Effect of environment on the selection of phase change materials for building wallboards using multi-criteria decision methods and Building Energy Simulations

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ABSTRACT

One of the greatest global challenge and an indispensable requirement for sustainable development in the building sector is the reduction of greenhouse gas emissions and energy consumption. For this purpose new technologies as phase change materials (PCM) are currently being studied for its potential to improve the energy efficiency and reduce energy usage in buildings.

This research aims to analyze the selection of Bio-PCMs for building wallboards and roofs by a comparison between multi-criteria decision methods (MCDM) and Building Energy Simulations (BES). Ashby approach is employed for determining figure of merits (FOM) to grade PCMs performance. Moreover, BES are performed to: (a) further contrast the MCDM ranking of PCM and (b) numerically assess the thermal behavior and estimate the energy consumption with the incorporation of the PCMs. The results found discrepancies between the MCDM and BES, demonstrating the importance that the environment variables play to appropriately assess the performance of PCM.

INTRODUCTION

The building sector was identified as one of the key sectors to achieve drastic greenhouse gas emission reductions. On the one hand, buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions only in the European Union (EU) (ECOFYS, 2015). For this reason, new technologies in buildings were introduced to improve the energy efficiency and reduce energy usage in buildings, such as the one presented by Baetens et al., 2010, who exposed the importance of thermal insulation materials applied in the building envelope or phase change materials (PCM). The use of PCM as storage medium for both cooling and heating applications appreciably reduces the energy demand of the building sector due to the high latent heat of the PCM at low temperature (Thambidurai et al., 2015). In this regard, the scientific community has been developing studies of PCMs building applications over the past decade. Although, free cooling potential showed promising capabilities toward space cooling applications, it has not yet been widely commercialized and implemented in residential sectors (Thambidurai et al., 2015).

PCM as building materials to improve the performance of heating, ventilation and air-conditioning (HVAC) systems has been tested as an energy efficiency measure. Rastogi et al. (2015) developed a selection and performance assessment of PCM for HVAC in a room house. Turnpenny et al, (2000) studied the reduction of air conditioning, using an innovative ventilation system using PCM. Reducing air conditioning and improve energy efficiency in buildings using PCM latest generation variable volume was performed by Parameshwaran et al. (2010).

On the other hand, the selection of the most appropriate PCM is a crucial component for the design and development of the building. Comparing candidate materials, ranking and choosing the best material, are one of the most important stages in the material selection process. To accomplish the selection, efforts need to be extended to identify the criteria that have a major influence in the engineering application to eliminate unsuitable alternatives and select the most appropriate choice using simple and logical methods (Fernández et al., 2010). The proper choice of PCM depends on factors such as their physical and thermochemical properties. In this regard, it has been demonstrated that the material selection process can be developed for a systematic and efficient approach as a multi-criteria decision-making (MCDM) problem. In this direction, the application of material selection has been developed for PCM in energy storage. Fernández et al., (2010) conducted the selection of PCM materials for sensible thermal energy storage between 150–200 °C by the CES Selector software. Additionally, Khare et al., (2013) presented the selection of PCM materials to evaluate sensible heat storage between 500–750 °C by the software package - Granta Design's CES Selector

In contrast, simulations that assess the thermal behavior of PCM in buildings provide essential information of the energy consumption and could improve the design process of the building. For this purpose, several numerical models have been developed to assess the thermal behavior of PCM. In this regard, Al-Saadi et al. (2013) presented a review of the different models. According to this study, one of the most used and validated model is the finite difference algorithm. The vast majority of software that uses the finite difference algorithm has been validated to appropriately use the model. In this sense, the most advanced and well-validated software that uses the finite difference algorithm is EnergyPlus, which called the model as CondFD. Some of the studies mentioned in the review have pointed the importance of having actual weather data to accurately predict the behavior of PCM in EnergyPlus. Furthermore, is crucial to take into account the sensitive behavior of a simulation due to parameters like air infiltration and internal thermal loads and occupancy schedules (Tardieu et al., 2011). On the other hand, other studies presented a good agreement between the simulated and measured data. However, it is worth to mention that before 2012, the EnergyPlus's CondFD model gave some unreasonable results related with the heat flux and temperature distribution in horizontal placements as stated by Shresta et al. (2011). For these reason, the EnergyPlus team developed several studies with the purpose of debugging the CondFD model based on experimental validation taking into account the ASHRAE 140 Standard (Lee et al. 2015). After 2012, EnergyPlus released the version 7 of the software that currently includes the validated CondFD model. More recently, Lee et al. (2015) performed a verification of the CondFD model in version 8 against measured data. The results demonstrated a maximum difference between the real and simulated results of less than 5%, which lead to the conclusion that the performance of PCM could be accurately predicted by the CondFD algorithm. More recent studies have highlighted the debilities of the CondFD model when assessing active systems such as a radiant floor by Mazo et al. 2012. The main concern when assessing these systems is that the model does not take into account the two-dimensional effect of heat conduction. However, for passive application of PCM, the CondFD model has been well validated as mention before. Even, a more recently study of Al Saadi el at., (2015) pointed out that although the CondFD model needs a revision on the associated simulation schemes for more accurate and less time consuming approaches, it shows a good agreement with EnergyPlus results for exterior and interior wall surfaces. Therefore, the CondFD model of EnergyPlus is one of the most advanced and accurate software tools to appropriately assess the passive application of PCM in buildings.

