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THERMAL PERFORMANCE AND ECONOMIC EVALUATION OF SMALL OFFICE INTEGRATED WITH PCM IN A SOUTHERN BRAZILIAN CLIMATE

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Abstract. The edification sector is responsible for 40% of the world's energy demand. In order to decrease this energy demand, this paper studied the influence of adding phase changing materials (PCM) in a typical Brazilian building and to perform an economic viability study for its large scale application in a southern Brazilian climate. These materials are characterized by storing thermal energy in the form of latent heat during hot periods, therefore increasing the building's overall thermal inertia and decreasing the energy demand for thermal acclimatization. Numerical simulations were performed in the software Energy Plus with a standard edification developed by the U.S Department of Energy with changes in its' building envelope in order to adapt the model to the Brazilian conditions. One material with six different phase change temperatures of 21°C through 26°C are compared with the base scenario without PCM in order to determine the most suitable for the location. The simulation's results are also used to perform an economical analysis, determining if it is economically feasible to use phase changing materials in the studied conditions. The results showed a 16,26% decrease in HVAC energy consumption and a payback period of approximately 31,7 years.

Keywords: PCM, Energy efficiency, Economic evaluation, Phase Change materials, Energy simulation.

1. INTRODUCTION

The world is currently facing a challenge unprecedented in human history. The increasing need of thermal comfort in developed and in development countries is being opposed by a need to decrease the consumption of the world's limited resources. The building sector (comprising residential and commercial edifications) is responsible for about 40% of the global energy consumption (Li et al., 2019). Additionally, about 61% of this energy is being used for air cooling and with a tendency to increase at least until 2050 (Al-Yasiri and Szabó, 2021). In Brazil, the commercial building sector is increasing its energy consumption in a 2,6% per year rate, higher than the residential sector at 1,5% per year (EPE, 2021). For this reason, it is necessary to find solutions to increase the energy efficiency in this sector.

One of the possible ways to solve this dichotomy is the use of Phase Change materials (commonly abbreviated for PCM). They have this name due to the ability to use thermal energy from the environment in order to change its physical phase from solid to liquid, storing energy.

The PCM are currently being in various applications with different transition temperatures in different sectors such as thermal envelope for COVID-19 vaccines and thermal storage of solar energy (Reji Kumar et al., 2020). The PCM are also commonly being used in buildings in different forms as passive thermal regulation system (Drissi et al, 2019). These materials are added to the building's envelope as microencapsulated powders inserted inside mortars and concrete or as macroencapsulations of different formats attached to the walls, roofs or ceilings (Berardi and Gallardo, 2019). Actually, all materials are phase change materials at some temperature, however, in the context of the edification sector, a phase change material has transition temperature around the human thermal comfort, approximately 18°C to 30°C.

Due to this property, the PCMs will become liquid when the temperature is higher than the transition temperature, storing thermal energy, preventing the heat to be transmitted to the edification, thus reducing the necessity of the HVAC system to remove heating and decreasing its energy consumption. This phenomenon usually occurs during the day in high temperatures.

In order to complete the cycle, the thermal energy stored during the day must be released, normally during the night period, in order for the PCM to be able to store more energy the next day. If this energy release does not occur, the PCM will not be able to store the same amount of energy, thus decreasing the efficiency of the product.

Therefore, two important properties for PCMs are the transition temperature and the latent heat capacity. The material needs to have a transition temperature allowing it to be able to change phase from solid to liquid in order to absorb heat during hot periods and change phase again from liquid to solid during cold periods. This is virtually impossible to accomplish every single day due to weather variations throughout the year, however it is possible to choose the one where the energy store is maximized. On the other hand, the amount of heat used to change phase is called latent heat capacity and higher this number more energy the material is able to absorb before changing phase completely and consequently more efficient in thermal energy storing.

Many works were developed, both experimentally and numerically, to assess the benefits of Phase Change Materials in the edification sector. Al-Yasiri and Szabó (2021), Berardi and Gallardo (2019), Drissi et al. (2019) e Ling; Poon (2013) provide revision works on the subject matter, summarizing many important information about current trends and techniques.

