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ENERGY SIMULATION OF PASSIVE DESIGN STRATEGIES APPLIED TO RESIDENTIAL BUILDINGS LOCATED IN SOUTHEAST BRAZILIAN CITIES

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Abstract. *The objective of this paper is to demonstrate the potential of energy consumption reduction in residential buildings located in southeast cities of Brazil through the application of passive design strategies. Taking into account a simple definition, the passive design strategies can be defined as a set of strategies that promotes energy consumption reduction by controlling heat flows through the elements of the building envelope. The study was developed through energy simulation employing the EnergyPlus software, which is specifically designed by the U.S. Department of Energy to model both energy consumption and water usage in buildings. The specification of climate conditions in the EnergyPlus software was stated by declaring a weather data file of Taubate (SP) city. The energy consumption simulations demonstrate that the natural ventilation use, windows glazing systems replacement by models with improved thermal properties, and the painting of external walls with low solar spectrum absorptance paint are some of the passive design strategies that lead to significant energy consumption reduction. The mean results demonstrate that is possible to reduce the building energy consumption in the range of 24% to 33% considering one or two air conditioning appliances per apartment.*
Keywords: *passive design strategies, building energy consumption simulation, EnergyPlus.*

1. INTRODUCTION

Buildings are the biggest primary energy consumer being worldwide responsible for about 40% of the total primary energy consumption and emitting approximately one-third of the total carbon dioxide emissions on a global scale (Wei and Shicong, 2017; Cunha, 2015; Georgiou, 2015). Thus, the buildings represent a key sector to promote energy consumption reduction measures aiming to contribute to the deceleration of global warming.

According to the Intergovernmental Panel on Climate Change (IPCC), for achieving the target of limiting the global warming to below 2 ºC it will be required at least 25% of reduction in the total carbon dioxide emissions in 2030 relatively to the 2010 levels, and net-zero emission around the year 2070. The buildings must reduce their carbon dioxide emissions by approximately 80% until the end of the century to enable achieving the targets of limiting global warming to below 2 ºC (IEA, 2013; Lucon et al., 2014).

One of the solutions appointed in the literature and already applied in many countries of the European Union and also in some countries of the Asia-Pacific Economic Cooperation (APEC) to meet the greenhouse gases emissions reductions targets established by the IPCC is the application of both the net-zero energy and the net zero-emission concept to the context of the building. When applied to buildings, these concepts generate definitions like Zero Energy Building, Net Zero Energy Building, Nearly Zero Energy Building, as well as a set of other definitions. Such definitions vary accordingly region to region, and depend on different understanding and definitions about primary energy, energy sources, energy carriers, verification metrics, and primary energy conversion factors (AlAjmi et al., 2015; Williams et al., 2016; Wei and Shicong, 2017).

Many authors point that a zero energy building can be qualitatively defined as a building with very low energy consumption when compared with a similar conventional building, independently of the definition. In other words, it is a building with high-energy efficiency, in which the energy consumption is met through local or nearby renewable energy generation (Pacheco and Lamberts, 2013; AlAjmi et al., 2015; Wei and Shicong, 2017; Cunha, 2015; Paoletti et al., 2017).

Even though the application of the zero energy building concept is more technically and economically feasible for the construction of new buildings, the strategies aiming the refurbishment of existing buildings is currently more important than the construction of new buildings with net-zero energy standards (Cunha, 2015). Such author cites the European Union as an example where approximately half of the buildings were constructed before the 1960 decade and, due to the low renovation rate, which is about 1% per year, it would be necessary almost one hundred years to renovate the building stock. AlAjmi et al. (2015) highlight that the challenges to meet net-zero energy in an existing building are greater than the ones found to new constructions, especially in a hot climate. The authors classify the measures to be adopted to get net-zero energy in buildings in two main qualitative steps, which are: (1) the reduction of energy consumption, especially to Heating Ventilation and Air Conditioning (HVAC) systems through energy efficiency measures, and (2) local renewable energy generation aiming to meet the remaining energy consumption.

The set of strategies that can be applied in a conventional building aiming to convert it in a net-zero energy building are categorized in the literature in three principal groups, which are passive design strategies, energy efficiency measures, and active design strategies. According to Aksamija (2016), these strategies can be classified as:

- **Passive design strategies**: the main target of these strategies is to control the heat flow through the building envelope elements seeking the best utilization of the local weather conditions to get both the thermal and luminous comfort with the lowest energy consumption possible. One example of such strategies is the improvement in thermal insulation of building envelope elements;
- **Energy efficiency measures**: basically, it consists in replacing ancient electrical appliances for new models with higher energy efficiency (certified with a high-efficiency seal for the competent institution) and also in controlling the operation schedules of such devices aiming to get the service wished with the lowest possible energy consumption;
- **Active design strategies**: consist of the local renewable energy generation, the most common one being the photovoltaic solar generation.

In this paper, the focus is the energy simulations considering just the application of passive design strategies compared to the same building without them. Simulations were developed in a residential building located in Taubate (SP) city (which has weather conditions characterized by the Brazilian bioclimatic zone 3). Details about the residential building baseline model and weather characterization of Taubate are provided in the material and method section.

