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SIMULATING THE EFFECT OF URBAN MORPHOLOGY ON INDOOR THERMAL BEHAVIOR: AN ITALIAN CASE STUDY

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ABSTRACT

The significant energy consumption imputable to buildings and the increasing concentration of buildings' in urban areas has encouraged researchers to develop rigorous procedures to predict building thermal-energy behavior in real urban contexts. The purpose of this paper is to employ the Inter-Building Effect methodology to examine variances in the year round thermal performance of Italian residential buildings located in three distinct urban contexts. To this aim, three existing residential buildings were modeled. Their energy performance was simulated in stand-alone configuration and in urban context to examine the impact of close spatial relationships among buildings in neighborhoods of varying density. The results confirm previous findings that buildings mutually impact the thermal performance of close buildings, and further demonstrate that this impact is correlated to urban density.

1 INTRODUCTION

The investigation of new solutions for buildings' energy efficiency optimization represents a key goal of sustainability research, given the large amount—approximately 36%—of energy consumption attributable to buildings, U.S Green Building Council (2011). Additionally, in urban centers all over the world, large shifts in population from rural areas to urban areas is occurring, United Nations (2007). In order to investigate and to propose innovative solutions for energy saving of the burgeoning urban building context, more sophisticated tools are being developed. The majority of these tools consist of dynamic simulation models which are able to predict the thermal-energy behavior of thermal zones with a small margin of error, such as in Neymark et al. (2002) and in Pisello, Goretti, and Cotana (2012).

At the same time, the common approach of the majority of these simulation efforts consists of considering each building as a stand-alone entity, without any neighborhood contextualization. Moreover, important contributions have been elaborated in order to demonstrate the large impact of the local environment in determining building thermal-energy performance, such as in He, Hoyano, and Asawa (2009) and for what concerns mutual shading among close buildings and its effect on solar radiation gains and the relative air-conditioning consumption, like in Capeluto and Shaviv (2001). The concept of evaluating building energy performance with respect to strategic urban morphology parameters has also considered the impact on lighting analyses, such as Stromann-Andersen and Sattrup (2011).

Other research efforts, e.g. in Pisello, Bobker, and Cotana (2012) have focused on the issue of density in housing from a building occupant's point of view, i.e. taking into account the influence of peer networks on energy conservation in residential neighborhoods such as in Xu, Pisello, and Taylor (2011), Xu et al. (2012), Xu, Taylor, and Pisello (2013) and Chen, Jain, and Taylor (2013). In particular, Xu et al. (2012) integrated models for simulating buildings and human networks in neighborhoods where occupants socially interact at different levels of closeness or friendship. Chen and Taylor (2013) identified a relationship between geospatial location of occupants and peer networks on energy conservation.

Recently research has focused on quantifying the impact of the presence of close buildings on the energy performance of control buildings through the Inter-Building Effect, a theory proposed by Pisello et al. (2012). In that contribution, the Inter-Building Effect is calculated as the difference in terms of building energy requirement for heating and cooling between each building when it is modeled as a stand-alone entity, as opposed to taking into account the realistic urban or sub-urban environment impacting its thermal-energy behavior. Simulation findings showed that the indoor thermal environment of the building considered in its real surrounding exhibited non-negligible difference with respect to the same building modeled in a stand-alone configuration. Additionally, these findings showed an interesting relationship with the climatological conditions that could cause temperature variances between 9°C and 13°C. The effect is quantified through the IBE (Inter-Building Effect) index, aimed at determining the same inaccuracy in terms of primary energy for heating and cooling. The findings of this study showed that these inaccuracies could be higher than 30% for the investigated locations in the US.