In the experimental field, Hunger et al. (2009) developed an apparatus containing self-compacting concrete with 5% wt. microencapsulated PCM. The experiment was subject to sinusoidal temperature variations in order to simulate a South European climate and a 12% decrease in the annual energy consumption was obtained. Muruganantham (2010) studied two houses with identical structures located in Phoenix, Arizona, United States, the only difference being one having a PCM mat installed in the interior wall while the other does not. The energy used to maintain the thermal comfort in the houses were measured for an entire year and the result showed a 24,2% decrease in the energy consumption, but with a 54-year payback period due to the PCM high initial cost.

In the numerical field, Alam et al. (2014) studied the thermal performance of a PCM enhanced single room house of 16m² virtually located in 8 different cities in Australia using the software Energy Plus. The authors used the "ZoneHVAC:IdealLoadsAirSystem" module in EnergyPlus for an ideal HVAC unit. A mat filled with PCM was used in all outdoor surfaces. The results varied from an annual energy consumption reduction of 17,1% in Brisbane and 23,5% in Adelaide and proposed the ideal phase transition temperature for each city.

Similarly, Brito and Akutsu (2017) made a similar study in 8 different Brazilian climates according to the Brazilian standard ABNT 15220-3 (ABNT, 2005) also using a mat filled with PCM on all outdoor surfaces. A 2,8 °C to 3,4 °C temperature reduction in the inner wall was obtained as a result.

Saffari et al. (2017) performed a study in a Department of Energy Prototype building in 57 different locations around the globe. A prototype building is a building simulation developed to simplify the process of testing different solution of energy efficiency measures. 16 different types of the most common commercial buildings in accordance to the ASHRAE 90.1 American standard (ASHRAE, 2016) were simulated and released to the public. The usual drywall was replaced by a plasterboard with 30% wt. microencapsulated PCM. The results showed a great variation with the climate. The best location was Johannesburg, South Africa with 22,7% decrease in the annual energy consumption and the worst was in Manaus, Brazil with 9% increase in the energy consumption. They also concluded that high altitudes places tend to have better efficiency with PCM.

Sovetova et al. (2019) performed a study in eight different cities in the middle east and India using a 20 mm layer of PCM in the outer wall. For each city, an ideal PCM transition temperature was selected with an economical evaluation. The maximum reduction in the building energy consumption was 34,26% with a payback period of approximately 28,56 years. They also concluded that the ideal transition temperature is closely related to the heating and cooling set points of HVAC system.

This paper objective is to numerically simulate the thermal performance of inserting commercially available macroencapsulated PCM in a typical Brazilian commercial building envelope and climate, and to evaluate the technical and economic viability. To the authors' knowledge, this is the first work to properly investigate the use of this type of PCM in commercial buildings in a Brazilian climate.

2. METHODOLOGY

2.1 Energy simulations

The influence of the insertion of PCM in the building envelope will be evaluated by comparing the annual energy consumption of the entire HVAC system of a building without PCM and other with PCM with different phase change temperatures. The PCM will be added both to the wall and the roof structures.

The software used in the simulations is the Energy Plus, a free source software developed by the department of energy of the United States. This software is capable of performing a range of numerical building energy simulations and include the capacity to model entire HVAC systems, conduction, convection and radiation calculations and shading calculations.

Furthermore, the software is capable of modeling Phase Change Materials in the CondFD module (short for Conduction Finite Difference Method) in the walls and roofs heat conduction calculations. The method is based in an energy balance in the nodes as shown in Eq. (1) (Berkeley et al., 2018):

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2}\left(k_w \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} + k_w \frac{T_{i+1}^j - T_i^j}{\Delta x} + k_E \frac{T_{i-1}^j - T_i^j}{\Delta x} \right) \tag{1}$$

Where C_p is the specific heat capacity, ρ is the density, k is the thermal conductivity of the material. T is the temperature, Δx is the length of the node and Δt is the time step. The subscripts i indicate the node and j the time step. The difference of this method is the capacity of the specific heat to be changed in function of the temperature, allowing different enthalpy changes in different temperatures. In this manner, the great enthalpy changes in small temperature changes, characteristic of phase change is possible following Eq. (2) and Eq. (3) for iteration:

$$C_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \qquad (2)$$

$$h_i = HTF(T_i) \qquad (3)$$

2.2 Climate Characterization

As mentioned in the introduction section, the climate characteristics of a certain location are essential in the evaluation of PCM efficiency. Therefore, every energy simulation needs to be performed in a specific location. In the present paper, the simulations will be performed virtually in the city of Maringá, in the northern region of Paraná State, Southern Brazil.