1.1 Objective

The main objective of this paper is to demonstrate the potential of reducing the energy consumption in Brazilian southeast residential buildings (with weather conditions characterized by bioclimatic zone 3) by applying adequate passive design strategies through energy simulations with EnergyPlus software. The second goal of this paper is to demonstrate that it is possible to meet practically the thermal comfort conditions of Brazilian southeast cities, with similar weather conditions of Taubate (SP), through the application of adequate passive design strategies with a significant reduction on the need of air conditioning systems.

1.2 Justification of the theme choice

The main justification for this research is the urgent need of promoting mitigation measures aiming to decelerate global warming. Considering that buildings are the world biggest primary energy consumer, they become a key sector to promote mitigation measures, since they have to gradually reduce their carbon dioxide emission to around 80% until the end of the century to keep a chance of maintaining the global warming below to 2 ºC (Lucon et al., 2014). Another justification is the scarcity of research about the application of zero energy buildings concepts in hot climate regions such as the case of most Brazilian cities.

2. MATERIAL AND METHOD

In the sequence, the steps adopted in the construction of the residential building baseline model are described in detail.

2.1 Geometrical characterization, constructive features and floor plan thermal zoning of the residential building baseline model

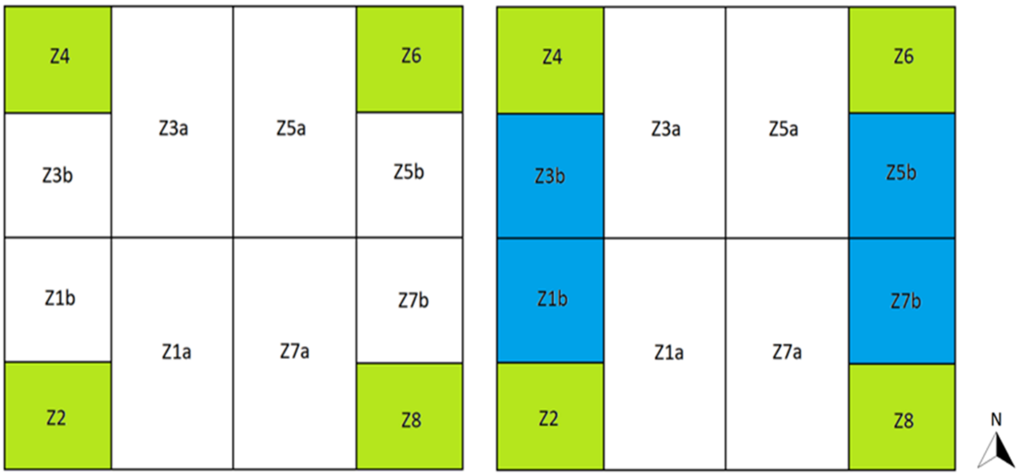
The first step adopted to carry out this research was the definition of a residential building baseline model and its location. The geometrical characterization of the baseline model was elaborated through available literature data of the constructive features of Brazilian residential buildings compiled by Teixeira et al. (2015). Among the constructive features data, the essential ones considered in the baseline model definition was the number of floors, geometrical aspects of the buildings, useful area of apartments, number of bedrooms, number of bathrooms, and the living room and kitchen areas. After adaptations, a building floor plan was designed by employing the AutoCad 2018 student version. The dimensions of the apartment environments were defined considering the most frequent range of values found by Teixeira et al. (2015) aiming to define a baseline model capable of representing a significant general case of southeast Brazilian residential building. After taking these considerations into account, the geometric characteristics of the residential building baseline model was set in a 12-story rectangular building with four apartments per floor and 88 m^2 of useful area per apartment.

Once done the geometrical characterization, the thermal properties and geometric features of the building envelope elements were modeled. The first step adopted was to model the wall's materials and their dimensions. To perform this task, a ceiling height of 2.8 m was considered, followed by the determination of the thermal properties and dimensional characteristics of the walls constructive materials by considering the ranges of values recommended in the Brazilian standard NBR 15220 (ABNT, 2003), which is a standard about both the thermal performance of buildings and Brazilian bioclimatic zoning. The chosen wall constructive material to external and internal walls was eight holes ceramic brick (with 0.09x0.19x0.19 m in its dimensions) because this is the most frequently constructive material found in the research of Teixeira et al. (2015). Other aspects, such as the window dimensions, the type of glazing systems, the flooring systems, and their thermal properties were determined considering both the recommended values of the Brazilian standard NBR 15220 and manufacturer catalog data.

After the geometrical characterization and the definition of constructive materials of the residential building baseline model, the location of the building was defined. The city chosen to represent a location in the southeastern region of Brazil was Taubate, which is situated at 23° 01' south latitude and 45° 33' west longitude in the region of Vale do Paraiba (São Paulo state). Taubate's territory covers an area of about 625 km^2 and its population is around 300 thousand inhabitants. The weather can be characterized by a tropical climate with dry winters and rainy summers (Dos Santos; Fish, 2016). Throughout the year, the temperature varies from 12 ºC to 31 ºC, being rare the cases with the temperature above 35 ºC or below 10 ºC (INMET, 2020).

The thermal comfort conditions to Taubate were estimated through a Givoni bioclimatic chart following the approach recommended in Brazilian standard NBR 15220 (ABNT, 2003). The specification of a complete set of weather data was performed through the declaration in the simulation program of a weather data file containing compiled data (representing a typical meteorological year) by the National Institute of Meteorology (INMET) and available in the epw format in the EnergyPlus homepage.