In this sense, there are several studies that have assessed the thermal performance of PCM through BES. Tokuç et al. (2015) performed an experimental and numerical investigation on the use of PCM in building roof in Istanbul. Other studies like the one performed by Castilho et al (2014) and Vautherol et al. (2015) have performed BES in a school building and dwellings respectively, in order to assess the capabilities of PCM in reducing energy requirements. Finally, Rastogi et al. (2015) compared the results of the MCDM method with the ones obtained with PCM-Express concluding that, MCDM method could be used to accurately select PCM to be applied in buildings.

Nevertheless, the aforementioned studies have ignored the effect of environmental conditions in the thermal performance of PCM whether they use MCDM methods or BES as assessment tool. Given this considerations, this study aims to contrast the performance between MCDM and BES for the selection of Bio-PCM wallboards for buildings. In this study, three preference ranking-based MCDM were developed to choose the best Bio-PCM alternative. For these methods, a list of all the possible choices from the best to the worst suitable materials were obtained taking in consideration different material selection criteria. In addition, BES are performed to assess the thermal performance and estimate the energy savings of a social dwelling with the incorporation of the Bio-PCMs as wallboards. The simulation was performed in three different climatic macro-zones of Ecuador where accurate meteorological data were available. Finally, the MCDM and the simulation results were contrasted to further analyses the ranking obtained in this study.

MATERIALS AND METHODS

This section include the definition of the decision making problem for material selection, Ashby approach and figure of merits (FOMs), Simulation methodology and cases

Definition of the decision-making problem for material selection

PCM utilize the latent heat of phase change to control temperatures within a specific range. The energy used to alter the phase of the material, given that the phase change temperature should be around the desired comfort room temperature and it should lead to a more stable and comfortable indoor climate. For the material selection of Bio-PCM in buildings for HVAC, it is necessary to present the desired properties that should be required from Bio-PCM. The properties of the Bio-PCM are selected based on bibliography (Baetens et al., 2010):

- High heat of fusion per unit volume and unit weight, and high specific heat. To gain more effect from latent heat storage with a small as possible volume of Bio-PCMs.
- Phase change temperature suitably matched to the application.
- Chemical stability and low corrosion.
- Harmless or nontoxic during fire or if the encapsulation is ruptured during regular use.
- Reproducible crystallization without degradation.
- Small volume change during solidification to avoid a collapse in the structure.
- High thermal conductivity to disperse heat through more rapidly.

Given this consideration, five alternatives of the Bio-PCM are assessed in this study:8 BioPCM-Q21, BioPCM-Q23, BioPCM-Q25, BioPCM-Q27, BioPCM-Q29. The properties of the alternatives with their quantitative data are given in Table 1.

Since the study in question aims at selecting the best material for regulating temperature within human comfort limits, phase change temperature becomes the single most important screening criterion. Hence, our initial selection of materials was limited to those exhibiting phase change in the temperature range of comfort related with the climate. Density, thermal conductivity and latent heat of fusion are the primary factors that determine the performance of a PCM. The higher the density, easier it is to store a larger amount of material in a small volume. Similarly, higher the latent heat of fusion better will be the thermal stability provided by the use of respective Bio-PCM. Additional parameter like specific heat capacity, setting and melting enthalpy helps to determine the performance of the PCM in the sensible heating/cooling zone. Hence these parameters have been selected to help in the evaluation process of the candidate materials. The rank of the properties in table 1 is derived from the bibliography based on PCMs (Baetens et al., 2010), (Rastogi et al. (2015)

Ashby approach and figure of merits (FOMs)

A popular MODM tool widely used by the scientific community for various screening and selection problems is the Ashby approach. This technique was first proposed by Ashby et al. (2000). The underlying principle dictates that the performance (P) of any engineered system can be determined as a function of its functional (F), geometric (G) and materials (M) parameters. This statement can be mathematically represented as:

$$P = f(F, G, M) \tag{1}$$

Here, f denotes 'function of'. However, each of the aforementioned parameters operates independently of the rest and their collective output determines the overall performance. Hence, Eq. (1) can be rewritten as:

$$P = f(F) \cdot f(\,G) \cdot f(M) \tag{2}$$

Since, the aim of this study is to comparatively rank the Bio-PCMs for generalized operation; we will only concern ourselves with the materials parameters.

