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Optimization of building envelope design for nZEBs in Mediterranean climate: Performance analysis of residential case study

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HIGHLIGHTS

- Dynamic simulation tool and multi-objective optimization algorithm are combined.
- Design criteria for residential nZEB in Mediterranean climate are discussed.
- Passive strategies for opaque and transparent building envelope are compared.
- PCM, cool roof, different walls' and window technologies, shading systems are examined.
- Minimization of energy demand is studied, by assuming discomfort as constraint.

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ABSTRACT

Design criteria for a residential nZEB in Mediterranean climate are discussed. The integrated design procedure focuses on the problem of a large number of available building variants concerning the building envelope. The aim is to search the ones that minimize winter and summer energy demand without compromising thermal comfort.

The adopted methodological approach combines the use of dynamic energy simulation tool (EnergyPlus), based on a one-dimensional conduction finite difference solution method, and a constrained multi-objective optimization algorithm. For four cities (Madrid, Nice, Naples, Athens), several passive strategies are compared: thermal properties of the building envelope, adoption of phase change materials with different melting temperatures, cool roof solutions, several window/wall ratio values, some external and internal shading systems. The results allow to evidence that it is difficult to understand the best trade-off between summer and winter performance, by assuring high standard of thermal comfort when the aim is to reach NZEB objectives in Mediterranean climate. However, some guidelines are indicated, starting from the discussed results.

1. Introduction: nZEBs in Mediterranean climate

Economic and environmental challenges have contributed to intensify, in recent years, national and international efforts to promote sustainable growth. Building sector can help to accelerate progress towards sustainable development through, for example, more sustainable use of natural resources, efficiency in the use of energy and valuation of ecosystem impacts [1].

Buildings are responsible for more than one third of the total energy use and associated greenhouse gas emissions, both in developed and developing countries [2]. While buildings embody significant environmental impact, they also represent one of the sectors where significant mitigations can be achieved at low cost for the society.

Residential and commercial buildings consume approximately 60% of the world's electricity [3]; in Europe, the residential sector requires 27% of the total energy and it contributes proportionally to the emission of CO_2 [4]. Some studies show the impact of energy efficiency measures related to refrigerators, washing machines, air conditioners, televisions and heating and cooling service [5,6]. Huang and Hwang [7], for residential apartments in Taipei, have

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Nomenclature

ΔE_c	percentage reduction of the cooling demand [%]
c_p	specific heat [J/kg K]
EER	energy efficiency ratio of chiller [$W_{thermal}/W_{electric}$]
f_d	decrement factor
g	solar factor [%]
M_s	thermal mass [kg/m^2]
PMV	predicted mean vote [–]
PPD	predicted percentage of dissatisfied [%]
s	thickness [m]
S/V	surface to volume ratio [m^{-1}]
T_f	melting temperature of PCM [°C]
T_{mr}	mean radiant temperature [°C]
T_o	operative temperature [°C]
U	stationary thermal transmittance [W/m^2 K]
U_g	glass thermal transmittance [W/m^2 K]
$U_{partition}$	thermal transmittance of partition [W/m^2 K]
U_r	thermal transmittance of roof slab [W/m^2 K]
U_{slab}	thermal transmittance of the slab on the ground [W/m^2 K]
U_w	thermal transmittance of wall [W/m^2 K]
WWR	window-to-wall ratio [%]
Y_{IE}	periodic thermal transmittance [W/m^2 K]
Ms	thermal mass of a building component [kg/m^2]

Greek letters

α_{solar}	solar absorptance [%]
$\varepsilon_{infrared}$	infrared emissivity [%]
λ	thermal conductivity [W/m K]
ρ	density [kg/m^3]
φ	time lag [h]
χ	internal areal heat capacity [kJ/m^2 K]

observed that cooling demand could increase of 31%, 59%, and 82% over current levels respectively for the 2020s, 2050s, and 2080s. Thus, they have underlined an urgent need to regulate the excessive use of cooling systems, also by remodeling existing buildings with passive design measures.

More in general, the results in terms of energy footprint show that the generalization of the living standards from the so-called highly developed countries to the rest of the world would require a substantial increase in the global energy use rates. Discussions and new solutions for energy efficiency in building sector are thus indisputable [7].

Recently, the aim to reduce energy consumption in buildings has led to Zero Energy Building (ZEB) goal. In Europe, the recast of Energy Performance of Buildings Directive (2010/31/EU) [8] requires that "Member States shall ensure that by 31 December 2020, all new buildings are nearly zero-energy buildings and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". According to EPBD recast, "nearly zero-energy building – nZEB" means an edifice that has a very high energy performance, and the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

The efforts done in these years through application of EU Directives on the energy efficiency have improved significantly the energy performances of new constructions (above all for what concerns the behavior in the heating season) and partially of the stock of existing buildings, but the path to fully achieve the nZEB objective seems still long.

In this paper, the design criteria for a residential nZEB built in Mediterranean climate are discussed. According to this aim, first of all, the present nZEB standards for residential sector in Europe are discussed, then a brief review of design solutions investigated by researchers is proposed.

1.1. nZEB standards in Mediterranean climate

Presently, the nZEB concept is described with a wide range of approaches [9,10]. The most important issues are: the metric of the balance, the balancing period, the types of energy use included in the balance, the kind of energy balance, the accepted renewable energy supply options, the connection to the energy infrastructure, the requirements of energy efficiency and the indoor microclimate. As stated by Marszal et al. [11], four general principles concerning the ZEB definitions have to be considered: Net zero site energy; Net zero source energy; Net zero-energy costs; Net zero-energy emissions.

The European Commission overview document [12] has established that the definition of nZEB is a task that should be defined at national level. Today, where there is a numerical indicator for residential buildings, the energy demand varies between 33 kW h/(m^2 y) in Croatia and 95 kW h/(m^2 y) in Latvia, with a majority of countries aiming at 45–50 kW h/(m^2 y). Few Member States have adopted objectives that go beyond nZEB requirements, and thus the targets of net zero-energy buildings (ZEBs) in Netherlands, positive-energy buildings in Denmark and France, carbon neutral new buildings in Germany and zero carbon standard in the UK. The report of Erhorn and Erhorn-Kluttig [13] shows that, in terms of envelope technology, buildings have brick-concrete walls or wooden frame. Transmittance value (U-value) for wall varies between 0.07 and 1.97 W/(m^2 K); the mean value for the roof slab is 0.14 W/(m^2 K). Existing nZEBs have generally low-e-coated triple-glazed windows with an average thermal transmittance of 1.14 W/(m^2 K); the examples with double glazing are mostly located in Southern Europe.

By considering the report about the progress of Member States [14], for buildings already completed, the improvement compared to national requirements ranges between 21% (France) to 90% (Portugal). Moreover, the renewable integration has minimum value of 21% in France and maximum value in Italy (67%), meanwhile additional costs compared to conventional building are not always declared: in Italy, it is 378 €/m^2, while in Bulgaria it is around 130 €/m^2.

In various studies carried out by the Passive House Institute, it has been shown that passive house is an ideal basis for the definition of the Nearly Zero Energy Building. Several examples are available in many European countries. At the Polytechnic University of Timisoara [15], an experimental program was developed to demonstrate that the application of passive house design principles could be an alternative solution for energy-efficient buildings, by reflecting the Romanian local climate conditions, materials, and construction techniques. Really, during the design phase, passive design strategies and available renewable sources should be carefully considered. AlAjmi et al. [16] have demonstrated, for hot climate, the possibility of converting a public building from inefficient energy consumer into a nZEB through cost effective energy efficient measures and integration of solar energy systems. Moreover Colclough et McGrath have described how a low-energy building has achieved nearly zero energy heating through the addition of a solar domestic hot water and space heating system with a seasonal thermal energy store [17].

However, as underlined by Lu et al. [18], there is no exact approach for the design and control of buildings to achieve the nearly/net zero energy target. This is mainly due to complex interplay of energy production/consumption/storage systems as well as the automatically and manually controlled systems/elements in highly integrated buildings. Thus, energy forecasting models are essential to building energy control and operation [19]. About it, Connolly et al. [20] have proposed a review of different computer tools that can be used to analyse the integration of renewable energy. More recently, Li et al. [21] have developed high fidelity energy forecasting model for a building cluster with multiple buildings and distributed energy systems; this utilizes multi-objective optimizations to determine the operation strategies: building temperature set-point, energy storage charging and discharging schedules, etc. By means of hybrid Genetic Algorithm and Monte Carlo simulation approach, for a cluster of Net Zero Energy Buildings, Garshasbi et al. [22] have shown that about 60–100% of total daily generated renewable energy was consumed by NZEBs. The minimum grid dependency was observed in June and July where around 11.2% and 9.9% of required electricity was supplied from the central energy grid, respectively.

Discussions about existing nZEBs suggest that the objective of nearly zero consumption, mainly for Mediterranean residential sector, can be achieved only through a mix of solutions that must be evaluated in every single case. Passive bioclimatic solutions (i.e., choosing natural and local materials, using thermal inertia and natural ventilation), high efficient active systems (equipment and HVAC plants) and the most effective use of the renewable energies (not only solar, but also micro wind turbines, geothermic etc.) should be integrated.

1.2. Passive technologies and bioclimatic approach for nZEB design

The "nearly zero energy challenge in warm and Mediterranean climates" report identifies ten main strategies to design nZEB in Mediterranean climate [23], recognizing also that the inhabitants' involvement is a key element. First of all, this report underlines that the bio-climatic urban development, the housing typology and orientation can positively or negatively affect the energy and environmental performance of building. An accurate use of both green areas and water, attention to the climatic factors, the use of natural and local materials as well as an accurate selection of the materials for covering and flooring can also contribute to the reduction of energy need and to improve comfort in winter and summer, inside and outside the dwellings. Agugliaro et al. [24] have examined the concept of bioclimatic architecture. Italy, Spain and Brazil are the countries with higher interest in this matter. However, among the more modern strategies, there are: thin building integrated photovoltaic films on buildings; spraying of water on roofs; placement of buried pipes as heat exchangers, for pre-heating and cooling the ventilation air.

nZEB design requires correct mix of active and passive systems, of renewable energies and integration of monitoring system. In our brief review, according to the aim of the proposed study, only measures for improving the behavior of the building envelope are considered. Omrany et al. [25] have identified some efficient walls' solutions: Trombe walls, autoclaved aerated concrete walls, double skin walls (DSFs), phase change materials (PCMs) and green walls. Duan et al. [26] recently have compared the thermal performance of two different types of Trombe walls: one is equipped with an absorber plate pasted on the thermal storage wall (Type I) and one with absorber plate placed between glass cover and thermal storage wall (Type II). They have concluded that in Type II, the energy and exergy efficiencies are greater than in the first type, under the same operational conditions.

De Gracia et al. [27] have presented a new type of ventilated facade with macro-encapsulated PCM. Two identical test-cubicles, located in Puigverd de Lleida (Spain), were monitored during summer 2012. The experimental results have demonstrated the high potential of night free cooling effect in reducing the cooling loads; it can prevent successfully the overheating effect between the PCM solidification and melting periods, being the temperature of the air inside the cavity even lower compared to the outdoor environments during the peak load.

The experimental study of Rehman [28] has showed that if the standard building material, i.e. solid concrete, is retrofitted with polyisocyanurate and reflective coatings or completely replaced with energy-efficient dry insulation material wall, energy savings up to an average of 7.6–25.3% can be achieved. Ibrahim et al. [29] have presented a new thermal insulating rendering based on silica aerogels. Results show that the optimum rendering thickness is in the range of 1.7–4.4 cm and the payback period in the range of 1.4–2.7 years depending on the climate. Iyi et al. [30] have analyzed the impact, on the behavior of the DSF, of the tilt angles of venetian blinds, as well as their position. Moreover, Barbosa and Ip [31] have identified three groups of parameters affecting the thermal and energy performance of buildings with DSFs. These are the 'façade' parameters, which comprise the features of the cavity and the external layer of the façade; the 'building' parameters, which are those related to the physical configurations of the building; and the 'site' parameters, which are related to the effects of the outdoor environmental conditions on the building and the DSF behaviors. Peng et al. [32] have shown that a ventilated photovoltaic double-skin facade at Berkeley can reduce net electricity use by about 50% compared with other commonly used glazing systems.

The use of PCMs in buildings seems to be quite beneficial. Indeed, PCMs can decrease energy consumption, shift the peak loads of cooling energy demand, decrease temperature fluctuations by providing a thermally comfortable environment, and reduce the electricity consumption. A review of PCM applications for cooling purposes and about factors affecting the effectiveness of PCMs has been by Souayfane et al. [33]. Kenisarin and Mahkamov [34] have analyzed the state of the art in R&D on integration of phase change materials into building structures for their passive thermal control as gypsum wallboards, concretes, porous and other materials. Alam et al. [35], by using five different phase change temperature ranges, with reference to eight Australian cities, have concluded that potential of PCMs strongly depends on local weather, thermostat range, thickness and surface area. Different PCMs were found to be effective during times of the year. Depending on local weather, the integration of PCMs is resulted in 17–23% annual energy savings, with the exception of hot and humid cities like Darwin.

