measurements and the model's predictions are described in the last section.

Building thermal model

The developed building thermal model must fulfill two requirements: it must model properly all the prevalent heat transfer rates which are characteristic to building thermal behaviors under summer conditions, and it must take into account the effect of the urban fabric surrounding the building.

Building thermal behavior in summer conditions

In the present paper, the focus is done on buildings without cooling systems. During summer periods, the thermal regulation of such buildings is entirely ensured by actions of the occupants (Fabi et al., 2012). A distinction is made between three types of actions from the occupant. Actions which directly affect the building thermal characteristics are referred as actions of "type 1". They correspond to the opening of the windows for natural ventilation, and the activation of solar shadings (Bui et al., 2019; Hong et al., 2017; Mavrogianni et al., 2014; Piselli et Pisello, 2019). Actions which modify the distribution and the amplitude of the internal gains within the buildings are referred as actions of "type 2". Under hot conditions, an occupant might prefer to stay in the cooler rooms, or to avoid the usage of gas cookers (Bui et al., 2019; Hong et al., 2017; Mavrogianni et al., 2014; Piselli et Pisello, 2019). There are also type 3 actions. These are actions that have no impact on the building thermal characteristics but which allow the occupants to increase their comfort (drinking, changing clothes, resting (Bui et al., 2019; Hong et al., 2017)).

In summer conditions, solar radiation is one of the major thermal stresses on buildings. The way the solar radiation

heats up the building greatly depends on the shading effects of the surrounding solar masks (topography, other buildings, trees, balconies, etc.), and of the windows (optical properties, dimensions, and nature and use of the shading devices).

Under summer conditions, the air temperature difference between the indoor and outdoor environment is lower than under winter conditions, but the heat exchanges between indoor and outdoor air are intensified when windows are opened to enable natural ventilation. The cooling heating rate resulting from natural ventilation is very sensitive to the outdoor air temperature and to the wind pressure loads on the facade.

The thermal models implemented in popular building simulation software such as TRNSys (Solar Energy Laboratory, 2007) and EnergyPlus (S. Department of energy, 2014) already incorporate features for modelling specific aspects of summer building thermal behavior. They incorporate advanced windows + shadings models with a possibility to provide schedules for the control of those openings by the occupants. They offer a full control of the internal heat production due to the activities of the occupants. They incorporate models of outdoor solar masks. They also incorporate, or they propose in the form of an additional module, an AirFlow Network model (AFN) to model natural ventilation air flows and their thermal effects.

However, the thermal models implemented in popular building simulation software do not incorporate features for modelling the effects of the urban environment on the outdoor air temperature and on the building wind pressure loads.

Effect of the urban fabric on the building thermal loads

Popular energy models use weather data to determine the thermal solicitation of the buildings. Available weather data are representative of outdoor thermal conditions in rural areas. However, the urban fabric modifies the outdoor thermal conditions. Those variations happen at two distinct scales: the city scale (gradients over 100 meters length scales), and the district scale (gradients over much shorter distances).

At the city scale, the air temperature and humidity variations are designated by the term Urban Heat Island (UHI). They result from modifications of the energy budget at the soil surface, between the rural area where weather data are monitored, and the urban area. At the district scale, the air temperature and humidity variations are due to very local phenomena, such as air stagnation in shaded areas, or hot air discharge from air conditioning systems.

At the city scale, the variations of the vertical wind velocity profiles are due to a modification of the soil roughness due to the presence of buildings in the city. At the district scale, buildings form obstacles to wind flow. The wind bypasses these obstacles, resulting in a very inhomogeneous distribution of wind speed and direction in the urban canopy. This complex flow affects the

building pressure loads and the external convection heat transfer rate.

At the city scale, the variations of incoming solar and thermal radiation heat transfer rates are negligible. At the district scale, the surfaces located near the building of interest form solar mask. They reduce the building visibility to the sky vault, which modifies its outdoor thermal radiative environment.