The first step towards implementation of the Ashby approach is to determine the screening parameters. In our case, this has been limited to identification of suitable Bio-PCMs which are able to operate in the temperature range of the different climate. A list of such potential candidates is listed in Table 1.

$$FOM_1 = T_f \tag{3}$$

Here, T_f represents the Phase change Temp The second step involves determination of suitable FOMs. Since the primary objective of Bio-PCMs is to store maximum amount of thermal energy in a minimum amount of space, the first FOM can be derived as:

$$Q = m \cdot \Delta h = \rho \cdot v \cdot \Delta h \tag{4}$$

Here, Q represents the total heat extracted during the phase change process. While the symbols $m, \rho, v\ and\ L$ denote mass, density, volume and latent heat respectively. Eq. (4) can be modified to obtain the second FOM by isolating the materials parameters to the right hand side of the equation. Thus, Eq. (4) can be rewritten as:

$$FOM_2 = \frac{Q}{v} = \rho \cdot L \tag{5}$$

*Table 1. List of selected BioPCMs and their thermo-physical propertie*s (Baetens et al., 2010), figures of merits and Rank of results for Quito (Rank 1), Francisco de Orellana (Rank 2) and Guayaquil (Rank 3)

Material	**Heat of fusion** $[\frac{kJ}{kg}]$ (Δh)	**Melting Temp. [°C]** (T_m)	**Specific heat capacity in solid state,** $[\frac{kJ}{kg*K}]$ (Cp_s)	**Specific heat capacity in liquid state** $[\frac{kJ}{kg*K}]$ (Cp_l)	**Thermal conductivity in solid state** $[\frac{W}{mK}]$ (k_s)	**Thermal conductivity in liquid state** $[\frac{W}{mK}]$ (k_l)	**Density in solid state** $[\frac{kg}{m^3}]$ (ρ_s)	**FOM_1 (Phase change Temp.) [°C]**	**FOM_2 (heat extracted per unit volume)** $10^3\ \rho\ \Delta h$	**FOM_3 (thermal inertia)/** $\alpha = \frac{k}{\rho \cdot C_p}$	**Rank 1**	**Rank 2**	**Rank 3**
Bio-PCM Q21	225,6	20-22	2,73	0,83	0,21	0,19	235	21	53,02	0,00033	1	5	5
Bio-PCM Q23	245,5	22-24	1,822	0,65	0,21	0,19	235	23	57,57	0,00049	3	4	4
Bio-PCM Q25	236,9	24-26	1,813	1,031	0,21	0,19	235	25	55,62	0,00049	4	1	3
Bio-PCM Q27	251,3	26-28	1,77	0,99	0,21	0,19	235	27	59,06	0,00050	5	2	2
Bio-PCM Q29	260,7	28-30	2,22	0,271	0,21	0,19	235	29	61,26	0,00040	2	3	1

Eq. (5) represents the amount of heat extracted per unit volume. This gives a direct measurement of the amount of thermal energy storage density of any Bio-PCMs per unit volume. Hence, it can be employed as a ready reference for comparative analysis.

Additionally, another important factor that determines the performance of Bio-PCMs with respect to space heating/cooling applications is its thermal inertia. A lower thermal inertia implies a better response time and lower temperature fluctuations for the required application. Thermal diffusivity of any material is generally regarded as a direct measurement of its thermal inertia. Physically, thermal diffusivity represents the ratio of a body's ability to conduct heat to its ability to store it. Mathematically, it is represented as:

$$FOM_3 = \alpha = \frac{k}{\rho \cdot C_p} \tag{6}$$

Here, α denotes the thermal diffusivity of the material. The symbols k and C_p represent thermal conductivity and specific heat capacity of the material respectively. Mathematically, a higher value of thermal diffusivity, the rate of energy transfer within the system would be more. In terms of Bio-PCM it implies that a larger mass would be involved for creating the required thermal balance, instead of localised phase transition. This would ensure a better temperature regulation and faster response for systems employing macroencapsulation or other form of bulk morphological installations. These three FOMs have been used for the ranking purposes.

Simulation methodology

Building energy simulations are performed to further contrast the obtained ranking with MCDM method and assess the thermal performance and the energy savings that Bio-PCM can achieve.

To perform the BES, EnergyPlus is used as the calculation engine with the graphic user interface (GUI) – DesignBuilder. Regularly, the software uses the Transient Heat Conduction – CTF method to perform the simulations, which uses a single linear equation with constants coefficients to simplify the calculation of a multi-layered construction. However, this simplification is inappropriate when using Bio-PCM because it ignores the variation of the enthalpy with the temperature. Hence, Tindale (2005) recommends using the Conduction Finite Difference (CondFD) algorithm that calculates the temperature-enthalpy function to fluctuate the specific heat capacity of the material in each iteration. Moreover, a minimum of 12 time-steps per hour (30 in the present study) alongside the fully implicit first order difference scheme should be used for the numerical simulation. As mention in the literature review performed in the introduction, the CondFD model is one of the most advanced and well-validated algorithms to assess Bio-PCM in buildings. For this reason, the model is not being validated with actual measured data.

On the other hand, since the simulation entirely depends on the definition of the temperature-enthalpy function, utter attention must be taken to properly define the enthalpy-temperature curve in DesignBuilder. The quality in the data will lead to accurately assess the performance of Bio-PCM. In this case, the simulations are performed using the data of Bio-PCM already available in the software.

Simulation cases

The aim of the simulation is to numerically assess the thermal behavior and estimate the energy consumption of a social dwelling with the incorporation of PCM in wallboards and rooftops in three different climatic macro-zones of Ecuador of which there are accurate meteorological data. Ecuador has three macro-zones, which are Coast, Highlands and Amazon regions as can be seen in Figure 1. These macro-zones present different climatic conditions that are controlled by the height above sea level of each region. The Coast region has a rainy and a dry season, with mean temperatures that oscillates between 36 and 23°C, respectively. The highland region has a rainy-cold and a dry season with mean daily temperatures between 13 and 18°C respectively. The amazon region presents rains throughout the year and its mean temperature is 25°C (Vega and Jara, 2009).