Panayiotou et al. [36] have evaluated the application of macro-encapsulated PCM, on the envelope of a typical dwelling in the Mediterranean region. The energy saving achieved by the addition of PCM layer on the envelope of the test cubicle, compared to the base case (no insulation), is resulted between 21.7 and 28.6%.

A novel active building integrated photovoltaic thermoelectric wall system has been proposed by Luo et al. [37]; the simulation results showed that when indoor air temperature is 24 °C, the thickness and thermal conductivity of insulation is 0.04 m and 0.05 W/m K, this wall can reduce about 70% daily heat gain compared with traditional wall in typical day simulation. Instead, building integrated photovoltaic-thermal multifunctional roofing panel has been developed by Chen [38].

Cool and green roofs are two innovative techniques to reduce building energy requirements for cooling and to improve indoor thermal comfort conditions. In recent years, important experimental and numerical studies have been carried out to demonstrate cool roof efficacy in different climatological contexts [39,40] and for different construction and occupancy typologies. Recently, Pisello and Cotana [41] have discussed the possibility of applying an innovative "cool roof" solution, consisting of a prototyped cool clay tile, on a traditional residential building in central Italy. The year-round analysis has shown that the proposed cool roof solution produces a maximum effect of decreasing summer peak indoor overheating of the attic by up to 4.7 °C. Moreover, the study of Revel et al. [42] has confirmed that significant improvements can be obtained also by working on the facade, especially for high-rise buildings. Of course, the design criteria affect greatly both technologies, as stated by Ascione et al., by means of extended studies, with reference to cool colors [43] and vegetation on the building roof [44].

The increase of insulation levels as well as of airtightness and the enhancement of solar control capabilities are useful aspects in the design of components, but the role of dynamic thermal properties on the energy performance cannot be underestimated. As underlined by Aste et al. [45], the positive effect of thermal capacity appears to be relevant for moderate climates and intermediate seasons, where it can work as a stabilizing factor of the thermal dynamics of the whole building system.

Design optimization problems of window size and façade orientation have been investigated many times. Mangkuto et al. [46] have presented a simulation study to investigate the influence of window-to-wall ratio (WWR), wall reflectance and window orientation on various daylight metrics and lighting energy demand, in simple buildings located in tropical climate. The optimum solution, with the least mean distance from the utopia points, has resulted the combination of WWR $\approx$ 30%, wall reflectance of 0.8, and south orientation. Goia [47] has studied the optimal WWR in different European climates for an office building with the aim to minimize energy use for heating, cooling and lighting. The results have indicated that ideal values can be found in the range 0.30–0.45. Only south-oriented facades could require WWR values outside this range in very cold or very warm climates. Firlag et al. [48] have pointed out that for residential building, the use of automated shading systems can reduce the site energy in the range of 11.6–13.0% and that the control algorithms have a strong influence on the effectiveness of shades. Basing on the thermal performance of a reference room located in the climate region of Coimbra, Amaral et al. [49] have concluded that large glazing areas facing north are not particularly poor in terms of thermal performances, since gains through sky diffuse radiation compensate partly the thermal losses.

Finally, Bruno et al. [50] have presented a parametric analysis for an innovative prototype of passive building, located in south Italy and for residential use. Their main conclusions are:

- transparent surfaces with low solar gain coefficients south facing are penalizing;
- an appropriate insulation thickness in the ground floor must be chosen;
- a fixed overhang on south exposure slightly modifies the energy performance indexes;
- the role of free cooling during the nocturnal hours, is substantial in summer;
- windows with triple pane are also appropriate for the south exposure;
- the employment of sand and wood panels in dry assembled walls confers them appropriate thermal inertia reaching satisfactory thermal dynamic characteristics.

2. Motivation of a new study: aims and methodology

Nearly or net zero edifices can be built only if in the early design stage, designers have appropriate building performance information for a certain destination of use and climatic condition. Very often, building configuration is selected basing on designers' experiences that could ignore performance of new envelope technologies or achievable efficiency of actual active systems. Really, designers should consider the largest number of design possibilities, and solve a multidisciplinary problem with contrasting objectives (e.g. minimization of costs and energy demand, maximization of indoor comfort). Surely, a correct design approach requires building energy performance simulations, but this procedural method is time-intensive and involves complex processes.

According to this aim, the proposed investigation want suggest original guidelines for design nearly zero-energy building in typical Mediterranean climate. More in detail, optimization techniques, coupled with building performance simulation tools, are used to support designers in identifying the most suitable sets of technical solutions for building envelope, in order to guarantee at the same time a comfortable indoor environment and a minimum energy use.

About this matter, Echenagucia et al. [51], for office building in Palermo, Torino, Frankfurt and Oslo, have investigated different configurations by varying thickness of the masonry walls; number, shape and placement of windows; glazing characteristics of the windows. Also Lin et al. [52] have studied designing envelope configurations of office building with the low construction cost and energy consumption. Moreover, several studies have discussed innovative methodologies for optimizing the thermo-physical properties of the building envelope [53] and for select the mix of renewable energy systems [54] also considering three design objectives [55] and thus minimization of cost, minimization of energy consumption and maximization of occupant comfort level.

As said also in Section 1.2, several articles have proposed studies about the use of building technologies and optimization techniques to support designers. However, there are not papers that analyze, for residential kind of use, multiple configurations for building envelope by varying, simultaneously, transparent components, different technologies for opaque walls, spectral characteristics of roof, thickness and type of insulation material. Moreover, not very often, applications of innovative solutions as double layers of PCM are discussed, and the charging and discharging cycle are not simulated assuming that both indoor and outdoor loads are present.

Briefly, in this paper a multi-objective optimization is applied in order to provide the best compromise between transparent envelope solutions, thermal mass of the building and radiative characteristics of roof in simple residential building located in four different cities of the Mediterranean climate. Results could be usefully considered by designers because these allow to know effect of selection for numerousness kind of solutions. Moreover, results could orient experimental research with the aim to deepen certain solutions for hot climate.

The proposed approach for case study is shown in Fig. 1. It consists of optimization process with two sequential phases.

First of all, the multi-objective optimization problem is posed. The methodology for solving an optimization problem can be subdivided in several main steps, that, also using the analysis framework suggested by Samuelson et al. [56], can be summarized as following:

a. Select objective functions (Section 3.1);
b. Define problem constraints (Section 3.2);

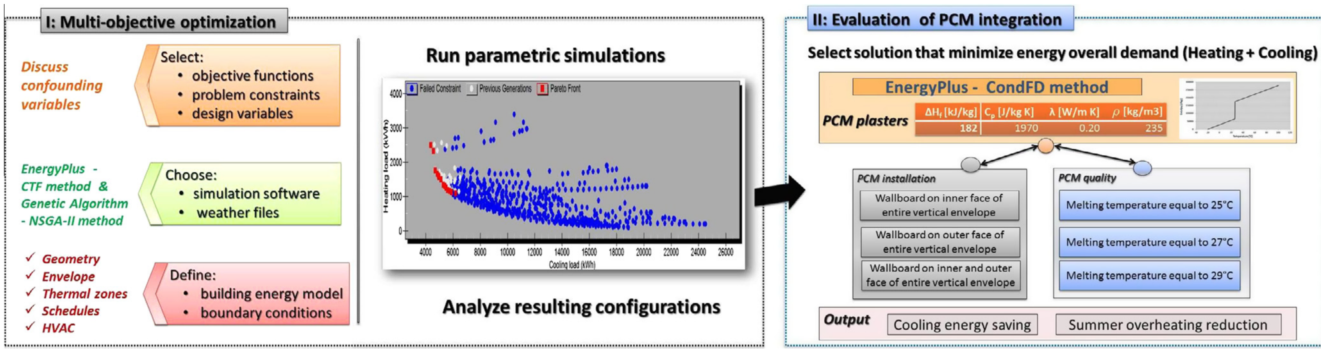


Fig. 1. Outline of adopted methodological approach.

c. Choose design variables and discuss potential confounding variables (Section 3.3);
d. Choose simulation software and appropriate weather files (Section 3.4);
e. Describe model and specify model assumptions (Section 3.5);
f. Run parametric simulations and detect the configurations of design variables that minimize selected objectives (Section 4).

Since several solutions can represent optimal trade-offs, the decision-maker can select the best one according to his criteria [57]. In particular, final outcome is the Pareto front [58], which is the set of the non-dominated solutions. In the proposed approach, among Pareto points, three solutions will be selected and discussed for further analysis:

- optWint: solution that minimizes the heating demand;
- optSum: solution the minimizes the cooling demand;
- optTOT: solution for which the energy overall demand is minimized.

Only for the configuration that minimizes the energy overall demand, also the application of a PCM plaster on internal or external side of all vertical facades has been taken into account. Numerical tools can simulate materials with variable properties such as PCMs by using one-dimensional conduction finite difference solution algorithm. CondFD discretizes walls, floors, and ceilings into several nodes and uses an implicit finite difference scheme to numerically solve the appropriate heat transfer equations. This method is very reliable, but models require higher computational power; moreover the coupling of different numerical schemes is too complex. Moreover time steps ⩽3 min should be used. In this paper, to avoid very long computational timing, PCMs have been considered only in the second step of procedure with discrete evaluations performing dedicated simulations. Different melting temperatures have been analyzed for a commercial product (see Section 5 for technical data) with the aim to minimize summer energy need. The percentage reduction of the cooling demand (ΔE_c), for all considered scenarios, has been evaluated and the improvement of indoor comfort conditions as well as the overheating risk with PCM adoption have been examined.

3. Case study: optimization problem and building description

The analysis framework presented in the previous section is explained in detail for the case study.

3.1. Objective functions

In order to evaluate the optimized solutions, the following two targets have been taken into consideration:

- Minimization of heating load [kW h]: energy demand to set comfort operative temperature during the winter period considering heat losses through building envelope, ventilation and inner gains;
- Minimization of cooling load [kW h]: amount of heat energy to be removed from a house to maintain indoor design temperature due to sensible and latent heat gains.

3.2. Constraints

As underlined by Carlucci et al. [59], very often optimization algorithms have been used to maximize the energy performance of buildings, by giving secondary importance to thermal comfort and usually neglecting visual comfort and the indoor air quality.

The proposed study takes into account the indoor thermal comfort, using the hours of discomfort as limiting constraint for determining the Pareto front solutions. More in detail, it has been chosen that the annual value of discomfort hours should be less than 350 h. Comfort conditions have been expressed as the combination of humidity ratio and operative temperature included in the ASHRAE 55-2004 (Fig. 2) summer or winter clothes' regions.

For these outputs, the operative temperature is simplified to be the average of the air temperature and the mean radiant temperature. For the cooling and heating seasons, the 0.5 Clo and 1.0 Clo levels were used, respectively. This option implies that solutions failing the constraint requirement are not included on the Pareto Front.

3.3. Design variables

These are the elements of the model that are to be allowed to vary during the optimization analysis. More in detail, tested parameters include several early-design phase decisions, such as window to wall ratios, glazing components, external and internal shading systems, spectral characteristics of last layer of roof slab and opaque envelope constructions by varying technology, thickness and type of insulation material.

More in detail, the WWR has been varied between 15% and 80% assuming an optimization step of 2%. Several solutions of double and triple-glazed windows have been considered by varying the type of glass: clear, low-emissive (LoE) spectral coating and selective coating (LoE Spec Sel). Overhangs and projection Louvre have been tested as external shading system. Different blade depths have been selected but all systems are made of white painted steel. Blind with medium reflectivity slats, drapes and shade roll have been compared for internal shade.

Table 1 shows all variables concerning typologies of glazing and shading system. Please, note that U_g is glass thermal transmittance and g is the solar factor.