The Brazilian standard ABNT 15220-3 (ABNT, 2005) classifies Brazil in eight different bioclimatic regions. The regions were defined according to their thermal and humidification needs. For each bioclimatic region, different passive strategies and construction characteristics are proposed such as wall types and wall-to-window ratio. Maringá is defined as a type 1 climate, with four defined seasons with both heating and cooling needs.

The Köppen-Geiger classification is a general way of assessing climates around the world. It classifies the climates in three letters according to the temperature and humidity characteristics. Maringá is classified as a Cfa climate, meaning a warm temperature, fully humid with a hot summer climate (Alvares et al., 2013). Some examples of cities with the same general climate are Madrid in Spain, Tokyo in Japan and Brisbane in Australia.

2.3 Building Characteristics

The building used for the energy simulations in this work is commercial small office DOE (Department of Energy) prototype building. The prototype buildings are a set of the 16 most common buildings in the United States (Deru et al., 2011). For each building, a full modeling of the internal equipment, HVAC system, building envelope and operation schedules was modeled in accordance with the ASHRAE standard 90.1-2016 (ASHRAE, 2016). These simulations were made in order to facilitate the process of testing new energy efficient techniques such as Phase Change Materials. The EnergyPlus files for these simulations are available in the United States department of energy website. Figure 1 show the external view of the small office building with a total floor area of 511,46 m².
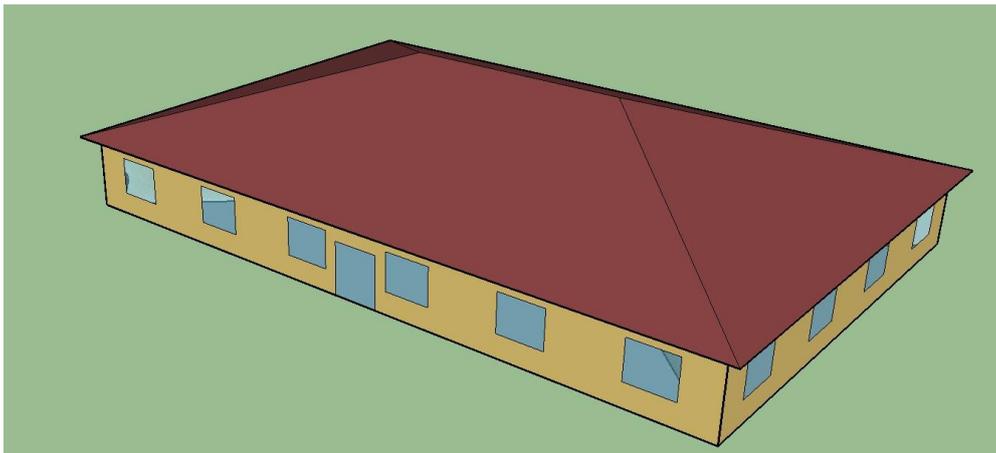

Figure 1- External view of the simulated building

The building envelope is typical of constructions in the United States where some works with PCM, such as Muruganantham (2010), were already performed. However, this paper objective is to use typical Brazilian wall and roof constructions, which were modified to more accurately simulated the Brazilian reality.