Subsequently, simplifications recommended in EnergyPlus manuals were adopted in the thermal zoning of the floor plan. It was considered in this step the possibility of possession of one or two air conditioning appliances per apartment. The final geometry of the floor plan obtained after the thermal zoning is a square shape of 20 m on its sides, divided into a total of twelve thermal zones and being each apartment represented by three thermal zones. Fig.1 presents a schematic representation, not in scale, of the thermal zoning. The green painted region (named as Z2, Z4, Z6, and Z8) represent the air conditioning of suites of each apartment, and the blue painted region (named as Z1b, Z3b, Z5b, and Z7b) represent the air conditioning of the living rooms. The first (Fig.1a) and second case (Fig.1b) correspond to an air conditioning of respectively 17% and 40% of the apartment useful floor area. As shown in Fig.1, the residential building baseline model is considered to be oriented according to the cardinal directions of wind rose.



(a) (b)

Figure 1. Schematic representation of the floor plan thermal zoning: (a) one air conditioning appliance per apartment; (b) two air conditioning appliances per apartment

Source: elaborated by the author

2.2 Occupation pattern, family economic profile, monthly electricity consumption and electrical appliance characterization of the residential building baseline model

After the thermal zoning, the features related to the occupation pattern of the apartments, such as monthly electricity consumption, possession of electric appliances, occupation rate profile, schedule of occupation, schedule of electric appliances utilization, and the schedule of the active metabolic rate of family members were modeled.

The family size was modeled considering data from the Brazilian Institute of Geography and Statistics (IBGE, 2018), according to which in 2018 the average birth rate of Brazilian families was 1.77 children per woman, thus four people were assumed as the family size. The economic family profile was modeled considering the procedures recommended by the Brazilian Association of Research Companies (ABEP, 2019), and considering the ABEP criteria, it was estimated that the families have an average gross income of about twelve minimum wages, of economic class B1.

After defining the size and economic profile of the family one model of average electricity consumption per apartment was constructed aiming to calibrate the simulation's parameters of the residential building baseline model. To construct the electricity consumption model, it was considered data from Tavares and Fritsche (2007), whose work researched the correlation among average electricity consumption of Brazilian families, family income, useful area of the apartments, and the family's size. The average value of monthly electricity consumption found per apartment to the features considered in the residential building baseline model was 291.3 kWh (1.05 10^9J in SI units).

The possession profile, specific features of electric appliances, features of the lighting system, and air conditioning device features were modeled considering data from the Brazilian labeling program (PBE, in Portuguese), national electricity conservation program (PROCEL, in Portuguese), and manufacturer catalog data. The lighting power per unit floor area was sizing considering a fluorescent lighting system and applying lumino-technical calculation. Following such steps, the average lighting power per unit floor area was estimated to be 5.6 W/m^2.

After the lighting system sizing, the heating, ventilation, and air conditioning system (HVAC) was modeled. The possession possibility of one or two split units of air conditioning appliances, type wall-mounted, per family was considered, and the values of variables needed to HVAC system specification in the EnergyPlus was determined. The suite and living room were chosen as the preferred location for the air conditioning system installation. After that, the heating and cooling capacities of the air conditioning appliance were previously estimated through thermal loads simulations employing online simulators available in manufactures homepages.

Considering the previous results of cooling capacity obtained from online manufactures thermal loads simulators was possible to determine that a 12000 BTU/h (3.52 kW in SI units) air conditioning appliance was adequate to promote thermal comfort to the considered environments. In sequence, a direct expansion air conditioning system with reverse cycle and fixed speed compressor was chosen as the most likely to be found in Brazilian residential buildings. Then, all the models of wall-mounted air conditioning appliances, with the features previously described and labeled by the Brazilian labeling program in the year of 2014 (it was considered an average age of 6.5 years for every electrical appliance), was chosen. The average coefficient of performance (COP) was determined to result in a COP of 2.95, after the application of a performance degradation coefficient of 3% due to the equipment used. Table 1 presents a summary of the main defining parameters assumed to the residential building baseline model.

Table 1. Specification of main defining parameters to the residential building baseline model

Parameters classification	Parameters of the residential building baseline model	Values
Geometrical characteristics	number of floors of the building	12
	number of apartments per floor	4
	useful area per apartment	88 m^2
Occupation characteristics	family size	4 people
	active metabolic rate of occupants	46 W/m^2 to 116 W/m^2
electricity consumption and electrical appliances power characteristics (excluding HVAC systems)	monthly average electricity consumption per apartment	291.3 kWh (1.05 10^9 J)
	lighting power per unit floor area	5.6 W/m^2
	total electrical appliances power (excluding HVAC systems) per unit floor area	50 W/m^2
Heating Ventilation and Air-Conditioning system (HVAC) characteristics	cooling capacity	12000 BTU/h (3.52 kW)
	coefficient of Performance (COP)	2.95
Thermal properties of building envelope elements	external walls (0.09x0.19x0.19 m eight holes ceramic bricks); thermal properties defined by ABNT (2003)	$\lambda^{(1)}$ = 0.35 W/m.K $\alpha^{(2)}$ = 0.58
	windows glazing (0.004 m thickness simple clear glazing)	λ = 1 W/m.K SHGC$^{(3)}$ = 0.82

