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Thermal stress reduction in cool roof membranes using phase change materials (PCM)

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ABSTRACT

A considerable amount of energy is used in the building sector for air conditioning purposes. Additionally, the building sector contributes to the urban heat island (UHI) phenomenon which causes temperature rise in urban areas. Cool roof is an emerging passive cooling technology that can contribute to reduce the cooling energy use in buildings and to mitigate the UHI effects in the urban area. Cool roofs and reflective coatings, despite of being effective in terms of reducing the cooling thermal loads in buildings and decrease the UHI, can suffer from extreme thermal stress which negatively influences their lifespan and performance. Thermal energy storage (TES) is a promising technology which can be applied together with cool roof technology to decrease the extreme thermal stress due to solar radiation as well as providing thermal inertia to the building. In this study, simulation-based optimization will be used to optimize the PCM melting temperature when integrated into a polyurethane-based cool roof membrane to reduce the thermal stress of the cool roof and also to improve the annual energy performance of the building. The optimization results showed that the application of PCM and cool roof technologies together can reduce the severe thermal stress of the cool roof membrane when the optimization objective is the annual thermal stress of the cool roof. On the other hand, when PCM melting temperature is optimized to reduce the annual energy needs, higher annual energy savings could be achieved with acceptable reductions in the cool roof membrane thermal stress.

1. Introduction

Global warming is a critical issue in the world which endangers the life on earth. Hazardous emissions such as CO_2 are the main motivators of this negative climatic phenomenon. The building sector is responsible for consuming roughly 32% of the global final energy use and emitting roughly one-third of all greenhouse gas emissions [1,2].

In Europe, buildings consume about 40% of energy, of which 50% of this comes from heating, ventilation, and air conditioning. For this reason, reduction of space air-conditioning requirements in buildings is of a high importance to ensure the energy efficiency in this sector [3–5].

Further on, a substantial rise in cooling energy demands is expected by 2050. The estimated growth in cooling demands is about 150% globally and about 300%–600% in developing countries [6]. Moreover, the building sector also contributes to the urban heat island (UHI) phenomenon in urban areas, in which elevated surface and air temperature could be felt in urban areas compared to outskirts [7]. Accordingly, a serious global effort towards energy efficiency in buildings is essential to decrease building energy demand growth while maintaining thermal comfort and improved quality of life for occupants both in indoor and outdoor environment.

Passive cooling techniques could be effective methods to improve the cooling energy performance in buildings [8,9] by moderating the temperature fluctuations in building zones, thus offering long-term energy efficiency and indoor thermal comfort [10,11].

Cool roof is an emerging passive cooling technology which can contribute to reduce cooling demand in buildings and UHI effects. Further on, it can improve the thermal comfort of occupants, reduce the HVAC size, decrease the roof surface temperature, and extend the life of the roofing system [12,13]. Cool roofs have exterior

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surfaces or coatings that reduce solar absorption and increase thermal emittance. They maintain lower surface temperatures and decrease heat flows into the building [14]. However, the high solar reflectance created by cool roofs may increase heating energy requirements and building energy use during heating seasons especially in heating dominant weather conditions [14].

Due to the importance of cool roofs for building energy efficiency enhancement, many important international building energy-efficiency standards such as ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code, and California's Title 24 have adopted cool-roof credits or requirements [15].

In addition, many authors have investigated and analyzed the potential benefits that cool roof technology can offer to increase the cooling energy performance in buildings, and to improve the urban microclimate [16] based on experiments or simulation techniques [17]. For example, Stavrakakis et al. [18] experimentally and numerically analyzed the influence of the cool roof technology in a school building in Greece under Mediterranean climate zone. They concluded that the application of a cool roof can achieve annual energy savings up to 7.4%, and cooling energy savings up to 50%, when heat pumps are used. In another study, Zinzi and Agnoli [19] numerically studied the effect of cool roofs on the energy performance of residential buildings in various Mediterranean cities using the DesignBuilder energy simulation software [20]. It was found that cool roofs could be considerably energy-efficient in the central and southern Mediterranean areas, particularly in insulated houses, where the increase of heating demand is limited. Further on, Gagliano et al. [33] investigated the thermal and environmental behavior of cool roofs, green roofs, and traditional roofs using numerical simulation. They found that both green and cool roofs can substantially contribute to energy saving and bring environmental benefits compared to highly-insulated typical roofs, which require thick insulation in comparison to cool roofs and green roofs to have better performance.

Cool roofs and reflective coatings, despite of being effective in terms of reducing the cooling thermal loads in buildings and decreasing the UHI, can suffer from extreme thermal stress which negatively affects their lifespan and workability [22]. In fact, aging and weathering can reduce the solar reflectance of cool roofing materials. High temperatures can accelerate damaging chemical reactions and degradation in materials, cause loss of volatile components, and soften some polymers. Temperature fluctuations caused by solar radiation and weather conditions, either gradual or sudden can create thermal stress due to differential thermal expansion [21].

By the advent of technology and advancement in material science, new doors have been opened towards innovative design in the field of building science and renewable energies to achieve further energy efficiency in these sectors. Thermal energy storage (TES) is a promising technology that can enhance the energy efficiency in the building and industry sectors [23]. Particularly, TES is a technology which can lead to a low-carbon future by reducing the energy use in buildings due to their high thermal capacity and their capability to create a balance between diurnal and nocturnal energy demand [24]. TES materials can store a high amount of energy in terms of sensible heat and latent heat. Materials used for latent heat storage are known as phase change materials (PCM) [25–30]. PCMs are distinguished because of their high latent heat capacity which allows them to accumulate a high amount of energy in small temperature intervals resulting in a considerable increase in the thermal mass of building components or the building envelope when incorporated in it [31–33].

Cool roof by itself is an innovative technology; however, when applied together with PCM can overcome some of its weaknesses, specifically, heat stress due to solar radiation and ambient temperature. So far, however, there has been little discussion about durability enhancement of a cool roof membrane using PCM in the literature.

As an example, in a recent study, Pisello et al. [22] developed a new composite material made of a polyurethane liquid water resistant cool membrane enhanced with non-encapsulated PCM melting at 25 °C and with 148 kJ/kg heating of fusion, acting as shape stabilized thermal buffer additive. Afterwards, they experimentally analyzed the influence of TES on decreasing the thermal fluctuations of the polyurethane cool roof membrane under solar radiation hitting building roof surfaces. Their results showed that inclusion of PCM could improve the spectral reflectance in the near infrared region of the solar spectrum up to 10%, and could maintain the required flexibility of the membrane together with its superficial finishing characteristics.