Lamberts et al. (2006) performed a study regarding the most common constructions types used in offices in Brazil. The most common wall type, and the type used in the simulations, is composed of an inner and outer mortar layer of 2,5 cm with a 10 cm layer of a 6-hole hollow brick. The PCM layer will be added in the inner part of the wall in accordance

to the studies of Markarian and Fazelpour (2019), Tunçbilek et al. (2020) and Hagenau and Jradi (2020). Figure 2 show the wall construction without and with the PCM layer.
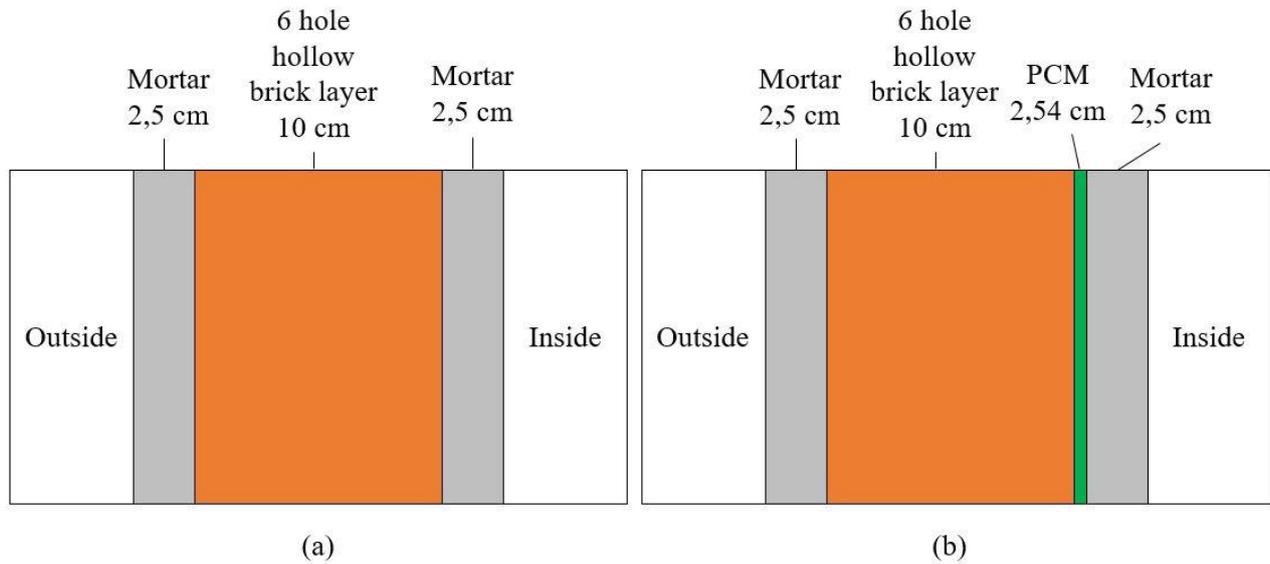

Figure 2 - Wall construction type (a) without PCM and (b) with PCM

On the other hand, the type of roof construction is based on the most common type of tiles in Brazil, the ceramic tile (Michels, 2007) and a structure common of small height buildings of 0,8 cm layer of ceramic tiles, 0,4 cm of asphalt shingles and a 1,6 cm layer of wood as lining. Figure 3 show the roof construction type without and with a PCM layer.
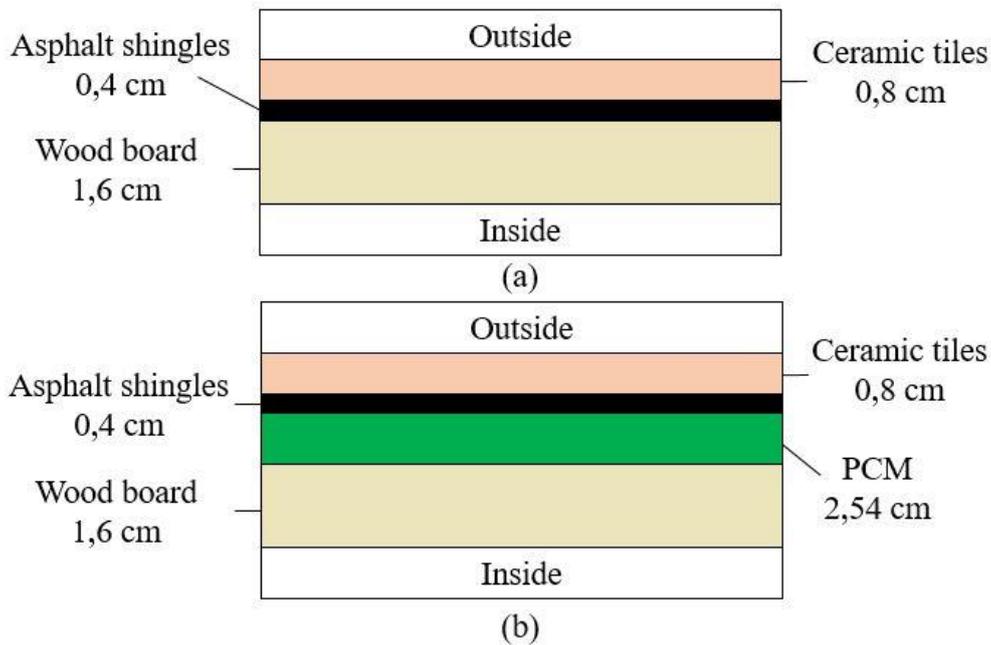