Existing models dedicated to urban fabric effect

The models used to simulate the city-scale thermal effects are called urban canopy models (UCMs). Those models simulate the energy budget at the surface of the city. A survey of the existing UCMs was proposed by (Grimmond, 2010). The UCMs can be used online (coupled with a full meso-scale atmospheric simulation tool, which requires a lot of computational resources), or offline (the thermal solicitations of the urbanised surface are directly extracted from a weather data file). The latter option is more computer efficient, but it is less accurate because the temperature evolution of the air located in the urban boundary layer, i.e. above the city, is not modelled. A compromise was developed by (Bueno et al., 2012) who combined an UCM and a simplified thermal model of the urban boundary layer. Their model was implemented in the simulation tool Urban Weather Generator (UWG).

District Scale Models (DSMs) are dedicated to the simulation of district-scale thermal effects. They model the heat transfers in the various forms (solar and thermal radiation, convection, conduction, latent...) in and around groups of buildings. The degree of precision of the DSMs can vary greatly. The models with the highest level of precision (SOLENE-Microclimate (Musy et al., 2015), EnviBatE (Gros et al., 2016), ENVI-Met (Bruse et al., 1998)) generate a 3D mesh in the air volume to estimate explicitly the whole 3D wind velocity and temperature fields; they also generate a fine mesh of the building surfaces to be able to predict accurately the distribution of the radiative heat transfer rates over those surfaces. The intermediated level of precision (SOLENE, City-SIM (Robinson et al., 2009; Frayssinet, 2018) is attained with models which still mesh finely the outdoor building surfaces for radiative heat transfers, but which use a simplified model to predict the air velocity and temperature distributions. Most of the DSMs require either high computer resources to perform long term simulations, or a strong expertise to establish the district thermal models, or both. Moreover, the building thermal models they contain are limited, in terms of functionalities, compared to the thermal models implemented in the popular building simulation software (especially concerning the windows shading options). DSMs must then be coupled to building simulation software to provide relevant simulation results (Lauzet et al., 2019). The coupling between a DSMs and a building simulation software requires a high expertise. It could be a great value to avoid this kind of model and use a simpler tool, more computer efficient and still precise inside

building in order to perform long term simulations (a summer period for example).

The wind distribution at district scale (without buoyancy effect) can be estimated separately using any computational fluid mechanics (CFD) software. Due to the Reynolds invariance (Van Hooff, 2010), only a limited number of simulations are needed to cover all the possible incoming wind speed and direction values. Those simulations are then performed as pre-processing simulations. The establishment of the CFD model might need some expertise if it is built with a general-purpose CFD software. However, dedicated tools such as UrbaWind (Fahssis et al., 2010) were recently developed to ease the model settings.

Description of the tool chain

The proposed model is an assembly of models contained in three simulation tools. The resulting chain tool is represented in Figure 1.

The software EnergyPlus is used to simulate the thermal behaviour of the building of interest. To model the natural ventilation effects, this tool uses an Air Flow Network (AFN), which has been successfully compared to experimental data by Gu, (2007). EnergyPlus also models the effect of close and distant solar masks on the building external solar radiation loads.

The urban heat island is modelled with Urban Weather Generator (UWG). UWG modifies air temperature and humidity values from the rural weather file to produce an urban weather file. UWG requires an extensive set of informations about the city morphology, and the thermal characteristics of the building population within the city to predict accurately the amplitude of the urban heat island effects.

The software UrbaWind is used to determine the pressure coefficients near the building openings. UrbaWind models require a geometrical representation of the urban morphology around the building of interest. Simulations are performed for wind directions varying between 0 and 360 degrees with an increment of 45°. The predicted pressure coefficients are then introduced in the EnergyPlus building model through the interface DesignBuilder.