The relative humidity in each region varies according to the topography, which generates several microclimates. Therefore, is not possible to standardize a relative humidity for each region. For this reason, three cities that represent each climatic macro-zone of Ecuador are chosen for this study. These cities are (a) Quito for the Highland region with a cold and semi-humid weather (b) Guayaquil for the Coast region with a warm and humid weather and (c) Francisco de Orellana for the Amazon region with a warm and very humid weather. (Figure 1).

It has to be mentioned that in Ecuador, the hourly temperature oscillation is more representative than the daily or monthly oscillation. For instance, in Quito the hourly oscillation is around 9°C whereas the daily and monthly temperature oscillation is 4 and 1.5°C respectively. This behavior is similar in all the climatic zones of Ecuador. Therefore, the results described in this study will be considered as the mean value of the hourly data represented in one day as in Figure 1.

The reference building is a generic social dwelling designed by the Ministry of Urban Development and Housing (MIDUVI) of Ecuador, which is given to the beneficiaries of the housing allowance. The social dwelling was designed to shelter four people in a space of 36 m^2 (Figure 2) which represents an occupancy density of 0.111 people/m^2. For simulation purposes, this occupancy density is considered as continuous throughout the day and night generating an internal thermal gain of 4 W/m^2 including lighting and equipment (CIBSE, 2004).

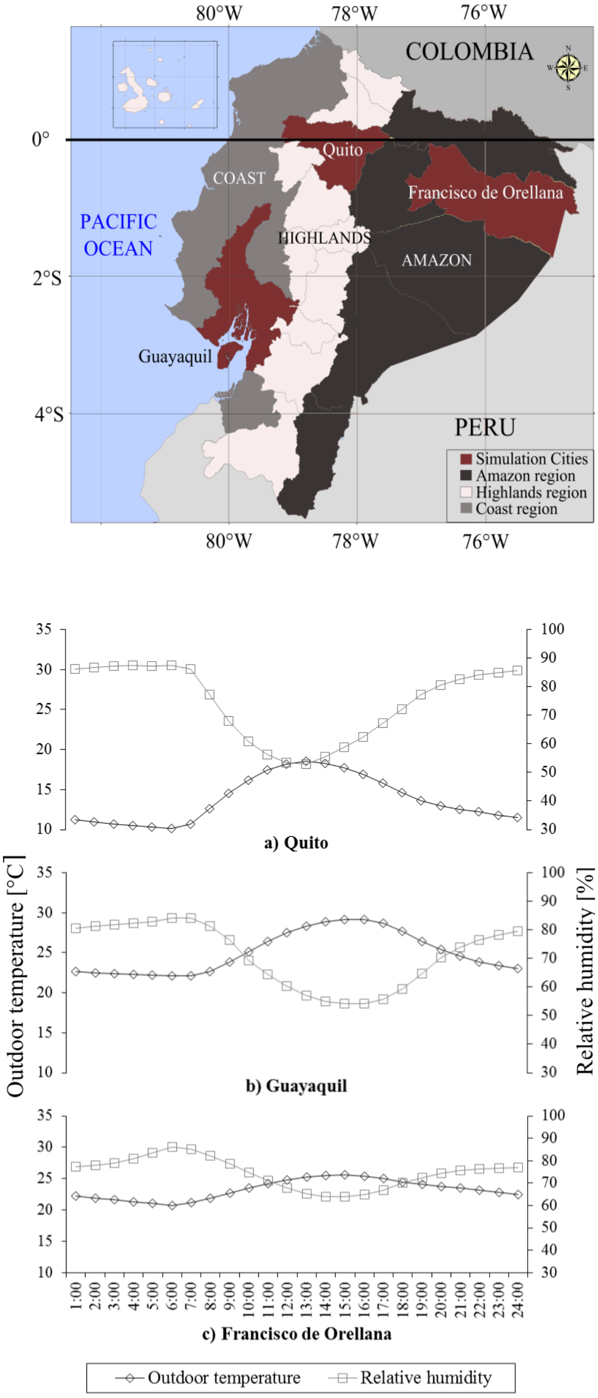


Figure 1. Representative cities for each climatic macro-zone Coast, Highlands and Amazon of Ecuador. Quito for the Highland region with a cold and semi-humid weather, Guayaquil for the Coast region with a warm and humid weather and Francisco de Orellana for the Amazon region with a warm and very humid weather. On the right, distribution of the outdoor temperature and relative humidity in the different cities for a typical day

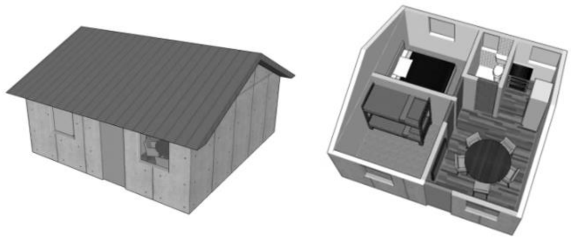


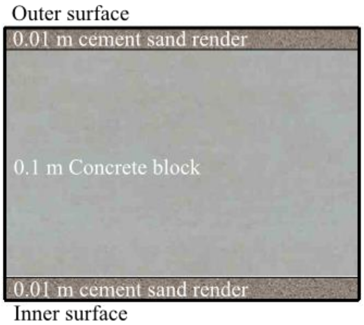
Figure 2. Schema of the generic Ecuadorian social dwelling designed by MIDUVI of Ecuador, The social dwelling was designed to shelter four people in a space of 36 m^2. The dwelling has two bedrooms, one bathroom and a kitchen-dinning-living shared room.