Figure 3 - Roof construction type (a) without PCM and (b) with PCM

Another building element important to the energy simulation is the HVAC system control. Saafi and Daouas (2019) and Sovetova et al. (2019) showed that the cooling set point is closely related to optimal phase change temperature. For this reason, it is important to define a set point to provide thermal comfort for most of its users but do not expend unnecessary energy. The set point used for simulation is 23°C for cooling and 21°C for heating in accordance to the Brazilian standard ABNT 16401-1 (ABNT, 2008).

2.4 PCM material

The Phase Change Material used in this paper is a macroencapsulated organic fatty-acid named BioPCM. This product has a high latent heat energy capacity and high specific heat capacity compared to other materials available in the market (Muruganantham, 2010) (Saafi and Daouas, 2019). Additionally, the product can have different forms of encapsulation such as plasterboard panels and tiles, however for this application a mat filled with the material was chosen due to the facility of installation in walls and roofs. The thickness of the product was set to 2,54 cm, which is a commercial available thickness.

The consumer is able to select the material with a phase change temperature ideal for the application. In order to determine this ideal material for the application, six different phase change temperatures of 21°C, 22°C, 23°C, 24°C, 25°C and 26°C were tested. This range was selected in accordance to the work of Brito and Akutsu (2017), stating that the ideal phase transition temperature normally is between 1°C and 3°C above the internal environment average temperature. Therefore, the range is between the heating set point to 3°C above the cooling set point.

In order to facilitate the presentation of the results, this work will adopt the convention of naming the material changing phase in 21°C of PCM21, the one changing phase in 22°C of PCM22 and so on. The enthalpy curves used in the simulation were taken from the work of Alam et al. (2014).

3. RESULTS

The first item to be made is the validation of the model to be simulated. Tabares-Velasco et al. (2012) performed a work for testing the use of Phase Change Materials in several different situations and concluded the software is capable of modeling those problems. Moreover, Muruganantham (2010) performed both an experiment and numerical simulations to prove that EnergyPlus model is valid for phase change simulations.

Additionally, the DOE prototype buildings are simulations already validated by researches for its use in various situations, including the use of phase change materials (Saffari et al., 2017). Therefore, the model is considered to be validated for the simulations.

3.1 Ideal PCM phase change temperature

As stated in the methodology section, six different phase change temperatures were selected in order to discover the ideal for this specific application. Therefore, seven separate simulations were performed, one for case without a PCM layer (hereafter called the standard case) and 1 for each transition temperature to be studied.