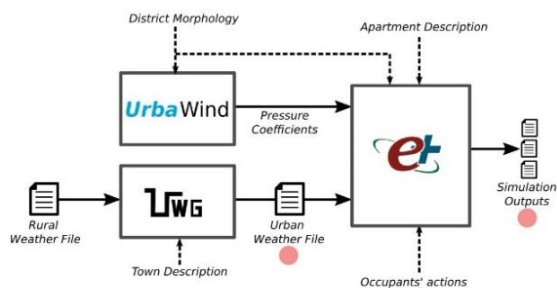


Figure 1: Simulation tool chain (Blue dot represent the measured simulation input data, red dot represents the measurement that are used to test the accuracy of the simulation tool chain)

The proposed simulation tool is then a tool chain composed of 3 robust and validated simulation tools. The coupling between the different tools is only a one-way coupling which does not require computational expertise. It takes into account the major urban effects on the outdoor thermal parameters which predominantly affect the building behaviour in summer conditions: the solar shadings at various distance from the building facade, the city-scale variation of the air-temperature (UHI), the city-scale variation of the velocity profile, and the district scale distribution of the wind velocity and its impact on the pressure coefficients.

The main limitations of the proposed simulation tool are the absence of specific models to evaluate the air and surface temperature inhomogeneities in the urban canopy. To overcome this limitation, a DSMs would be needed which would result in a gap in term of complexity of for the model implementation and in calculation speed.

Measurement Campaign

The simulation tool chain was designed to estimate the indoor thermal conditions in urban buildings under summer meteorological conditions. This simulation tool chain needs to be confronted to measurements values in order to assess the accuracy of its predictions. For this reason, an in-situ measurement campaign was conducted in Lyon during the summer of 2020. This campaign is detailed in this section.

Case studies

In order to cover the diversity of urban fabrics and building designs found in typical French cities, buildings from different construction periods were selected as case studies. Here are presented the measurements results for two apartments included in buildings which correspond to the following construction periods:

- the Industrial period; building from the late 19th century, early 20th century.
- The contemporary period; building which are subject to the last thermal regulation in France (RT2012).

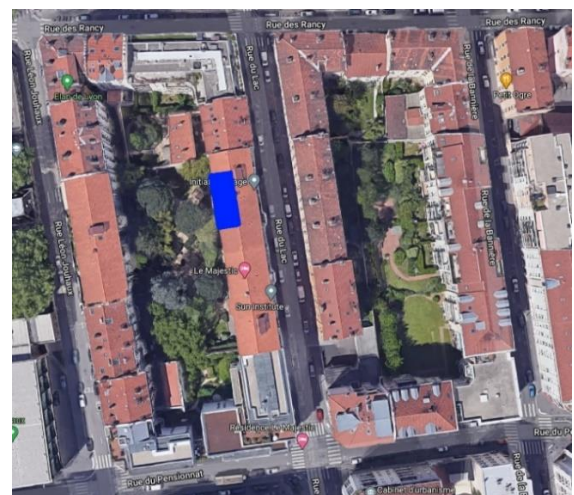


Figure 2: Urban fabric of the industrial period (The blue rectangle corresponds to the studied apartment)

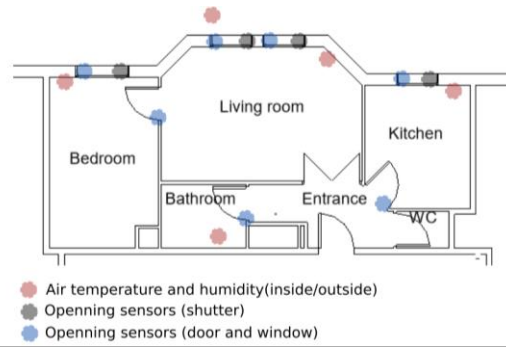


Figure 3: Industrial apartment plan and sensors location

Industrial building apartment

This building is located in the 3rd arrondissement of Lyon. In this district, the buildings arrangement forms closed blocks, as it is shown in the Figure 2.

The walls of the industrial building are made of concrete, with a thermal insulation on the inside face. The studied apartment is a west facing mono-oriented apartment (in blue in the figure 2). It is facing toward the core volume of the block. It is located on the 6th floor out of 7. Its plan is given in the figure 3.

Contemporary building

This building is located in the 9th arrondissement of Lyon. Here the urban fabric is composed of detached collective buildings (Figure 4). It is less dense than the previous case study, which might result in a higher exposition of the building to solar radiations and wind loads.