Given the Inter-Building Effect important implications for urban design, building and environment energy assessment methods, such as Scherba et al. (2011), Ascione et al. (2010), Pisello et al. (2013), our research objective consists of the evaluation of the inter-building effects in terms of indoor operative temperature profiles of three strategic urban configurations in a typical Italian city. In particular, existing representative residential buildings are modeled through EnergyPlus, a dynamic simulation tool, in their real surrounding contexts: (i) the historical center of the city, (ii) the newer urban environment, and (iii) the garden suburb of the city. The research objective of this paper is to investigate the impact of surrounding buildings with increasing urban density levels, defined through synthetic indexes, and to interpret the IBE results with respect to the urban morphology characterization.

2 METHODOLOGY

In order to evaluate the buildings' mutual impact in terms of thermal performance, three residential urban and sub-urban neighborhoods were chosen for characterizing the Inter-Building context in Italian cities. A city in central Italy, Perugia, was chosen, in order to identify the peculiar urban Italian morphology (Figure 1). The procedure consists of a preliminary urban assessment followed by a technical and architectural analysis of the building features specifically concerning Italian construction typicality, ENEA (2005). The collected data represent the input parameters used for elaborating the dynamic simulation models by EnergyPlus, U.S. Department of Energy (2013). The three considered neighborhoods, which represent the case studies of this work, were simulated to investigate their year-round performance. One residential building within each neighborhood was chosen in order to quantify the Inter-Building Effects in terms of indoor monthly operative temperature. The Inter-Building Effect calculation was carried out through the comparison between the free-floating conditions of the control-building modeled in stand-alone configuration with respect to the same control-building modeled into its real urban surrounding, following the calculation procedures defined in Pisello et al. (2012). Additionally, the proposed methodology was applied to define the daily operative temperature profiles in severe summer and winter conditions, in order to quantify the impact of surrounding buildings on the indoor thermal-comfort conditions in several urban contexts. The analysis of the results reported in this paper allowed the identification of the Inter-Building Effect in different Italian urban contexts characterized by different typical urban density levels. It also demonstrates that, particularly in historical centers, the inter-building effects may lead to inaccuracies in determining indoor operative temperature through dynamic simulation.

3 DESCRIPTION OF THE CASE STUDY

3.1 Urban Layout Characterization

With the final purpose of quantifying the Inter-Building Effect of real residential buildings in three urban contexts characterized by different density levels, three EnergyPlus models were developed. As previously mentioned, three characteristic areas were chosen to investigate: (i) a very dense urban environment, (ii) a dense urban environment, and (iii) a non-dense urban environment (Figure 1). The first context is located in the historical center of Perugia, a medium-size city in central Italy with ancient Etruscan origins and a city center characterized by Middle Ages layout (Figure 2). The residential building is a XVI century building with four floors. The technical features of this building are reported in the following section of this paper. The second context is located at the close periphery of the city, where many residential buildings were built around 1960-1970, before the enforcement of the first Italian building energy efficiency regulation (Asdrubali et al. 2008) (Figure 3). The third context is located in a garden suburb of the same city, along the west side of the center, in the direction of the main urban expansion of the considered city (Figure 4). The choice of these three areas was guided by both urban and technical-architectural reasons. The analysis of the urban layout of the city and urban density measurement was carried out in terms of h/d ratio, which is a commonly used urban morphology parameter calculated as the ratio between the building height and the frontal distance between two facing buildings, such as in Kruger, Pearlmutter and Rasia (2010); Johansson (2006). In particular, the three h/d ratios present a mutual relationship as determined in Equation (1):

$$\frac{\left.\frac{h}{d}\right|_{i}}{\left.\frac{h}{d}\right|_{ii}} \approx \frac{\left.\frac{h}{d}\right|_{ii}}{\left.\frac{h}{d}\right|_{iii}} \approx 2.5 \qquad (1)$$

where the case “i” represents the very dense urban area, the case “ii” the medium density area, and the case “iii” describes the non-dense area. The linear growth of h/d ratio was chosen in order to investigate the thermal IBE extent with increasing urban concentration described by h/d parameter.

Figure 1: Aerial view of Perugia, Italy area and its urban morphology.