$^{(1)}$ Thermal conductivity, $^{(2)}$ solar spectrum thermal absorptance, $^{(3)}$ Solar Heat Gain Coefficient

Source: elaborated by the author

After the lighting and air conditioning systems sizing, the electric power per unit floor area due to other electrical appliances was modeled in a similar process to that performed for the lighting system. In this case, the only difference is in the fact that this variable was used to calibrate the residential building baseline model aiming to meet the electricity consumption of 291.3 kWh (1.05 10^9 J in SI units) previously predicted. After the calibration, it was possible to get a small deviation of approximately 0.5% between the modeled monthly household electricity consumption and the values predicted by the simulations, when adopting 50 W/m^2 as the power of electrical appliances per unit floor area. After calibration, the simulations showed that the energy consumption is partitioned into 15.2% due to the lighting system; 28.8% due to the air conditioning system; and 56.0% due to the other electrical appliances for the case of one air conditioning appliance per apartment. In the case of two air conditioning appliances per apartment, these values are 11.7%, 45.3%, and 43.0%, respectively to the systems previously cited.

3. RESULTS AND DISCUSSIONS

The set of passive design strategies simulated in this research were: the installation of thermal insulation layers on the external walls (considering the expanded polystyrene as a reference), external walls with low solar spectrum absorptance paints, natural ventilation utilization, glazing surfaces replacement by models with better thermal properties, and the installation of shading devices (overhangs and fins) on glazing surfaces of the north facade. Each of the referred strategies was individually simulated and in the sequence, they were simulated together aiming to determine the contribution of each of them to the electricity consumption reduction and the maximum possible reduction when all of them are simultaneously considered.

3.1 Simulation of glazing surfaces replacement for models with improved thermal properties

Three glazing properties are especially important to study the impact of glazing surface replacement on the energy consumption, which is the Solar Heat Gain Coefficient (SHGC), the thermal transmittance (U-value) and the luminous transmittance (τ) (Georgiou, 2015). The SHGC can be defined as the fraction of total solar heat incident by radiation on a glazing surface that is transmitted from de outside environment to the inside of the room. The thermal transmittance can be defined as the heat flow per unit of the area through the mass of glazing due to conduction when there is a 1K temperature gradient between the outside and inside surface. The luminous transmittance can be defined as the fraction of the total visible light incident on a glazing surface that is transmitted from the outside to the inside environment (Westphal, 2016). Currently, there is no defining standard to determine the best ranges of values of solar heat gain coefficient and the experience demonstrates that the use of low values of SHGC to hot climate regions and highest values to cold climate regions seems to be the more adequate choice (Georgiou, 2015).

In the simulations performed in this research, models of glazing with low values of SHGC were chosen. Many combinations of solar heat gain coefficient, thermal transmittance, and luminous transmittance were studied. After the simulations, it was possible to conclude that window glazing systems with high values of selectivity index (defined as the ratio between luminous transmittance and SHGC) and low values of SHGC are the more adequate to hot climate regions. The reason for that is that at the same time they reduce the amount of solar heat absorbed through the windows they permit the entry of a considerable amount of natural lighting. The simulations also demonstrated that choosing a glazing system with very low U-value (or very high thermal resistance) does not lead to energy consumption reduction. The best range of values found in the simulations to glazing properties was the SHGC smaller than 0.4, U-value between 3 to 4 W/m^2.K and τ bigger than 0.4 (Chiaradia, 2020).

One glazing system that complies with the described ranges is the Cool-lite SKN 144 II model manufactured by the CEBRACE manufacturer (Westphal, 2016). The choice of the Cool-lite SKN 144 model is mainly justified by its low value of SHGC, which is 0.27, this represents a reduction of 67% in the SHGC when compared with the initial glazing system (which was a 4 mm thickness simple clear glazing with 0,82 of SHGC value). Another reason is that this model has a relatively high value of the selectivity index, which is 1.67.

The simulations demonstrated that through the replacement of simple clear glazing by the Cool-lite SKN 144 II model, it is possible to reduce the annual electricity consumption in the range of 8.4% to 13.1%, respectively to the cases of one or two air conditioning appliances per apartment.

3.2 Simulation of thermal insulation layers installation on the external walls

The increase in the thermal resistance of walls is one of the most common strategies applied in European Union countries aiming to reduce energy consumption with space heating. Paoletti et al. (2017) studied 411 cases of nearly zero energy buildings in countries of European Union and concluded that the thermal transmittance of envelope elements is always very low, ranging, typically, from 0.12 W/m^2.K to 0.20 W/m^2.K, which corresponds (in the inverse order) to the thermal resistance ranging from 5.0 m^2.K/W to 8.3 m^2.K/W. In the case of hot climate regions, the simulations carried out in this research indicate that increasing the thermal resistance of external walls does not lead to significant energy consumption reduction, and depending on the thickness of the thermal insulation layer, the energy consumption can increase. This phenomenon occurs because by increasing the thermal insulation of the external walls, the flow of heat generated by internal thermal loads from the internal to the external environment is reduced. Figure 2 presents the annual electricity consumption variation as a function of external walls thermal resistance to some cases of installations of expanded polystyrene (EPS) layers for the case of one air conditioning appliance per apartment.