To simplify the calculation, a single zone is considered in the simulation. On the other hand, despite the different climatic macro-zones of Ecuador, this dwelling has been built in every zone of the country, with the same construction materials (concrete for walls and metal sheet roofing). Depending on the region, the materials selection as well as the design has been performed neglecting the effects of the environment conditions. Referring to the materials, they do not prevent the building for radiation heat gains in the warmest regions. In addition, solar protection systems were not considered from the design perspective. In contrast, the material does not keep the internal heat gains during night, which is important in the coldest regions. Consequently, as demonstrated by Beltran et al. (2015), the conditions within the building are inappropriate to ensure a healthy and comfortable environment inside the building with the additional shortcoming of being energetically inefficient

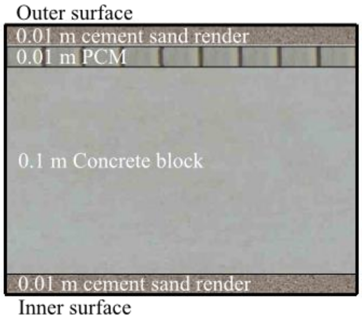
For this reason, the present study has the additional purpose of suggest an improvement to these buildings by using PCM on the wallboards (Figure 3). The envelope materials improvement is only considered for the walls and roof, because, those elements of the buildings present the highest thermal gains and losses during the day (Beltran et al. 2015). With these configurations, the thermal resistance for the envelope materials is presented in table 2. Two different tests are performed in order to assess the thermal performance of the Bio-PCMs through BES: (a) an operative temperature distribution on one-year span and (b) a comparison between the outdoor and the indoor operative temperature. These analyses are performed through a comparison between the reference case and the improved case. Furthermore, an analysis of the energy performance of the PCM compared with the reference case is presented.

Table 2. Thermal resistance for wall and roof

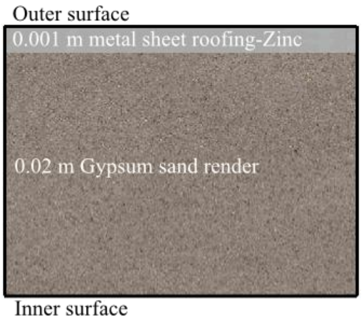
Material	**Walls - U [W/m^{2}K]**	**Roof - U [W/m^{2}K]**
Bio-PCM-Q21	3,31	4,61
BioPCM-Q23	3,31	4,65
BioPCM-Q25	3,31	4,65
BioPCM-Q27	3,31	4,65
BioPCM-Q29	3,31	4,65



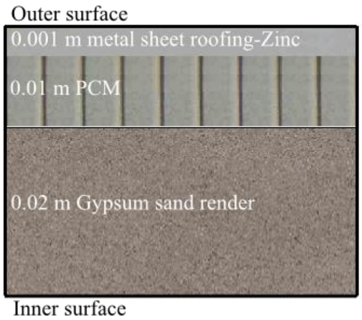
a) Reference wall



b) Improved wall with PCM



c) Reference roof (not to scale)



d) Improved roof with PCM

Figure 3. Construction configuration for reference case and the improved case with the PCM (not to scale) a) Reference wall, b) Improved wall with PCM, c) reference roof and d) improved roof with PCM

In addition, to contrast the obtained ranking with the MCDM method, a comparison between the estimated energy savings achieved by the Bio-PCMs in the different regions of Ecuador is calculated using the Eq. (7) (ASHRAE, 1999).

$$Improvement\ (\%) = \frac{R-I}{B} \cdot 100 \qquad (7)$$

Where R is reference case consumption, I is improved case consumption and B is base line consumption

This equation compares the energy consumption between the reference case and the improved cases

Thus, an HVAC system is included in the simulations to obtain a result of the annual energy demand for every case. However, for the simulation to be comparable, a preliminary parametric simulation is conducted to determine the temperature and relative humidity set points that obtain zero discomfort hours for all regions (Table 3).

This analysis demonstrated that heating, cooling as well as a dehumidification systems are needed in Quito to assure zero discomfort hours due to the temperature variation between day and night (i.e. approximately 9°C).

In contrast, in the warm and humid climate of Guayaquil and Francisco de Orellana, there is only need of cooling and dehumidification due to its elevated temperature and relative humidity during day and night.

Table 3. HVAC system set-points

	Heating [°C]	Cooling [°C]	Relative humidity [%]
Quito	20.5	26,0	35,0
Guayaquil	-	26,0	45,0
Francisco de	-	26,0	45,0

RESULTS

This section presents the results of the Ashby approach and figure of merits (FOMs) and simulation

Results of Ashby approach and figure of merits (FOMs)

The performance grade of various PCMs according to the proposed Figures of Merit, approach are listed in Table 1.