In another study, Roman et al. [34] compared the application of a cool roof and PCM in terms of UHI reduction and minimizing the heat flux entering from roof surfaces into the building. Their simulation results showed that the cool roof technology can effectively reduce the UHI, where the PCM technology can considerably reduce heat fluxes entering from roof surface into the building. In addition, they added that the combination of an asphalt roof with a PCM layer can be an effective solution to scale down UHI effects.

Similarly, a simulation-based study carried out by Pisello et al. [35] compared four different roofing technologies with regards to their cooling energy benefits. Their solutions included roof covered with a bitumen sheet membrane, a roof covered with a cool membrane, a PCM-integrated cool roof membrane, and a PCM-integrated bitumen membrane. It was concluded that a PCM-integrated cool roof membrane can reduce the cooling energy use by about 11%, whilst a PCM-integrated bitumen membrane can decrease the cooling needs up to 12.6% compared to the prototype with only bitumen membrane.

The literature review carried out shows that combining cool roof and PCM innovative technologies can offer substantial cooling energy savings, and further on, can enhance the performance of the cool roof membrane. Actually, a trade-off between these two technologies can bring benefits from both the cool roof technology and PCM technology. In fact, the cool roof technology reduces solar heat gains into the building through their highly reflexive surfaces and accordingly decrease UHI phenomenon, and on the other hand, the PCM technology can store a high amount of heat coming from roof surface and more importantly moderate the temperature fluctuations in the cool roof membrane.

However, to the best authors knowledge, no report has been found so far using numerical simulation and optimization to find out the optimum PCM melting temperature to reduce cool roof membrane heat stress, and to improve the overall energy performance of the building. Actually, an important question that needs to be asked, however, is how the application of the cool roof together with PCM can influence the HVAC requirements in a building.

Thus, in the present study, simulation-based optimization will be used to optimize the PCM melting temperature when implemented together with polyurethane-based cool roof membrane, on one hand, to decrease the deteriorating heat stress on the cool roof membrane, and on the other hand, to reduce the annual HVAC energy use under different warm temperature climate regions.

2. Methodology

2.1. Reference building prototype

To implement the new cool roof and PCM passive strategies, a multi-family residential apartment was selected from ASHRAE Standard 90.1–2013 prototype building models and slightly modified [36]. The ASHRAE Standard 90.1 prototype building models were developed by the Pacific Northwest National Laboratory in

Table 1
Roof construction of the reference building.

Layers	Material	D (m)	λ (W/m K)	ρ (kg/m^3)	C_p (kJ/kg K)	R (W/m^2 K)
1	Polyurethane cool roof membrane	0.006	0.305	1144	1.381	–
2	Insulation	–	–	–	–	0.0299
3	Gypsum board	0.0127	0.1600	800	1.090	–

Table 2
Roof construction of CR+PCM prototype building.

Layers	Material	D (m)	λ (W/m K)	ρ (kg/m^3)	C_p (kJ/kg K)	R (W/m^2 K)	h(kJ/kg)
1	Polyurethane cool roof membrane	0.006	0.305	1144	1.381	–	–
2	PCM	0.02	0.2	880	2.000	–	160
3	Insulation	–	–	–	–	0.0299	–
4	Gypsum board	0.0127	0.1600	800	1.090	–	–

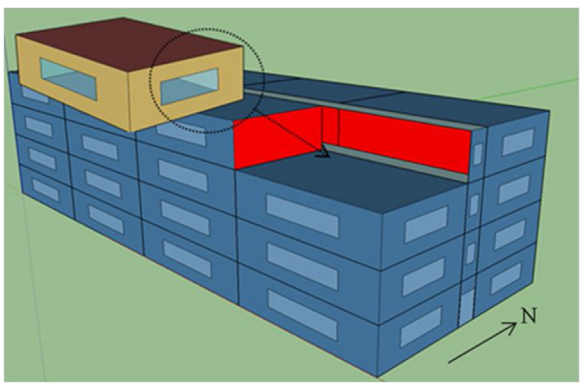


Fig. 1. Reference building prototype.

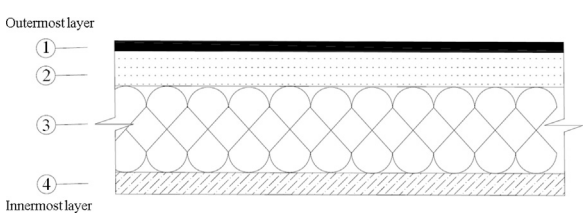


Fig. 2. Structural section of the roof construction of CR+PCM prototype building.

support of the U.S. Department of Energy (DOE) Building Energy Codes Program. These building prototypes are simulated in different climate zones and could be mapped to other climate regions for international use [37]. The mid-rise apartment building is a 3100 m^2 four-story building (Fig. 1).

Each level has four conditioned residential units and a corridor, however, the first floor has an office zone which has a different occupancy period. The building has a rectangular shape (46.32 m × 16.91 m), with aspect ratio of 2.74, window-to-wall ratio of 20%, and floor-to-ceiling height of 3 m. The whole ceiling is insulated and exterior walls are steel-framed. To add the cool roof membrane and the PCM layer into the building roof, the building envelope was slightly modified. Table 1 and Table 2 show the roof construction properties of the reference building with only cool roof membrane (reference) and the building prototype enhanced with cool roof and PCM technologies (CR + PCM), respectively. The properties of the cool roof membrane were derived from the experimental study already performed by Pisello et al. [38]. The white cool roof membrane has 30% optimized white paste and presents a high solar reflectance value of above 85% (300–2500 nm). Also, the structural section of the CR + PCM is illustrated in Fig. 2. In the present study, two macro-encapsulated panels of Rubitherm [39] with total thickness of 20 mm were considered. These panels are

Fig. 3. Rubitherm CSM PCM panel [42].

available in two thicknesses of 10 mm and 15 mm weighting 0.5 kg per panel filled with RT PCM. The storage capacity of a 10 mm of CSM panel is equivalent to 46 Wh/kg. Adding more than 20 mm of PCM may help to further decrease the cool roof membrane thermal stress, but it may create melting and freezing cycle issues.