The choice of the case study was also guided by the purpose to characterize both the winter and summer impact of Inter-Building Effects. To this aim, a temperate climate location with severe winter but also hot summer climatological conditions was chosen. The main location and climate features of Perugia, Italy are reported in Table 1.

Figure 2: Aerial view of the very dense urban area ("i" case study).

Figure 3: Aerial view of the dense urban area ("ii" case study).

Figure 4: Aerial view of the non-dense urban area ("iii" case study).

3.2 Characterization of the Case Study Buildings

As previously mentioned, particular attention was paid to select representative buildings in terms of architectural typology, envelope materials, and thermal energy performance. To this aim, three residential buildings constructed before the enforcement of any Italian building energy efficiency regulation in 1976 were chosen, which similar traditional envelope materials, Pisello et al. (2013). Consequently, there are a few differences between the three typologies of opaque envelope and the findings of the thermal performance assessment can be attributed to the Inter-Building phenomenon more immediately. Additionally, the majority of Italian residential buildings is made of non-insulated envelopes, that makes this study more representative of the built Italian panorama.

The detailed characteristics of each envelope system are reported in Tables 2-4. The same data were used in the dynamic simulation models of the case studies.

Table 1: Main positioning and climatological characteristics of the case study.

Longitude	12°23'1"68 E
Latitude	43°5'51"72 N
Height above sea level	493 m (average value)
Heating season	October 15th – April 15th
Cooling season	-

4 NUMERICAL ANALYSIS

4.1 Elaboration of the Models and Dynamic Simulation

To quantify the Inter-Building Effect, three models of three real Italian urban blocks were developed within the EnergyPlus modeling environment. Three additional models were also developed only considering each control-building as a stand-alone entity, in order to compare the realistic scenario with the single-building configuration. All these models were elaborated by setting all the data concerning the opaque envelope properties as reported in Tables 2-4. Additionally, the characteristics of the window systems, which are the same for the three considered buildings, are reported in Table 5.

Given that the inter-building analysis focused on the indoor thermal performance assessment, the specific technologies for heating and cooling were not considered and the buildings were modeled and simulated in free-floating conditions, in order to avoid possible discrepancies due to different performance levels for the three case studies. The occupancy of the base case model (before the calibration procedure) was characterized by a 0.0169 people/m^2 which metabolism is 0.9 met each. Generic internal gains due to equipment such as computers, television, other technologies correspond to 3.07 W/m^2, with 0.2 value of radiant fraction. The domestic hot water production is described through an overall value of 0.53 l/m^{2}day. The lighting system produce an overall internal gain of 5W/m^{2}100lux, taking into account the low performance level of common lighting system in old residential buildings in Italy. The luminaires are of suspended type, which radiant fraction corresponds to 0.42. No task lights were modeled, in order to avoid singularities in energy behavior interpretation.

4.2 Calibration and Validation of the Models

The three case study models are elaborated by analyzing: (i) the architecture of each building, (ii) the envelope materials, (iii) the thermal-energy technologies, (iv) the indoor thermal behavior and the electricity consumption, where possible. In particular, the in-field collected data were useful in order to describe the geometry of each building and to calibrate and validate the dynamic simulation models, in order to achieve reliable evaluation about the indoor thermal behavior affected by the IBE.

The calibration and validation procedure was carried out by following Ashrae (2002), coherently with DOE (2008). All the criteria expressed in these three reference documents consist of the integrated analysis of the mean bias error (MBE) and of the coefficient of variation of the roof mean squared error (CV_{RMSE}), to quantify the quality of the model prediction in terms of energy use and indoor thermal behavior. The occupancy of each accessible residential unit was analyzed and the choice of the calibration parameter was therefore carried out. The "i" case study was constituted by 4 residential units, and the accessible apartment was not continuously occupied, thus the year-round energy bills were not representative of the building energy performance. Therefore an indoor thermal monitoring setup was installed in two thermal zones of the apartment, in order to collect the air temperature measurements every 10 minutes from April 21st, 2013 to June 18th, 2013. The "ii" and the "iii" case studies were continuously occupied by families, and the electricity and natural gas bills were collected for one whole year, from June 2010 for "iii" case study, and from January 2012 for "ii" case study.