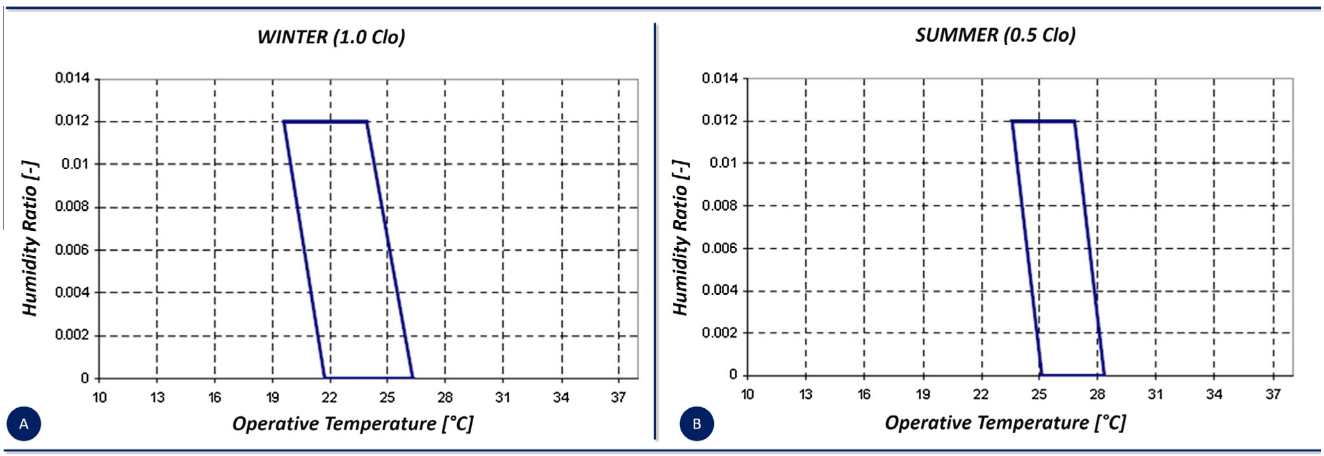


Fig. 2. Comfort range according to the standard ASHRAE 55-2004.

For all simulations, the window frame has been considered wooden made meanwhile the window blind type and the local shading type have been put on all exposures.

In order to determine the effect of internal inertia, six types of walls were developed, by assuming similar values of stationary thermal transmittance (U) and periodic thermal transmittance (Y_{IE}) within the limits indicated by energy saving regulations.

The solutions selected for building envelope take into account the most common technologies in selected countries and also some interesting market solutions for high performance building. Indeed, considering TABULA WebTool [60] to understand characteristics of national residential buildings stock, the case study has been modeled according to technologies diffused after the Second World War and thus with use of reinforced concrete for the structural parts (i.e., pillars, beams and joists) and hollow clay blocks or concrete blocks with external insulation for the opaque vertical envelope. Ceiling and floor with insulated reinforced concrete or mixed brick-concrete slab are mostly diffused. Moreover, taking into account existing NZEBs [12], it is obtained that these have or structure with cellular concrete insulated with polystyrene or brick walls insulated with mineral wool (e.g. in France). The ceilings are usually made of reinforced concrete with mineral-wool insulation.

Table 1
Variable for glazing components.

Variable	Description
Window to wall ratio	
	Min value 15%; Max value 80% Optimization_step 2%
Glazing type	
	– Dbl Clr 6/13/6 Argon: $U_g \approx 2.55$ W/(m^2 K), g = 0.70
	– Dbl LoE (e2 = 1) 6/13/6 Argon: $U_g \approx 1.55$ W/(m^2 K), g = 0.56
	– Dbl LoE Spec Sel 6/13/6 Argon: $U_g \approx 1.33$ W/(m^{2}K), g = 0.42
	– Dbl Refl 6/13/6 Argon: $U_g \approx 2.55$ W/(m^2 K), g = 0.34
	– Trp LoE Spec Sel (e2 = e5 = 1) 4/10/4/10/4 Argon: $U_g \approx 0.81$ W/(m^2 K), g = 0.51
	– Trp LoE 3/13/3 Argon: $U_g \approx 1.62$ W/(m^2 K), g = 0.68
	– Trp LoE Spec Sel (e2 = e5 = 1) 6/13/6/13/6 Air: $U_g \approx 1.22$ W/(m^2 K), g = 0.36
Local shading type	
	– No shading
	– Projection Louvre from 0.5 to 1.5 m
	– Overhang from 0.5 to 2.0 m
Window blind type	
	– None
	– Blind with medium reflectivity slats
	– Drapes open weave medium
	– Shade roll – medium opaque

In Italy, often, external walls are made of autoclaved aerated concrete blocks with external thermal insulation but also wood and wood-fiber walls. The most diffused slab type is mixed brick and cement with insulation.

Taking into account previous analysis, Fig. 3 describes layers for studied walls ("s" thickness, "λ" thermal conductivity, "c_p" specific heat, "ρ" density). In detail, Wall 1 is made of innovative interlocking brick with holes filled with rock-wool insulations meanwhile bricks of Wall 4 have holes filled, at the last phase of productive process, with expanded polystyrene (EPS). Wall 2 and wall 5 are made of autoclaved cellular concrete with different values for density. Moreover, Wall 6 is a traditional brick wall with hollow blocks and external wooden fiber insulation. Finally, by taking into account development of studies and new available technologies regarding earthquake engineering, Wall 3 is based on cross-laminated panels (XLAM).

Table 2 shows the value of thermal transmittance and the main dynamic parameters as periodic thermal transmittance, internal areal heat capacity (χ), thermal mass (M_s), decrement factor (f_a) and time lag (ϕ).

Moreover, for all kind of walls, different insulation materials have been tested as well as different thicknesses (5, 10, 15, 20 cm). More in detail, four insulation materials have been chosen: expanded polystyrene ($\lambda \approx 0.035$ W/m K $\rho \approx 30$ kg/m^3), rock-wool ($\lambda \approx 0.047$ W/m K, $\rho \approx 92$ kg/m^3), wood fiber ($\lambda \approx 0.038$ W/m K, $\rho \approx 50$ kg/m^3), panel of wood and Portland cement ($\lambda \approx 0.075$ W/m K, $\rho \approx 40$ kg/m^3).

Selected floors differ both for the materials whose are composed as well as for the production process. More in detail, the first type is the most diffuse technology in Europe (roof 1) and thus it is a brick-concrete floor with external insulation (EPS). Instead, the second type is a wooden roof with cross-laminated elements. The material layers of the roof are reported in Fig. 4 and all performance parameters are indicated. The optimization problem includes different thicknesses of insulation material (5, 10, 15, 20 cm) for both roof types.

With reference to all simulated configurations, an insulated concrete structure has been considered for the slab on the ground ($U_{slab} \approx 0.25$ W/(m^2 K), $Y_{IE} \approx 0.001$ W/(m^2 K)). The partition walls have wooden structures, with clay plasters on both the sides ($U_{partition} = 0.76$ W/m^{2}K).

With reference to the radiative behavior of the sun-exposed surfaces of the roof, multiple sets of solar reflectance and infrared emissivity have been considered.

More in detail, 15 discrete values have been considered for the solar absorptance of the outer roof surface (i.e., 'α_{solar}' ranges

Wall 1	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
UNIPOR	0.300	0.100	1000	900
External plaster	0.020	0.900	1000	1800

Wall 4	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
Thermok30	0.300	0.095	1000	730
External plaster	0.020	0.900	1000	1800

Wall 2	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
Ytong	0.300	0.091	1000	730
External plaster	0.020	0.900	1000	1800

Wall 5	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
GASBETON	0.300	0.149	1000	1200
EPS	0.040	0.035	920	30
External plaster	0.020	0.900	1000	1800

Wall 3	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
Clay plaster	0.025	0.440	1000	1440
Wood Fiber	0.050	0.038	1600	50
XLAM	0.120	0.130	1800	500
Wood Fiber	0.040	0.043	2100	180
External plaster	0.020	0.900	1000	1800

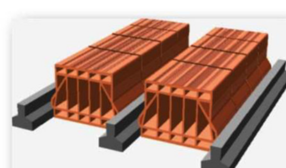
Wall 6	s [m]	λ [W/m K]	c_p [J/kg K]	ρ [kg/m³]
Inner plaster	0.010	1.100	1200	1960
Brick wall	0.250	0.15	1000	800
Wood Fiber	0.110	0.075	1810	40
External plaster	0.020	0.900	1000	1800

Fig. 3. Description of layers for investigated walls.

Table 2
Thermo-physical parameters for investigated walls.

	U [W/m² K]	M_s [kg/m²]	χ [kJ/m² K]	f_d	φ [h]	Y_{IE} [W/m² K]
Wall 1	0.312	326	40.5	0.047	19.98	0.015
Wall 2	0.286	275	38.3	0.063	18.72	0.018
Wall 3	0.292	161	49.2	0.121	13.02	0.035
Wall 4	0.298	275	38.6	0.069	18.32	0.020
Wall 5	0.298	417	46.3	0.019	21.22	0.006
Wall 6	0.300	260	42.9	0.079	15.49	0.024

Roof 1	s [m]	λ [W/m K]	ρ [kg/m³]	c_p [J/kg K]
Water-proofing	0.01	0.13	800	2100
EPS	0.12	0.035	30	920
Cement mortar	0.06	1.40	2000	1000
Slab	0.24	R=0.42 m² K/W		
Internal plaster	0.01	0.70	1400	1000



Roof 2	s [m]	λ [W/m K]	ρ [kg/m³]	c_p [J/kg K]
Water-proofing	0.01	0.13	800	2100
Cement mortar	0.06	0.13	380	1000
Wood fiber ins.	0.10	0.044	180	2100
X-LAM roof	0.12	0.13	500	1600
Internal plaster	0.01	0.90	1800	1000

	U [W/m²K]	M_s [kg/m²]	χ [kJ/m² K]	f_d	φ [h]	Y_{IE} [W/m²K]
Roof 1	0.27	146	84.7	0.64	4.53	0.173
Roof 2	0.26	127	41.6	0.16	14.7	0.041

Fig. 4. Description of layers for investigated roofs.

between 0.2 and 0.9), and 6 values can be attributed to the infrared emissivity (i.e., '$\varepsilon_{infrared}$' ranges between 0.4 and 0.9). Due to the large experimental researchers in this field [61,62] in matter of non-white cool materials, in our investigations, all combinations among the aforementioned values have been considered in the optimization study.

According to [56], parameters that are not under the designer control, should be specify because these may affect the optimal solutions. For proposed case-study, the design parameters will be tested with one unique level of internal plug-loads (see Section 3.5) assuming conventional values for a household of four people. People and plug-load have been modeled with typical schedules for residential kind of use, but further study will be done because some authors have found that although people use energy, the physical building characteristics largely determine how much it is used [63]; instead some others underline that residents, with greater environmental knowledge, could lead to energy saving in households [64].

3.4. Simulation software and weather files

For this project, the predicted performance and the optimization problem are determined by developing the energy model for the house by means of dynamic energy simulations. An interface program of EnergyPlus [65], i.e., DesignBuilder [66], has been used. Among the capabilities of the program, there is the possible use of a Genetic Algorithm (GA) based on the NSGA-II method [67], which is widely used as a "fast and elitist multi-objective" method providing a suitable trade-off between a well converged and a well distributed solution set. For our scopes, the maximum number of generations has been set to 200 and it is typically in the range 50–500. This value reflects the complexity of the analysis. Each generation includes at most 20 designs.

The computational domain is the whole year, thus simulations run for all months and both daily or monthly results are available; moreover the time interval between two consecutive energy balances has been fixed equals to 6 per hour.

The building performances have been simulated in Madrid (Spain), Nice (France) Naples (Italy) and Athens (Greece). These cities are characterized by different climatic conditions, and thus the variability of Mediterranean climates of European Countries is well-represented (Fig. 5). In this way, it is possible to investigate the effect of different envelope solutions characterized by high thermal resistance in Mediterranean climates (where, commonly, the cooling demand is comparable or higher than the heating request).

Synthetically, according to the climate classification of Köppen [68]:

- Madrid: Mediterranean climate with mild cool/cold winters and hot summers;
- Nice: hot-summer Mediterranean climate, enjoying mild winters with moderate rainfall and hot, dry, and sunny summers;
- Naples: mixed marine and continental Mediterranean climate with cool, wet winters and hot, dry summers;
- Athens: subtropical Mediterranean climate with alternation between prolonged hot and dry summers and mild winters with moderate rainfalls.

The design impacts have been studied in typical weather years (IWEC data files) for taking into account high probability conditions. These have been arranged by ASHRAE Research Project 1015 from up to 18 years (1982–1999 for most stations) of DATSAV3 hourly weather data originally archived at the U.S. National Climatic Data Center [65,69].

3.5. Model description and simulation assumptions

The case study is a single-storey building, with a rectangular shape and a net conditioned building area of around 140 m^2. The "surface" to "volume" ratio (S/V) is equal to 0.94 m^{-1}. It could be a single detached house (Fig. 6) with two bedrooms and bathrooms and a living room with an open kitchen. When residential building is considered, according to [60], net floor area can range between 60 and 220 m^2 by taking into account houses with 2/3 floors. The proposed case study has only one floor with intermediate characteristics also because, several NZEBs under construction in European regions, have only one floor (e.g. Maison DOISY in France, CorTau House in Italy [70]).

In order to define reliable thermal loads, four typologies of thermal zones have been assumed (Table 3), according to classifications and requirements specified by the Standard UNI 10339 [71]. The Air Change Rate has been fixed to 0.5 h^{-1}, in order to guarantee the required comfort conditions fixed by the standard UNI EN 15251 [72], Italian but derived by the European homologous. For occupancy schedule and plug-loads, standardized factors of ASHRAE Standard 90.1-2004 have been used [73].