It should be noted that, since almost all zones with occupants of the building prototype are similar, in the present study, only one zone of the building prototype was considered for simulation to reduce the computational cost of simulations (Fig. 1). The roof and external walls of this zone are exposed to outdoor boundary condition and the interior partitions are considered to be adiabatic.

2.2. PCM characterization

In the present study, Rubitherm CSM containing RT50 PCM [41] was used (Fig. 3). This macroencapsulated PCM features considerable latent heat capacity in narrow temperature ranges, and the PCM can be filled in with different temperatures depending on the application and desired melting range. Moreover, the non-corrosive aluminium case creates high heat transfer between the CSM surface and outter boundaries. Another advantage of CSM macroencapsulated PCM is that it can be directly integrated into existing envelopes.

To analyze the PCM impact on the building envelope, the enthalpy-temperature (h-T) curve of the selected PCM has to be introduced into the numerical model. In this study, the methodology which was proposed by Feustel (Eq. (1) [40] was used to create the h-T curve of the PCM, using physical properties of Rubitherm CSM containing RT50 PCM (Table 3):

$$h(T) = c_{p,const}T + \frac{h_2 - h_1}{2} \times \left\{ 1 + tanh\left[\frac{2\beta}{\tau}(T - T_m)\right]\right\} \quad (1)$$

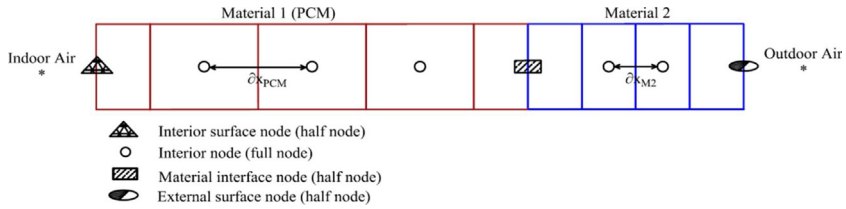


Fig. 4. One-Dimensional node mapping for conduction finite difference model in EnergyPlus, adopted from [52].
*NB: CR: cool roof; No CR case is a built-up roofing with solar reflectance of 0.65.

Table 3
Physical properties of Rubitherm CSM containing RT50 pure PCM [41].

Physical property	Value
Specific heat	2 kJ/kg K
Thermal conductivity (both phases)	0.20 W/m·K
Melting area	45–51 °C
Heat storage capacity (Combination of latent and sensible heat in a temperature range of 43 °C–58 °C)	160 kJ/kg
Maximum operation temperature	70 °C

where c_p is specific heat [kJ/kg·K], T temperature [°C], h specific enthalpy [kJ/kg], β inclination [–], τ width of the melting zone [K], and T_m melting temperature [°C].

To analyze the influence of various PCM peak melting temperature on the heat stress or temperature fluctuations reduction of the cool roof membrane, hypothetical PCM peak melting temperatures were considered from 10 °C to 50 °C with reference temperature at −20 °C and melting range of 4 °C. Moreover, the density change of the PCM due to liquid and solid transition was negligible and the PCM enthalpy was considered constant. Since a wide range of PCM melting temperature should be studied and this requires a considerable number of simulation and optimization, a methodology which was proposed by Saffari et al. [43] was used to iteratively select the PCM h-T curve which decreases the time-consuming process of h-T curve introduction to the simulation program at the beginning of each simulation with different PCM peak melting points, so that, simulation and optimization are continued until the optimum h-T curve is found.

2.3. Air conditioning system

A packaged terminal heat pump with constant volume fan control, direction expansion (DX) cooling coil, and electric heat pump according to baseline building HVAC system types recommendations of ANSI/ASHRAE/IES Standard 90.1–2013 [44] was selected to simulate the energy needs in the building. HVAC system schedules were matched to the occupancy schedules, and to control the indoor air quality, for all zones, a dual set point thermostat with dead-band operative temperature control was selected according to the recommended indoor temperatures for energy calculations of BS EN 15251 [44]. The thermostat control was set to 20 °C for heating and 26 °C for cooling, as recommended for residential buildings and living spaces. Furthermore, relative humidity ratios for dehumidification and humidification were considered to be 60% and 25%, respectively, within the recommended design criteria of BS EN 15251 [44] for the humidity in occupied spaces.

2.4. Dynamic energy simulation

EnergyPlus v8.7 [45] was used to carry out the simulations on an Intel(R) Core(TM) i7–3540 M processor at 3.00 GHz with 8.00 Gigabyte memory running EnergyPlus 8.7.0 under Windows 7 Professional x86_64 operation system.

EnergyPlus whole-building energy simulation software is a powerful building energy and comfort simulation tool for modelling the heat transfer in the building envelope, the energy requirements of the building, and human thermal comfort. EnergyPlus uses both BLAST and DOE-2 programs. It has numerous highlighted characteristics such as heat balance load calculations, integrated loads, system and plant calculations in same time step, user-configurable HVAC system description, simple input and output data formats to facilitate the virtualization of the results [46], simulation of PCM and materials with variable thermal conductivity [47]. In addition, new modules and/or control strategies could be developed and integrated into the program as subroutines using energy management system (EMS) [48]. EnergyPlus uses a conduction finite difference (CondFD) algorithm to simulate PCM in the building envelope. In this algorithm the building envelope is discretized into various nodes (Fig. 4) which could be selected optionally depending on the boundaries and required accuracy. Then, the algorithm numerically solves the heat transfer equations using Crank-Nicholson or fully implicit finite difference methods (FDM) which could be selected by the user [49–51]. The CondFD method is coupled with an h-T function to include the specific heat change due to phase change process which reads enthalpies at different temperatures introduced by the user. Afterwards, since an iterative implicit scheme is used in CondFD algorithm, the node enthalpies get updated at each iteration and, then, they are used to make a variable c_p.

Many studies have been carried out to validate EnergyPlus algorithms. For example, the PCM algorithms were verified and validated against analytical verification (Stefan Problem), comparative testing (against Heating 7.3) and empirical validation (DuPont Hotbox) by Tabares-Velasco et al. [53,54]. According to their findings, some cautions should be taken into account when simulating PCM such as: (1) short time steps equal or less than 3 min should be used; (2) PCM with strong hysteresis could not be accurately simulated; and (3) if accurate hourly analysis is needed, smaller node space (equal to 1/3 of the default value) should be used [70]. Further on, in many studies, simulation results obtained by PCM model of EnergyPlus were validated against experimental data. As an example, Auzeby et al. [55] validated the simulation results of indoor air temperature of their building model with field measured data from a greenhouse and a maximum error of 2.6 °C, mean error of 0.1 °C, and standard deviation of 0.7 °C were found. Besides, Sage-Lauck et al. [56] validated their building energy model against measured data. Comparison of the observed room air temperature of the west unit of a house with the simulated room air temperature in a summer month showed 1.6 °C and 1.0 °C root mean squared error (RMSE) for hourly average zone temperature and daily maximum temperature, respectively. The disparities were considered to be due to uncertainties in occupants behavior or occupancy schedule. In the current study, the simulation time step in all models was set to 1 min and the node discretization of 3 was selected, otherwise inaccuracies may happen in simulation results [54].