The building walls are also made of concrete but there is a higher thermal insulation here. The studied apartment is located on the top floor of the building. It is a crossing apartment (in blue in the figure 4). Its main orientations are North and South. The plan of the contemporary apartment is shown in the figure 5.

Input data for the simulation

The district morphology was extracted from Google Earth which provides 3D representations of urban areas all over the world. The apartment shapes and dimensions were measured in-situ, drawn on the software Revit, and exported to DesignBuilder to build the EnergyPlus models. The wall compositions of the contemporary apartment were directly given extracted from architects plans. The wall compositions of the industrial apartments were deduced from the building wall composition database Tabula (Rochard, 2015). The rural weather file is provided by Météo France from data measured in the weather station of Lyon-Bron.

For each test case, the UWG model was parametrized with urban data collected over a 300m square area around the building.

In-situ measurements

The in-situ measurement setup followed two purposes. The first purpose was to monitor the type 1 occupant actions in order to properly parametrize those actions in EnergyPlus (those measurements are identified with a blue dot in the figure 1). The second purpose was to measure some output and intermediate quantities

predicted by the simulation chain-tool to evaluate their accuracy (identified with red dot in the figure 1). The resulting sensor locations are given in the figures 3 and 5.

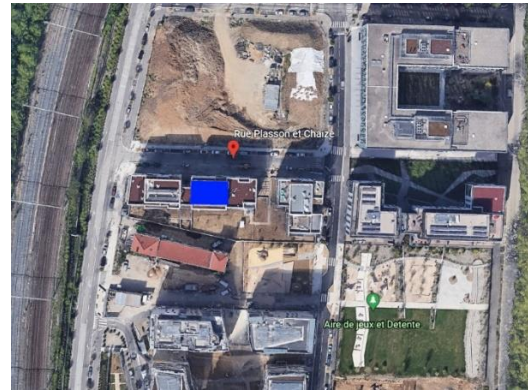


Figure 4: Urban fabric of the contemporary period (The blue rectangle corresponds to the studied apartment)

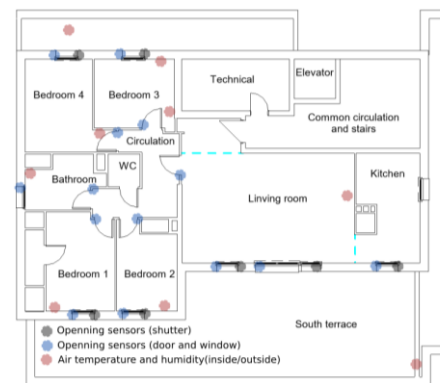


Figure 5: Contemporary flat plan and sensors location

The occupants' actions on the opening (shutters, doors and windows) is measured with binary contact sensors. Each window is equipped with one contact sensor for the window's opening, and one contact sensor for the blinds. Each door is equipped with one contact sensor. Additionally, an interview was done with one occupant of each apartment at the end of the measurement period, in order to reconstitute the occupant's presence schedule, and to substitute the sensor measurement data in case of measurement failure.

The outdoor air temperature is monitored to determine the relevance of the Urban Heat Island predictions. Each apartment is equipped with one or two shaded outside air temperature and humidity sensors (1 for the mono-oriented apartment and 1 on each side of the crossing one).

Then to assess the accuracy of the building model predictions, simulation output quantities are measured (Piselli et Pisello, 2019; Rodler et al., 2018): the indoor air temperatures and humidity in different living rooms (red dots in figures 3 and 5).

The models and the accuracy of sensors are listed in the table 1. All sensors communicate with a gateway using the protocol ENOCEAN. This gateway transfers the data to an online server using a 4G key.

Table 1: type of sensors

Measured variable	Sensor	Accuracy
Internal temperature and humidity	Nodon	$\pm 0.16^{\circ}\text{C}$
External temperature and humidity	FAFT60 from Eltako eelectronics	$\pm 0.3^{\circ}\text{C}$ $\pm 5\%$
Manipulation of doors and windows	Nodon	-
Manipulation of shutters	TRIO2SYS from O2LINE	-

The measurements were performed during summer 2020. It began on the 3rd of July 2020, and ended during October 2020. During this summer season, outdoor air temperature over 35°C were measured at the rural station.

