Energy Efficiency (2017) 10:1081–1098
DOI 10.1007/s12053-016-9504-1

ORIGINAL ARTICLE

Suitable thermal insulation solutions for Mediterranean climatic conditions: a case study for four Greek cities

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Received: 15 June 2015 / Accepted: 22 December 2016 / Published online: 7 January 2017

Abstract The selection of thermal insulation solutions has to satisfy many criteria: energy performance is the obvious one, structural and safety performance is a prerequisite, and environmental and economic aspects are those that can make the difference. However, especially when buildings operate under the Mediterranean climates, where outdoor conditions have to be mitigated by the building fabric throughout the year, the contribution of an insulation solution to indoor thermal comfort is also an important issue. In this approach, an integrated decision support system was applied to assess thermal insulation practices used commonly in residential buildings in the Mediterranean area. The system assesses the buildings' elements over their life cycle, with thermal comfort being evaluated by means of the PMV/PPD index. Twenty-three thermal insulation configurations were considered, with different locations (internal, middle, external), materials (expanded polystyrene, extruded polystyrene, stone wool), and thicknesses. As the results showed, the position and the thickness of the insulation materials have a large impact on the energy consumption, the overall environmental impact, and the life cycle cost of the building, while thermal comfort was affected to a lesser degree.

Keywords Thermal insulation · Thermal comfort · Life cycle assessment · Embodied energy · Environmental performance · Mediterranean region

Nomenclature

COP	Coefficient of performance
CTIS	Total cost (life cycle) (€)
DSS	Decision support system
ECTIS	Total primary energy consumption (life cycle) (MJ)
EIATIS	Total environmental impact assessment (life cycle) (unit of factor)
EPS	Expanded polystyrene
ETICS	External thermal insulation composite system
LCA	Life cycle assessment
LCC	Life cycle costing
NR	Normalized value of assessment factor (−)
PC	Value of assessment factor per citizen of the country where the methodology is applied (unit of factor)
PMV	Predicted mean vote
PPD	Predicted percent of dissatisfied people (−)
R	Value of assessment factor (unit of factor)
RAC	Room air conditioner
Rating	Total rating (−)
SW	Stone wool

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TIR Thermal insulation regulation
XPS Extruded polystyrene

Subscripts
i Thermal insulation solution
g Assessment factor

Introduction

The environmental impact of buildings includes both their energy consumption during their lifetime and the production of construction and demolition waste. Thickness and the positioning of insulating materials in opaque building elements are major factors that affect both the energy performance and the overall environmental impact of a building. Those two features of insulation do affect not only the thermal transmittance of the building fabric but also its thermal mass and its hygrothermal performance. Thus, insulation determines not only the energy performance of a building but also the resulting indoor environmental quality as well. The latter is usually not considered by studies aiming at the optimization of the selection of thermal insulation solutions for various' buildings elements.

Balaras (1996) performed an extensive review and provided the classification of all the factors that affect the performance of thermal mass. Furthermore, several simplified design tools used for the calculation of the cooling load and the indoor air temperatures of a building were identified. Asan (2000) evaluated the optimal insulation position by taking into account the maximum time lag and the minimum decrement factor in six thermal insulation configurations. The minimum decrement factor results from the placement of the insulation half in the inside surface and half in the outside surface of the wall. The placement of half of the insulation thickness in the middle of the wall and the half in the outside surface of the wall results in high time lags and low decrement factors. Ozel and Pihtili (2007) analyzed the optimum position of insulation in 12 different external wall configurations. The time lag and the decrement factor for the configurations in summer and winter conditions are the two main factors that were used in order to determine the optimal solutions. The optimal energy performance was found to be the configuration of the insulation placed at the outdoor surface of the wall and that the thickness of the insulation materials placed in the indoor and outdoor surfaces of the walls should be equal. Bolatturk (2008) determined the optimum insulation thickness on external walls of buildings in Turkey based on annual heating and cooling loads. For cooling loads, the results show that the optimum insulation thickness varies between 3.2 and 3.8 cm and for heating period from 1.6 and 2.7 cm. Vaidya et al. (2009) developed a methodology for improving energy efficiency in relation to cost optimization. The amount of design effort invested, the scheduling of effort, and the energy performance are the three main parameters of the proposed methodology. The analysis concluded with significant results of several cost interactions among energy measures. Slavković and Radivojević (2014) evaluated the embodied energy of external walls of seven typical residential building types in Serbia. Four different scenarios and four different insulation materials were included in the study. All thermal insulation configurations satisfy the maximum thermal transmittance values of the current legislation. The results indicate that local insulation materials are more preferable regarding the consumed recurrent embodied energy.

This is even more critical in the case of refurbishment and energy upgrading of existing buildings, where improving thermal comfort is a main requirement. In particular climates, excessive building insulation may lead to the total increase in energy consumption causing the anti-insulation effect. Friess et al. (2016) performed detailed simulations of a typical office building in order to study the anti-insulation effect. The results of the study indicate that buildings in the Mediterranean climate are most susceptible to the anti-insulation effect, but the efficiency loss does not exceed 1% of the overall energy consumption.

Baglivo and Congedo (2015) evaluated precast multi-layered walls for zero energy buildings in warm climates by performing a multi-criteria analysis with the use of an optimization tool. The results indicate that energy efficient precast multi-layered walls can be obtained with lightweight solutions. Baglivo et al. (2014) evaluated high-energy efficiency external walls for zero energy buildings in the Mediterranean climate according to the ITACA Protocol for environmental sustainability by carrying out a multi-criteria analysis. A single optimal solution cannot be determined, but there is a set of possible external wall configurations that can be selected at the design phase. The assessment of the optimal cost and technical solutions in multi-family buildings in the Mediterranean climate was carried out by Zacà et al.

(2015). A representative multi-family building was chosen, and several energy saving measures were applied in order to reduce the energy consumption. The implementation of the specific measures results to the reduction of the primary energy consumption by up to 90%, and CO_2 emissions decrease up to 88% with respect to the reference building.

Sierra-Pérez et al. (2016) performed and extensive life cycle assessment (LCA) of insulation materials that are applied in façade systems in Spain. The external thermal insulation system combined with any type of insulation was found to be the most optimal configuration, while the environmental impacts of the insulation materials selected vary significantly.

Regarding the particular thermal insulation–thermal comfort nexus, Hong et al. (2009) investigated the effect of England's warm front energy efficient refurbishment scheme on winter thermal comfort in low-income dwellings. The study was carried out before and after the retrofitting of thermal insulation. It was found that retrofit insulation resulted in the increase of the indoor temperature by 1.19 K. For the same temperature range, the predicted mean vote (PMV) index was found to under-predict the actual thermal comfort conditions and consequently resulted in higher neutral temperature of 20.4 °C, compared to 18.9 °C in which the average warm front households were found to be comfortable.

Djuric et al. (2007) analyzed how the insulation thickness of the building's envelope, the supply water temperature, and the heat exchange area of the radiators influence the thermal comfort, the energy consumption, and the investment cost. EnergyPlus (Crawley et al. 2001) building energy simulation software and GenOpt (GenOpt 2015) generic optimization program were used for this. Thermal comfort was taken into account by applying the predicted percent of dissatisfied people (PPD) method. The thicker insulation layers resulted in the highest total cost. Eben Saleh (1990) evaluated the thermal performance of different configurations, types, and thicknesses of insulation materials in buildings by utilizing a software tool based on the thermal response factor method. It was found that in hot climates, the presence of thermal insulation leads to significant improvement in energy performance of the building, regardless of its location, internally or externally. This finding was confirmed by a recent study by Fokaides and Papadopoulos (2014). The proper location of insulation was demonstrated to have a positive influence on the transient heat transfer from the walls and the roof of the building. A better performance was achieved when locating insulation on the outer side of the building's envelope.