The types of appliances included in the design are typical for a new house of this size with the highest energy label. LED lamps (50–90 lm/W) have been chosen.

The building has a hydronic air-conditioning system, for both the space heating and the summer cooling. Four pipe fan-coils have been used for the sensible loads' control in both the seasons, with hot water produced by a condensing gas boiler and chilled water provided by an air-cooled chiller (energy efficiency ratio, at rated conditions, equal to 3.3 $W_{thermal}/W_{electric}$).

During the winter, the dwelling is heated at 20 °C, every days, from 6.00 to 9:00, from 12:00 to 14:00 and from 18:00 to 23:00. In summer, the house is cooled at 26 °C with the same daily schedule.

Considering available data on existing buildings [60], the hydronic air-conditioning system is the most diffused and it can be considered the reference type for the proposed case study.

Finally, conventional heating and cooling periods have been considered in order to compare the efficiency of proposed solutions with reference to the same operational conditions in the various countries. The heating period has been assumed starting from the 15 November and ending at 31 March. About the cooling period, this begins the 15 May and finishes at the end of September.

4. Results of optimization analysis and discussion

Firstly, a discussion about optimal solutions for each city is proposed; then a statistical elaboration of the search space variables within the Pareto line is presented. This elaboration can be applied to develop a wider knowledge of selected solutions with experimental approach. This is also our further step by means of a multi activity test-room developed by Department of Engineering of University of Sannio [75]. Moreover, results of this stage can allow several further post-Pareto analysis. At the designer level, the optimal Pareto solutions could represent a pre-elaborated material, ready to be used for select the more suitable technologies for NZEB design in Mediterranean climate.

4.1. Analysis of optimal solution for investigated cities

The solution of optimization problem for Madrid (Fig. 7) generates a Pareto front with around 42 points. A global overview allows to remark that highly insulated walls and roof are optimal solutions. Indeed, almost all wall types require 15–20 cm of insulation and only 7 points are characterized by roof types with less than

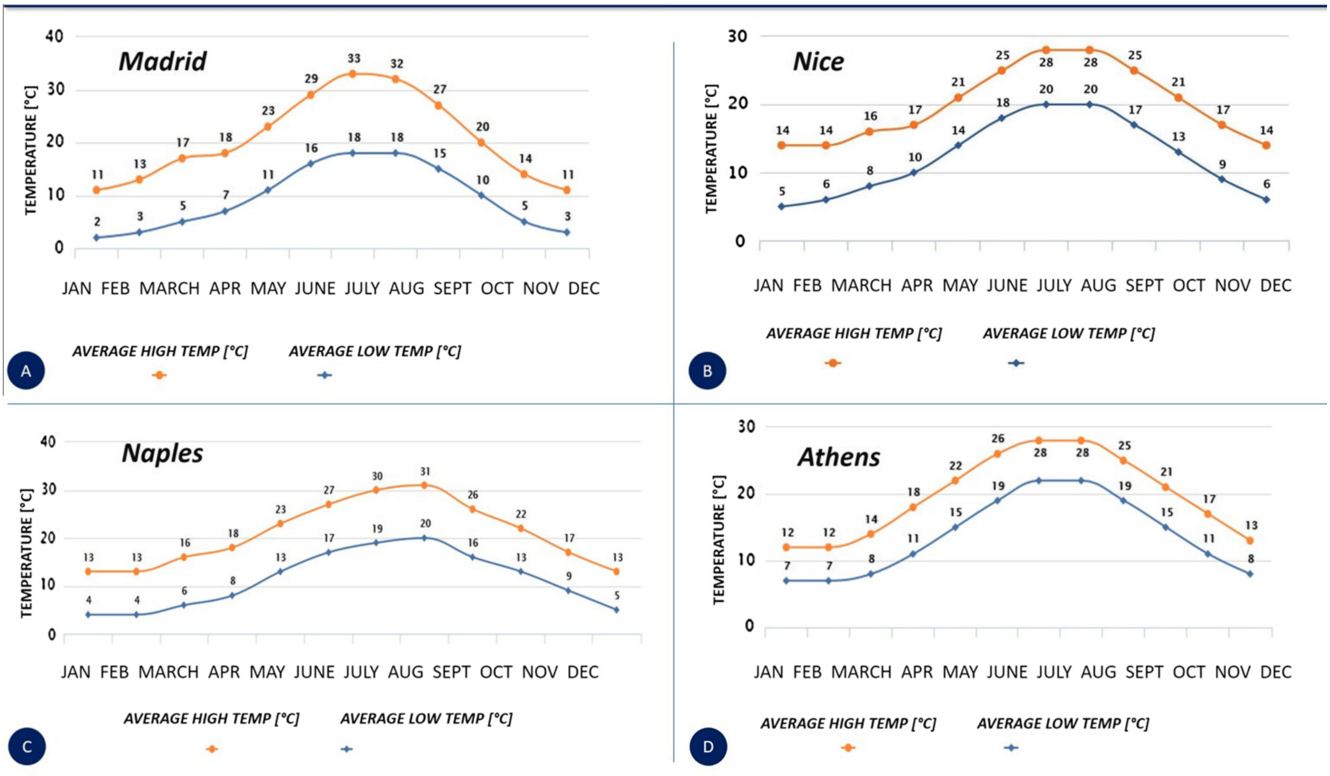


Fig. 5. Average climatic data in the period 2002–2012.

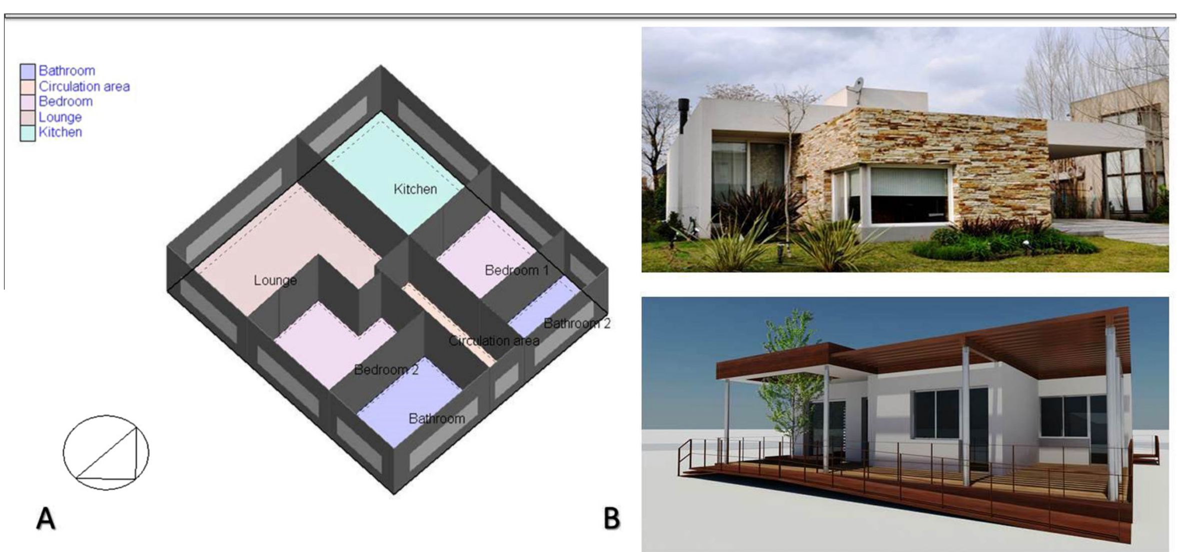


Fig. 6. (a) Case study internal plant; (b) examples of actual project of new NZEB detached house.

Table 3
Main data concerning the simulated building – thermal zones.

	Appliance	Lighting
Kitchen	30 W/m^2	3.5 W/m^2
Dining room	3.1 W/m^2	3.5 W/m^2
Bathroom	2.0 W/m^2	3.5 W/m^2
Bedroom	3.6 W/m^2	3.5 W/m^2

20 cm of insulation. WWR has a mean value of 45% with maximum value of 79% (for one solution with overhang and shade roll). Most of the solutions have triple selective windows and overhang as external shade. The lower value (14.8 kW h/m^2 y) of heating demand is obtained with brick wall (4th type in Fig. 3) and 15 cm of expanded polystyrene and with wooden roof with 20 cm of wood fiber insulation and waterproofing membrane characterized by lowest solar reflectance (10%) and medium thermal emittance (0.5). Triple selective glazing windows ($U_g \approx 0.81$ W/m^2 K, $g = 0.51$) are recommended with overhang system (0.5 m) and internal blinds; the window wall ratio is 23%. The minimization of the cooling demand requires the adoption of traditional brick (wall 6) with external EPS insulation (15 cm)

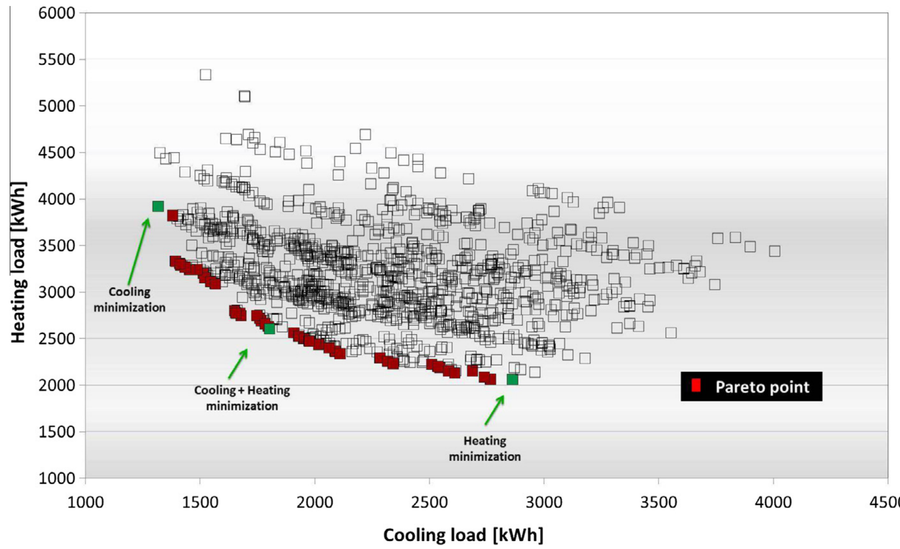


Fig. 7. Madrid – results of the optimization study.

and wooden roof (medium insulated, $U_r \approx 0.26$ W/m^2 K). WWR becomes 39% with double selective windows and both external (overhang, 2.0 m) and internal (shade roll) shade systems. The minimum value of total demand for heating and cooling (31.7 kW h/m^2 y) can be obtained with Wall 4 (Fig. 3) and insulation with rock-wool (10 cm), the adoption of brick-concrete roof slab with external insulation (20 cm of EPS) and cool membrane ($\alpha_{solar} \approx 0.2$, $\varepsilon_{infrared} \approx 0.9$). Triple low-emissive windows should be selected only with external shade (overhang, 0.5 m) for an overall WWR around 45%.

Table 4, for these three optimal solutions, summarizes the main performance indexes. For each scenario, walls and roofs should be very insulated. All solutions have very low value of periodic thermal transmittance and good properties of attenuation and time lag. In the last scenario, it is very important select roof with high thermal mass and medium value of internal heat capacity while φ is not the maximum possible (same value than summer optimization).

Fig. 8 shows the solutions of optimization problem for Nice; 55 points give the Pareto front. More in detail, most of solutions have very low thermal transmittance for walls (15–20 cm of insulation) and, with the exception of 7 points, roof has always 20 cm of insulation meanwhile only five configurations are not characterized by cool finishing. The mean value of WWR is 47% and, generally, triple glazing windows are recommended; if double glazing systems are considered (10 points), these should have selective coating. Usually, external shade must be preferred.

Briefly, the minimum energy request during winter period is 7.8 kW h/(m^2 y). This value can be obtained by considering very insulated wall with termok30 block (wall 4) and 10 cm of rock-wool ($U \approx 0.18$ W/m^2 K), wooden roof slab with 20 cm of insulation ($U \approx 0.16$ W/m^2 K) and a waterproof membrane with medium value (0.5) for infrared emissivity and high value for solar absorptance (0.9). As regard the glazed envelope, the optimal window to wall ratio is 29% with installation of triple selective glazing system (4/10/4/10/4 argon) and both external (0.5 m projection Louvre) and internal (drapes) shading systems. The lowest value of cooling demand is 17 kW h/(m^2 y) and it is related to configuration with autoclaved cellular concrete (wall 5), by adding 5 cm of expanded polystyrene and brick-concrete roof slab with external insulation (10 cm of EPS) and cool membrane ($\alpha_{solar} \approx 0.2$, $\varepsilon_{infrared} \approx 0.9$). In this case, the optimal window to wall ratio is 37% with triple selective system (6/13/6/13/6 air), internal shade roll and external projection Louvre (1.0 m). Globally, the solution that minimizes the overall demand (34 kW h/m^2 y) for heating and cooling, requires adoption of very insulated wall with termok30 block (wall 4) and 10 cm of EPS ($U_w \approx 0.16$ W/m^2 K), cool brick-concrete roof with external insulation (20 cm of EPS, $U_r \approx 0.16$ W/m^2 K). The Pareto point is characterized by very high WWR (61%), with triple selective windows (6/13/6/13/6 air) and only external projection Louvre (1.0 m).