2.5. Optimization

A generic optimization program (GenOpt v3.1.1) [57] was selected because of its capabilities in solving optimization problems corresponding to the building energy performance, where parametric analysis is not feasible or efficient. GenOpt has gained increasing interest among authors [58,59] for its flexibility to interface with any simulation program that calculates the objective function with no need to modify or recompile either program, taking into account that the simulation program reads its input from text files and writes its output to text files; such as EnergyPlus. Optimization algorithms in GenOpt algorithm library could be selected optionally by user based on their need, or even new algorithms could be implemented into the program by advanced users. GenOpt has been developed to efficiently find the independent variables that yield better performance of physical systems. It performs optimization of a user-defined cost function such as, annual energy use, thermal comfort, etc. using various numerical optimization algorithms that could be chosen by the user.

The cost function measures a quantity that should be minimized. Generally, the optimization problems addressed by GenOpt could be described as shown in Eq. (2):

$$\min_{x \in X} f(x) \tag{2}$$

where $f : X \to \mathbb{R}$ is the user-specified objective function, X is a user-specified constraint set for x, which consists of all possible design alternatives, and the cost function $f(\cdot)$ measures the system performance.

In the present study, the optimization design parameter is the peak melting temperature of the PCM layer of the roof, which is an independent continuous variable and can take any value on the real line, and is box-constrained between lower and upper bounds as shown in Eq. (3):

$$\mathrm{x} = \left\{ \mathrm{x} \in \mathbb{R}^n | l^i \le x^i \le u^i, i \in \left\{1, \ldots, n\right\} \right\}, \tag{3}$$

subject to constraint: $-\infty \le \mathrm{l}^i < \mathrm{u}^i \le \infty$ for $i \in \left\{1, \ldots, n\right\}$, where $f : \mathbb{R}^n \to \mathbb{R}$ is the objective function, $x \in X \subset \mathbb{R}^n$ is the set of design parameters, X is the possible set for x,$l \in \mathbb{R}^n$ is the lower bound, and $u \in \mathbb{R}^n$ is the upper bound for design options.

In the current study, two different optimization scenarios were taken into account. In Scenario 1, it is intended to optimize the PCM peak melting temperature to reduce the annual sum of mean daily temperature of the cool roof membrane external surface. To do this, Eq. (4) was implemented into the EnergyPlus subroutine using EnergyPlus Runtime Language and EMS. Eventually, the optimization algorithm minimizes the heat stress function as shown in Eq. (5).

$$\overline{\Delta T}_{annual} = \frac{1}{n}\sum_{i=1}^{n}\left[\frac{1}{h}\sum_{t=1}^{h}(T_{max} - T_{min})\right] \tag{4}$$

$$f_{ts}(x) = \overline{\Delta T}_{annual}(x) \tag{5}$$

where $\overline{\Delta T}_{annual}$ is the annual sum of mean daily temperature of the cool roof, n number of days in a year, h number of hours in a day, T_{max} maximum temperature recorded in a day, T_{min} minimum temperature recorded in a day, $f_{ts}(x)$ the cost function to reduce the thermal stress of the cool roof membrane.

On the other hand, the objective in Scenario 2 is to find an optimum PCM peak melting point to minimize the total annual electricity consumption of the heat pump. For this reason, the annual total electricity consumption of the heat pump was defined in the output parameters of EnergyPlus (Eq. (6)) and then linked with GenOpt as the final objective function to be minimized (Eq. (7)):

$$E_{tot} = E_c + E_h + E_f \tag{6}$$

$$f_{tot}(x) = E_{tot}(x) \tag{7}$$

where E_{tot} is annual total electricity consumption of the heat pump, E_c, E_h, and E_f are annual cooling, heating, and fan electricity consumption of the heat pump, respectively, f_{tot} (x) the cost function to reduce the annual total electric energy use of the heat pump.

To minimize the above-mentioned objective functions and solve the optimization problem, a hybrid optimization method based on generalized pattern search (GPS) [60] and particle swarm optimization (PSO) [61] algorithms, was selected. The GPS method compares each trial solution with the best previous solution. Further discussion can be found in Lewis et al. [62]. On the other hand, PSO algorithms are from a family of *meta*-heuristic population-based and stochastic optimization techniques initially proposed by Kennedy and Eberhart [61]. This hybrid global optimization algorithm initially performs a PSO on a mesh according to the user-defined number of generations $n_g \in N$. Then, it starts the Hooke-Jeeves GPS algorithm, using the continuous independent variables of the particle with the lowest cost function value. The advantage of this hybrid algorithm is since PSO algorithm is a global optimization algorithm, it is less likely to get trapped into the local minima, compared to Hooke-Jeeves GPS algorithm [63].

In the present study, von Neumann neighborhood topology, a population size of 25 particles with a maximum of 1500 generations, a seed of 1, a cognitive acceleration constant of 2.8, a social acceleration constant of 1.3, a velocity clamping with a maximum velocity gain of 4 and a constriction gain of 0.5 were defined in the optimization algorithm [63,64].

2.6. Köppen-Geiger climate classification

The updated Köppen-Geiger [65] main climates classification is used as a reference to the selected climates in the present paper. In this classification there are five letters to classify the world into five major climate regions according to the average annual precipitation, average monthly precipitation, and average monthly temperature which are A: equatorial, B: arid, C: warm temperate, D: snow, and E: polar. Moreover, the level of precipitation is defined as W: desert, S: steppe, f: fully humid, s: summer dry, w: winter dry, and m: monsoonal. More details are provided regarding temperature as h: hot arid, k: cold arid, a: hot summer, b: warm summer, c: cool summer, d: extremely continental, and F: polar frost.