The iterative calibration method was applied by fitting the occupancy schedules with the real investigated occupants' attitudes, with the final purpose to obtain MBE and CV_{RMSE} values lower than ±5%, as the most restrictive condition to be satisfied following the guidelines.

For the validation process, the simulations were run by taking into account real weather boundary conditions (weather file .epw) continuously monitored during the study period in two weather stations located in the close proximity of the three case studies, managed by University of Perugia, Italy. Thus the values of global solar radiation, direct solar radiation, outdoor dry bulb temperature, relative humidity, wind main direction and velocity were collected every 10 minutes in order to elaborate the hourly weather files of the two locations from June 2010 to June 2013.

4.3 Dynamic Simulation

The dynamic simulations were run for all the six models, consisting of the three case studies with and without the built environment characterization, in order to describe the hourly indoor thermal behavior of each building. The weather file selected for simulating this thermal behavior corresponds to the weather file of the city center. This weather station is not far from the three buildings considered in the case study. The hourly data represent the Typical Meteorological Year selected in Europe WMO Region 6: Italy database and corresponding to the Perugia 161810 (IGDG) weather station, U.S. Department of Energy (2013a). Additionally, the choice of the same weather file for running the simulations of all the buildings was guided by the purpose to avoid further differences in computing, not attributable to the inter-building phenomenon. The simulations were run for the overall July and January period, in order to evaluate the IBE in the hottest-sunniest summer period and the coldest winter conditions in Perugia, Italy. The time step was setup at 10 minutes and the overall hourly average values were evaluated in the post-process.

5 DISCUSSION OF RESULTS

The indoor thermal behavior of the three case study buildings was analyzed in both stand-alone and inter-building configuration. Figures 5-7 represent the hourly operative indoor trend during summer and winter conditions of three days in July and January respectively. Large differences between the two considered scenarios were found, demonstrating the important Inter-Building Effect and the urban characterization roles in determining the realistic indoor thermal profile and, therefore, thermal comfort conditions. In the non-dense area, on the contrary, the same results report a negligible average IBE in both winter and summer. A further interesting development of this research for non-dense greener areas could deal with the effect of surrounding vegetation on the thermal-energy performance of buildings, in particular in garden suburbs. In fact, in very dense vegetation areas, even larger effect with respect to the one produced by surrounding buildings in urban areas, i.e. IBE, could be produced by high trees and other plants impacting the thermal-energy behavior of close building, in particular for what concerns the effect of solar gains through the windows and daylight availability.

In the very dense urban area, the maximum difference is registered in July, and it corresponds to 3.5°C, while the average difference of the analyzed days is 2.0°C. In both the cases, the building modeled within its surrounding is colder than the same building simulated as stand-alone, given the mutual shading effect of close buildings. The same IBE in winter is much lower, given (i) the lower impact of mutual shading, (ii) the lower solar radiation intensity in that period, and (iii) the small windows' surface with respect to the opaque surface of the envelope of the considered building. In fact the IBE produces an average temperature variation of 0.3°C, and a maximum impact of 0.5°C. Coherently with the previous results, in the dense-urban area (second case study) the average difference in terms of operative indoor temperature of the building is 0.6°C in summer days and 0.3°C in winter days, and the peak values are

0.7°C and 0.2°C in summer and winter respectively. In the non-dense area, the IBE analysis shows negligible differences between the stand-alone and the network configuration.