The present study focuses on determining the optimal positioning of thermal insulation also considering the insulation materials used. In the "Description of the case study building" section, the typical multi-family building used as a case study is being described. An introduction to the LCA framework adopted for the study is discussed in the "Description of the life cycle assessment framework" section. In the same section, the main features of thermal comfort as they occur in the specific problem and how they can be quantified along with all the other criteria used in the study are discussed, in order to use them in the decision support system (DSS). This upgraded rating system is being applied in the "Results and discussion" section for 23 different construction solutions as they appear in the case study building in the Mediterranean region. All the constructions solutions under study are heavy massive constructions. The results of the comparison are discussed in this section. The paper concludes in the "Conclusions" section.

Description of the case study building

The integrated evaluation of the optimal positioning of the insulation materials was carried out by performing an extensive life cycle analysis of the environmental, energy, economic, and thermal comfort performance of equivalent thermal insulation configurations implemented in all four external building elements for a given typology of a representative residential building located in the Mediterranean region. Expanded polystyrene (EPS), extruded polystyrene (XPS), and stone wool (SW) are three of the most widely used insulation materials in Europe. Data for thermal and physical properties of the insulation materials were derived from previous studies (Papadopoulos 2005; Pfundstein et al. 2007; Anastaselos 2009) and are presented in Table 1. There are further materials used, especially in the Middle East and North Africa part of the Mediterranean basin, like autoclaved aerated concrete blocks and panels, but they are rarely used with additional thermal insulation and hence do not fall within the scope of this research. On the other hand, super insulating materials, like aerogels as discussed by Stahl et al. (2012), although very promising, are still very expensive and not totally commercial

Table 1 Thermal and physical properties of the insulation materials under study

Properties	Stone wool	Expanded polystyrene	Extruded polystyrene
Density (kg/m^3)—EN 12667			
Min	30	15	25
Max	200	30	45
Thermal conductivity factor, λ (W/mK)—EN 13162, 13163, 13164			
Min	0.033	0.030	0.030
Max	0.040	0.039	0.038
Temperature application range (°C)—EN 14706			
Min	−100	−80	−60
Max	750	80	75
Resistance to vapor diffusion factor—EN 12086			
Min	1	20	50
Max	2	100	200
Reaction to fire class—EN 13501−1			
Min	A1	E	E
Compressive strength [kPa]—EN 826			
Min	5	50	100
Max	90	200	700

mature and can result in "overinsulating" for the climatic conditions of the Mediterranean and thus cannot be justified. In this line of approach, the three aforementioned materials (EPS, XPS, and SW) will be only considered.

Architecture and geometry of the building

In order to conduct this study, a multi-family residential apartment building (Fig. 1) was chosen (Papadopoulos et al. 2008b). It is a three-storey building with two apartments per floor, a total heated area of 684 m^2, a cooled area of 540 m^2, and a window to wall ratio of 17%. It is fairly representative for the urban multi-building stock in the Mediterranean area in countries like Greece, Cyprus, Italy, France, etc. (Theodoridou et al. 2011).

Building physics' features

The insulation materials used are of equivalent thermal and mechanical properties, specific for each building element's category: the thermal conductivity range for the EPS products is 0.034 to 0.039 W/mK, for XPS, between 0.033 and 0.038 W/mK; and for SW products, between 0.033 and 0.040 W/mK. Most common physical properties of the three insulation materials are reported in Table 1.

Typical configurations of the several building elements with different positioning of the insulating layer are presented in Fig. 2. In total, 23 different thermal insulation configurations were evaluated for four Greek cities each representing one of the four different climatic zones of Greece (Fig. 3). It has to be underlined that those Greek cities display climatic features similar to major cities in the Mediterranean region, as presented in Table 2. In addition, in Table 3, the main climatic variables for the regions under study are being reported.

The thermal insulation configurations considered satisfy the new energy regulation limits imposed by the Greek Regulation on the Energy Efficiency of Buildings (KENAK) (Ministry of Environment, Energy and Climate Change 2010) which resulted from the harmonization of the initial Energy Performance of Buildings Directive (2002/91/EC) and achieve the respective maximum thermal transmittance values. Regarding the vertical building elements, 12 conventional insulation configurations, eight with the installation of an external thermal insulation composite system (ETICS), and three with internal insulation are considered for all the climatic zones; they are presented in Table 4. Internal insulation is not common in new constructions and can result in increased cooling loads in such climates under specific circumstances; however, it is still a popular approach in building renovations and that is the main reason that is being considered here. The last two columns of Table 4 present the total thermal mass value (base on the admittance value of each construction) of each combination of configurations and their respective ranking. Additionally, Table 5 lists the main thermal mass parameters of the main configurations as they have been calculated for climate zone A. Not all 23 configurations are displayed since only the placement of the insulation layer and not the type of insulation material affects those figures.

Heating and cooling systems

The building features a central heating system, fed by an oil-fired boiler with an efficiency of 0.90. In the rooms, the heat is distributed by hydronic radiators. Thermostatic control is provided in each apartment, with set temperatures of 20 °C during daytime and a night

Fig. 1 The typical three storey multi-family building

setback at 15 °C. Typical ventilation and infiltration values were considered, of 1.0 air change per hour for the main rooms of two for the kitchen and of four for the sanitary rooms. The heating systems' design and efficiency can be considered as typical for good quality systems with some years of operations (Papadopoulos et al. 2008a).

With respect to cooling, the living room and the two bedrooms of each apartment are equipped with split unit type room air conditioners, having a

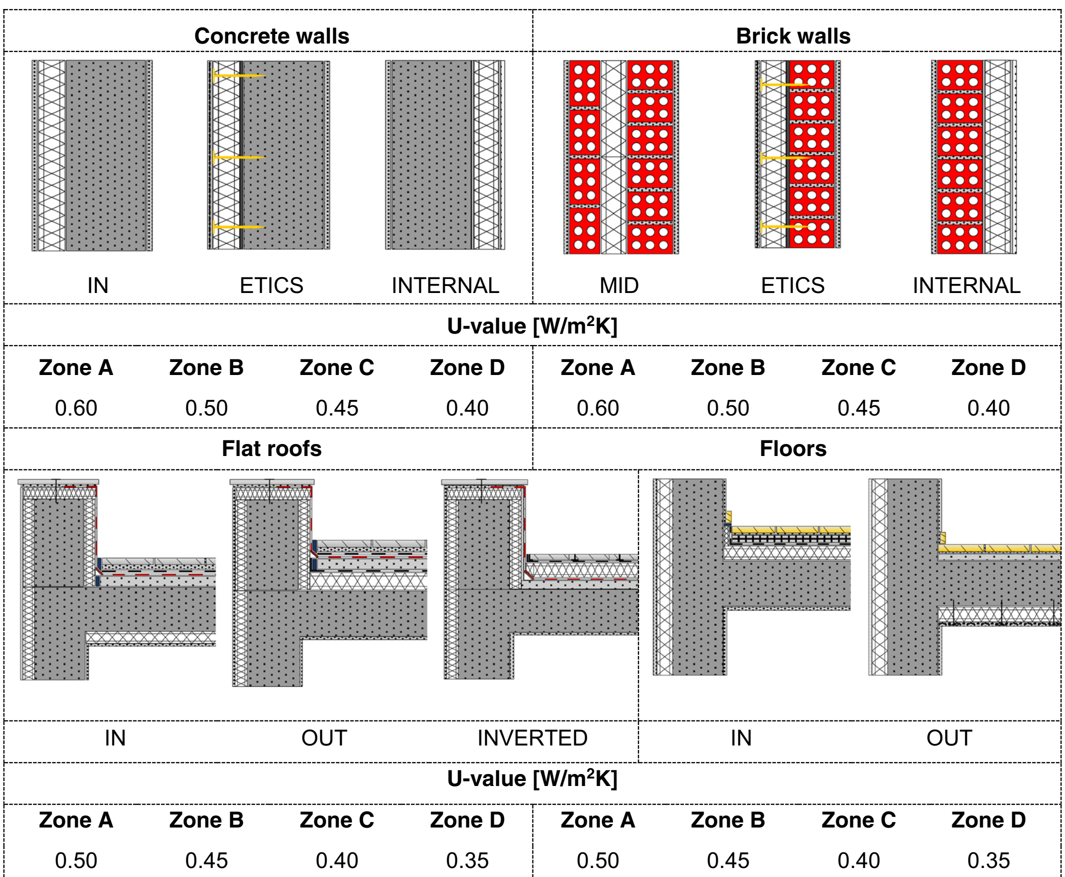

Fig. 2 Position of thermal insulation materials and *U* values of building elements