The values of the annual energy consumption of the entire HVAC system of the office were used as basis for comparison. These values are the sum of the electric energy consumed by the refrigeration cycle and the fans used for air circulation for both cooling and heating. The results are shown in Figure 4.
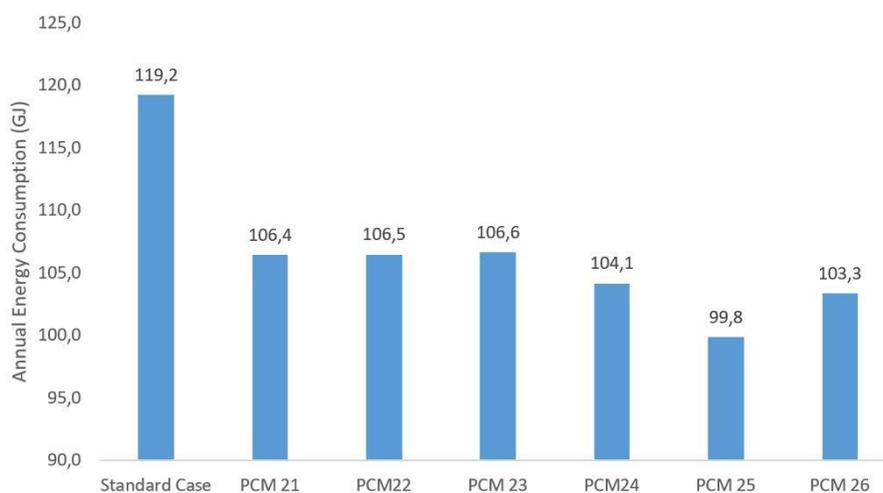

Figure 4 - Annual HVAC Energy consumption for the entire office

The analysis of Figure 1 demonstrates the potential of PCM use as a passive thermal control strategy. All PCM decrease the total annual energy consumption by more than 10%. However, PCM25 proved to have the best efficiency for the climate of Maringá with a decrease in the total HVAC energy consumption of approximately 16,27%. The annual reduction was of 19,4 GJ or approximately 5389 kWh of electric energy. This result is in accordance with the results presented by Saffari et al. (2017), which found that the best transition temperature for the Cfa climate of Brisbane, Australia was 25,19 °C.

Additionally, the fact that the ideal phase transition temperature was closer to the cooling set point than the heating set point means a higher need for cooling than heating according to the work of Sovetova et al. (2019). In fact, the total cooling need for the office building is approximately 118,9 GJ, much higher than the heating need of approximately 0,3 GJ.

Figure 5 shows the monthly difference in the total HVAC energy consumption for the office building for the standard case and the most efficiency case, the PCM25. The PCM25 case decreases the energy consumption in all months and seasons, however during the end of fall and winter, between May and August, the difference is decreased due to more mild outside air temperatures and less need for thermal acclimatization. The smaller monthly economy occurs in May with only 193,4 kWh decrease.

On the other hand, during the summer months, between December and March, the high temperature increases the need for cooling and the difference between PCM and standard case increases. However, is during September that the energy economy peaks with 730 kWh saved. This is due to the fact of a greater temperature variation in this period, with both hot and cold periods. This results demonstrated the capacity of the PCM to mitigate the effects of great temperature variations as demonstrated by Sovetova et al. (2019).
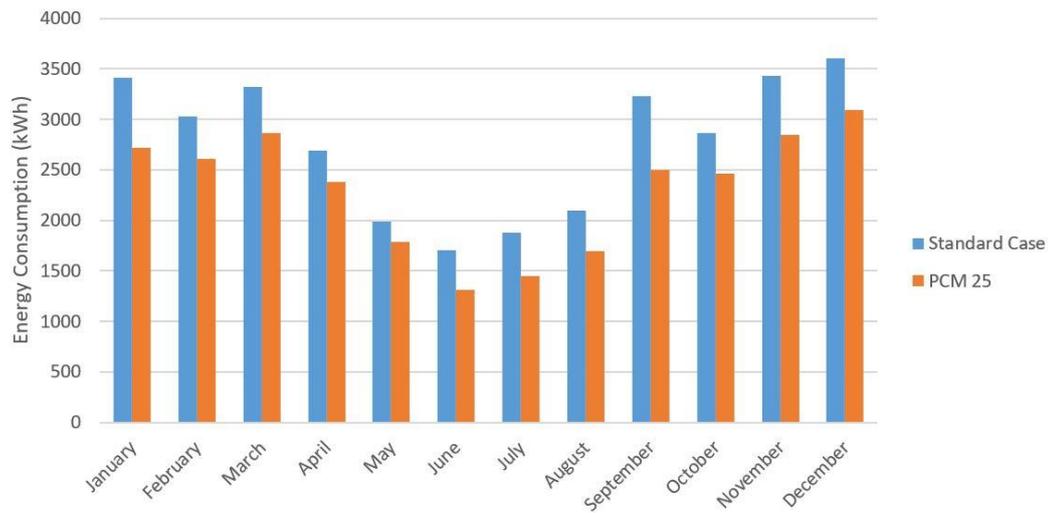