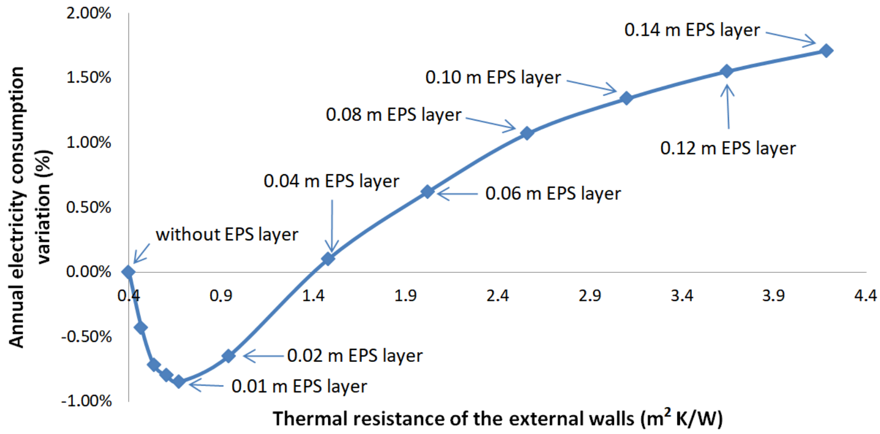


Figure 2. Annual total electricity consumption variation as a function of external walls thermal resistance
Source: elaborated by the author

The behavioral pattern shown in Fig.2 can be understood by analyzing how the portions of the annual consumed HVAC energy behave as a function of the thickness of the EPS layer. As can be seen in Fig.3, the energy consumption with space heating initially decreases at a rate greater than the increase in energy consumption with space cooling when thin thermal insulation layers are applied to the external walls. This behavioral pattern leads to a reduction in the total annual electricity consumption to a thickness of the EPS layer up to 0.01 m (which corresponds to an external wall thermal resistance of 0.67 m^2.K /W), as can be seen in Fig.2.

The 0.01 thickness of the EPS layer is an inflection point from which the application of additional layers of EPS, or in other words, an additional increase in the external walls thermal resistance does not lead to additional reductions in annual electricity consumption, causing, in fact, the opposite effect, as can be seen in Fig.2. A possible reason to this behavior is that above a certain value of external walls thermal resistance (which is 0.67 m^2. K / W for the case of one air conditioning appliance per apartment and baseline model features considered in this research), the annual reduction in space heating energy consumption does not compensate the annual increase in energy consumption with space cooling, as can be seen in Fig.3. The results found in this research demonstrated that the inflection point depends on the total air-conditioned area of each apartment. In this way, the behavior showed in Fig.2 is a little different when two air conditioning appliances per apartment is taking into account, however, the pattern of the existence of an inflection point is maintained and occur to 0.02 thickness of EPS layer (or 0.9 m^2.K/W of external wall thermal resistance).

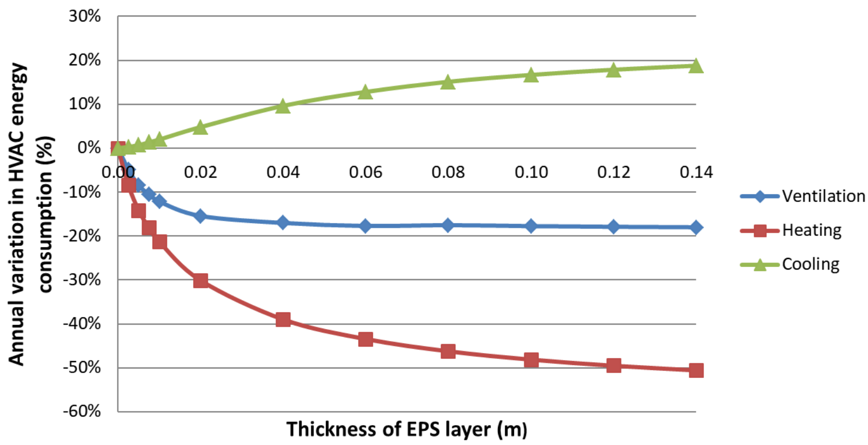


Figure 3. Variations in the shares of annual HVAC energy consumption as a function of EPS layer thickness
Source: elaborated by the author

The behavioral patterns showed in Fig.2 and Fig.3 indicate that in cold climate regions the increase in thermal resistance of the envelope elements leads to annual energy consumption reduction, as concluded by Pargana (2014) and Pajarskas (2017), considering that one of the main sources of energy consumption in these regions is the space heating. However, to hot climate regions, the results showed in Fig.2 and Fig.3 indicate that increasing thermal insulation of the envelope elements can lead to increase in annual energy consumption, as concluded by Pacheco and Lamberts (2013), since the space cooling is the main form of HVAC system energy consumption to these regions. More details about the influence of thermal insulation layers installation on external walls in the annual electricity consumption to buildings located in the southeast region of Brazil can be found in Chiaradia (2020).