Fig. 3 Climatic zones of Mediterranean region under study (Google Earth 2011)

seasonal average COP of 3. During the cooling period the RACs' thermostats are set at temperatures of 26 °C (no night setback). The room air conditioners' efficiency is lower than the one foreseen by the new EU regulations 626/2011 and 206/2012 but is typical for systems with an average age of 5 years (Cherem-Pereira and Mendes 2012).

Description of the life cycle assessment framework

The main assessment factors evaluated in this study are primary energy consumption, environmental impact, economic performance, and thermal comfort. The life cycle stages taken into consideration consist of the construction phase (which includes the production, transportation, and installation of the materials), the building's operation, the dismantling of the building, and the end-of-life management of the resulting demolition waste. Since no reliable statistical data on the life span of buildings are available, the conventional life span of 50 years is assumed (Famuyibo et al. 2013). The building at the end of its service life is considered to be deconstructed, and the resulting wastes are transferred to proper recycling facilities and landfill sites.

Environmental parameters

The environmental impact assessment is based on the LCA methodology. The importance of environment-related product information by means of LCA is broadly recognized, and LCA is considered to be one of the tools to help achieving sustainable building practices. LCA offers a comprehensive analysis which links actions with environmental impacts. At the same time, it provides quantitative and qualitative results and taking into consideration the link between system's functions and environmental impacts, it is easy to identify the issues that need improvement (Anastaselos 2009).

In this study, the environmental impacts categories that are thoroughly examined are as follows: Climate change, acidification, eutrophication, and photochemical oxidation. Every category is characterized by certain emissions (such as CO_2 equivalent, SO_2 equivalent, PO_4 equivalent, C_2H_4 equivalent respectively) that stem from specific

Table 2 Cities with similar climate features in the Mediterranean region

Zone	Greek cities	European cities in the Mediterranean region		Climate features
A	Rhodes (14)[a] (9174)[2]	Larnaca (22)[a] (11,858)[b]	Palermo (7)[a] (7179)[b]	Humid subtropical. Mild with no dry season, hot summer. Warm–humid. Humid subtropical (warm summer)
B	Athens (82)[a] (10141)[b]	Izmir (223)[a] (9927)[b]	Brindisi (78)[a] (5952)[b]	Humid subtropical. Mild with no dry season, hot summer. Warm–humid. Humid subtropical (warm summer)
C	Thessaloniki (384)[a] (6960)[b]	Madrid (474)[a] (7715)[b]	Istanbul (509)[a] (3611)[b]	Humid subtropical. Mild with no dry season, hot summer. Warm. Marine. Dry summer subtropical (Mediterranean)
D	Florina (953)[a] (5276)[b]	Milan (974)[a] (3038)[b]	Torino (851)[a] (2581)[b]	Humid subtropical. Mild with no dry season, hot summer. Mixed. Humid. Humid subtropical/humid continental (warm summer)

In parentheses are depicted the HDD (balance temperature 10 °C) and CDH (balance temperature 23 °C)

[a] Heating degree days (balance temperature 10 °C)

[b] Cooling degree hours (balance temperature 23 °C)

procedures within the life cycle of a building. At the environmental impact assessment phase, the indicators derived from CML 2 baseline 2000 method were used (CML 2001).

All the necessary data for building materials at the construction phase were acquired from results published recently (Anastaselos 2009; Hegger et al. 2006). For the output data, namely emissions from production, transportation, and installation, the SimaPro LCA software was used (PRé Consultants 2009), which is a life cycle analysis model with the embodied EcoInvent LCA database and cost–emission analysis system (Frischknecht and Rebitzer 2005).

Specifically for the operation period, oil and electricity emission factors used are presented in Table 6 (Hellenic Transmission System Operator 2014; Anastaselos et al. 2011a). In order to determine the electricity generation emission factors, the Greek electricity generation mix for 2013 was taken into account. It was based on lignite (46%), natural gas (24%), renewable energy sources (26%), and the remaining 4% being imports (PRé Consultants 2009).

Finally, for the dismantling and end of life management phase, the integrated building energy, environmental and economic assessment tool, namely ib3at©, was used (Anastaselos et al. 2011a). For these phases, all the necessary input data were taken from previous studies (Anastaselos 2009; Anastaselos et al. 2011a).

Energy parameters

For the operation phase, all the simulative calculations were carried out using the EnergyPlus simulation software (Crawley et al. 2001). Thermal bridges have been calculated according to International Organisation for Standardisation (2007).

The embodied energy of the building during the construction and maintenance phase, in collaboration with the total energy consumption related to the dismantling and end of life management of the building, was calculated with the use of ib3at© (Anastaselos 2009).

Economic parameters

The economic performance of the insulation configurations is determined with the life cycle costing (LCC) approach. The LCC approach includes the purchase and all associated costs (delivery, installation, etc.); the operating costs, including energy, maintenance, etc.; and the end of life costs, such as decommissioning and removal. LCC is widely used as a decision support tool in order to minimize the life cycle costs of an asset, while it can be also applied for the comparative evaluation of the actual costs for similar asset types (Grant and Ries 2013; Gluch and Baumann 2004).

The cost of supply and installation of building materials and components, the operation, maintenance, dismantling, and end of life management is based on market prices in the first half of 2014.

Table 3 Main climatic characteristics of the studied climate zones

Variable	Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry bulb temperature [°C]	Rhodes [A]	12.8	12.5	14.1	16.1	20.8	24.2	27	27.2	24.4	21.3	17.4	14.4
	Athens [B]	10.7	9.6	11.4	15.1	19.6	24.6	27.3	27.6	23.9	19.1	14.5	10.9
	Thessaloniki [C]	6.2	6.6	9.5	13.2	18.4	23.3	25.8	25.5	21.3	16	11.1	7.4
	Florina [D]	1.2	2.7	6.9	11	16.8	20.8	23.9	23.5	17.5	13.2	7.2	2.7
Relative humidity [%]	Rhodes [A]	72	71	72	73	73	66	64	67	68	70	75	75
	Athens [B]	67	67	66	61	62	51	50	52	57	66	72	69
	Thessaloniki [C]	77	69	58	69	61	53	55	58	66	75	71	81
	Florina [D]	81	74	65	65	64	58	52	55	66	72	79	82
Global horizontal radiation [Wh/m^2]	Rhodes [A]	2349	3185	4778	5926	7162	8092	8247	7306	5964	4241	2777	2205
	Athens [B]	2068	2815	4012	5144	6215	7479	7529	6626	5421	3522	2141	1809
	Thessaloniki [C]	1745	2895	3966	4894	6013	7098	7079	6243	4787	3187	1961	1485
	Florina [D]	1936	2565	3829	5140	6170	6810	7006	6314	5099	3209	2056	1765
Heating degree days [10 °C]	Rhodes [A]	6	6	1	0	0	0	0	0	0	0	0	1
	Athens [B]	17	32	11	2	0	0	0	0	0	0	0	20
	Thessaloniki [C]	119	98	50	2	0	0	0	0	0	1	24	90
	Florina [D]	273	205	114	29	0	0	0	0	0	10	94	228
Cooling degree hours [23°]	Rhodes [A]	0	0	0	1	188	1261	2971	3129	1234	313	10	0
	Athens [B]	0	0	0	8	175	1866	3232	3452	1278	130	0	0
	Thessaloniki [C]	0	0	0	6	369	1248	2491	2214	565	67	0	0
	Florina [D]	0	0	0	11	140	879	2087	1847	285	27	0	0