In order to evaluate the relative importance of individual steps involved, it becomes crucial to look the results drawn from each step independently. Beginning from FOM_1, the top materials for the climate of Quito (Rank 1) are Bio-PCM Q21, Bio-PCM Q29 and BioPCM Q23. These results are related to the activation of the melting temperature and the specific heat capacity in solid state. In Quito, Bio-PCM Q21 was the only material which its phase changed from solid to liquid. For this reason, this Bio-PCM should be used. In contrast, the other materials did not yield on a phase change operative temperature. For this reason, Bio-PCM Q29 and Bio-PCM Q23 should be used in the second and third place for the highest heat capacity in solid state. Similar results are related with Francisco de Orellana (Rank2) and Guayaquil (Rank 3). In case of Francisco de Orellana, Bio-PCM Q25 was between the phase change temperature ranges for longer time in the period assessed (one year). On the other hand, Bio-PCM Q21 and Bio-PCM Q23 were in liquid state most of the time. Meanwhile, Bio-PCM Q29 and Bio-PCM Q27 have reaches the phase change temperature less time than the other Bio-PCMs. Regarding Guayaquil, Bio-PCM Q29 was the material that was in phase change most of the time for this region.

Contrastingly though, when FOM_2 is taken into account to assess, the best obtained materials are Bio-PCM Q29 and Bio-PCM Q27 These materials have the largest heat storage capacity per unit volume and thus, provide a better temperature stabilization.

In case of FOM_3, the best materials were Bio-PCM Q21, Bio-PCM Q23 and Bio-PCM Q25. Since FOM_3 takes into account thermal inertia, these materials will react to phase change in a swift manner and thus, the thermal fluctuations will be minimized by their use. This knowledge implies that both, FOM_2 and FOM_3 derived for materials selection are conflicting in nature, that is, one can increase at the cost of the other.

For a commercial system, a best trade-off between conflicting objectives is required to ensure enhanced productivity and desirable output. Hence, it becomes necessary to determine suitable materials with optimum value of FOMs.

Simulation results

In order to understand the effect of the climate conditions in the thermal behavior of the Bio-PCMs, two tests were performed for all Bio-PCMs in the present study. The results showed that every material presented an improvement compared with the reference case. However, only the results obtained for the Bio-PCM Q23 are presented in this paper as a performance sample since the behavior is similar for all PCM assessed in this research.

Indoor operative temperature distribution

The indoor operative temperature distribution test was performed to compare the indoor thermal behavior between the reference and the improved case. In Quito and Francisco de Orellana there is a scattered distribution of the operative temperatures with no significant differences between the reference and Bio-PCM case as shown in the figure 4. Conversely, in Guayaquil the Bio-PCM material clearly maintains the majority of the hours below 30°C while the reference case is always above this figure. This is related with the high solar radiation in Guayaquil where the metal roofing system is ineffective to protect the building from the solar heat gains.

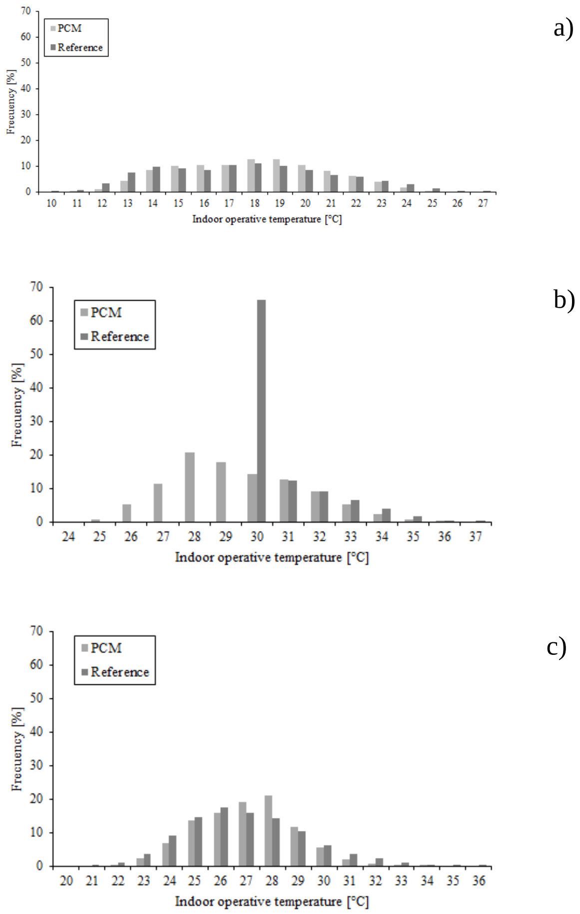


Figure 4. Results of the operative temperature distribution on one year span for the cities of a) Quito, b) Guayaquil and c) Francisco de Orellana.