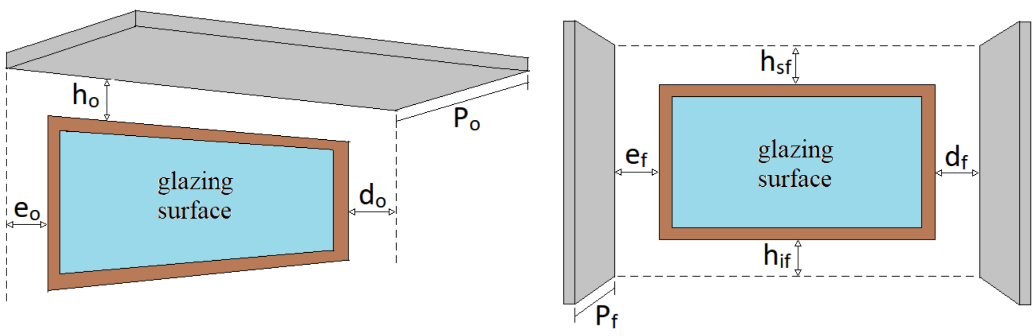
3.3 Simulation of painting the external walls with low solar spectrum absorptance paints

Initially, it was considered that the external walls were painted employing paints with median values of solar spectrum absorptance (α). The value initially considered to α was 0.50; in the sequence, a 15% increase in the alpha value was taken into account to estimate the natural aging effect of the paint (such value of aging effect increase is recommended by Silva, 2017). Thus, the initial value of solar spectrum absorptance considered in the simulations was 0.58. After that, the paint with the lowest solar spectrum absorptance found in the literature was chosen to carry out the simulation. The lowest value was found to snow white acrylic paint (manufactured by Suvinil manufacturer), whose absorption value in the solar spectrum is approximately 0.10.

The simulations showed that renewing the old painting by the new painting employing snow white acrylic paint has a great potential to reduce annual electricity consumption, being a possible reduction in the range of 10.1% to 12.1%, respectively, to the case of one or two air conditioning appliances per apartment. The major contribution of renewing the painting by assuming the paint with the lowest value of solar spectrum absorptance was to the space cooling energy consumption, to which one the reduction of annual electricity consumption ranged between 29.3% and 36.3%, respectively to the case of one or two air conditioning appliances per apartment.

3.4 Simulation of the installation of solar shading devices in the glazed openings of the north facade

The simulations of the shading of glazed openings were carried out considering the installation of overhangs and fins in the windows and doors glass (French doors) of the north facade. Many combinations of dimensions of overhangs and fins were taken into account, the Fig.4 shows the definition of dimensional parameters considered in the simulations.



(a) (b)

Figure 4. Dimensional parameters of overhangs and fins: (a) overhang; (b) fin
Source: elaborated by the author

In Figure 4, letters e_f, e_o, d_f, and d_o represent the left and right extensions of the overhangs and fins from the glazing surface edge, being their values adopted in 0.20 m for all of them. The values of h_{sf} (the distance of fins superior edges above the top of the glazing surface), h_o (height of overhang above glazing surface edge), and h_{if} (the distance of fins inferior edges below the bottom of the glazing surface) were adopted in 0.10 m. The values of P_o (depth of overhang) and P_f (depth of fin) were adopted ranging from 0.50 m to 1.00 m.

The simulations demonstrated that the potential in reducing annual electricity consumption through the installation of overhangs and fins in glazing surfaces of the north facade, considering the values of depths previously mentioned, range from 1.6% to 2.4% to the case of one air conditioning appliance per apartment. To the case of two air conditioning appliances per apartment, the simulations demonstrated a maximum annual electricity consumption reduction of 2.0% when the depth of overhangs and fins is adopted at 1.00 m.

3.5 Simulation of natural ventilation use

To simulate the natural ventilation in EnergyPlus software, it was necessary to define a complex set of parameters. Some of these parameters are schedules of temperature set points for thermal zones for which natural ventilation is available, maximum and minimum values of opening factors of both glazing and opaque surfaces, maximum and minimum values of temperature gradients between indoor and outdoor environments for which natural ventilation is available, dimensional aspects of the facades, coefficients of wind pressure on each facade, among others. A more detailed procedure of the natural ventilation simulations described in this research can be found in Chiaradia (2020). Table.2 presents a summary of the main variables considered in the natural ventilation simulations.

Table 2. Values of the main variables taken into account to natural ventilation simulations

Opening factor of glazing surfaces(1)	windows 0, 0.25 and 0.5	French doors 0, 0.25, 0.5 and 1
Temperature range of indoor environments for which natural ventilation is made available	20 ºC to 40 ºC	
Minimum and maximum values of the temperature gradient between indoor and outdoor environments for which ventilation is available	1 ºC to 20 ºC	

(1)Defined as the fractions of the total windows or doors area that can be opened

Source: elaborated by the author

The simulation results showed that is possible to reduce the annual electricity consumption in the range of 7.7% to 10.2% through adequate natural ventilation utilization. The major impact of natural ventilation was in the space cooling energy reduction, to which the reduction ranged from 25.7% (when two air conditioning appliances per apartment is considered) to 43.9% (when one air conditioning appliance per apartment is considered). The reason to the lower contribution of natural ventilation in reducing the space cooling energy consumption when two air conditioning appliances per apartment is taken into account lies in the fact that greater the number of air conditioning appliances in an environment the smaller the mass of air not yet conditioned, thereby reducing the potential contribution of natural ventilation.