Simulation Results

Accuracy of UWG predictions

Figures 6 and 7 show outdoor air temperature values from the UWG predictions (orange line), from the in-situ outdoor measurements (blue line), and from the rural weather (green line), for both test cases. The figure 6 shows the outdoor air temperature values over the whole measurement campaign. For the industrial building, there was a failure with the outdoor air temperature sensor from the 22nd of August. Figure 7 focuses on the period between the 8th of august and the 22nd of August.

The comparison between the outdoor air temperatures measured in the rural area (green) and in the urban area (blue) reveals the evolution of the UHI effects. The temperatures are similar during the day. The UHI mostly takes place during the night with higher outdoor air temperatures in the urban area. During the night, the amplitude of the UHI varies between 0°C (around August 20th) and 5°C. The UHI amplitude is slightly higher at the location of the industrial building (bottom curve) than at the location of the contemporary building.

For the industrial building (bottom curves), the measured temperatures show some peak during the daytimes: those peaks are due to direct solar radiation which heats up the thermal shield of the sensor. Unfortunately, a portion of this heat reaches the temperature sensor. The temperature peaks during daytimes were not observed by the outdoor sensor of the contemporary building, because this sensor was located in a shaded area.

UWG clearly overestimates the UHI effects during the night by predicting higher outdoor temperature values. Indeed, night time UWG temperature predictions (orange) are sometimes fairly higher than the outdoor measured temperatures (blue). Some investigations are still ongoing to identify the origin of those overestimations. However, some aspects of the UWG predictions are encouraging. UWG predicts no UHI during the day, which corresponds to the measurement observations. Also, UWG predictions follow quite well the evolution of the UHI amplitude among the nights: during the nights where no UHI was observed, UWG predicts a little UHI, and during the nights when a substantial UHI was detected, UWG predicts a high UHI amplitude.

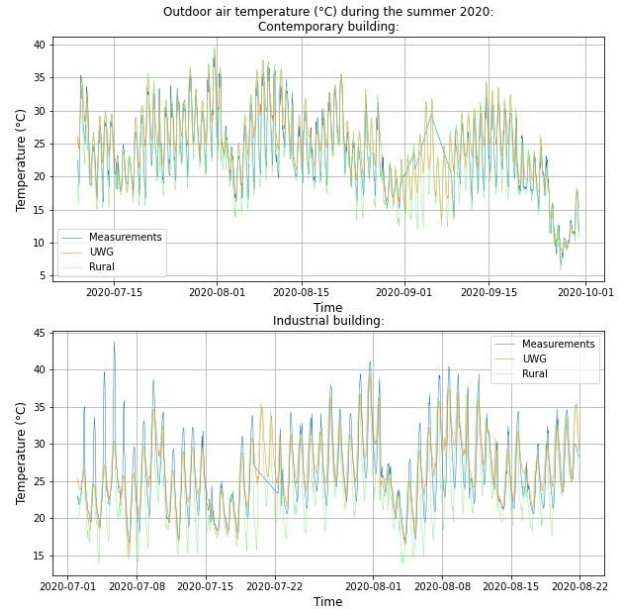


Figure 6: Outdoor air temperature for UWG (orange), measurements (blue) and the rural weather file (green) for both case study from July to September.