Further on, as already discussed by Saffari et al. [43] other factors such as wind characteristics, solar radiation, precipitation intensity, amount of cloud cover, daily temperature extremes, and altitude above sea level should be taken into account when comparing the results in different climate regions. For instance, by the increase of global solar irradiance, the solar heat gains on the building surfaces and specifically roof surface increase that directly impacts the heat transfer into the building envelopes and the energy balance of the whole system.

3. Results

3.1. PCM melting temperature optimization to reduce cool roof membrane thermal stress

In this section, the simulation-based optimization results to reduce the cool roof membrane thermal stress due to temperature fluctuations are presented (Scenario 1). From the presented results it could be generalized that in all studied climate zones the utilization of PCM together with cool roof membrane can effectively

Table 4
Optimum PCM melting temperatures to reduce the thermal stress of the cool roof membrane (Scenario 1).

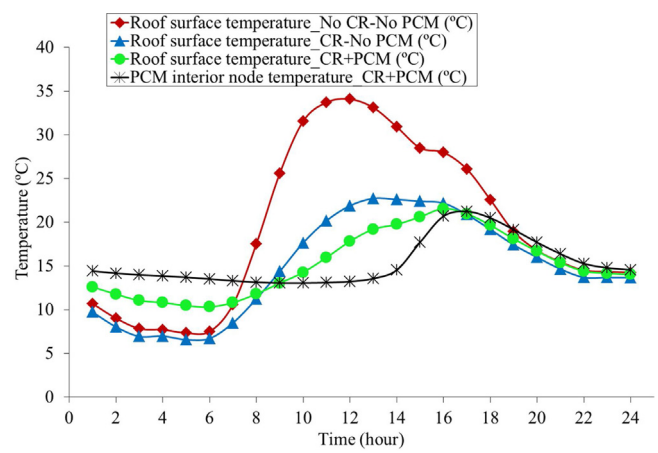
Köppen Geiger climate zone	City	$\overline{\Delta T}_{annual}$ (°C)		$\overline{\Delta T}_{annual}$ reduction(%)	T_{peak} PCM (°C)	Eh savings (kWh)	Ec savings (kWh)	Etot savings (kWh)
		Reference	CR+PCM					
BSk	Albuquerque	17.7	13.8	22.2	17.5	14.7	8.2	23.9
BSk	Midland	17.6	14.3	18.5	11.3	54.5	2.6	57.8
BSk	Ceduna	15.7	11.4	27.2	13.8	43.3	1.6	45.7
BSk	Del Rio	12.4	10.0	19.9	23.8	7.0	−1.4	6.3
BSh	Abu Dhabi	17.1	12.6	26.2	30.0	0.1	−2.4	−2.5
BWh	Phoenix	18.0	14.0	22.3	17.5	11.0	13.7	25.2
BWh	Las Vegas	16.4	13.4	18.2	10.0	29.9	4.9	35.6
BWh	Brisbane	14.0	9.9	29.1	20.0	10.8	6.9	17.8
BWk	Madrid	16.2	12.1	25.1	15.0	29.4	7.1	37.3
Cfa	Tokyo	13.6	10.7	21.0	15.0	39.6	1.3	41.8
Cfa	Perugia	10.7	7.6	28.6	17.5	−3.0	4.7	2.8
Cfa	Milan	14.4	10.7	25.8	16.3	21.0	5.9	28.2
Cfa	Berlin	9.4	7.1	24.3	13.8	18.0	1.5	20.9
Cfa	Johannesburg	15.5	10.3	33.6	16.3	35.3	0.8	36.7
Cfb	Paris	10.3	7.6	25.5	15.0	28.6	2.5	31.8
Cfb	Ankara	15.7	11.6	26.2	12.5	−23.2	3.1	−17.4
Cfb	Tehran	14.3	10.9	23.8	26.3	4.0	2.6	6.8
Csb	Seville	17.3	12.7	27.0	17.5	15.1	9.1	24.7
Csa	Barcelona	11.6	8.8	23.9	10.0	28.2	−0.1	28.6
Csa	Cagliari	11.6	8.7	25.0	20.0	7.6	4.8	12.7
Csa	Palermo	8.9	6.8	24.0	21.3	7.2	2.0	9.4
Csa	Nice	9.7	7.7	20.7	20.0	12.0	4.6	17.1
Csa	Adelaide	12.9	9.3	28.3	15.0	33.0	2.3	36.0
Cwa	Hong Kong	7.5	5.4	28.4	26.3	1.3	−3.3	−4.8

reduce the annual average thermal stress of the cool roof membrane. The results presented in Table 4 show from 18% to about 30% reduction in the annual average thermal stress of the cool roof membrane surface. Additionally, it can be seen that the optimum PCM peak melting temperature to reduce the annual thermal stress of the cool roof membrane ranges from 10 °C to 30 °C. The authors of the present study would like to highlight that the benefits of PCM to reduce the thermal stress of the cool roof membrane is substantial in all climates if appropriate and optimized PCM melting temperature is used. This shows the high importance of numerical optimization when designing such advanced systems.

For example, in Abu Dhabi, Madrid, and Hong Kong about 26% (4.5 °C), 25% (4.1 °C), and 28% (2.1 °C) of the cool roof thermal stress could be reduced by using PCM with peak melting at 30 °C, 15 °C, and 26 °C, respectively.

Moreover, it can be seen that some energy savings could be achieved in all climates except Abu Dhabi, Ankara, and Hong Kong. Further explanations for this fact could be the elevated outdoor temperature during night which prevents the PCM of being solidified. This could be seen in annual cooling energy savings in AbuDhabi which are −2.4 kWh.

To have a more detailed analysis of the influence of PCM on the thermal stress reduction of the cool roof membrane, the simulation-based optimization results for a summer day under Madrid climate condition is illustrated in Fig. 5. It can be seen that in case of not using cool roof nor PCM the roof surface temperature reached about 35 °C, however, when the cool roof technology was used this maximum surface temperature reduced to below 25 °C. Then, when the PCM with peak melting of 15 °C was added into the roof construction the cool roof surface the temperature scaled down in hours with high solar radiation (09:00–16:00). The PCM interior node temperature shows the evolution of charging and discharging cycles of the PCM over 24 h. Furthermore, it should be added that in case of No CR-No PCM the daily thermal stress of the roof surface was about 27 °C, however, by adding a cool roof, this temperatures difference was reduced to 16 °C, and eventually when PCM was incorporated into the roof construction together with the cool roof technology the daily thermal stress decreased to 11 °C (in this specific summer day).