Table 5 summarizes stationary and dynamic parameters. It is in evidence that the walls have very low periodic thermal transmittance but, for the cooling minimization, a higher stationary thermal transmittance is admissible, meanwhile high thermal mass should be required. Both total and winter optimization points are characterized by very insulated roof, with very high time lag (21 h), but, for improving also the summer behavior, high thermal mass is needed. Finally, the 'annual' optimum point is defined by very insulated structures, with a periodic thermal transmittance lower compared to the limit value and by assuming cool roof with high thermal mass.

Results of numerical optimization for Naples are shown in Fig. 9. The Pareto front is composed by around 60 points. Wall

Table 4
Madrid: thermo-physical parameters for optimal wall and roof.

	U [W/m^2 K]	M_s [kg/m^2]	χ [kJ/m^2 K]	f_d	φ [h]	Y_{IE} [W/m^2 K]
Wall_opWint	0.13	279	38.7	0.016	21.7	0.002
Roof_opWint	0.16	145	41.4	0.043	21.5	0.007
Wall_opSum	0.20	269	42.9	0.057	16.9	0.011
Roof_opSum	0.26	127	41.6	0.158	14.7	0.041
Wall_opTOT	0.18	284	38.7	0.021	21.5	0.004
Roof_opTOT	0.16	532	67.0	0.051	14.7	0.008

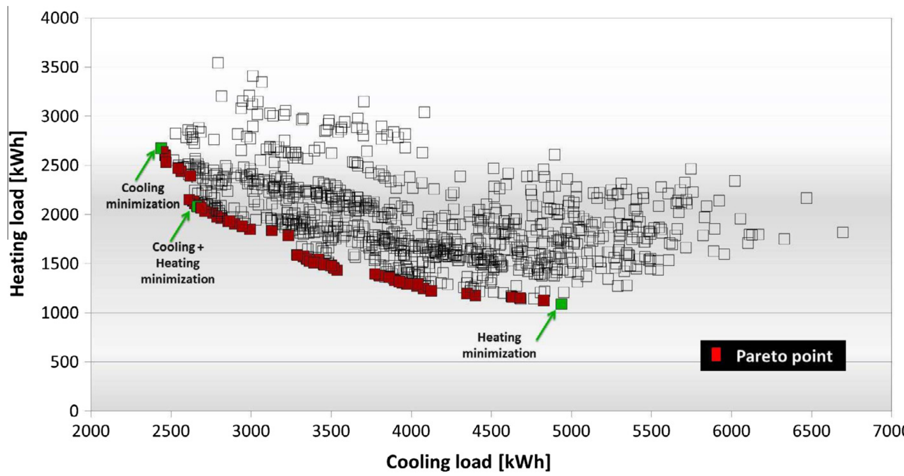


Fig. 8. Nice – results of the optimization study.

Table 5
Nice: thermo-physical parameters for optimal wall and roof.

	U [W/m² K]	M_s [kg/m²]	χ [kJ/m² K]	f_d	φ [h]	Y_{IE} [W/m² K]
Wall_opWint	0.18	284	38.7	0.021	21.5	0.004
Roof_opWint	0.16	145	41.4	0.043	21.5	0.007
Wall_opSum	0.27	417	46.3	0.017	21.3	0.005
Roof_opSum	0.28	529	67.1	0.057	13.6	0.016
Wall_opTOT	0.16	278	38.7	0.019	21.1	0.003
Roof_opTOT	0.16	532	67.0	0.051	14.8	0.008

types of autoclaved cellular concrete with different insulation materials and thicknesses are the most frequent solutions among optimal configurations. All points are characterized by very insulated roofs; for both proposed typologies, the thickness of insulation ranges between 15 and 20 cm and, except for 3 points, the optimal solar absorptance is 0.2 while the most diffused values for the infrared emissivity are 0.5, 0.8 and 0.9. Regarding the glazed envelope, the best solution is typically triple glazed window, since only 9 Pareto points are characterized by double windows; in any case, spectral selective components (Dbl LoE Spec Sel 6/13/6 in Table 1) should be selected. The external shading systems are always considered in the optimal configurations. More in particular, projection Louvre is the most suitable solution for 56% of the optimal points, equally distributed between different blade depths (37% for 0.5 m and 1.0 m); for this shading system, angle of 15° and 4 blades have been considered. For all other points, different kinds of overhang are suggested but the most frequent projections are 0.5 m and 2.0 m (both ≈32%). Internal shading systems are not very common, however installation of drapes should be preferred among considered types.

The minimum heating demand is around 7.4 kW h/m² and the design configuration is achieved with a traditional brick wall and external wooden fiber insulation and wooden roof slab with 20 cm of insulation ($U_r \approx 0.16$ W/m² K), by adding a waterproof membrane with medium value (0.5). Window to wall ratio should be equal to 67% and triple selective glazing system (4/10/4/10/4

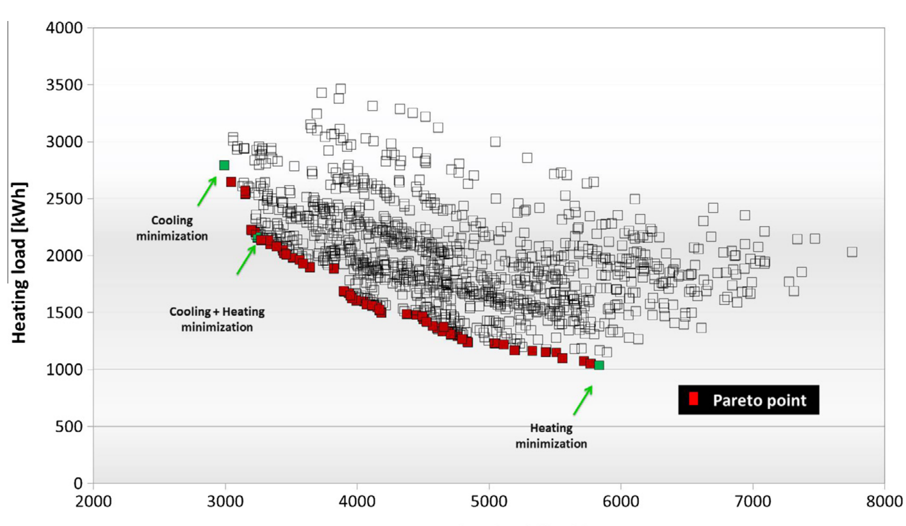


Fig. 9. Naples – results of the optimization study.

Table 6
Naples: thermo-physical parameters for optimal wall and roof.

	U [W/m^2 K]	M_s [kg/m^2]	χ [kJ/m^2 K]	f_d	φ [h]	Y_{IE} [W/m^2 K]
Wall_opWint	0.16	274	42.9	0.047	18.3	0.008
Roof_opWint	0.16	145	41.4	0.043	21.46	0.007
Wall_opSum	0.24	277	38.4	0.034	20.5	0.008
Roof_opSum	0.24	530	67.1	0.056	13.8	0.014
Wall_opTOT	0.21	279	38.4	0.024	21.4	0.005
Roof_opTOT	0.16	532	67.0	0.051	14.76	0.008

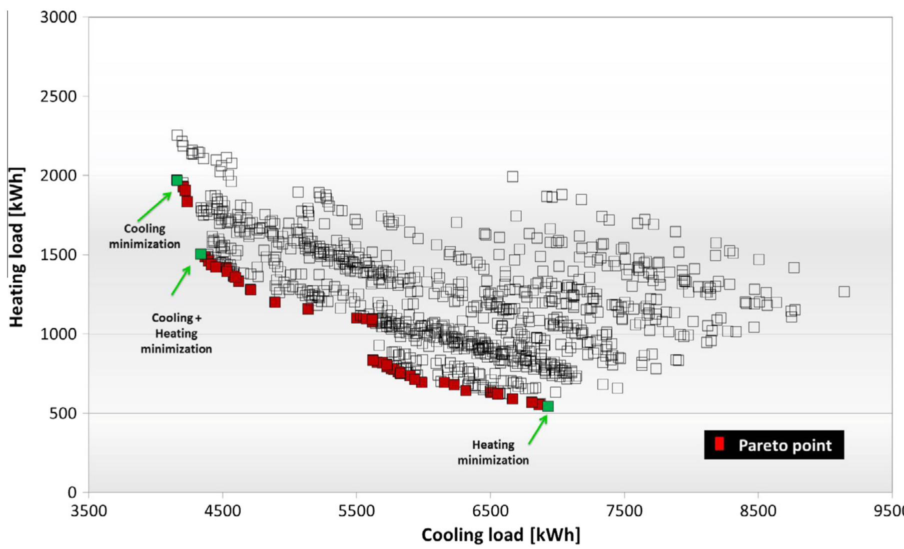


Fig. 10. Athens – results of the optimization study.

Table 7
Athens: thermo-physical parameters for optimal wall and roof.

	U [W/m^2 K]	M_s [kg/m^2]	χ [kJ/m^2 K]	f_d	φ [h]	Y_{IE} [W/m^2 K]
Wall_opWint	0.13	422	46.4	0.010	23.1	0.001
Roof_opWint	0.16	145	41.4	0.043	21.5	0.007
Wall_opSum	0.18	281	38.4	0.019	22.2	0.003
Roof_opSum	0.24	530	67.1	0.056	13.8	0.014
Wall_opTOT	0.11	281	38.7	0.014	22.42	0.002
Roof_opTOT	0.16	532	67.0	0.051	14.76	0.008

argon) should be installed only with external overhang (1.0 m). The minimization of cooling demand (21.4 kW h/m^2 y) requires wall of autoclaved cellular concrete (wall 2) with a panel of 5 cm of wood and Portland cement and selection of cool brick-concrete roof with external insulation (20 cm of EPS). Finally, the overall optimal solution is characterized by heating demand of 15.4 kW h/(m^2 y) and a cooling demand of around 23.2 kW h/(m^2 y). In this case, the same kind of wall but with only 10 cm of insulation is resulted and the adoption of cool brick-concrete roof with external insulation (20 cm of EPS). Window to wall ratio should be equal to 15% and triple selective windows (6/13/6/13/6 air) should be installed with external Louvre (1.5 m).

Table 6 summarizes stationary and dynamic parameters for Naples. By taking into account the wintertime, very insulated wall and roof should be chosen with good value of thermal inertia since the time lag is greater than 15 h and the periodic thermal transmittance is slightly lower than 0.01 W/m^2 K. Also for Naples, the roof should be very insulated and it is important also an high value of thermal mass. For what concerns the overall annual performance, for the wall, an intermediate value for the thermal transmittance between opWint and opSum should be select, higher value for thermal mass and time lag, and lowest value for Y_{IE}. The roof has the same insulation level of winter optimal solution but the same mass of summer best trade-off.