Figure 5 - Monthly comparison between the standard case and the ideal phase transition temperature

3.2 Economic Evaluation

In addition to the assessment of HVAC energy savings with Phase Change materials, the authors also performed an economic evaluation. The calculation will be based on the life-cycle cost analysis performed by Saafi and Daouas (2019). It takes into account the energy consumption savings over a period of n years, the inflation rate of the energy prices in the country (i) and the discount rate (d).

Equation (4) was defined by Saafi and Daouas (2019) as the life-cycle payback period PB, which is the number of years necessary for the costs for acquiring and installing the PCM will be equal to the amount of money saved in the period:

$$PB = \frac{\ln\left[1 - (d - i)\frac{C_{PCM}}{E_s}\right]}{\ln\left(\frac{1 + i}{1 + d}\right)} \tag{4}$$

Where C_{PCM} is the total cost of installation and E_s is the annual energy saving, all in Brazilian Reais. In order to estimate the total cost of acquiring and installing PCM in the office building, the work of Cascone et al. (2018) was consulted, where prices of PCM per kg and installation costs are available. The energy savings were calculated using the total HVAC electric energy savings, discussed previously in subsection 2.1 and multiplying by the cost of kWh practiced in Paraná State during the month of June 2022 (Copel, 2022).

The conversion value from Euro to real was made on June 12, 2022 in the value of 5,24 Reais per Euro. The energy inflation rate was obtained from IBGE (Brazilian Institute of Geography and Statistics) and calculated as an average annual value between 1999 and 2018 (Fioravante, 2018). The discount rate was obtained from financing lines offered by BNDES (Development National Bank) (CEBDS, 2014). Additionally, since PCM need to be imported, a 70% import fee was added to the final price. Table 1 summarizes all the data used in the economical evaluation.

Table 1 - Values used for the economical evaluation

Variable	Value	Unit
BioPCM Price	1,3	€/kg
Average PCM installation cost	4,36	€/m²
Total Wall area	221,8	m²
Total Roof area	598,8	m²
Conversion Euro to Real	5,24	R$/€
Energy Price	0,83	R$/kWh
Energy inflation rate	7	%
Discount rate	3,5	%
Import fee	70	%

Using Eq. (4) and the data from Tab. 1, a payback period of approximately 31,72 years is obtained. This is slightly higher than the 30-year building life cycle used by Saafi and Daouas (2019) and Souayfane et al. (2019). This is mainly due to the high cost of installation of approximately 239 500 Brazilian Reais or 45 700 Euros for the office building.

One important fact contributing to the high initial cost is the fact of these materials being imported. The high Real-Euro exchange rate and import fees increases the purchase prices of these products considerably. In order to PCM decrease the prices and its use make financial sense, companies must have financial incentives to manufacture these products domestically. The authors did not encounter any domestic producers in Brazil.

Other important factors are the discount rate and energy inflation rate. The discount rate is the currently interest rate used in the country for projects involving energy efficient measures. This value is often modified depending of government interest, economic development, etc. The energy inflation rate is the average increase in the electric energy over a period and it is also volatile. In order to assess these variables, an additional study was performed where the discount rate and the inflation rate varied and the impact in the payback period was evaluated. In Figure 6 the study is shown in details.