*NB: CR: cool roof; No CR case is a built-up roofing with solar reflectance of 0.65.

Fig. 5. Temperature profile of the roof construction; example of in a summer day (August 26th) in Madrid.

3.2. PCM melting temperature optimization to reduce annual total energy use

The results presented in Table 5 show the optimization results when selecting the optimum PCM peak melting temperature to reduce the annual electrical energy use of HVAC system (Scenario 2). From the results it could be seen that in all climates the annual total electricity could be reduced by applying macroencapsulated PCM on the roof construction together with a cool roof. These savings range from 6 kWh to 60 kWh.

For instance, in Ceduna, Brisbane, and Seville annual energy savings of 45 kWh, 28 kWh, and 37 kWh could be achieved by using PCM with peak melting temperatures at 13.8 °C, 13.8 °C, and 10 °C, respectively.

Table 5
Optimum PCM melting temperatures to reduce the annual heat pump energy use.

Köppen Geiger climate zone	City	$\overline{\Delta T}_{annual}$ (°C)		$\overline{\Delta T}_{annual}$ reduction (%)	T_{peak} PCM (°C)	Eh savings (kWh)	Ec savings (kWh)	Etot savings
		Reference	CR + PCM					
BSk	Albuquerque	18	14.3	19.4	10.0	30.6	4.1	35.6
BSk	Midland	18	14.3	18.5	10.0	57.0	2.4	60.1
BSk	Ceduna	16	11.4	27.2	13.8	43.3	1.6	45.7
BSh	Del Rio	12	10.4	16.7	11.3	23.6	0.0	24.1
BWh	Abu Dhabi	17	13.5	21.1	20.0	0.1	12.0	12.3
BWh	Phoenix	18	14.8	17.4	10.0	23.3	6.7	30.6
BWk	Las Vegas	16	13.4	18.2	10.0	29.9	4.9	35.6
Cfa	Brisbane	14	10.3	26.2	13.8	26.7	1.5	28.5
Cfa	Madrid	16	12.4	23.2	10.0	39.1	5.0	44.9
Cfa	Tokyo	14	10.8	20.5	10.0	47.8	0.7	49.4
Cfa	Perugia	11	8.1	24.0	12.5	2.7	2.6	6.3
Cfa	Milan	14	10.9	24.0	10.0	34.8	3.0	39.3
Cfb	Berlin	9	7.1	24.3	13.8	18.0	1.5	20.9
Cfb	Johannesburg	15	10.3	33.4	15.0	38.3	0.5	39.4
Cfb	Paris	10	7.8	24.3	12.5	30.6	1.3	32.6
Csb	Ankara	16	12.4	20.5	20.0	51.5	5.5	57.2
Csa	Tehran	14	11.8	17.4	10.0	21.7	2.3	24.5
Csa	Seville	17	13.4	22.8	10.0	31.9	4.3	36.8
Csa	Barcelona	12	8.8	23.9	10.0	28.2	−0.1	28.6
Csa	Cagliari	12	9.0	22.3	10.0	22.8	1.6	24.7
Csa	Palermo	9	7.0	21.2	12.5	15.5	−0.4	15.4
Csa	Nice	10	7.7	20.4	11.3	20.6	−0.3	20.8
Csa	Adelaide	13	9.3	28.2	13.8	34.9	1.5	37.1
Cwa	Hong Kong	7	6.0	19.8	15.0	9.9	−2.5	7.5

Generally, it can be seen that to reduce the annual energy use in the building the optimum PCM has lower peak melting temperature than when it is used to reduce the thermal stress of the cool roof. This is because of energy requirements in the heating period, since in this period PCM with lower temperature can be melted easier and provide more benefits. For this reason in climates with high heating energy requirements such as Milan and Madrid, the optimum PCM melting temperature to reduce the annual energy use is close to 10 °C, and in climates with higher cooling energy requirements such as Abu Dhabi the optimum PCM melting temperature is higher (20 °C). These results are in close agreement with previous findings [43].

Another interesting fact that could be seen from these results is that, despite of optimizing the annual energy use, in all cities annual thermal stress reduction from 16% to 27% could be achieved. These thermal stress reductions of the cool roof membrane despite of being, in general, lower that the results presented in the last section when the melting temperature was optimized to reduce the thermal stress of the cool roof membrane, but still offer considerable benefits.

3.3. Discussion

Herein, one should take into account that two different objectives were considered and optimized using single-objective optimization method. The objectives were to minimize the annual thermal stress of the cool roof membrane and to reduce the annual energy use. It has been seen that optimizing the thermal stress of the cool roof membrane can offer interesting reductions in thermal stress in the cool roof membrane thanks to the PCM technology and optimized melting temperature, with some energy savings in all cities except some regions with negative annual energy savings.

On the other hand, when the objective was to reduce the annual energy use, it was observed that apart from energy benefits, notable reductions in the thermal stress of the cool roof membrane could be achieved. So that, from these results it can be said that optimizing the annual energy use could be energy-beneficial with important effects on reducing the thermal stress on the cool roof membrane.

Further on, it should be considered that in the present study the PCM was only considered in the roof construction and the energy saving benefits due to the application of PCM with optimized melting temperature may increase by applying the PCM technology as an integrated design into the building envelope.

4. Conclusions

Cool roof technology is an effective way to reduce the cooling energy loads in the building environment and to scale down the UHI effects in cities. Further on, higher thermal comfort could be achieved for occupants. Cool roofs and reflective coatings can suffer from high thermal stress which can reduce the performance of the cool roof membrane. In the current study, a simulation-based optimization was carried out to investigate, on one hand, the benefits of PCM to reduce the thermal stress of the cool roof membrane, and on the other hand, its influence on the annual total energy performance.

The optimization results show that, in case of thermal stress optimization, under all studied climate zones, the application of PCM with meling temperature ranging from 10 °C to 30 °C with cool roof membrane as a thermal stabilizer layer can considerably decrease the annual thermal stress of the cool roof membrane (from 18% to 30%).

On the other hand, in case of optimizing only the annual energy use, higher energy savings from 1% to 6% could be achieved by using PCM with melting temperature ranging from 10 °C to 20 °C, however, also good reductions in the thermal stress of the cool roof membrane can be achieved.