Finally, Fig. 10 shows the Pareto front (44 points) for Athens. As in the other cities, optimal solutions require that roof and wall are well insulated, only 7 points do not require 20 cm of insulation for the roof, and 6 points have the solar absorptance of the outer roof surface higher than 0.2. Mean value for WWR is 47% and triple systems, for windows, are greatly preferable; otherwise when double windows are considered, these require selective coating. All solutions are characterized by external shading. Heating demand can be minimized until 3.90 kW h/m^2 y; this configuration requires wall of autoclaved cellular concrete (wall 5) with 20 of EPS and wooden roof with 20 cm of wooden fiber ($\alpha_{solar} \approx 0.9$, $\varepsilon_{infrared} \approx 0.5$). High percentage of glazed surface (75%) and triple windows with selective coatings are the main characteristics of transparent envelope meanwhile only external projections are required (0.5 m). When the aim is the minimization of cooling demand (30 kW h/m^2 y), aerated concrete blocks (wall 2) should be used with 15 cm of wood and Portland cement and brick-concrete roof with 12 cm of expanded polystyrene and cool membrane as

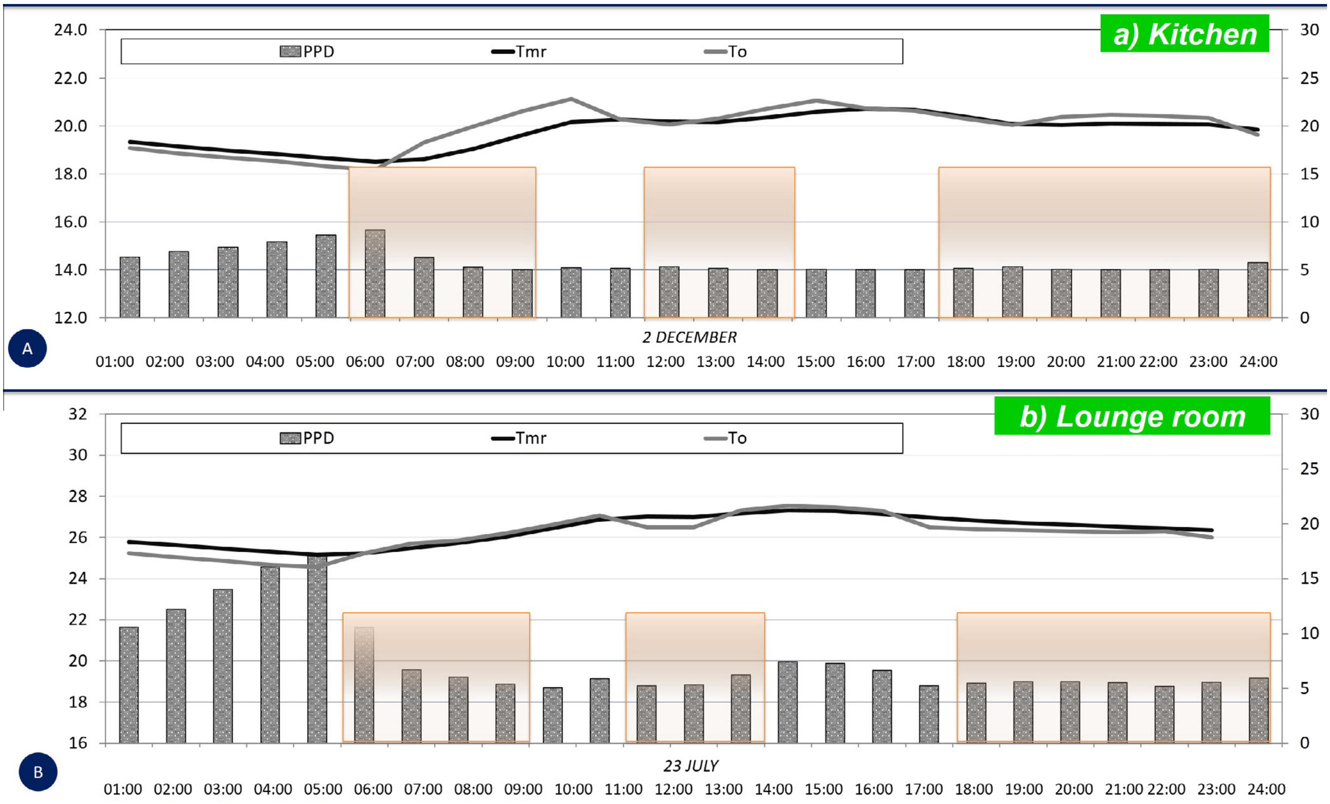


Fig. 11. Athens: indoor comfort analysis.

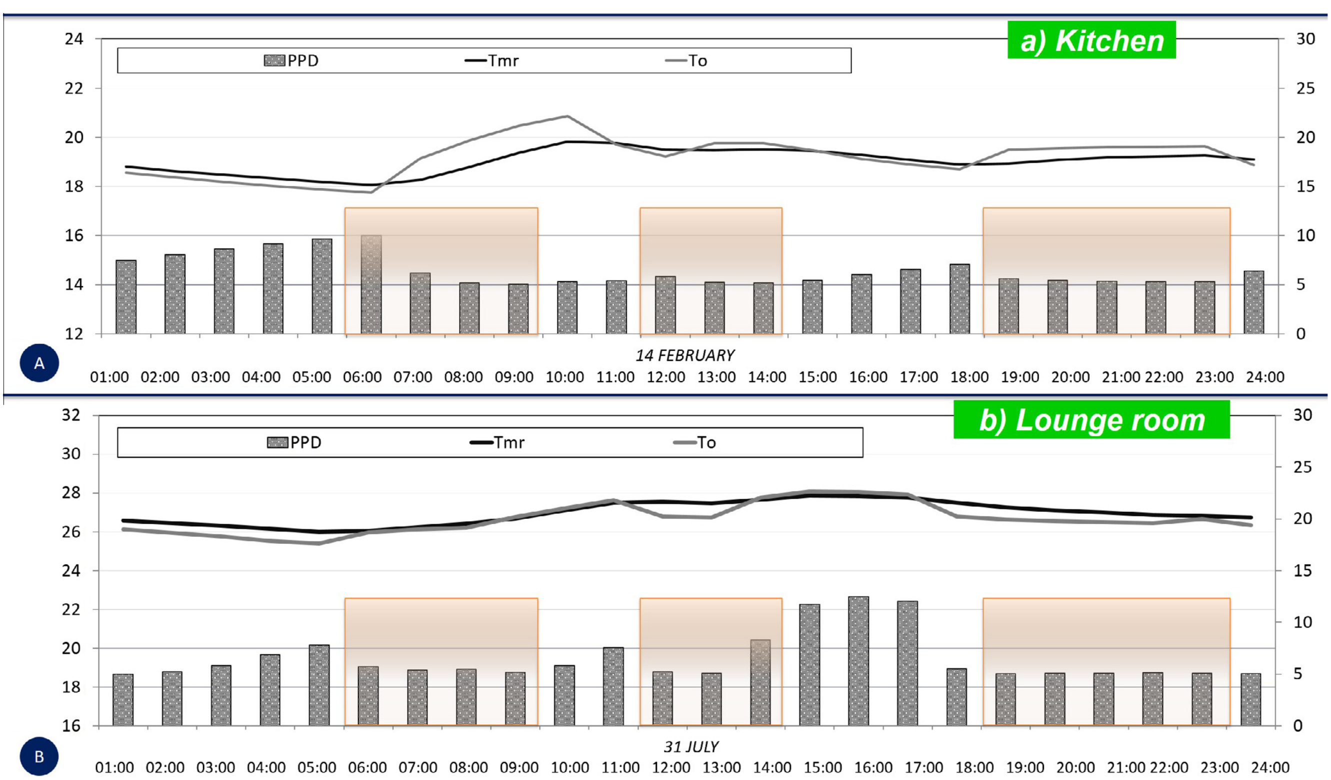


Fig. 12. Naples: indoor comfort analysis.

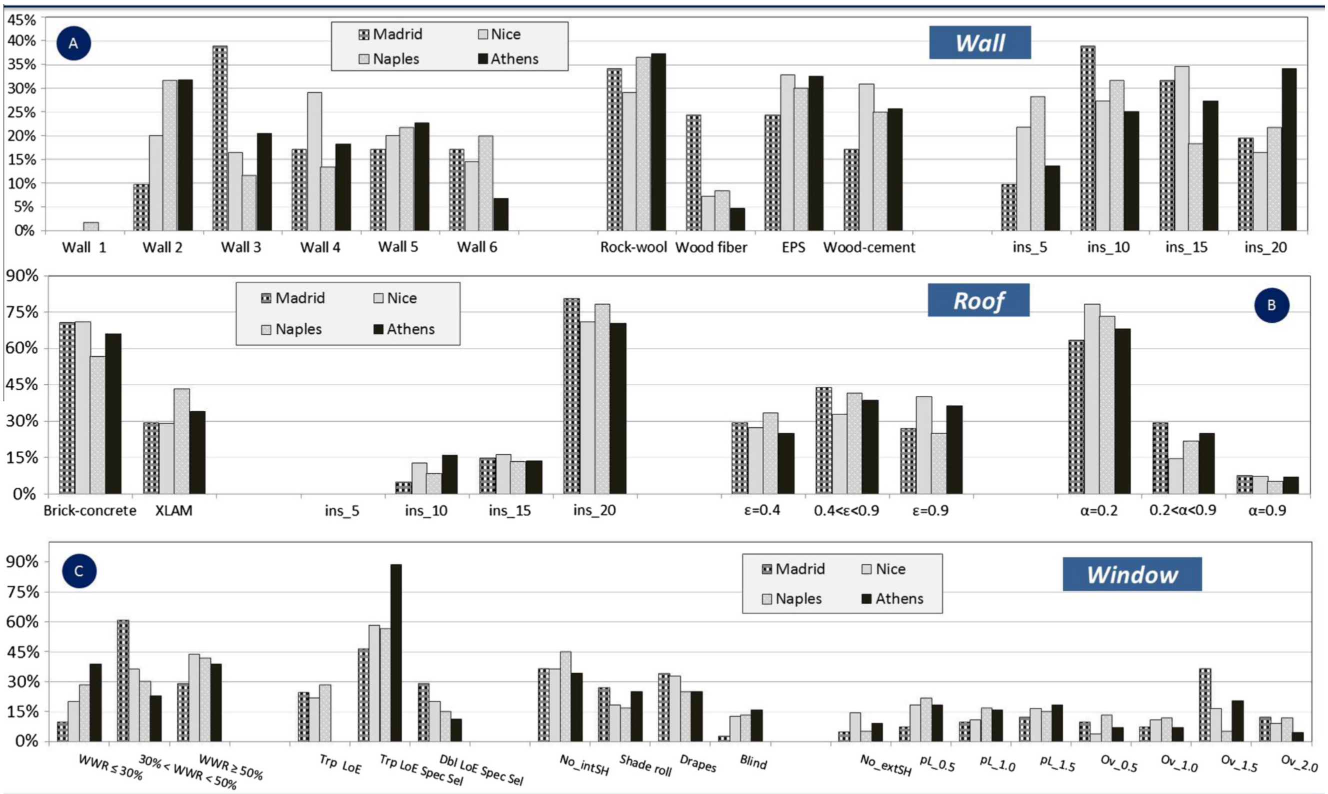


Fig. 13. Statistical post-Pareto analysis: (a) wall; (b) roof; (c) glazing envelope.

external covering ($\alpha_{solar} \approx 0.2$, $\varepsilon_{infrared} \approx 0.9$). WWR is 21% and triple selective systems are recommended for windows, with both external (1.5 m projection Louvre) and internal (shade roll) shades. The minimum value of the total energy demand is 42 kW h/(m^2 y) and the cooling demand has the greatest incidence. For the opaque envelope, wall 2 (Fig. 3) type is required with 15 cm of wood and Portland cement, and the same roof construction system that minimizes cooling demand, but considering 20 cm of insulation material. The window to wall ratio becomes 19% and triple selective windows with internal shade roll should be installed.

Stationary and dynamic parameters are summarized in Table 7. Wall thermal transmittance is very low, especially for optimal solution with low value of internal heat capacity. Minimization of cooling and total demand requires high thermal mass for the roof with an insulation level that assures also good performance during the winter. Time lag for walls is very long and periodic thermal transmittance is usually lower than 0.01 W/m^2 K.

All solutions have been investigated by assuming limited value for discomfort hours. Moreover, the analysis has been supported by evaluation of mean radiant temperature (T_{mr}), operative temperature profile (T_o) and of value of predicted mean vote (PMV) and percentage of dissatisfied people (PPD), according to European indications [74]. Globally, simulations demonstrate the optimality of indoor thermal-hygrometric conditions. More in detail, Fig. 11 shows, referring to Athens, for one day in February and in July, the previous indexes for two different rooms. Fig. 12 proposes the same analysis for Naples.

In the aforementioned figures, the hours when the HVAC system is turned on are pointed out. It can be seen that, in both cities, during typical winter days (also during the night), when the HVAC is turned off, the operative temperature remains in comfort range and the mean radiant temperature decreases only of around 1.5 °C compared with the operating hours. Operative temperature in Athens is averagely higher than in Naples. However, the hourly PPD values suggest that good hygro-thermal conditions are achieved. Considering the lounge room as representative house space, for one typical summer day, also during the HVAC no-operating time, the operative temperature stays in comfort range; this means that the selected configuration has good inertial performance. During the night, the PPD value rises up 10%; this is due also due to uncontrolled value of relative humidity that influences the PMV value and thus the percentage of dissatisfied people. More satisfactory conditions can be reached in Naples (Fig. 12b). Also during the night and when HVAC is turned off, the operative temperature does not rise over 27 °C and the mean radiant temperature has minor variations. Similar considerations can be done for the other cities. Thus, in conclusion, the suggested approach allows to minimize energy demand of building without compromising the indoor thermal comfort.

4.2. Post-Pareto analysis

Some general indications can be obtained from previous results. Thus, the percentage distribution of the values assumed by the input variables in all the non-dominated solution is presented in Fig. 13. More in detail in Fig. 13a, for building walls, suitability of technologies, type and thickness of insulation are shown for each city. Taking into account wall technologies, globally, the Pareto front does not include wall made with innovative interlocking brick with holes filled with rock-wool insulations (Wall 1 in Fig. 3). Wall made of autoclaved cellular concrete should be selected in Mediterranean climate. Indeed summing results for Wall 2 and wall 5, for Naples and Athens a percentage greater than 50% is obtained. Wall 6, probably the most diffused solution nowadays not appear a good compromise to minimize both heating and cooling request.