Table 4 Solutions under study (position of insulation in relation to the main building element: IN = inside, OUT = outside, MID = middle)

A/A	Brick walls	Concrete bearing walls	Floors	Roofs	Total thermal mass [W/K]	Rank
1	SW (MID)	XPS (OUT)	XPS (IN)	XPS (OUT)	4567	6
2	XPS (MID)	XPS (OUT)	XPS (IN)	XPS (OUT)	4565	13
3	EPS (MID)	XPS (OUT)	XPS (IN)	XPS (OUT)	4567	6
4	SW (MID)	EPS (OUT)	XPS (IN)	XPS (OUT)	4567	6
5	SW (MID)	XPS (OUT)	EPS (IN)	XPS (OUT)	4567	6
6	SW (MID)	XPS (OUT)	SW (IN)	XPS (OUT)	4567	6
7	SW (MID)	XPS (OUT)	XPS (IN)	EPS (OUT)	4567	6
8	SW (MID)	XPS (OUT)	XPS (IN)	SW (OUT)	4567	6
9	SW (MID)	XPS (OUT)	XPS (IN)	INVERTED (XPS)	4539	17
10	SW (MID)	XPS (OUT)	XPS (IN)	INVERTED (XPS)	4539	17
11	SW (MID)	XPS (OUT)	EPS (IN)	INVERTED (XPS)	4539	17
12	EPS (MID)	XPS (OUT)	EPS (IN)	INVERTED (XPS)	4539	17
13	ETICS (SW)	ETICS (SW)	XPS (IN)	XPS (OUT)	4557	15
14	ETICS (XPS)	ETICS (XPS)	XPS (IN)	XPS (OUT)	4557	15
15	ETICS (EPS)	ETICS (EPS)	XPS (IN)	XPS (OUT)	4560	14
16	ETICS (SW)	ETICS (SW)	SW (OUT)	XPS (OUT)	4732	2
17	ETICS (XPS)	ETICS (XPS)	XPS (OUT)	XPS (OUT)	4732	2
18	ETICS (EPS)	ETICS (EPS)	EPS (OUT)	XPS (OUT)	4735	1
19	ETICS (XPS)	ETICS (XPS)	XPS (OUT)	INVERTED (XPS)	4703	5
20	ETICS (EPS)	ETICS (EPS)	EPS (OUT)	INVERTED (XPS)	4706	4
21	INTERNAL (SW)	INTERNAL (SW)	EPS (IN)	EPS (IN)	2014	23
22	INTERNAL (EPS)	INTERNAL (EPS)	EPS (IN)	EPS (IN)	2439	22
23	INTERNAL (SW)	INTERNAL (SW)	EPS (OUT)	INVERTED (XPS)	2882	21

Table 5 Thermal mass values for different configurations of building elements (climate zone A)

Building element type	Name	Admittance W/m^2K	Decrement factor	Decrement delay h	K kJ/m^2K	Total area m^2
Walls	SW (MID)	4.39	0.32	9.81	109	276
	ETICS (SW)	4.36	0.43	6.27	109	
	INTERNAL (SW)	0.97	0.6	5.53	11	
Bearing Walls	XPS (OUT)	5.32	0.11	9.64	189	204
	ETICS (SW)	5.31	0.11	9.16	189	
	INTERNAL (SW)	0.97	0.19	8.84	11	
Floors	SW (IN)	3.95	0.26	9.21	72	240
	SW (OUT)	4.68	0.14	8.09	165	
Roofs	SW (OUT)	5.51	0.1	12.48	189	240
	INVERTED (XPS)	5.39	0.12	11.04	189	
	EPS (IN)	2.5	0.1	11.53	38	

Table 6 Fuel emission factors

Pollutant	Emission factor (g/kWh)	
	Fuel oil	Electricity
Methane (CH_4)	0.0002	0.7450
Carbon monoxide (CO)	0.0931	0.2094
Carbon dioxide (CO_2)	263.6343	850.0000
Nitrous oxide (N_2O)	0.0022	0.0229
Volatile organic compounds (NMVOC)	0.0047	0.0542
Nitrogen oxides (NO_x)	0.0205	1.2000
Particulate matter (PM)	0.0057	0.0648
Sulfur dioxide (SO_2)	0.1087	15.5000

Thermal comfort

In the world of engineering, thermal comfort is defined as the mental state of a person during which he expresses satisfaction with his thermal environment and does not want any change on the thermal conditions (ASHRAE 2004). Still, from a historical perspective, comfort can be described as the end-point of a technological quest driven by advances in engineering (Roberts 1997). The historical definition of thermal comfort describes more aptly its dynamic features, connects comfort with social development, and views it not only as a scientific theory but as a cultural phenomenon as well.

The expectation of people regarding thermal comfort continuously changes following the technological development of building technology which alters the thermal characteristics of indoor environments and, consequently, the way heat is transferred to and from people. In principle, determining comfort is a multivalent problem depending on many parameters (biological, psychological, environmental, external) and extending not only to the thermal conditions of an indoor environment but also to how these are maintained.

The specific climatic parameters of a space that affect the thermal comfort sensation of its occupants are air temperature, mean radiant temperature, air velocity, relative humidity, and atmospheric pressure. Positioning and thickness of an insulation layer in any building component affect significantly the two most important climatic parameters being air temperature and mean radiant temperature.

In principle, there are two distinct ways of estimating comfort in a room. The deterministic route of Fanger's PMV–PPD model (Fanger 1970) and all its successors, which originate from laboratory based research, and the stochastic approach, described by the adaptive comfort models that arisen from field based research (de Dear and Brager 1998; Nicol and Humphreys 2002). The latter are more suited for evaluating thermal comfort conditions in free running naturally ventilated building, like this is the case in the Mediterranean in the cooling period, where no mechanical cooling is used, as this was recognized already in the 1980s (Papadopoulos and Chrisomallidou 1979).

Deterministic models quantify the sensation of thermal comfort by using the predicted mean vote (PMV) index which is a function of air temperature, human activity, clothing type, radiant temperature, relative humidity, and air speed. Thus, it takes into account most of the parameters affecting thermal comfort. PMV is expressed with values that range from −3 (cold) to +3 (hot), 0 being the neutral, desirable condition, where only 5% of the people in the particular room are dissatisfied with the prevailing thermal conditions. It predicts the mean value of the subjective ratings of a group of people in a given environment. PMV values between −0.5 and +0.5 are considered very good conditions in engineering practice and correspond to less than 10% of the people in the environment being dissatisfied. The latter are defined as the predicted percent of dissatisfied people (PPD), a figure used as the quantitative measure of thermal comfort, being a direct function of PMV.

Stochastic models, on the other hand, relate comfort to a range of indoor operative temperature as a function of outdoor air temperature.

PMV and PPD were the indexes used to assess the thermal comfort conditions in the present study.