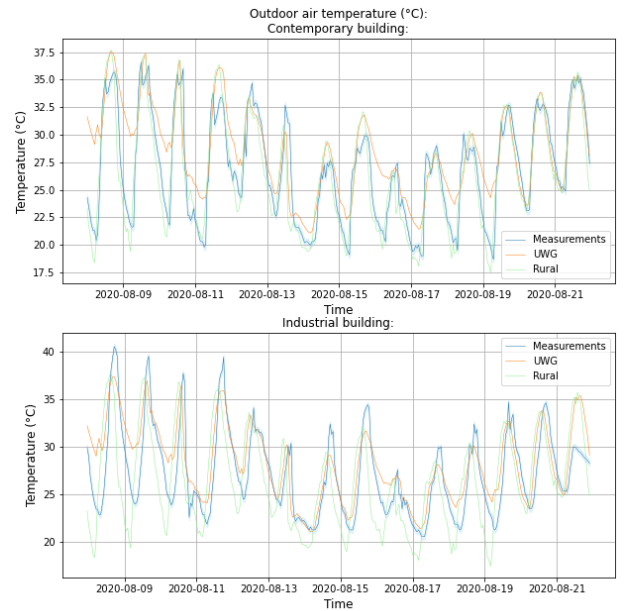


Figure 7: Zoom on the outdoor air temperature for UWG (orange), measurements (blue) and the rural weather file (green) for both case study from the 8th to the 22nd of August.

Figure 8 shows the cumulated distribution of the absolute error between the UWG predictions and the measured outdoor air temperatures. 75% of the error are below 3°C for both test cases. For the contemporary apartment, the mean error between UWG and the measured outside air temperature is 2,2°C and the RMSE is 2,9°C. For the industrial apartment, the mean error between UWG and the measured outside air temperature is 1,9°C and the RMSE is 2,6°C.

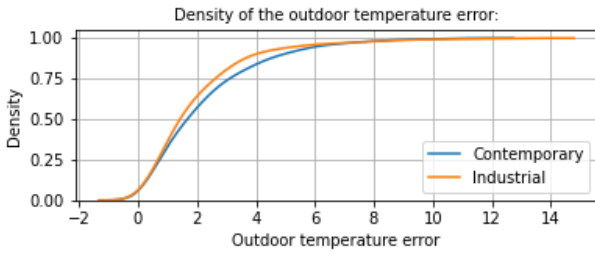


Figure 8: Density of the outside temperature error between the UWG weather file and the measured air temperature.

Accuracy of indoor ambience evaluations

The evolutions of the air temperature in the living room of both case studies are shown in the figures 9 and 10. The data of the figure 9 are for the whole measurement campaign. The figure 10 focuses on the period between the 2nd to the 16th of September. The measurements are drawn in orange, and the simulation predictions in blue. The outdoor air temperature of UWG are reminded in green lines.

Figure 9 shows that the trends of the indoor temperature evolutions are well reproduced by the simulations. The daily averaged simulated temperatures follow closely the daily average measured temperatures for both test cases, and during the whole measurement campaign. The curves do reveal any bias in the simulated temperature. This observation is particularly important because it means that the energy budget involving all kinds of thermal solicitations of the apartments (solar radiation, outdoor air temperature, outdoor thermal radiation, indoor loads) is well reproduced on a daily average basis by the simulation tool.

For the contemporary building (top curves of figures 9 and 10), the simulation seems to slightly overestimate the daily amplitude of the indoor temperature. This could be interpreted as an overestimation of the natural ventilation effects, which reduces significantly the indoor temperature during the night. During this period, the windows were opened but the shutters were partially closed, which might have reduced significantly the ventilation air flow. The parametrization of EnergyPlus is particularly delicate for this opening configuration.

For the industrial apartment, there is no overestimation of the daily temperature fluctuations: the amplitude of the simulated temperature is in great concordance with the measurements.

Figure 11 shows the cumulative distribution of the error between the simulation and the measured living room air temperature. In blue for the contemporary building and in orange for the industrial one. 80% of the errors are below 1,5°C for both. For the contemporary case study, the mean error between the simulation and the measured living room air temperature is 0,95°C and the RMSE is 1,3°. For the industrial case study, the mean error between UWG and the measured outside air temperature is 0,82°C and the RMSE is 0,99°C.