Table 2: Envelope characterization of case study (i): the residential building in very-dense urban context.

i. Very dense urban context building		
Opaque wall		
1. Outer layer Medium weight masonry	Thickness: 0.20 m Conductivity: 0.42 W/mK Specific Heat: 840 J/kgK Density: 1250 kg/m3	Properties (EN ISO 2007) Transmittance: 0.949 W/m2K Internal heat capacity: 104.00 kJ/m2K
2. Medium weight masonry	Thickness: 0.15 m Conductivity: 0.42 W/mK Specific Heat: 840 J/kgK Density: 1250 kg/m3	
3. Inner layer Gipsum plastering	Thickness: 0.02 m Conductivity: 0.40 W/mK Specific Heat: 1000 J/kgK Density: 1000 kg/m3	

Table 3: Envelope characterization of case study (ii): the residential building in dense urban context.

ii. Dense urban context building		
Opaque wall		
1. Outer layer Cement plaster	Thickness: 0.02 m Conductivity: 0.720 W/mK Specific Heat: 840 J/kgK Density: 1760 kg/m^3	Properties (EN ISO 2007) Transmittance: 1.202 W/m^2K Internal heat capacity: 152.088 kJ/m^2K
2. Brick	Thickness: 0.18 m Conductivity: 0.720 W/mK Specific Heat: 840 J/kgK Density: 1920 kg/m^3	
3. Air gap	Thickness: 0.05	
4. Brick	Thickness: 0.12 m Conductivity: 0.720 W/mK Specific Heat: 840 J/kgK Density: 1920 kg/m^3	
5. Innermost layer Gypsum plastering	Thickness: 0.15 m Conductivity: 0.4 W/mK Specific Heat: 1000 J/kgK Density: 1000 kg/m^3	

This same phenomenon is coherently visible through the analysis of the monthly average temperatures (Figures 8-10). In particular, the largest IBE was found in terms of mean radiant temperature, given that the main IBE contribution consists of the mutual shading among buildings and the relative radiant fraction modification. This monthly mean radiant temperature difference corresponds to 3.2°C in the very dense urban context in July, and 0.7°C in the dense urban context in the same month. The same difference in terms of air temperature is 2.8°C in the very dense urban area and it is 0.6°C in the dense urban area. The analysis concerning the non-dense urban context shows that the IBE is negligible in terms of monthly average temperature, in fact the maximum effect is represented by the mean radiant temperature in July.

This difference between the stand-alone and the inter-building configuration corresponds to 0.04°C. The inaccuracy in determining the monthly indoor operative temperature, which mainly affects the indoor thermal comfort perception and energy consumption for heating and cooling, as performed in Pisello, Goretti and Cotana (2012), corresponds to 3.0°C and 0.7°C in summer and to 2.4°C and 0.5°C in winter, for the "i" and the "ii" case respectively. Negligible effecte were calculated for considering inter-building effects in the "iii" case. An evident correlation between the inaccuracy in predicting the indoor thermal behavior of the case study buildings and the urban density characterization was found, demonstrating that the extent of such an inter-building phenomenon could be related to h/d values, in order to analyze buildings' thermal behavior in different urban contexts. In particular, the linear growth of h/d parameters does not correspond to linear IBE extent growth. The IBE increases by 4.55 and 4.61 times, in summer and winter respectively, between the "i" and the "ii" case study, where the ratio between h/d_i and h/d_{ii} corresponds to 2.5. By comparing the "ii" and the "iii" case studies, the IBE decrease is much higher, showing that the IBE phenomenon is significant in determining building indoor thermal performance if the h/d ratio is lower than about 1.5, which corresponds to an average monthly T_{op} difference of 0.4°C, by assuming the same linear tendency observed between "i" and "ii".