Overall ranking

For the evaluation procedure, the ib3at© tool was used, as it is an integrated building energy, environmental and economic assessment tool, which can also be used separately in order to optimize the materials and systems used in the various stages of a building's life time. The tool considers three main assessment factors: the primary energy consumption, the environmental impact, and the financial cost; each and every factor is analytically assessed during the four distinct stages of a building's life cycle. The calculation of the aforementioned factors takes place using analytical algorithms. The resulting values for every assessment factor are normalized by dividing them with the yearly total value for each specific assessment factor per citizen of the country where the methodology is applied. The lowest value of this ranking is the single optimal solution.

Thermal comfort is the additional assessment factor that had to be implemented in ib3at©. The assessment of thermal comfort and its contribution to the overall ranking of the thermal insulation solutions under evaluation is determined with the use of the PPD factor. The resulting values of the PPD are already normalized, so no further transformation to the ranking methodology is necessary. The final ranking is calculated from Eq. 1. The lowest value of this ranking is again the single optimal solution, while the implementation of weighting factors can be neglected. The methodology adopted, with the introduction of thermal comfort as an assessment factor, is schematically presented in the flowchart of Fig. 4.

$$\mathrm{Rating}_i = \sum_{g=1}^{f} \mathrm{NR}_{ig} = \sum_{g=1}^{f} \frac{\mathrm{R}_{ig}}{\mathrm{PC}_g} = \frac{\mathrm{ECTIS}_i}{\mathrm{PC}_{g=1}} + \frac{\mathrm{CTIS}_i}{\mathrm{PC}_{g=2}} + \frac{\mathrm{EIATIS}_i}{\mathrm{PC}_{g=3}} + \mathrm{PPD}_i \tag{1}$$

where

NR: normalized value of assessment factor (−)

ECTIS: total primary energy consumption (life cycle) (MJ)

CTIS: total cost (life cycle) (€)

EIATIS: total environmental impact assessment (life cycle) (unit of factor)

PC: value of assessment factor per citizen of the country where the methodology is applied (unit of factor)

PPD: predicted percent of dissatisfied people (−).

Results and discussion

The application of the methodology led to the calculation of the overall ranking and the determination of the single optimal solution for every climatic zone.

Final energy and thermal comfort

Final energy consumption for space heating (heating oil) and cooling (electricity) as well as PPD are depicted for the four climatic zones in Fig. 5. Solutions 20 and 18 (ETICS with EPS on walls, EPS externally on the floors,