In general, if the objective is to protect the cool roof membrane from severe thermal stress, especially in summer, PCM with higher melting range is recommended for reducing the thermal stress of the cool roof membrane since it can be melted with elevated outdoor temperature and high solar radiation and during night when the outdoor temperature drops down it can be solidified, otherwise, if PCM with lower melting range is selected it could be hardly discharged during night. On the other hand, if the objective is to gain

more annual energy savings, PCM with lower melting temperature is more appropriate to reduce the annual energy use since in winter with lower outdoor temperature and solar radiation it can store the solar energy during day and release it later when the outdoor temperature decreases.

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References

[1] IEA, Energy Technology Perspectives, IEA, 2016, pp. 14.
[2] European Commission, Technical Guidance-Financing the Energy Renovation of Buildings with Cohesion Policy Funding, European Commission, 2014.
[3] International Energy Agency, Energy Technology Perspectives 2012 Pathways to a Clean Energy System, International Energy Agency, 2012.
[4] The European Union expained, Energy, Sustainable, Secure and Affordable Energy for Europeans, European Commissioner for Energy, 2014.
[5] I. Nolte, D. Strong, Europe's Buildings Under the Microscope-A Country-by-country Review of the Energy Performance of Buildings, Buildings Performance Institute Europe (BPIE) Copyright, 2011.
[6] M. Saffari, A. de Gracia, S. Ushak, L.F. Cabeza, Passive cooling of buildings with phase change materials using whole-building energy simulation tools: a review, Renewable Sustain. Energy Rev. 80 (2017) 1239–1255.
[7] H. Akbari, C. Cartalis, D. Kolokotsa, A. Muscio, A.L. Pisello, F. Rossi, M. Santamouris, A. Synnefa, N.H. Wong, M. Zinzi, Local climate change and urban heat island mitigation techniques –the state of the art, J. Civil Eng. Manag. 22 (2016) 1–16.
[8] M. Iten, S. Liu, A. Shukla, A review on the air-PCM-TES application for free cooling and heating in the buildings, Renewable Sustain. Energy Rev. 61 (2016) 175–186.
[9] H. Omrany, A. Ghaffarianhoseini, A. Ghaffarianhoseini, K. Raahemifar, J. Tookey, Application of passive wall systems for improving the energy efficiency in buildings: a comprehensive review, Renewable Sustain. Energy Rev. 62 (2016) 1252–1269.
[10] International Energy Agency, Technology Roadmap: Energy Efficient Building Envelopes, Oecd, 2013.
[11] A. Cabeza, C. Castell, A. Barreneche, A.I. de Gracia, Materials used as PCM in thermal energy storage in buildings: a review, Renewable Sustain. Energy Rev. 15 (2011) 1675–1695.
[12] C. Piselli, M. Saffari, A. de Gracia, A.L. Pisello, F. Cotana, L.F. Cabeza, Optimization of roof solar reflectance under different climate conditions occupancy, building configuration and energy systems, Energy Build. 151 (2017) 81–97.
[13] A. Ganguly, D. Chowdhury, S. Neogi, Performance of building roofs on energy efficiency –a review, Energy Procedia 90 (2016) 200–208.
[14] J. Testa, M. Krarti, A review of benefits and limitations of static and switchable cool roof systems, Renewable Sustain. Energy Rev. 77 (2017) 451–460.
[15] H. Akbari, H.D. Matthews, Global cooling updates: reflective roofs and pavements, Energy Build. 55 (2012) 2–6.
[16] A.L. Pisello, 9–High-albedo roof coatings for reducing building cooling needs, in: Eco-Efficient Materials for Mitigating Building Cooling Needs, 2015, pp. 243–268.
[17] K.M. Al-Obaidi, M. Ismail, A.M. Abdul Rahman, Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: a literature review, Fron. Archit. Res. 3 (2014) 283–297.
[18] G.M. Stavrakakis, A.V. Androutsopoulos, J. Vyörykkä, Experimental and numerical assessment of cool-roof impact on thermal and energy performance of a school building in Greece, Energy Build. 130 (2016) 64–84.
[19] M. Zinzi, S. Agnoli, Cool and green roofs An energy and comfort comparison between passive cooling and mitigation urban heat island techniques for residential buildings in the Mediterranean region, Energy Build. 55 (2012) 66–76.
[20] DesignBuilder Software Ltd – home, (n.d.). https://www.designbuilder.co.uk/ (Accessed 22 August 2017).
[21] P. Berdahl, H. Akbari, R. Levinson, W.A. Miller, Weathering of roofing materials – an overview, Constr. Build. Mater. 22 (2008) 423–433.
[22] A.L. Pisello, E. Fortunati, C. Fabiani, S. Mattioli, F. Dominici, L. Torre, L.F. Cabeza, F. Cotana, PCM for improving polyurethane-based cool roof membranes durability, Sol. Energy Mater. Sol. Cells 160 (2017) 34–42.
[23] A. de Gracia, L.F. Cabeza, Phase change materials and thermal energy storage for buildings, Energy Build. 103 (2015) 414–419.
[24] A. Cabeza, Thermal energy storage (TES) systems for cooling in residential buildings, in: L.F. Cabeza (Ed.), Advances in Thermal Energy Storage Systems, Elsevier, 2015, pp. 549–572.
[25] M.E. Barreneche, A.I. Navarro, L.F. Fernández, Improvement of the thermal inertia of building materials incorporating PCM. Evaluation in the macroscale, Appl. Energy 109 (2013) 428–432.
[26] L.F. Cabeza, I. Martorell, L. Miró, A.I. Fernández, C. Barreneche, Introduction to thermal energy storage (TES) systems, in: L.F. Cabeza (Ed.), Advances in Thermal Energy Storage Systems, Elsevier, United Kingdom, 2015, pp. 1–28.
[27] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, Prog. Mater. Sci. 65 (2014) 67–123.
[28] P. Tatsidjodoung, N. Le Pierrès, L. Luo, A review of potential materials for thermal energy storage in building applications, Renewable Sustain. Energy Rev. 18 (2013) 327–349.
[29] P. Arce, M. Medrano, A. Gil, E. Oró, L.F. Cabeza, Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe, Appl. Energy 88 (2011) 2764–2774.
[30] S. Wu, 4 – Heat energy storage and cooling in buildings, in: M.R. Hall (Ed.), Materials for Energy Efficiency and Thermal Comfort in Buildings, Woodhead Publishing, United Kingdom, 2010, pp. 101–126.
[31] A.M. Khudhair, M.M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Convers. Manage. 45 (2004) 263–275.
[32] M.M. Farid, A. Sherrif, 16– Phase change materials for energy storage and thermal comfort in buildings, in: M.R. Hall (Ed.), Materials for Energy Efficiency and Thermal Comfort in Buildings, Woodhead Publishing, United Kingdom, 2010, pp. 384–398.
[33] M. Saffari, A. de Gracia, S. Ushak, L.F. Cabeza, Economic impact of integrating PCM as passive system in buildings using Fanger comfort model, Energy Build. 112 (2016) 159–172.
[34] K.K. Roman, T. O'Brien, J.B. Alvey, O. Woo, Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities, Energy 96 (2016) 103–117.
[35] A.L. Pisello, V.L. Castaldo, F. Cotana, Dynamic thermal-energy performance analysis of a prototype building with integrated phase change materials, Energy Procedia 81 (2015) 82–88.
[36] ASHRAE, 90.1 Prototype Building Models Mid-rise Apartment, 2016, https://www.energycodes.gov/901-prototype-building-models-mid-rise-apartment (Accessed 7 September 2016).
[37] B.A. Thornton, M.I. Rosenberg, E.E. Richman, W. Wang, Y. Xie, J. Zhang, H. Cho, V.V. Mendon, R.A. Athalye, B. Liu, Achieving the 30% Goal: Energy and Cost Savings Analysis of Ashrae Standard 90. 1–2010, 2011, http://www.osti.gov/scitech/biblio/1015277 (Accessed 23 August 2017).
[38] A.L. Pisello, V.L. Castaldo, G. Pignatta, F. Cotana, M. Santamouris, Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation, Energy Build. 114 (2016) 180–190.
[39] Rubitherm® Technologies GmbH, (2017). http://www.rubitherm.de/ (Accessed 4 February 2017).
[40] H.E. Feustel, C. Stetiu, Thermal Performance of Phase Change Wallboard for Residential Cooling Application, U.S. Department of Commerce National Technical Information Service, 1997.
[41] Rubitherm® Technologies GmbH, RT50 Data sheet, (2017). https://www.rubitherm.eu/media/products/datasheets/Techdata_-RT50_EN_31052016.PDF (Accessed 28 July 2017).
[42] Rubitherm® Technologies GmbH-CSM modules, (2017). http://www.rubitherm.de/english/pages/02h_air_heating_systems.htm (Accessed 16 August 2017).
[43] M. Saffari, A. De Gracia, C. Fernández, L.F. Cabeza, Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings, Appl. Energy 202 (2017) 420–434.
[44] BS EN 15251:2007, Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics Contents, (2007) 1–52.
[45] U.S. Department of Energy, US Department of Energy, EnergyPlus, Energy Efficiency and Renewable Energy, 2017, http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm (Accessed 31 July 2017).
[46] U.S. Department of Energy, EnergyPlus engineering reference: the reference to EnergyPlus calculations, in: US Department of Energy, 2016, pp. 1–1722.
[47] Guide for Module Developers Everything You Need to Know about Developing Modules and Modifying EnergyPlus, October. (2010).