6 CONCLUSIONS

This paper presents the results of an investigation of the impact of varying urban morphologies in a real urban context on the thermal performance of residential buildings. The Inter-Building Effect methodology was applied to three typical residential buildings in Italy, which were modeled and simulated in both the stand-alone configuration and the building-network configuration. The three case studies were represented by three existing buildings located in Perugia, a medium-sized city in central Italy, characterized by temperate climate conditions. The historical center was modeled in order to represent the very-dense urban context; the dense suburban context was modeled to represent an average citywide characterization; and finally a garden suburb of the city was modeled to describe the thermal behavior of a single family house. The choice of these three representative cases was guided by the urban density characterization through the h/d parameter, in order to describe the same urban density variation and finally to compare the results in terms of indoor operative temperature. All the dynamic simulation models were calibrated and validated through experimental monitored data concerning: the indoor air temperature, the electricity consumption, and the weather boundary conditions of the specific area.

The findings demonstrated that the indoor operative temperature of the two first case studies (very-dense urban context and dense urban context) is largely impacted by the presence of close buildings. The highest differences in summer were up to 3.5°C in terms of indoor operative temperature. Negligible effects were found in the non-dense context, where the future development of this study consists of the evaluation of the impact of the surrounding vegetation on the thermal-energy performance of the control building.

These important results have confirmed that the extent of surrounding buildings' effect is not negligible in order to execute rigorous predictions about the indoor thermal behavior, in particular in very-dense urbanized areas, which are typical of all the historical cities in Italy and other countries. The numerical analysis showed that this IBE produces an important effect when the h/d ratio is up to about 1.5. Future development of this research should examine the implications of variances in indoor operative temperature on primary energy requirements for heating and cooling. Additionally, as already mentioned, the effects of the vegetation on the thermal-energy behavior of buildings located in garden suburbs should be examined. Given the Inter-Building Effect observed variance in indoor operative temperature with varying urban morphology and building density, city-scale simulations should be executed to estimate the aggregate error in estimating buildings' neighborhoods and cities' primary energy requirement due to the IBE impact. Tools that explicitly tie buildings geospatially together such as Geographic Information Systems might productively be integrated with EnergyPlus simulations in order to represent the inter-building phenomena with varying urban layout and climate context.

Table 4: Envelope characterization of case study (iii): the residential building in non-dense urban context.

iii. Non-dense urban context building		
Opaque wall		
1. Outer layer Plaster (dense)	Thickness: 0.02 m Conductivity: 0.5 W/mK Specific Heat: 1000 J/kgK Density: 1300 kg/m^3	Properties (EN ISO 2007) Transmittance: 1.186 W/m^{2}K Internal heat capacity: 203.40 kJ/m^{2}K
2. Brickwork	Thickness: 0.12 m Conductivity: 0.620 W/mK Specific Heat: 800 J/kgK Density: 1700 kg/m^3	
3. Air gap	Thickness: 0.025	
4. Concrete block	Thickness: 0.25 m Conductivity: 1.630 W/mK Specific Heat: 1000 J/kgK Density: 2300 kg/m^3	
5. Innermost layer Gypsum plasterboard	Thickness: 0.19 m Conductivity: 0.25 W/mK Specific Heat: 1000 J/kgK Density: 900 kg/m^3	

Table 5: Windows characterization of the three case studies.

Glazing system		
1. Outermost pane Generic clear glass	Thickness: 0.006 m Solar Transmittance: 0.775 W/mK Outside solar reflectance: 0.071 Inside solar reflectance: 0.071	Thermal transmittance: 2.665 W/m^{2}K Total solar transmission (SHGC): 0.703 Direct solar transmission: 0.604 Light transmission: 0.781
2.Window gas type Air	Thickness: 0.013 m Conductivity: 0.42 W/mK Specific Heat: 840 J/kgK Density: 1250 kg/m^3	
3. Innermost pane	See layer 1.	

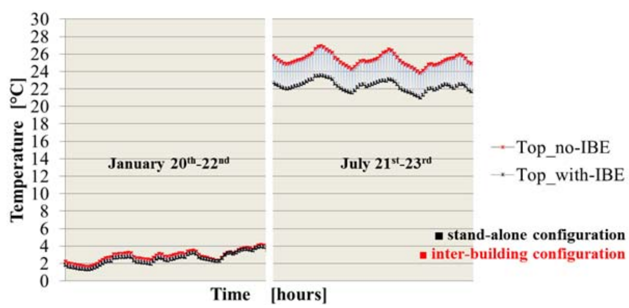

Figure 5: Operative indoor temperature during January and July of the building in very dense context (i).