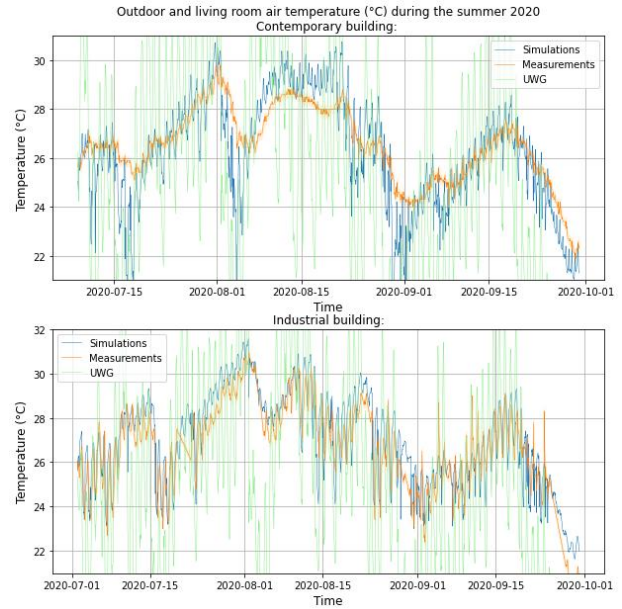


Figure 9: Simulated (blue), measured (orange) air temperature in the living room and outside air temperature (green) from July to September

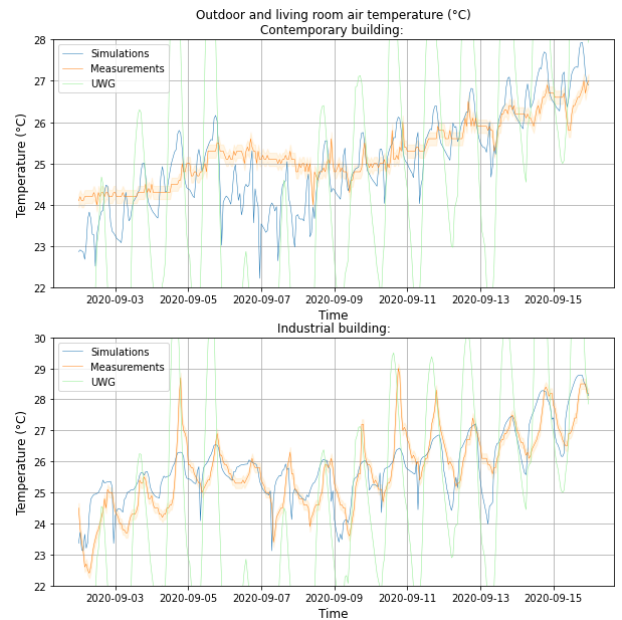


Figure 10: Zoom on the living room air temperature simulated (blue), measured (orange) and the outside temperature (green) from the 2nd to the 16th of September

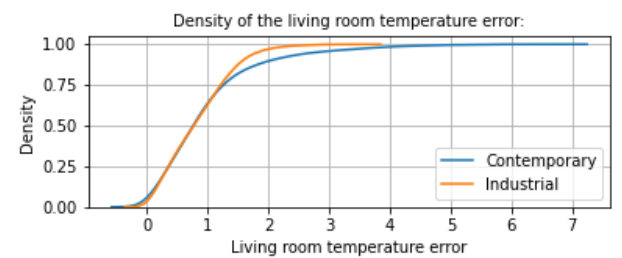


Figure 11: Density of the living room temperature error between the simulation and the measurement.

The figure 12 and 13 show the evolution of the air relative humidity in the living room of both apartments. The

measurements are drawn in orange, and the simulation predictions in blue.

For both buildings, the simulated inside air relative humidity follows quite well the measurements. There isn't a presence of an offset and the daily variation of the simulation and the measurement are quite similar.

Figure 14 shows the cumulated distribution of error between the simulated and the measured living room air relative humidity. 80% of the errors are below 5% for the industrial building and below 7% for the contemporary one. For the contemporary case study, the mean error between the simulation and the measured living room air relative humidity is 4,3% and the RMSE is 5,6. For the industrial case study, the mean error between UWG and the measured outside air relative humidity is 3,1% and the RMSE is 4,1.