3.6 Simulation of the combination of the passive design strategies mentioned in the previous sections

This section presents the results of the energy simulation of all passive design strategies when considered together. The passive design strategies considered in this research were glazing surfaces replacement by models with improved thermal properties, installation of thermal insulation layers on the external walls, painting external walls with low solar spectrum absorptance paints, the use of natural ventilation and the installation of shading devices on the north-oriented glazing surfaces.

The results demonstrate great potential in reducing the HVAC annual electricity consumption, which ranged from 72.9% (for two air conditioning appliances per apartment) to 82.3% (for one air conditioning appliance per apartment). Taking into account the total annual electricity consumption, the results indicate a potential reduction ranging from 23.7% (for one air conditioning appliance per apartment) to 33.1% (for two air conditioning appliances per apartment). The results for all design strategies considered in this research when simulated together is presented in Tab.3.

Table 3. Results for all passive design strategies considered in this research when simulated together

Annual electricity consumption type	One air conditioning appliance per apartment	Two air conditioning appliances per apartment
Space heating	118.8%	84.9%
Space cooling	-86.8%	-78.1%
Mechanical ventilation	-76.9%	-66.6%
Total annual HVAC electricity consumption	-82.3%	-72.9%
Total annual electricity consumption	-23.7%	-33.1%

Source: elaborated by the author

It is possible to get some interesting conclusions from Table 3, such as the fact that the results demonstrate clearly that a certain set of passive design strategies that is adequate to energy reduction consumption in a hot climate region is not necessarily the best choice for a cold climate region. It may be seen that the set of strategies presented in Tab.3 led simultaneously to both the space cooling energy consumption reduction and space heating energy consumption increase, indicating, thus, that the choice of the best set of passive design strategies to be applied in a building strongly depends on the local climate conditions. Depending on the region of analysis, it is practically possible to eliminate the need for air conditioning, since the results presented in Tab.3 indicate that is possible to reduce the space cooling energy consumption to values close to 90% (-86.8%) when one air conditioning appliance per apartment is considered. There is a great opportunity for energy consumption reduction by applying passive design strategies in residential buildings located in Brazilian southeast cities belonging to bioclimatic zone 3, the results presented in Tab.3 indicate an existing reduction potential ranging from 23.7% to 33.1% to, respectively, one or two air conditioning appliances per apartment.

The range of annual electricity consumption reduction previously mentioned represents a reduction in annual carbon dioxide emission per apartment ranging from 90 kg to 126 kg. This estimation is based on an equivalent carbon dioxide emission pattern of 88 $kgCO_2eq/MWh$ ($8.39\ 10^{-11} kgCO_2eq/J$ in SI units) and an electrical power transmission losses of 19.2% in the average Brazilian electricity generation mix (EPE, 2018a; EPE; 2018b). For a 12-story residential building with four apartments per floor (such as the case studied in this research), it represents a total annual reduction in carbon dioxide emission ranging from 4,330 kg to 6,050 kg.

4. CONCLUSION

The main results found in this research indicate that the installation of thermal insulation layers on the external walls does not lead to annual energy consumption reduction above a certain value of thermal resistance. In other words, the super-thermal insulation of envelope elements, with the same intensity as the applied in European countries, cannot lead to annual building energy consumption reductions in the case of hot climate regions. The value of limiting thickness for the application of the EPS layer on the external walls found in this research to which occur annual electricity consumption reduction is 0.01 m (to the case of one air conditioning appliance per apartment). This value of thickness leads to an annual electricity consumption reduction of less than 1%, as can be seen in Fig.2; this means that the installation of thermal insulations layers to the case studied in this research does not lead to significant energy consumption reduction and therefore can be not economically and technically viable.

The results demonstrate that painting the external walls with low solar spectrum absorptance paints, using natural ventilation and replacing glazing surfaces by models with better thermal properties, present a great potential for reducing the total annual electricity consumption of residential buildings located in southeast Brazilian cities and classified in bioclimatic zone 3. The annual electricity consumption reduction for these three passive design strategies ranged, respectively, from 10.1% to 12.1%, from 7.7% to 10.2%, and from 8.4% to 13.1%, when considering one or two air conditioning appliances per apartment. The installation of shading devices on north-oriented glazing surfaces does not present great potential in reducing the annual electricity consumption since the values ranged in around 2%, therefore, this passive design strategy can be not economically and technically viable in some cases of Brazilian southeast residential buildings.

When simulated together the passive design strategies studied in this research lead to a very significant reduction in the space cooling energy consumption. The results presented in Tab.3 indicate a potential reduction ranging from 78% to 87%, which means that the use of air conditioning appliances was almost completely dispensed.

Finally, the simulation of all passive design strategies considered in this research demonstrates that an annual electricity consumption reduction ranging from 23.7% to 33.1% is possible to be reached in residential buildings of Brazilian southeast region. This range of annual electricity consumption reduction leads to an amount of evited equivalent carbon dioxide emissions ranging from 4330 kg to 6050 kg in the annual base to the building as a whole taking into account the cases, respectively, of one or two air conditioning appliances per apartment. This range of reductions in annual electricity consumption and dioxide carbon emission demonstrates that applying passive design strategies is an important step toward the sustainability of buildings and plays an important role in getting the net-zero-energy building standards.