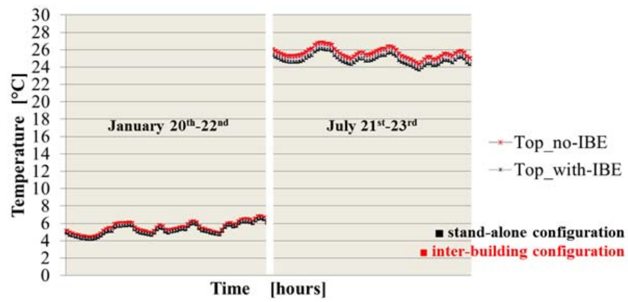

Figure 6: Operative indoor temperature during January and July of the building in dense context (ii).

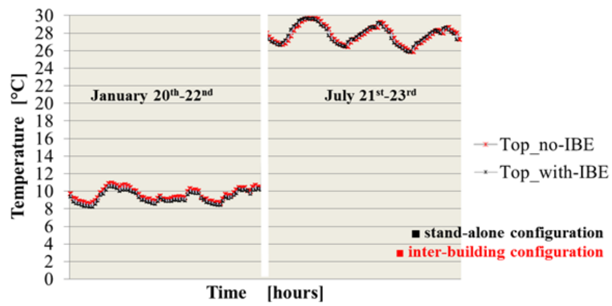

Figure 7: Operative indoor temperature during January and July of the building in non-dense context (iii).

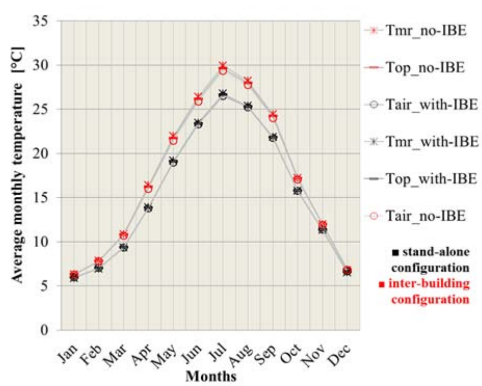

Figure 8: Average monthly temperatures of the building in very dense urban context.

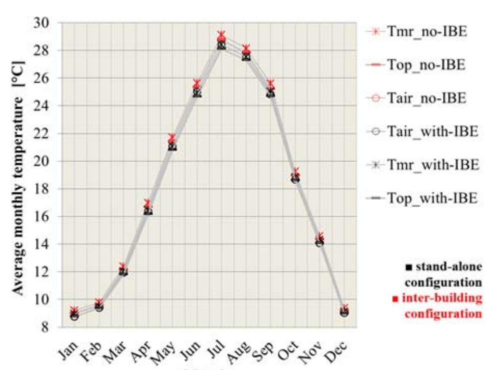

Figure 9: Average monthly temperatures of the building in dense urban context.

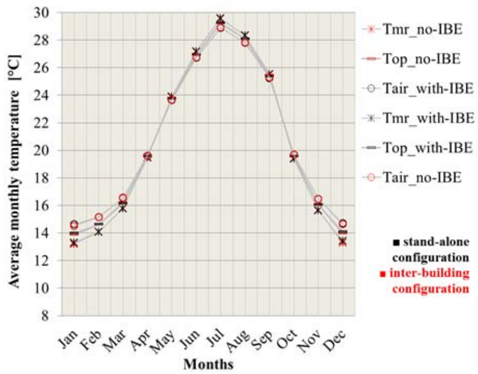

Figure 10: Average monthly temperatures of the building in non-dense urban context.

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