Comparison between indoor and outdoor temperature

This test was performed to contrast the variation of outdoor and indoor temperature for the reference and Bio-PCMs cases on an hourly basis. It is notable that the temperature fluctuation between day and night is elevated in Quito and Guayaquil (i.e. 7°C). On the contrary, in Francisco de Orellana the temperature difference between day and night is only about 5°C (Figure 5). This behavior is evident in the reference case where the indoor temperature follows the distribution of the outdoor temperature. Contrariwise, the Bio-PCM case maintains a uniform distribution during the day which in some cases acts as a detrimental side effect. In Guayaquil for instance, the Bio-PCM maintains the indoor temperature around 28°C whereas the reference case maintains it 1°C less during the morning. During the afternoon when the outdoor temperature reaches its highest peak, the Bio-PCM material maintains the temperature 2°C below the one obtained by the reference case.

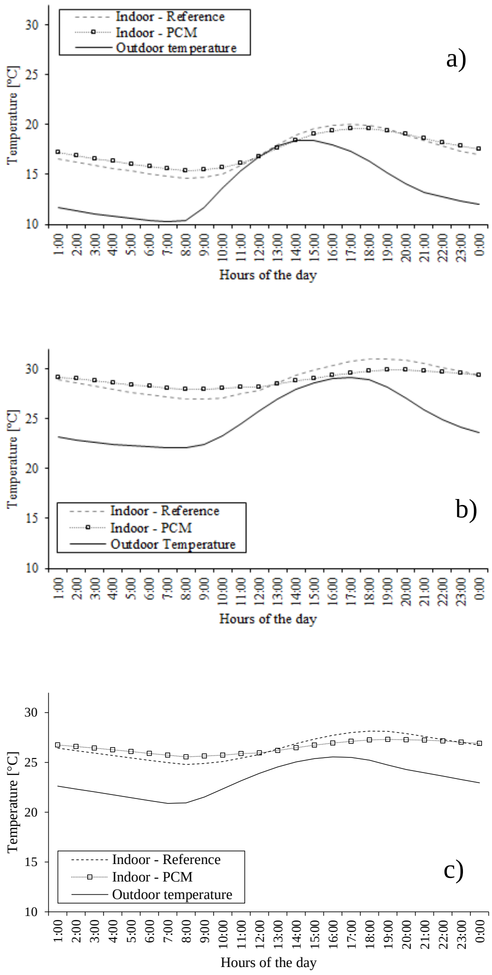


Figure 5. Comparison between indoor and outdoor temperature for the cities of a) Quito, b) Guayaquil and c) Francisco de Orellana

Energy performance

Finally, the energy performance of the different analyzed cities is presented in Figure 6. The results shows that in Quito the PCM present a good performance in order to keep the temperature of the dwelling, thus reducing the energy loss trough the wallboards and roof with the corresponding reduction on its heating demand. However, in Guayaquil and Francisco de Orellana that present a warm and humid weather, it is clear that the PCM reduce the capacity of the dwelling to lose heat through the wallboards and roof, therefore, the cooling demand is increased.

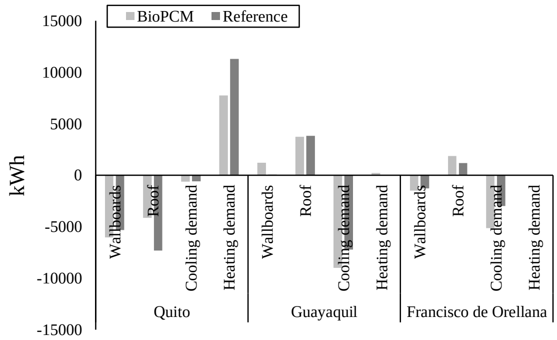


Figure 6. Energy performance of the different analyzed cities

DISCUSSION

This approach considered in this research can aid decision makers in moving towards to a regulation policy, which improves the energy savings in Ecuadorian buildings between 10-25% as is given in Figure 7. The method could also be applied more widely with appropriate adaptation, so could contribute for energy efficiency in buildings around the world.

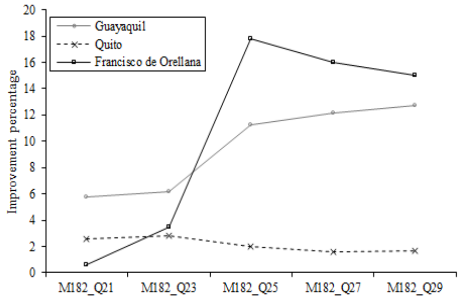


Figure 7. Improvement percentage of the Bio-PCMs materials

In order to contrast the obtained ranking with the MCDM method, a BES was performed considering the social dwelling as conditioned. In addition, this analysis is used to establish the phase change material that obtained the highest energy savings in every climatic macro-zone of Ecuador.

Rastogi et al., (2015) developed a selection of materials in PCM for HVAC using figures of merit to numerically identify the relative performance of participating candidates. The principal criteria for the material selection were the phase change temperature, density, heat of fusion, specific heat capacity and thermal conductivity. In addition, the top ranked PCMs were selected for a simulation study using open source software PCMs Express based on finite difference mathematical model and enthalpy method for simulation.