Rock-wool and EPS insulations are dominant solutions in each city meanwhile adoption of wood fiber insulation is not suitable.

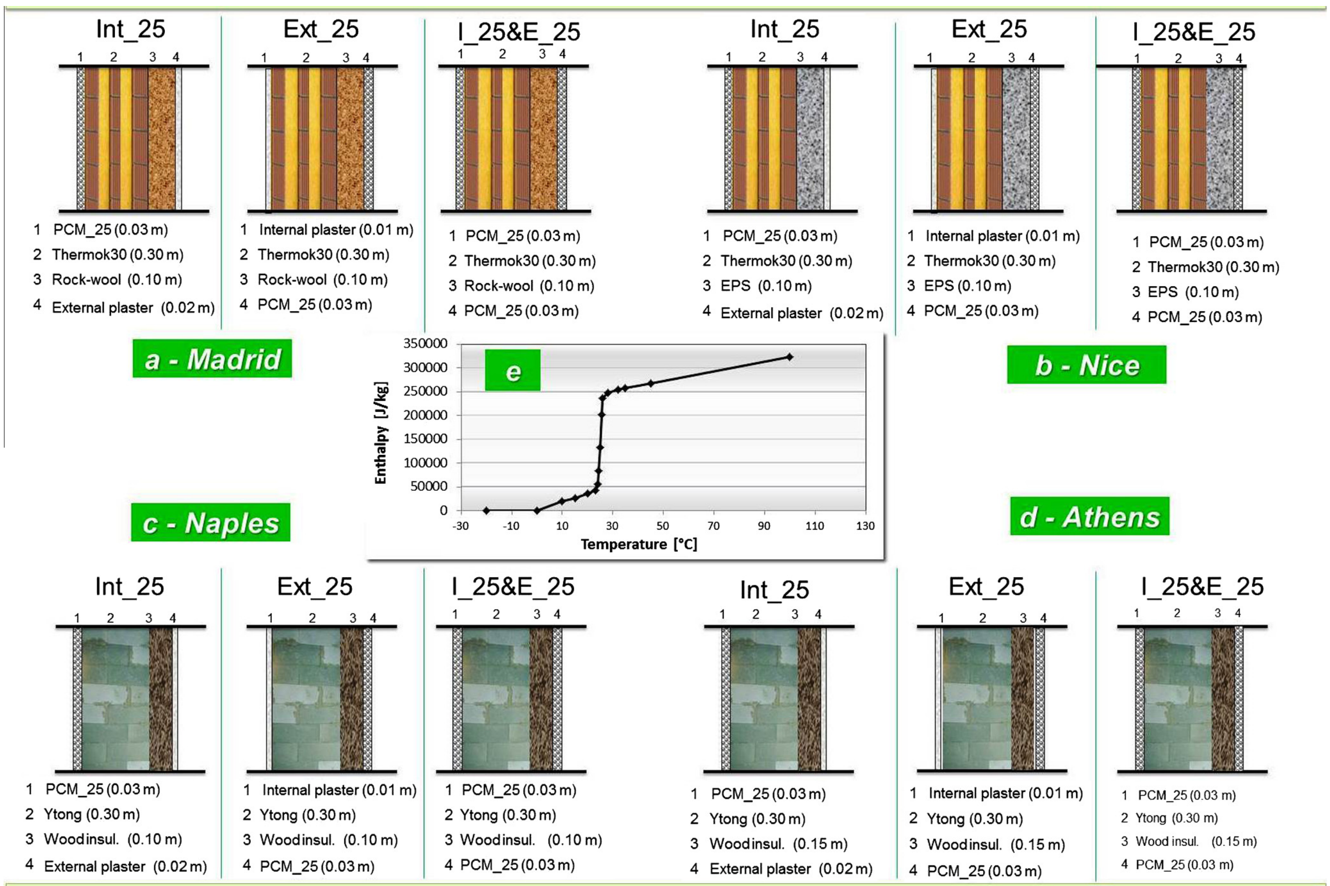


Fig. 14. Simulated configurations with PCM: (a) Madrid; (b) Nice; (c) Naples; (d) Athens; (e) temperature-enthalpy function.

This is due for rock-wool insulation, at high value of density that assures better performance also during the summer and for expanded polystyrene, at lowest value of thermal conductivity. Insulation thickness should be higher than 5 cm and a value between 10 and 15 cm is preferable.

Fig. 13b shows distribution of optimal configurations for roof slab. It is quite clear that mixed brick-concrete roof is the best compromise for the proposed minimization objectives, as well as the insulation level should be very high; 20 cm is optimal thickness for around 70–80% of points in each city. The results allow to remark that adoption of cool paints assures optimal performance (α_{solar} = 0.2 for 70% of points) meanwhile great variability has been obtained for thermal emissivity.

Double clear or low emissive or reflective windows are not included in the Pareto front (Fig. 13c). The best solution for transparent envelope is the adoption of triple selective window. Window to wall ratio varies but value between 30% and 50% could be appropriate in Mediterranean climate mainly because heat gain during the winter allows to reduce heating demand greatly. Instead there is not clear indication about inner and outer shading system; more in general drapes could be preferred and overhang with depth of 1.5 m or projection Louvre with blade depth of 0.5 m.

Finally, in Mediterranean climate, for minimizing the heating demand, different solutions can be preferred for walls, but the Pareto front does not include Wall 1 (in Fig. 3) nor construction system based on cross-laminated panel (XLAM). Moreover, it should be installed wooden roof with 20 cm of wooden fiber and waterproof membrane with medium value (0.5) for infrared emissivity and high value for solar absorptance. In each city, the best solution for transparent envelope is the adoption of triple selective windows (4/10/4/10/4) with $U_g \approx 0.81$ W/(m^2 K) and solar factor of 0.51.

Analogously, some clear indications can be obtained for the minimization of cooling demand. For opaque envelope, brick-concrete roof should be selected, and external finishing with high thermal reflectance are suitable too. Conversely, the same considerations than in wintertime can be done for wall system. Windows should be triple selective systems and both external and internal shading systems (more in detail shade roll) are required.

When the aim is to reduce the overall energy demand, walls should have $M_s \geqslant 250$ kg/m^2 and aerated concrete blocks or bricks with integrated insulation should be selected. Brick-concrete roof with external insulation ($U_r \approx 0.16$ W/m^2 K and $M_s \approx 500$ kg/m^2) and cool membrane as external covering ($\alpha_{solar} \approx 0.2$, $\varepsilon_{infrared} \approx 0.9$) are the most common best solutions for the roof slab. Optimal WWR changes greatly, instead triple glazing windows with selective coating and external shading appear to be the best solutions for transparent envelope.

5. PCM integration: cooling reduction and comfort improvement

A last analysis concerns the integration of phase change material as finishing layer of wall. The reference building for evaluation of potential reduction of cooling demand is the annual optimal solution shown in the previous section. This study indeed would like to investigate real commercial products. Therefore, the considered gypsum plasterboards have been chosen according to the market availability. Fig. 14 describes drawings of the PCM location and size for each city assuming melting temperature of 25 °C. For

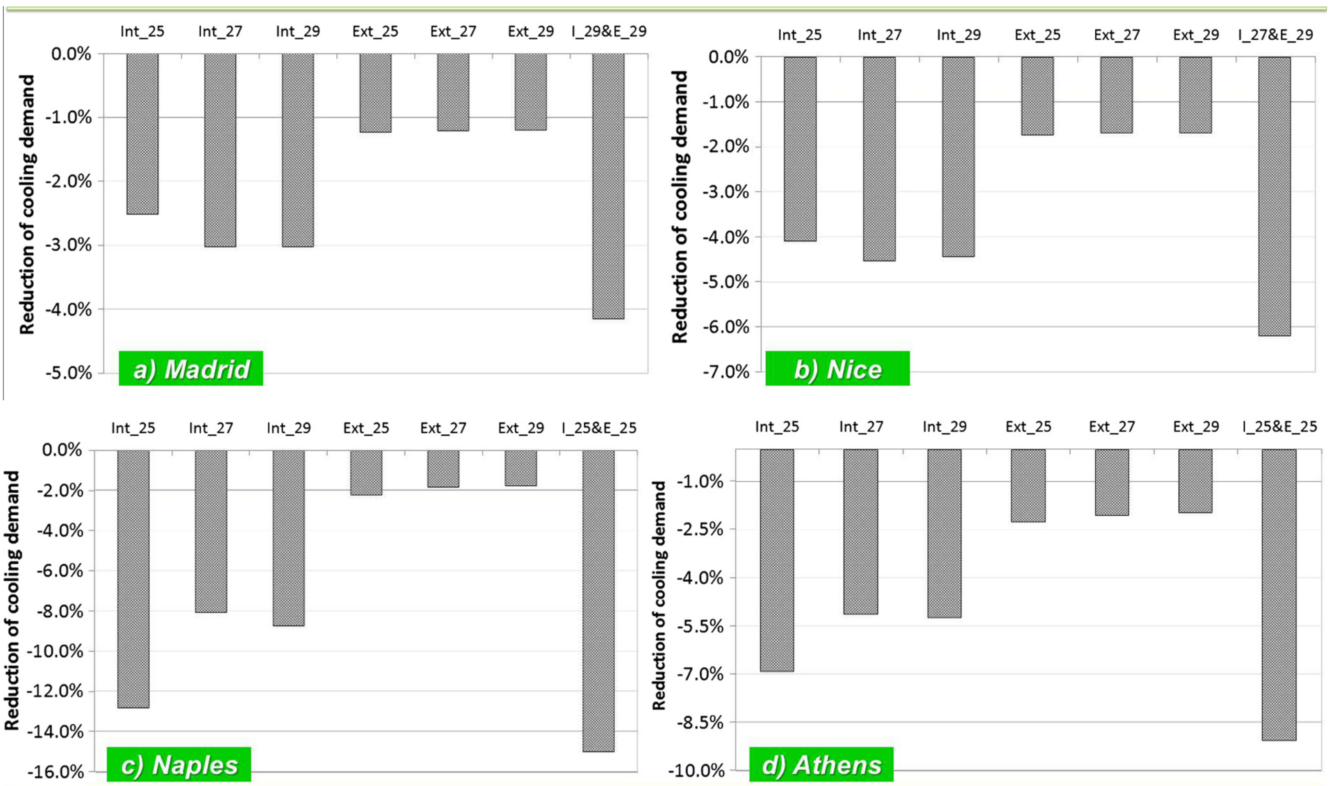


Fig. 15. Percentage reduction of cooling demand: (a) Madrid; (b) Nice; (c) Naples; (d) Athens.

considered material, the latent heat of fusion is 182 kJ/kg, the conductivity is 0.20 W/(m K), the specific heat is 1970 J/(kg K) and the density is 235 kg/m^3.

Parametric analysis has been done by varying melting temperatures and thus considering 25 °C, 27 °C and 29 °C. Since the starting point is the configuration that minimize the annual energy demand and considering the peculiarities of Mediterranean climate, these values have been chosen with the aim to reduce above all the cooling need. Firstly, the three configurations for inner and outer side have been considered separately. Then, by assuming the best melting temperature for inside and outside applications, the last simulation investigates the effect of the contemporary application of two PCMs, one on the inner side and the other one on the outer façade.

EnergyPlus can simulate materials with variable properties such as PCMs by using one-dimensional conduction finite difference solution algorithm. The user can choose between two different formulations. According to the EnergyPlus Engineering References: the first one is a semi implicit and based on the Crank-Nicholson scheme and the second one is the fully implicit scheme, that is first-order in time. In this study, the temperature-enthalpy function has been defined through a set of inputs that specify 16 pairs of combinations 'temperature/enthal py', by means of a tabular form. The tabular function considers the entire temperature range, from −20 °C to 100 °C (Fig. 13e). The 0.5 °C temperature variation, during the phase change, has been defined just to show the function and in order to model a real material instead of a theoretical one.

The experimental results, proposed by Barzine et al. [76], have shown that, if PCM is not used with proper control strategy, it may lead to an increase in the air-conditioning energy required. In order to work efficiently, a combination of "night ventilation" and "free cooling" method should be applied in which low temperature outdoor air at night is used to discharge the PCM inside the building. This is important to allow cooling and recrystallization of the PCM, so that it can be able to absorb heat during a period of hot days.

Night ventilation is an energy-saving strategy, by means of natural or mechanical ventilation during the night hours [77]. EnergyPlus allows to control the operation of natural ventilation using a predefined ventilation rates (a maximum air change rate modified by operation schedules) or to calculate the ventilation rates using wind and buoyancy-driven pressure, opening sizes and operation, crack sizes etc. within EnergyPlus Airflow Network. Using this model, Oropeza-Perez et al. [78] have shown that natural ventilation could help to cool down the building. However, the conditions must be correct. Moreover, it is important to optimize the natural airflow within the building according to outdoor wind speed, incident air angle, size of windows, percentage of the openings. This is not the aim of this paper, thus natural ventilation has not be optimized in this paper.