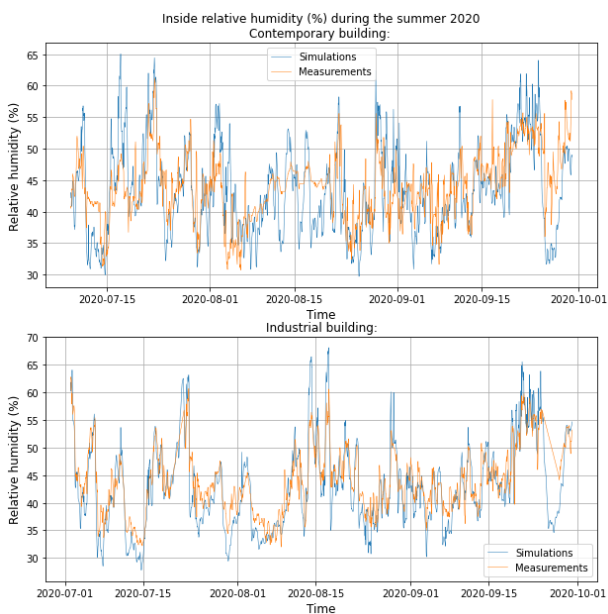


Figure 12: Simulated (blue), measured (orange) air relative humidity in the living room from July to September

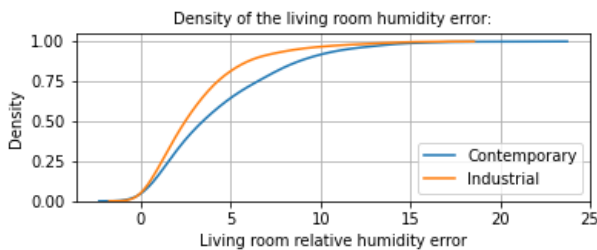


Figure 14: Density of the living room relative humidity error between the simulation and the measurement.

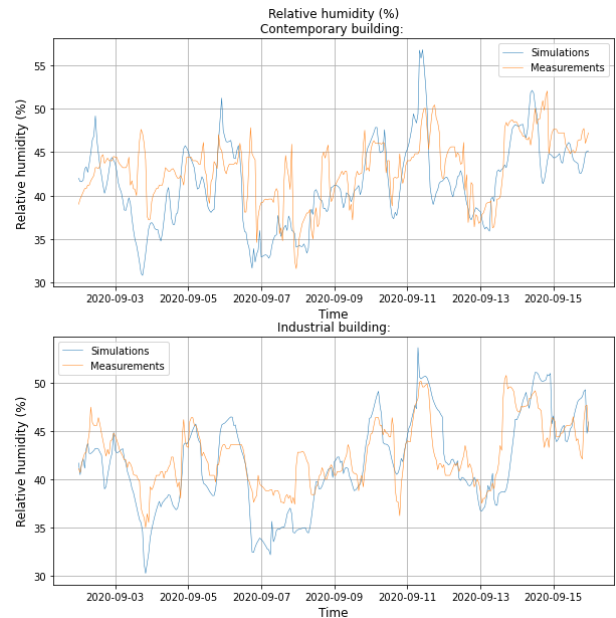


Figure 13: Zoom on the living room air relative humidity simulated (blue), measured (orange) from the 2nd to the 16th of September

Conclusion

A simulation chain of tools was presented in this paper. It is a simple chain of tools that do not use dynamical coupling, and is computer efficient. Indeed, it is fast and perform long term simulations. It takes into account the major urban effects on the outdoor thermal parameters which predominantly affect the building behaviour in summer conditions. The main limitations of the proposed simulation tool are the absence of specific models to evaluate district scale distribution of outdoor air and surface temperatures. To overcome this limitation, a DSMs would be needed which would result in a gap in term of complexity for the model implementation.

A campaign of in-situ measurements was conducted in Lyon during summer 2020 in order to confront the simulation tool chain with measurement.

The accuracy of the tool UWG, which use a rural weather file and a description of the Town to calculate an urban weather file is quite good. Indeed, UWG detects well when there is and isn't an effect of the UHI but it overestimate its effect.

The accuracy of the indoor ambiance is really good. For both case studies, the simulated air temperature and humidity follow the measurements. The daily variation is also quite well simulated.

This simulation chain of tools is able to determine the indoor ambiance of a building during summer and heat waves conditions. Air temperature and humidity are decisive parameters for the assessment of thermal comfort. With this simulation tool chain, it is possible to evaluate the comfort inside buildings during heat waves and summer conditions.

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