[48] P.G. Ellis, P.A. Torcellini, D.B. Crawley, Simulation of Energy Management Systems in EnergyPlus, in: Build. Simul. 2007, U.S. Department of Commerce National Technical Information Service, 1346-1353, 2007.
[49] EnergyPlus, EnergyPlus v8.7 Input Output Reference: the Encyclopedic Reference to EnergyPlus Input and Output, (2017).
[50] P.C. Tabares-velasco, C. Christensen, M. Bianchi, C. Booten, Verification and Validation of EnergyPlus Conduction Finite Difference and Phase Change Material Models for Opaque Wall Assemblies, 2012.
[51] D.B. Crawley, C.O. Pedersen, F.C. Winkelmann, M.J. Witte, R.K. Strand, R.J. Liesen, W.F. Buhl, New, Energyplus: capable and Linked, J. Archit. Plann. Res. 21 (2004) 292–302.
[52] U.S. Department of Energy (DOE), EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations, U.S. Department of Energy (DOE), 2016, pp. 1444.
[53] P.C. Tabares-Velasco, C. Christensen, M. Bianchi, Verification and validation of EnergyPlus phase change material model for opaque wall assemblies, Build. Environ. 54 (2012) 186–196.
[54] M. Tabares-Velasco, P.C. Christensen, C. Bianchi, Alidation methodology to allow simulated peak reduction and energy performance analysis of residential building envelope with phase change materials, in: 2012 ASHRAE Annual Conference June 23–27, National Renewable Energy Laboratory, San Antonio, Texas, 2012.
[55] M. Auzeby, S. Wei, C. Underwood, J. Tindall, C. Chen, H. Ling, R. Buswell, Effectiveness of using phase change materials on reducing summer overheating issues in UK residential buildings with identification of influential factors, Energies 9 (2016) 605.
[56] J.S. Sage-Lauck, D.J. Sailor, Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building, Energy Build. 79 (2014) 32–40.
[57] M. Wetter, Design optimization with GenOpt, Build. Energy Simul. User News 21 (2000) 200 http://simulationresearch.lbl.gov/wetter/download/userNews-2000.pdf.
[58] S.J. Rempel, Optimization of passive cooling control thresholds with GenOpt and EnergyPlus, in: Simulation Series, The Society for Modeling and Simulation International, 2015, pp. 103–110.
[59] B.J. Futrell, E.C. Ozelkan, D. Brentrup, Optimizing complex building design for annual daylighting performance and evaluation of optimization algorithms, Energy Build. 92 (2015) 234–245.
[60] R. Hooke, T.A. Jeeves, Direct search solution of numerical and statistical problems, J. ACM 8 (1961) 212–229.
[61] J. Kennedy, R.C. Eberhart, Particle swarm optimization, in: Proceedings of IEEE International Conference on Neural Networks, Piscataway, NJ, 1995, pp. 1942–1948.
[62] R.M. Lewis, V. Torczon, M.W. Trosset, Direct search methods: then and now, J. Comput. Appl. Math. 124 (2000) 191–207.
[63] M. Wetter, GenOpt(R) Generic Optimization Program User Manual Version 3. 1.1, 2016.
[64] N. Soares, A.R. Gaspar, P. Santos, J.J. Costa, Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates, Energy Build. 70 (2014) 411–421.
[65] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the köppen-geiger climate classification updated, Meteorol. Z. 15 (2006) 259–263.