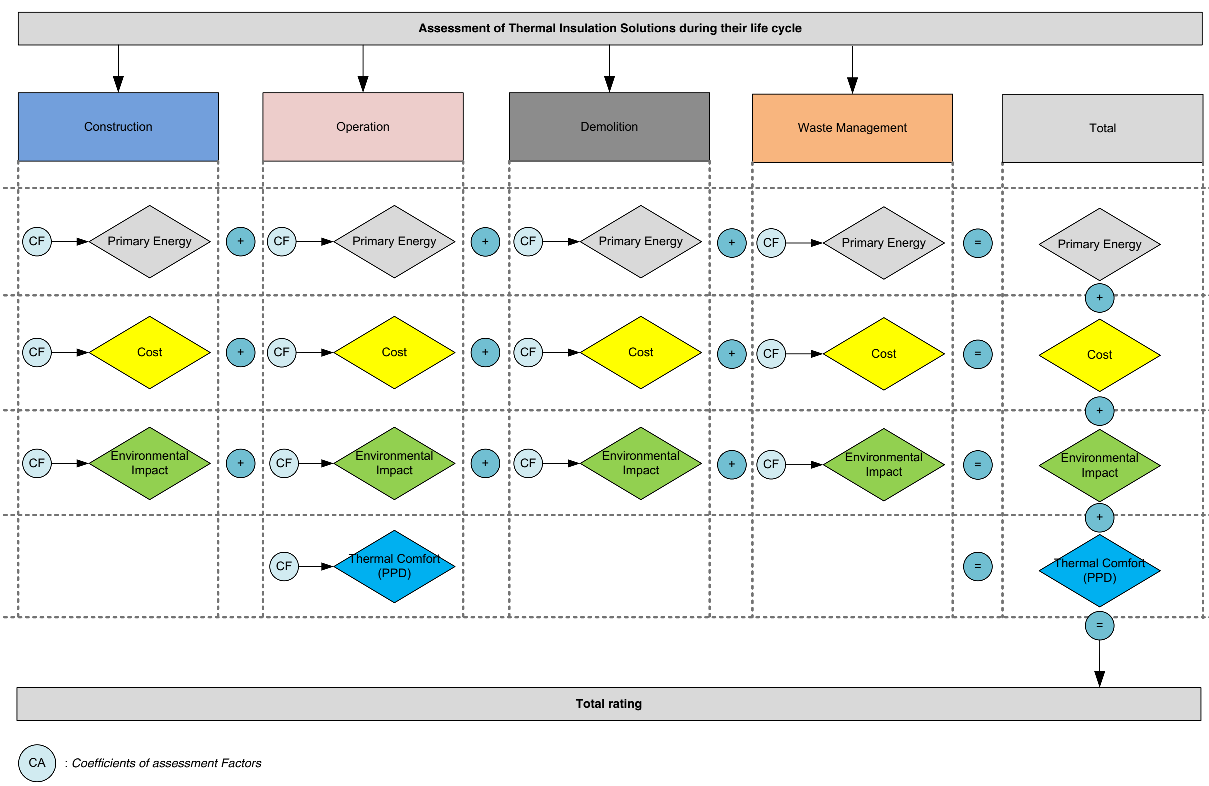

Fig. 4 Methodology adopted

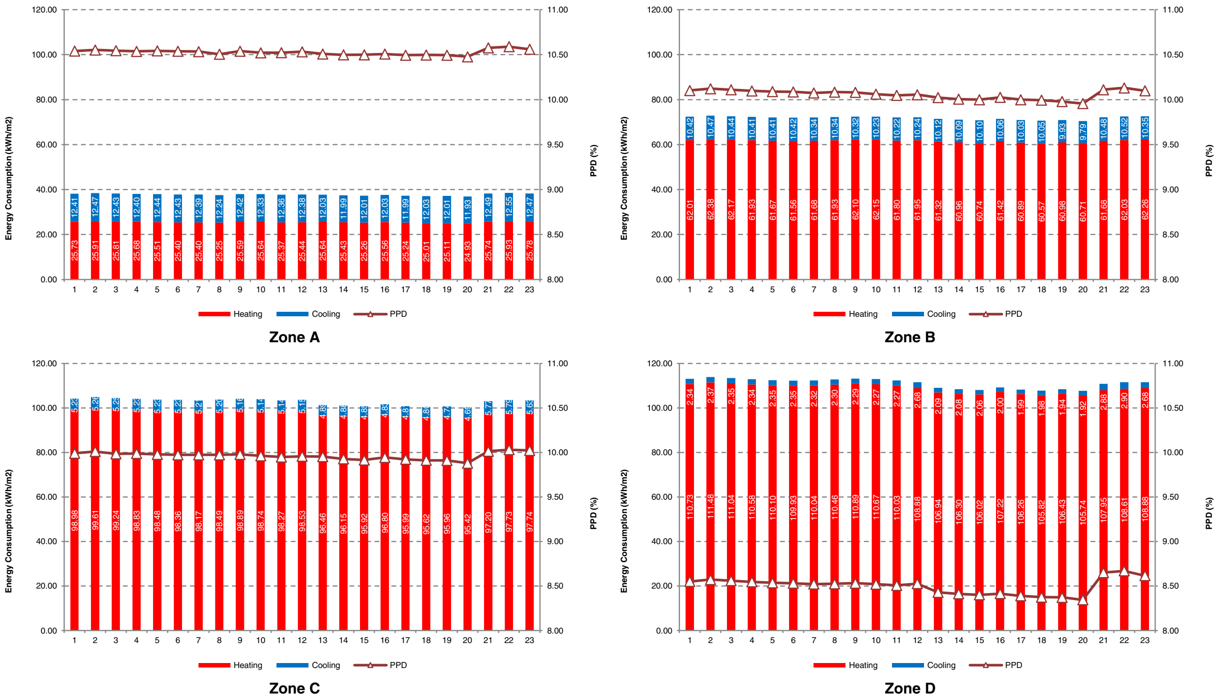

Fig. 5 Final energy consumption and PPD of the thermal insulation configurations

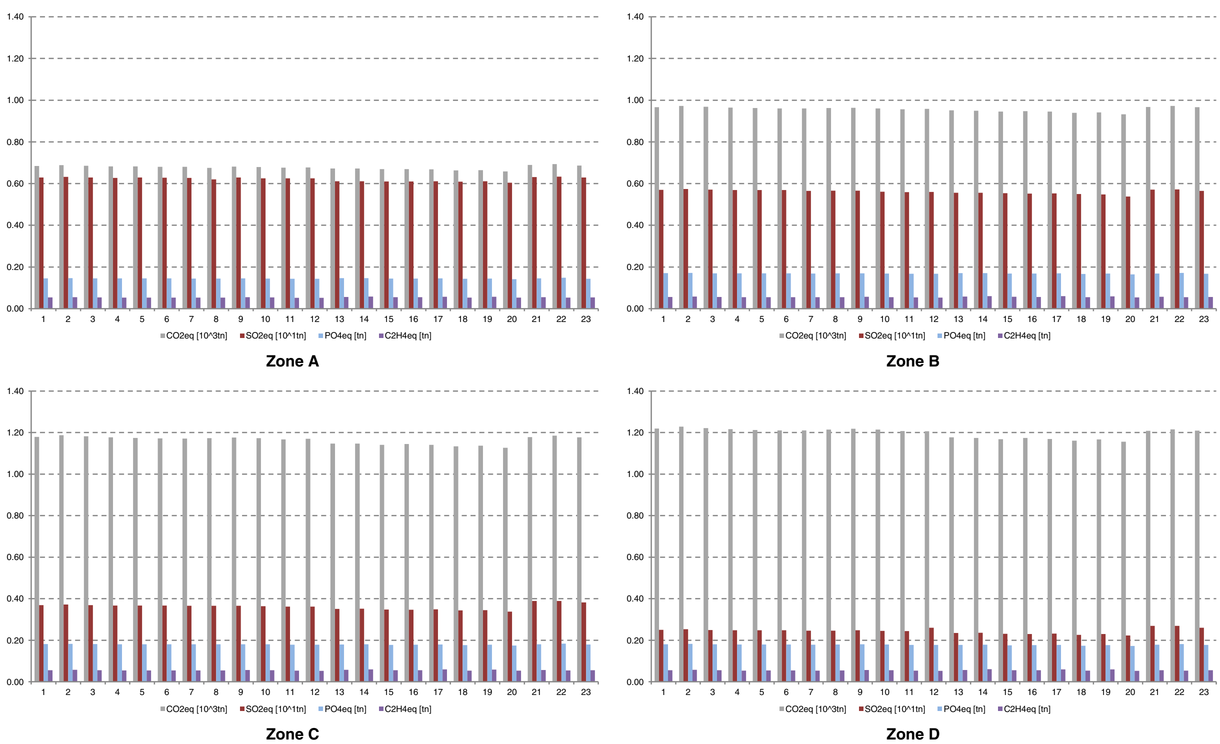

Fig. 6 Environmental impact assessment (CO_2eq, climate change; SO_2eq, acidification; PO_4eq, eutrophication; C_2H_4eq, photochemical oxidation)

and XPS with inverted roof technique and externally on the roofs, respectively) are the ones presenting the lowest final energy consumption for both heating and cooling and PPD index. In general, solutions with external insulation on the vertical building elements are performing better both for heating and cooling conditions. The increased thermal mass of those solutions has a positive effect on thermal comfort and energy consumption, both for the heating and cooling periods, a point confirmed also by other studies (Anastaselos et al. 2011b). Solution 20 which is, albeit by a small margin, the overall best, featuring again the insulation layer externally, consumes 4.09, 3.22, 4.68, and 5.75% (from the warmer to the colder climatic zone) less energy than the worst solution 2 and results in 0.72, 1.66, 1.97, and 2.73% less dissatisfied people.

Regarding the overall performance of the various insulation materials that are used in ETICS, solutions 13, 15, and 17 (SW, EPS, XPS, respectively) have to be compared as they only differ in the type of the insulation material used in the vertical building elements (load bearing walls of reinforced concrete and non-load bearing brick walls). The results indicate that EPS is the preferable material to be used in ETICS, as it has from 0.28 to 0.46% (from the warmer to the colder climatic zone) and 0.47 to 0.63% lower life cycle primary energy consumption compared to XPS and SW, respectively. The differences are admittedly small, expressing a tendency rather than a determining value. On the other hand, with increasing insulation thickness, for example, if/when the energy performance regulation will become stricter, the differences may become bigger.

Environmental impact assessment

The environmental impact assessment of the 23 solutions is presented in Fig. 6. Solutions 20 and 18 are, again, the ones performing better, followed by solutions 9–11. The latter are using a combination mainly of SW, which is environmentally more benign than EPS during the construction and end of life management phase. The overall best solution is again 20, which compared to the worst solution 2 results in 20.71, 14.86, 13.60, and 14.30% (from the warmer to the colder climatic zone) less environmental impact. The difference is more intense in the warmer climatic zone A, where due to the increased cooling demand, more electricity is required to drive the cooling equipment and hence higher pollutants' emissions are occurring.

Overall ranking

The overall ratings, as well as the rating per each separate criterion, of the thermal insulation solutions are presented in Fig. 7 for one climatic area only, due to reasons of brevity. Figure 8 displays the overall ranking for all climatic zones respectively. Regarding the cost, solution 20 is again better than solution 2 by 14.58, 11.60, 10.25, and 9.34% (from the warmer to the colder climatic zone) due mainly to the operational phase and the cost of the insulation material: EPS is quite cheaper than XPS, and ETICS systems are in general more expensive than internal insulation solutions.

The two best solutions, 20 and 18, do not differ substantially in the ranking points. They are using the same positioning of the insulation layer and only the insulation material differs.

The conventional construction practice used in Greece, and not only, until the very last few years, namely the double brick wall construction with the insulation material between them, insulation being placed externally on the concrete bearing elements and insulation placed internally for the floor, the best solution is 11 (SW in the brick wall, XPS on the bearing elements and the inverted roof, and EPS on the floor), which ranks overall third in climatic zones B and C and fourth in climatic zones A and D.

For the internal insulation solutions, the results vary: solution 23 (SW with gypsum board on the walls, EPS on floors, and XPS on the inverted roof) can be easily implemented for the energy upgrade of existing buildings. It is the best internal thermal insulation solution for all climatic zones. It achieves an overall good final energy performance for heating and cooling aggregated. However, it has a rather poor performance, as it ranks in the 16th, 13th, 20th, and 18th place, respectively, when considered on the base of the primary energy consumption. This is due to the fact that the internal insulation has a slightly higher energy consumption for cooling (which was also observed in the other two internal insulation configurations). The electricity used to cover the cooling demand is linked to high emissions (particular SO_2) due to the use of lignite fired power plants and, hence, to a poor environmental performance.