With conservative approach, without evaluate in this phase of study if the required airflow rate is achievable by the simple openings of windows, only an air exchange rate of 1.5 h^{-1} has been fixed during the assumed cooling period, from the 00:00 to the 06:00 to favor PCM performance. It can be assumed that it is supplied by a fan with a pressure head equal to 200 Pa. According to technical data, it could be a typical mechanical ventilation system for a conditioned floor area of 140 m^2. This implies, by assuming a fan efficiency equal to 0.7 and a volumetric flow rate of 0.22 m^3/s (it is the equivalent of 1.5 ACH considering the building volume of 517 m^3), a required power of around 62 W. This value has been multiplied by the number of operating hours (6 h) and the cooling period (138 days) and an electric energy demand equal to 51 kW h has been calculated.

More in detail, first investigation takes into account the percentage reduction of the cooling demand (ΔE_c) for all considered scenarios. Fig. 15 shows the achieved results.

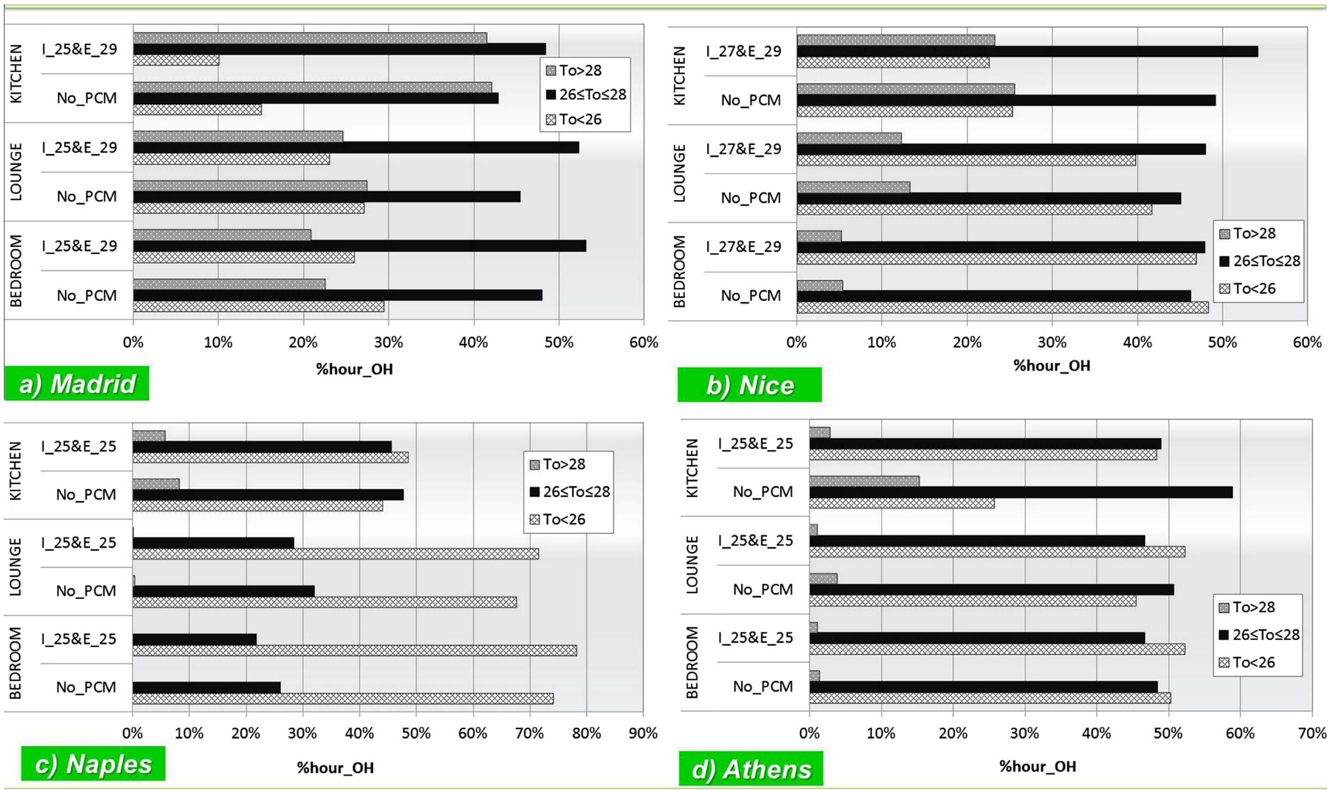


Fig. 16. Percentage of overheating hours: (a) Madrid; (b) Nice; (c) Naples; (d) Athens.

Starting from Madrid, application on external side, for each melting temperature, determines a reduction of cooling demand of around 1.2%. More interesting is the integration of PCM with $T_f = 27$ °C or 29 °C on inner side; in these two cases, $\Delta E_c \approx -3.0\%$. The adoption of two layers with same melting temperature (29 °C) on two different sides allows cooling energy saving of around −4.2%.

By considering Fig. 15b, for Nice, the application on inner side of PCM appears to be more interesting whatever is the melting temperature; however, the adoption of $T_f = 27$ °C assures greatest energy savings (≈−4.4%). The reduction of cooling demand is always around 1.7% when PCM is applied on outer side. When two PCMs are considered, by using $T_f = 27$ °C on internal wall and $T_f = 29$ °C on external wall, the reduction becomes −6.2%. Annually, it means that the overall energy demand (≈4800 kW h for the reference case) can be reduced of around 4.8%. It is interesting to note that PCM activation point is reached also during the wintertime. Indeed, the combined effect of radiation, external temperature and indoor gains can cause, during the early afternoon of some days, the increase of wall temperature. More in detail, melting temperature of 25 °C or 27 °C can determine a reduction of heating demand of 1.5% both with external and internal application.

Naples seems to have the greatest potentiality for PCM adoption. Fig. 15c shows that, also in this case, the integration on the inner side is the more promising solution since, with melting temperature of 27 °C, a $\Delta E_c \approx -8.8\%$ can be achieved. If T_f is 25 °C, this reduction becomes −12.8%. By using this PCM for both sides, cooling demand could be reduced of around 15%. The annual energy demand (≈5800 kW h in reference scenario) is characterized by $\Delta E_c \approx -10\%$. Also in this case, the phase change material completes its fusion cycle during some winter days especially with $T_f = 25$ °C and external application since the heating demand is reduced of around 2.5%. Also for Athens (Fig. 15d), the fusion cycle is optimized when material is positioned on inner side and, in particular when $T_f = 25$ °C, $\Delta E_c \approx -6.9\%$. Considering this fusion temperature for two PCMs on inner and outer sides, the cooling demand could be reduced until −9.1%. The choice to use 25 °C also for the external wall allows to reduce also the heating demand of around −1.75. This results contributes to reduce the overall demand (5900 kW h), globally, of around −7.5%. It should be noted that the inner application of phase change material provides a longer lifetime.

The obtained results suggest that, even if the thermostatic control induces small fluctuations of the indoor air building temperature, the location of phase change materials on the internal wall surfaces could be useful because the trend of the temperature inside the layer of PCM depends also from other causes. The total heat flow through the walls – and thus the temperature of the PCM layer for the charging/discharging cycle – depends by climate, building utilization and structural design. More in particular, the outdoor forcing cause, in Mediterranean climate, can determine the fusion of PCM also during the winter period, thus the choice of a low melting temperature induces a PCM extra-utilization in the coldest months.

It is evident that the thermal wave transmission through the wall depends by the structure stratigraphy, insulation and thermal inertia of building envelope. When these have been optimized, also PCM could contribute to reduce cooling demand meaningfully in some case (e.g. Naples).

As further analysis, the improvement of indoor comfort conditions and the overheating risk with PCM adoption have been examined. More in detail, for reference configuration (No_PCM) and for the best configuration according to the energy saving, the values of operative temperature and mean radiant temperature have been evaluated. About these, the risk of overheating has been estimated using the percentage of hours of cooling period in which the operative temperature (T_o) is in the following range (%hour_OH):

- $T_o \leqslant 26$: very comfortable conditions are assured inside the house;
- $26 < T_o \leqslant 28$: there is the possibility that the indoor environment is too hot and overheating conditions are realizable;
- $T_o > 28$: the risk of overheating is very frequent for occupants.

This analysis has been performed by considering the adoption of cooling system with schedule described in the previous sections. Fig. 16 shows, for months among May and September, the %hour_OH index for the case study, by considering three representative indoor spaces: bedroom, lounge room and kitchen. For Madrid (16a), in each room, the adoption of two PCMs determines the reduction of hours with temperature lower than 26 °C because the discharging cycle of PCM causes higher mean radiant temperature (e.g., for bedroom $T_{mr} \leqslant 26$ °C for 23% of hours of summer period without PCM and for 18% when PCMs are applied) than reference configuration. Moreover, also the time for which $T_o \geqslant 28$ °C is reduced also if slightly (1–2%) with application of PCMs. For Nice (Fig. 16b) same conclusions can be made, but, compared to Madrid, the percentage of hours with $T_o \geqslant 28$ °C is lower for each room. In the bedroom, the adoption of PCMs does not implies a significant improvement in terms of thermal comfort (%hour_OH ≈ 5% for $T_o \geqslant 28$ °C) while, in the kitchen, the amount of hours inside the range 26–28 °C is maximized. Naples (Fig. 16c) seems to have the better performances. Indeed, only the kitchen, in both cases, has low percentage of hours (8% for No_PCM and 6% for I_25&E_25) with temperature higher than 28 °C. The adoption of melting temperature of 25 °C allows to increase the hours with temperature below 26 °C and more comfortable conditions for the entire summer period. Finally, results for Athens are shown in Fig. 16d. The adoption of PCMs allows to reduce the hours of overheating risk from 15% to 3% in the kitchen. For all rooms, the percentage of hours with $T_o \geqslant 26$ °C increases. It should be remarked that PCMs reduce the value of mean radiant temperature and thus, by assuming the same value of air temperature (supplied by HVAC), the value of operative temperature is lower. Otherwise, by taking the same value of operative temperature, the HVAC system can operate with lower air temperature and the energy consumptions can be reduced without affecting the indoor comfort.

Some common considerations can be done by studying results for all the cities. The kitchen is the house space with worst indoor conditions. It depends, surely, from high value of inner gains and from its exposure (south-west). Adoption of shade systems could be further optimized or differentiated PCMs, with higher internal melting temperature, could be selected.

Anyway, solutions without PCM adoptions are optimized also in terms of indoor comfort, and this is evident especially for Athens and Naples.

6. Conclusion

The design of high-performance buildings, up to zero-energy buildings, is a multivariable problem, by including essential requirements such as energy and thermal comfort performance. In this study, optimization techniques, coupled with building performance simulation tools, are used to study the best trade-off among transparent envelope solutions, thermal mass of the building and radiative characteristics of roof. The case study is a small residential building located in four different cities typical of the Mediterranean climate: Madrid (Spain), Nice (France) Naples (Italy) and Athens (Greece).

In order to evaluate the optimized solutions, heating and cooling loads minimization have been considered as objectives function; moreover, the hours of discomfort have been assumed as limiting constraint for determining the Pareto front solutions.

Some general indications can be obtained from the results of case study. In Mediterranean climate, for minimizing heating demand, walls made of autoclaved cellular concrete or with bricks and integrated EPS or traditional brick wall with hollow blocks and external wooden fiber insulation can be selected. Minimization of cooling demand requires adoption of cool-colored roof, highly insulated. In any case, windows should be triple selective systems and both external and internal shading systems (more in detail, shade roll) are required.

When the aim is to reduce the overall energy demand, walls should have $M_s \geqslant 250$ kg/m^2 and aerated concrete block or brick with integrated insulation should be selected. Brick-concrete roof with external insulation ($U_r \approx 0.16$ W/m^2 K and $M_s \approx 500$ kg/m^2) and cool membrane as external covering ($\alpha_{solar} \approx 0.2$, $\varepsilon_{infrared} \approx 0.9$) are the most common solutions for the roof slab. Optimal WWR changes greatly, instead triple glazing windows, with selective coating and external shading, appear to be the best solution for the transparent building envelope. For what concerns the mean radiant temperature, operative temperature profile and percentage of dissatisfied people (PPD), the optimality of indoor thermal-hygrometric conditions has been underlined.

A last analysis has concerned the integration of phase change material as finishing layer of the walls. The obtained results suggest that the adoption of melting temperature of 25 °C on the inner side allows, in each city, reduction of cooling demand (from ≈−2% in Madrid to ≈−13% in Naples). The outdoor forcing cause in Mediterranean climate can determine the fusion of PCM also during the winter period, thus the choice of a low melting temperature induces a PCM extra-utilization in the coldest months. By combining this solution with the application of another PCM layer with high melting temperature, on the external side, the cooling energy saving is maximized. In this case, the optimal melting temperature depends greatly by the outdoor conditions of temperature and solar radiation.

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