5. REFERENCES

ABEP, 2019. “Critério de classificação econômica Brasil?”. Associação Brasileira de Empresas de Pesquisa. 25 Ago. 2019 < http://www.abep.org/criterio-brasil >.

ABNT, 2003. NBR 15220: *Desempenho térmico de edificações*. Associação Brasileira de Normas Técnicas, Rio de Janeiro.

Aksamija, A., 2016. “Regenerative design and adaptive reuse of existing commercial buildings for net-zero energy use”. *Sustainable Cities and Society*, Vol. 27, pp. 185–195.

AlAjmi, A., Abou-Ziyan, H. and Ghoneim, A., 2015. “Achieving annual and monthly net-zero energy of existing building in hot climate”. *Applied Energy*, Vol. 165, pp. 511–521.

Chiaradia, C.E., 2020. *Aplicação do conceito de edificações de energia zero e seu impacto nas cidades por meio de parâmetros técnicos, tecnológicos e ambientais*. master's thesis, Faculdade de Engenharia de Guaratinguetá, Guaratinguetá, Brasil.

Cunha, F.A.O., 2015. *Estudo de estratégias e tecnologias de climatização para atingir edifícios nZEB*. master's thesis, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal.

Dos Santos, T.A. and Fish, G., 2016. "Temperatura e precipitação: futuros cenários do município de Taubaté, SP, Brasil". *Ambiente & Água - An Interdisciplinary Journal of Applied Science*, Vol. 11, pp. 1068–1087.

EPE, 2018a. "Balanço energético nacional 2018". Empresa de Pesquisa Energética. 05 Fev. 2018 < http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes>.

EPE, 2018b. "Anuário estatístico de energia elétrica 2018". Empresa de Pesquisa Energética. 05 Fev. 2018 < http://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes >.

Georgiou, G., 2015. *Assessing energy and thermal comfort of domestic buildings in Mediterranean region*. Ph.D. thesis, University of Loughborough, Loughborough, England.

IEA, 2013. "Transition to sustainable buildings, strategies and opportunities to 2050: executive summary ". International Energy Agency. 21 jun. 2018 < https://www.oecd-ilibrary.org/energy/transition to-sustainable-buildings_9789264202955-en>.

INMET, 2019. "Normais climatológicas do Brasil". Instituto Nacional de Meteorologia. 10 jan. 2019 < http://www.inmet.gov.br/portal/>.

IBGE, 2018. "Projeção da população 2018: número de habitantes do país deve parar de crescer em 2047". Instituto Brasileiro de Geografia e Estatística. 26 dez. 2018 <https://agenciadenoticias.ibge.gov.br/pt/agencia-home.html>.

Lucon, O., Urge-Vorsatz, D., Zain Ahmed, A., Akbari, H., Bertoldi, P., Cabeza, L.F., Eyre, N., Gadgil, A., Harvey, L.D.D., Jiang, Y., Liphoto, E., Mirasgedis, S., Parikh, J., Pyke, C. and Vilarino, M.V., 2014. "Buildings". *In Climate Change 2014:Mitigation of Climate Change, Contribution of Working Group III to the Fith Assessment Report of the Intergovernmental Panel on Climate Chance-IPCC.* Cambridge, United Kingdom.

Pacheco, M. and Lamberts, R., 2013. "Assessment of technical and economical viability for large-scale conversion of single family residential buildings into zero energy buildings in Brazil: Climatic and cultural considerations". *Energy Policy*, Vol. 63, pp. 716–725.

Pajarskas, K., 2017. *Achiecing a nearly zero energy building (nZEB) status for a residential house in Filand*. bachelor's thesis, South-Eastern Finland University of Applied Science , Kouvola, Finland.

Paoletti, G., Pascual Pascuas, R., Pernetti, R. and Lollini, R., 2017. "Nearly Zero Energy Buildings: An Overview of the Main Construction Features across Europe". *Buildings(MDPI)*, Vol. 7, pp. 43–65.

Pargana, D., Pinheiro, M.D., Silvestre, J.D. and Brito, J., 2014. "Comparative environmental life cycle assessment of thermal insulation materials of buildings". *Energy and of Buildings*, Vol. 82, pp. 466–481.

Tavares, S.F. and Fritsche, I.D., 2007. *AET N° 01/04 - Desenvolvimento de uma metodologia para criação de uma base nacional de dados sobre o consumo específico de energia*. work execution order, Universidade Federal de Santa Catarina, Florianópolis, Brasil.

Teixeira, C.A., Invidiata, A., Sorgato, M.J., Melo, A.P., Fossati, M. and Lamberts, R., 2015. *Levantamento das características de edifícios residenciais brasileiros*. technical report, Centro Brasileiro de Eficiência Energética em Edificações, Florianópolis, Brasil.

Williams, J., Mitchell, R., Raicic, V., Vellei, M., Mustard, G., Wismayer, A., Yin, X., Stephen, D., Shakil, M., Yang, Y., Parkin, A. and Coley, D., 2016. "*Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard*". *Building Engineering*, Vol. 6, pp. 65–74.

Wei, X. and Shicong, Z., 2017. *APEC 100 Best Practice Analysis of Nearly/Net Zero Energy Building*. APEC Project: EWG 02 2015A, China Academy of Building Research and China Passive Building Alliance, Beijing, People's Republic of China.

6. RESPONSIBILITY NOTICE

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