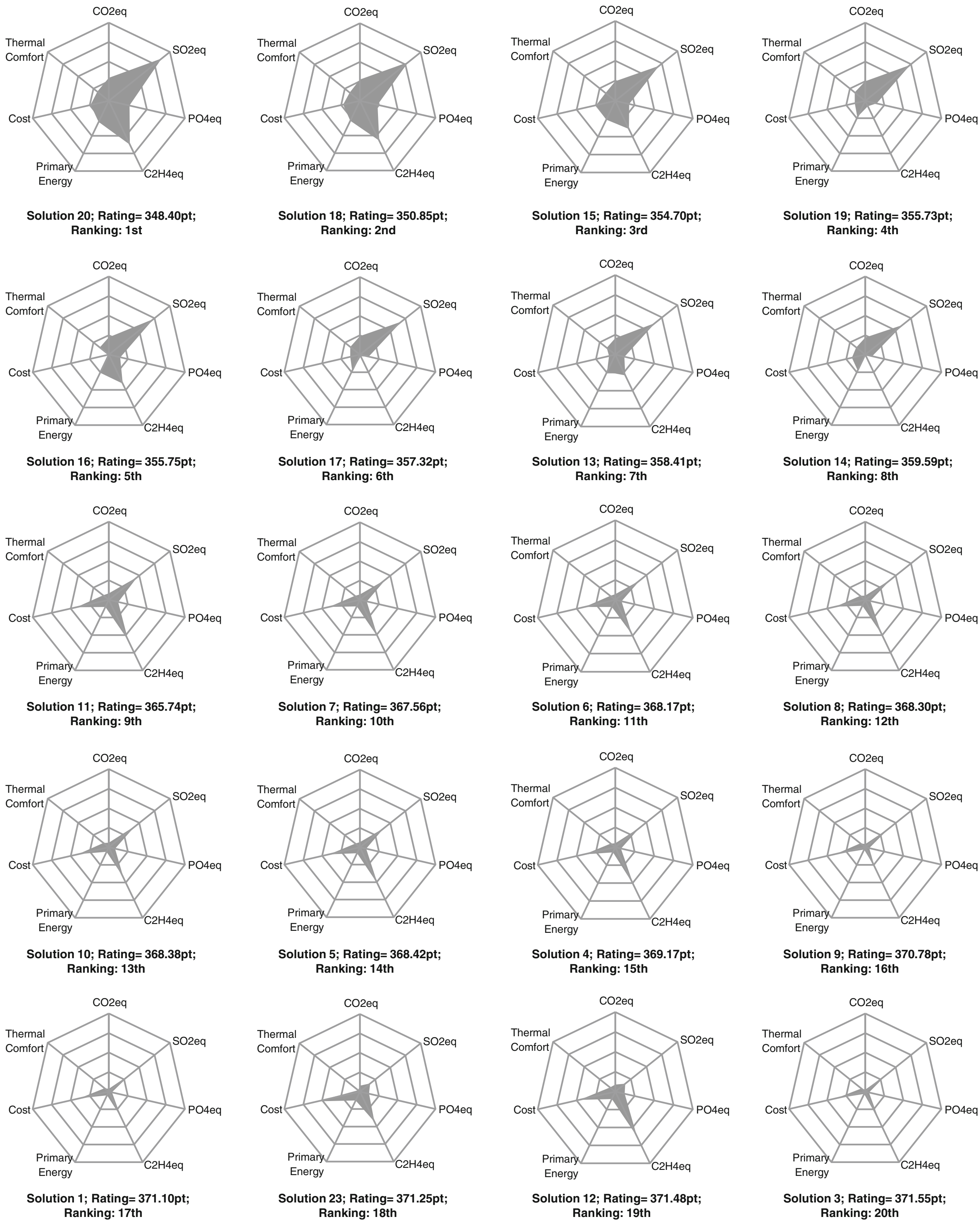

Fig. 7 Overall rating of thermal insulation configurations for climatic zone D

Fig. 8 Final ranking

Final ranking

	Zone A	Zone B	Zone C	Zone D
1st	20	20	20	20
2nd	18	18	18	18
3th	15	19	19	15
4th	19	15	15	19
5th	16	16	16	16
6th	17	17	17	17
7th	13	13	13	13
8th	14	11	14	14
9th	8	14	11	11
10th	11	12	12	7
11th	12	10	10	6
12th	10	7	7	8
13th	7	23	8	10
14th	6	8	6	5
15th	4	6	5	4
16th	23	5	4	9
17th	5	9	9	1
18th	1	4	1	23
19th	9	21	3	12
20th	3	1	23	3
21th	21	3	2	21
22th	2	22	21	2
23th	22	2	22	22

: Double brick wall construction *: ETICS* *: Internal insulation*

Comparing regulations with regard to thermal comfort requirements

A quite interesting remark that can be drawn from the interpretation of the results is the rather small percentage reduction of the PPD with respect to the increase of the insulation's thickness and the resulting reduction of the building elements' *U* value. To evaluate this, a sensitivity analysis was carried out, and the maximum requirements for the *U* values of the building elements set by KENAK were compared.

In general, the results reveal marginal differences regarding thermal comfort, but this was expected since all configurations of the buildings are conditioned by the same heating and cooling systems at the same thermostatic set points, while the differences on the building elements' *U* values were negligible and in their thermal mass limited. Those occurred only in the floor and roof which are representing together 40% of the total envelope's area. Even when the difference in thermal mass was bigger, the particular types of heating and cooling systems that are convective systems do not have the capacity to utilize the additional storage capacity. This is the case only when radiative systems are used, which can heat up the building elements, leading to a significant differentiation in thermal comfort conditions between the different construction solutions. In this line of approach, even a 2% difference has to be considered as important.

Finally, it has to be noted that although insulation materials and their location on the building elements were assessed with respect to most of their thermophysical properties, soundproofing and fireproofing were not considered, as this would fall beyond the purpose of this study.

Conclusions

The aim of this study was to evaluate in a most comprehensive way the impact of thermal insulation position in the building elements under Mediterranean conditions. This was done by using a validated, integrated decision support tool and incorporating into the analysis thermal comfort as a further assessment factor. The predicted percent of dissatisfied people index was chosen to quantify thermal comfort. The analytical calculation of PPD and its implementation to the rating methodology have led to the determination of thermal comfort's contribution to the overall ranking.

The methodology was applied for the integrated evaluation of 23 equivalent thermal insulation solutions in various Mediterranean climatic conditions, as they are represented by four Greek cities. The type, thickness, and positioning of the most common insulation materials were found to clearly affect the final energy consumption, the overall environmental impact, the life cycle cost, and the prevailing indoor thermal comfort conditions of a building. The study considers "concentrated" insulation and not "distributed" insulation (thermal blocks, aerated blocks, etc.).

As the results indicate, the implementation of external insulation with the use of expanded polystyrene as an insulation material for the external walls and floors (as part of an external thermal insulation composite system) together with the use of extruded polystyrene in a flat roof construction, as part of an inverted roof technique, was found to be the optimal solution for all four climatic regions considered.

Thermal comfort was proven to be affected considerably from 0.75 to 2.75% by the positioning of the insulating materials in opaque building elements, since it is mainly influenced by the thickness of the material, as well as by the selection of the heating and cooling system to be used.

Overall, it has been acknowledged that external thermal insulation is the better option for residential buildings, although internal one can also lead to acceptable results providing, hence, an alternative for cases where technical or legal reasons make external insulation practically difficult to implement.

A final conclusion that can be drawn is that the stricter regulations imposed due to the implementation of the first Energy Performance of Buildings Directive and, in particular, of its recast in 2010 have marked a move from the traditional double brick wall construction with the insulation in the cavity towards a single brick wall with external thermal insulation, due to the increase in insulation thickness, which makes double brick walls no more feasible, both technically and in terms of economics. The energy efficiency of the building stock can only profit from this development.