The study demonstrates that higher the inflation rate, smaller is the payback period. This result is in accordance to the literature (Saafi and Daouas, 2019) and is in perfect sense with the fact that if energy prices are higher, the benefits of having an energy efficiency measure, and therefore using less energy, will be greater and the payback period will decrease. Moreover, higher the discount rate higher the payback period. This is also in accordance to the literature (Saafi and Daouas, 2019) and to the fact that a higher interest rate will increase the cost of the project without generating any benefits.
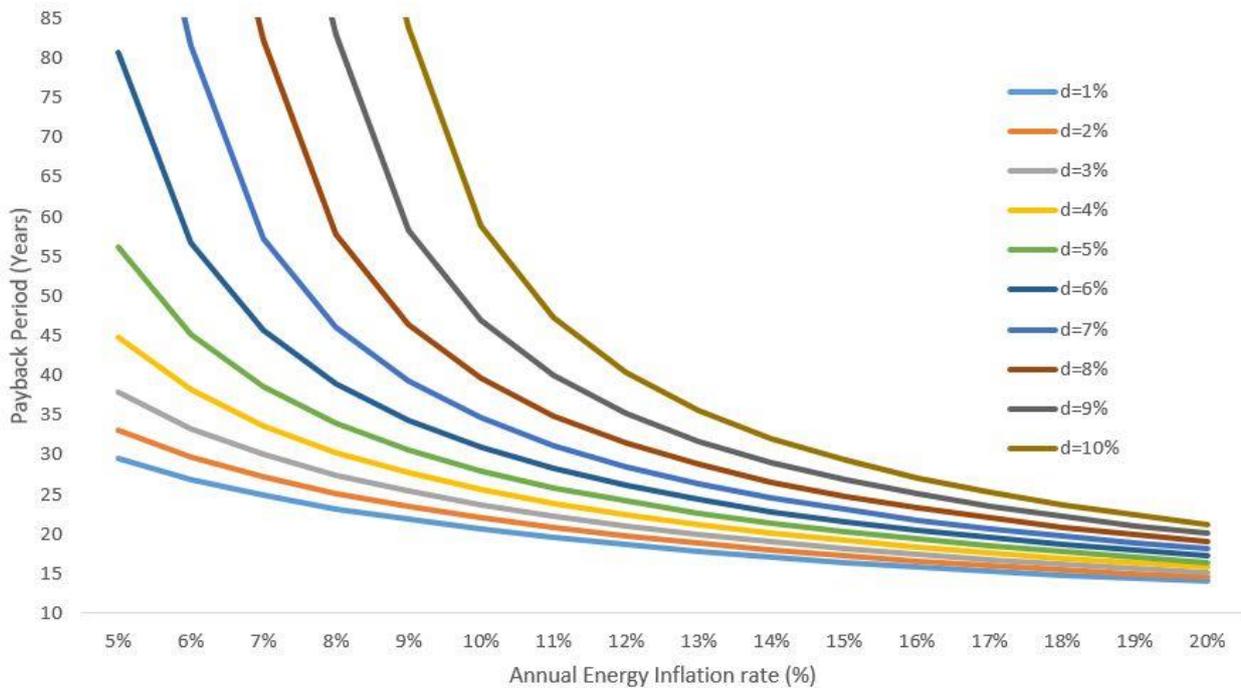

Figure 6 - Economic evaluation of the insertion of PCM in the studied building.

4. CONCLUSIONS

In this paper, numerical simulations and economical evaluations were performed to measure the impact of the insertion of Phase Change material in a small office of 511 m² in typical Brazilian building envelope. The final remarks are:

- The PCM decrease the total HVAC electric energy consumption for the phase transition temperature of 21°C, 22°C, 23°C, 24°C, 25°C and 26°C in at least 10% compared to the building without PCM.
- The best transition temperature for this specific application is 25°C with an energy saving of 16,27% compared to the building without any PCM.
- The PCM decrease the HVAC energy consumption in all months of the year, however these values were higher during the summer months.
- The life-cycle payback period of the installation of PCM in a small office building in the city of Maringá is approximately 31,7 years, which is slightly higher than the usual life span of a modern edification of 30 years.
- The high payback period obtained was mainly due to high initial cost. If domestic products are available in the future, the payback could be decreased significantly.
- The Energy inflation rate is inversely proportional to the payback period, while the discount rate is directly proportional with the payback period.

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