In case of Rastogi et al., (2015) the simulation were executed for an unconditioned building in a span of a year (8670 h), as is in our study. To maintain the human comfort temperature (21–26 °C), a conventional system of brick masonry walls, concrete cement roof and ceiling compared with the PCM was used, whereas, in our study we assessed the performance of a conventional brick masonry for walls and a metal roofing sheet improved with PCM in three different climatic macro-zones of Ecuador. The thickness of each wallboard is considered to be 15 mm, while we considered a 10 cm brick with a 1 cm PCM for the wallboard and roof. The other boundary conditions being the night ventilation, window in outer wall (occupying 40% area of the total wall) and equivalent radiator output of 50 W/m^2. In our study, we consider natural ventilation in the unconditioned case and a HVAC and dehumidification systems for the conditioned case in every climatic macro-zone. Furthermore, 10% of window to wall ratio was used as the reference case and the internal gains value was considered as a typical dwelling (4 W/m^2).

Even though the results of Rastogi et al., [15] showed a good agreement between the MCDM and simulations methods, it did not take into account the effect of the environment to assess the performance of PCM. In fact, there is no clear information about the climate conditions surrounding the assessed building. However, taking into account that they only analyses the operative temperature of an air-conditioned building, the results are similar to the ones obtained in Quito in the present study. This means that the thermal performance is appropriate for the entire day in cold and semi-humid climates.

Nevertheless, as demonstrated in the present study, in warm climates, PCM could perform inappropriately during night. This fact demonstrates the discrepancies between both methods. Furthermore, it proves the importance of assessing the impact of the environmental variables in the evaluation of PCM.

Likewise, other studies have performed BES in order to assess the performance of PCM. Castilho et al. (2014) evaluated PCM in a school building with large thermal gains due to computational equipment (i.e. 28 W/m^2). The PCM was incorporated in the roof and walls of the rooms as in our study. Moreover, they performed the assessment considering the rooms with and without HVAC systems. Although, they performed an hourly assessment of the indoor temperature performance, they neglected the effect of the surface temperature and the thermal gains and losses of the wallboards. In our study, these parameters are claimed to have an impact on the thermal perception of the occupants. On the other hand, Vautherot et al. (2015) performed BES to assess the energy requirements and discomfort hours by using different PCM in a dwelling. They compare the energy requirements for the HVAC system with the discomfort hours associated with every PCM, whereas we compared the energy requirements achieving zero discomfort hours in order to the simulation to be comparable. Furthermore, they overpass the fact that the hourly variation of the indoor temperature affects the thermal comfort of the occupants. However, our simulation results are in some level of agreement with those obtained by them regarding the fact that the appropriate selection of HVAC system's set points affects the thermal performance of the PCM.

The correspondence between the FOMs and the simulation method demonstrate the importance that the environment variables plays to appropriately assess the performance of Bio-PCMs. In addition, these results are explained by the thermal behavior assessment previously made in this study. For example, in a warm and humid place, using Bio-PCM during night is rather detrimental because the dwelling cannot evacuate all the heat gained during the day, which generate a higher demand of refrigeration. These kinds of considerations are overlooked when evaluating PCM with the MCDM method, which generates the discrepancies in the results.

Finally, several studies about the lifetime of the PCMs has been performed (De Gracia et al. 2010), (De Gracia et al. 2014), (Kylili, A., & Fokaides, 2016). The lifetime of the systems under investigation; 50, 75, or 100 years which is expected for the case of BioPCMs.

To determine quantities required in the building, the general rule is 1.5 of BioPCM™ per cubic meter (m^3) of interior space. In this, research a simple economic analysis for the BioPCMs application in Buildings should be take into account 36m^2 floor space x 2.2 high ceiling = 79.2 m^3. In this case, the quantity of BioPCMs is about 118.8 kg of material, which have a price of 4158 \$. This information appear on the website of BioPCMs.

CONCLUSIONS

In this paper, the material selection problem for Bio-PCMs for buildings was solved utilizing a decision model and BES. The model includes FOMs. The best choices were dependent of the operation range temperature for different Bio-PCMs. For this reason, it is necessary to know the climate condition in order to select the adequate Bio-PCM.

The BES were carried out to contrast the results of the MCDM method which led to the conclusion that a thermal assessment of the BioPCM is necessary to better understand the behavior of the materials during the operation with the effect of the environmental conditions as well as the indoor conditions. This fact is clearly demonstrated by the simulation results. Depending on the climate conditions, Bio-PCM has different thermal behavior that could be an improvement in some cases and disadvantageous in others. For this reason an extensive assessment of the climate condition should be made before actually apply this strategy in unconditioned buildings.

In addition, Bio-PCMs present a good thermal behavior during day and night in cold places, especially at night, when the Bio-PCM maintains the indoor temperature on a constant comfortable temperature. On the other hand, the thermal performance during day and night is different in warm and humid places. During the day, the Bio-PCM prevents the heat evacuation of the building which in fact generates a warmer space compared with the reference building. Nevertheless, PCM present a good performance during afternoon keeping the indoor temperature below the outdoor temperature. For these reasons, in the case of unconditioned buildings, PCM are preferable to be installed in buildings located in cold places since it has a good performance throughout the entire day. For unconditioned buildings located in warm places, PCM has a better performance during afternoon. On the other hand, if social dwellings were designed to use HVAC systems, it is clear that PCM could represent an improvement in all climatic macro zones of Ecuador. In this sense, the Bio-PCM Q25 and Q29 have the better performance among all assessed PCM in this study.

Furthermore, this methodology could also be used with appropriate adaptation to other places of the world and it could contribute for energy efficiency and greenhouse mitigation in buildings around the world.

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