Acknowledgements The authors would like to thank the Greek State Scholarships Foundation for funding the first author's post-doctoral research in the framework of the program "IKY fellowships of excellence for postgraduate studies in Greece—Siemens program". Grant Number SR 22051/13.

References

Anastaselos, D. (2009). Integrated evaluation system for thermal insulation solutions with emphasis on reuse and recycling potential. Ph.D. Thesis, Aristotle University Thessaloniki, School of Engineering, Department of Mechanical Engineering. Thessaloniki (in Greek).

Anastaselos, D., Giama, E., & Papadopoulos, A. M. (2009). An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. *Energy and Buildings, 41*, 1165–1171.

Anastaselos, D., Oxizidis, S., & Papadopoulos, A. M. (2011a). Energy, environmental and economic optimization of thermal insulation solutions by means of an integrated decision support system. *Energy and Buildings, 43*, 686–694.

Anastaselos, D., Theodoridou, I., Papadopoulos, A. M., & Hegger, M. (2011b). Integrated evaluation of radiative heating systems for residential buildings. *Energy, 36*, 4207–4215.

Asan, H. (2000). Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view. *Energy and Buildings, 32*, 197–203.

ASHRAE, Standard 55–2004: Thermal environment conditions for human occupancy (2004). Atlanta, Georgia: American Society of Heating Refrigeration & Air conditioning Engineers.

Baglivo, C., & Congedo, P. M. (2015). Design method of high performance precast external walls for warm climate by multi-objective optimization analysis. *Energy, 90*, 1645–1661.

Baglivo, C., Congedo, P. M., & Fazio, A. (2014). Multi-criteria optimization analysis of external walls according to ITACA protocol for zero energy buildings in the mediterranean climate. *Building and Environment, 82*, 467–480.

Balaras, C. A. (1996). The role of thermal mass on the cooling load of buildings. An overview of computational methods. *Energy and Buildings, 24*, 1–10.

Bolatturk, A. (2008). Optimum insulation thickness for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Building and Environment, 43*, 1055–1064.

Cherem-Pereira, G., & Mendes, N. (2012). Empirical modeling of room air conditioners for building energy analysis. *Energy and Buildings, 47*, 19–26.

CML 2 baseline method 2000 (2001). Centre for Environmental Studies (CML), University of Leiden. http://www.leidenuniv.nl/interfac/cml/ssp/lca2/index.html. Accessed 01 May 2015.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J., & Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings, 33*, 319–331.

de Dear, R. J., & Brager, G. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions, 104*, 145–167.

Djuric, N., Novakovic, V., Holst, J., & Mitrovic, Z. (2007). Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools. *Energy and Buildings, 39*, 471–477.

Eben Saleh, M. A. (1990). Impact of thermal insulation location on buildings in hot dry climates. *Solar and Wind Technology, 7*, 393–406.

Famuyibo, A. A., Duffy, A., & Strachan, P. (2013). Achieving a holistic view of the life cycle performance of existing dwellings. *Building and Environment, 70*, 90–101.

Fanger, P. O (1970). Thermal comfort : analysis and applications in environmental engineering. Copenhagen: Danish Technical Press.

Fokaides, P., & Papadopoulos, A. M. (2014). Cost-optimal insulation thickness in dry and mesothermal climates: existing models and their improvement. *Energy and Buildings, 68*, 203–212.

Friess, W., Rakhshan, K., & Davis, M. (2016). A global survey of adverse energetic effects of increased wall insulation in office buildings: degree day and climate zone indicators. *Energy Efficiency*, 1–20.

Frischknecht, R., & Rebitzer, G. (2005). The ecoinvent database system: a comprehensive web-based LCA database. *Journal of Cleaner Production, 13*, 1337–1343.

GenOpt (2015). Berkeley Lab. http:// http://simulationresearch.lbl.gov/. Accessed 01 May 2015.

Gluch, P., & Baumann, H. (2004). The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment, 39*, 571–580.

Google Earth (Version 6.1.0.5001) (2011). Mountain View, California, Google Inc., http://www.google.com/earth/index.html. Accessed 01 May 2015.

Grant, A., & Ries, R. (2013). Impact of building service life models on life cycle assessment. *Building Research & Information, 41*, 168–186.

Hegger, M., Auch-Schwelk, V., Fuchs, M., Rosenkranz, T. (2006). Construction materials manual. Munich, Institut für internationale Architektu-Dokumentation GmbH & Co. KG. http://www.detail.de. Accessed 01 May 2015.

Hellenic Transmission System Operator S.A. (2014). Monthly energy balance report of the system—September 2014. http://www.admie.gr. Accessed 01 May 2015.

Hong, S., Gilbertson, J., Oreszczyn, T., Green, G., Ridley, I., & the Warm Front Study Group. (2009). A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment, 44*, 1228–1236.

International Organisation for Standardisation (2007). ISO 14683: 2007: Thermal bridges in building construction — Linear thermal transmittance — Simplified methods and default values. Geneva: International Organisation for Standardisation.

Ministry of Environment, Energy and Climate Change (2010). Regulation on the Energy Efficiency of Buildings. Athens: Ministry of Environment, Energy and Climate Change.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings, 34*(6), 563–572.

Ozel, M., & Pihtili, K. (2007). Optimum location and distribution of insulation layers on building walls with various orientations. *Building and Environment, 42*, 3051–3059.

Papadopoulos, A. M. (2005). State of the art in thermal insulation materials and aims for future developments. *Energy and Buildings, 37*, 77–86.

Papadopoulos, M., & Chrisomallidou, N. (1979). Thermal comfort perception and the role of insulation. *Technika Chronika, Scientific Review I, 2*, 43–53.

Papadopoulos, A. M., Oxizidis, S., & Papandritsas, G. (2008a). Energy, economic and environmental performance of heating systems used in Greek buildings. *Energy and Buildings, 40*, 224–230.

Papadopoulos, A. M., Oxizidis, S., & Papathanasiou, L. (2008b). Developing a new library of materials and structural elements for the simulative evaluation of buildings' energy performance. *Building and Environment, 43*, 710–719.

Pfundstein, M., Gellert, R., Spitzner, M., Rudolphi, A. (2007). Insulating materials. Principles. Materials. Applications, Edition Detail. Munich.

PRé Consultants (2009). SimaPro LCA software Version 7.1, http://www.pre.nl/simapro. Accessed 01 May 2015.

Roberts B. (1997). The quest for comfort, London. Chartered Institute of Building Services Engineers.

Sierra-Pérez, J., Boschmonart-Rives, J., & Gabarrell, X. (2016). Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions. *Journal of Cleaner Production, 113*, 102–113.

Slavković, K., & Radivojević, A. (2014). Evaluation of energy embodied in the external wall of single-family buildings in the process of energy performance optimization. *Energy Efficiency, 8*, 239–253.

Stahl, T., Brunner, S., Zimmermann, M., & Ghazi Wakili, K. (2012). Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. *Energy and Buildings, 44*, 114–117.

Theodoridou, I., Papadopoulos, A.μ., & Hegger, μ. (2011). A typological classification of the Greek building stock. *Energy and Buildings, 43*, 2779–2787.

Vaidya, P., Greden, L., Eijadi, D., McDougall, T., & Cole, R. (2009). Integrated cost-estimation methodology to support high-performance building design. *Energy Efficiency, 2*(1), 69–85.

Zacà, I., D'Agostino, D., Congedo, P. M., & Baglivo, C. (2015). Assessment of cost-optimality and technical solutions in high performance multi-residential buildings in the Mediterranean area. *Energy and Buildings, 102*, 250–265.