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Optimization of thermal insulation material and thickness for building energy efficiency in Mediterranean climates based on life cycle perspective

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Abstract
Optimizing thermal insulation thickness to save energy and reduce carbon emissions in Mediterranean climates is important. Many standards and regulations on energy efficiency or thermal insulation focus insulation thickness without considering life cycle energy efficiency or environmental impacts. This may lead to unexpected and undesirable results. A new approach for identifying the optimal insulation material and thickness has been applied to a multi-storey residential building in a Mediterranean climate in Turkey. The approach considers life cycle energy consumption, carbon emissions and cost. Energy performance is calculated with details of occupancy, lighting system and internal gains. Results are compared with those of the same building in a cold climate region to show how climate affects life cycle energy and carbon performance. The results of the study show that if insulation thickness is not optimized for a material's entire life cycle, it may end up being less efficient, more expensive, and have greater carbon emissions than expected, especially in Mediterranean climates.

Keywords
Thermal insulation thickness, Life cycle energy analysis, Life cycle carbon emission analysis, Life cycle cost analysis.

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1. Introduction

1.1. Background information and literature overview

The International Energy Agency reports that 'buildings are responsible for 40% of total energy consumption and 30% of greenhouse gasses emissions' (UNEP, 2015). Hence energy efficiency in buildings is a relevant topic for many countries due to factors related to the environment, economy and energy consumption. Each country has determined its own future targets about energy efficiency and carbon emissions of buildings. The European Union (EU) has issued the 'The 2020 package', which targets a 20% carbon emission reduction, 20% improvement in energy efficiency and supplying 20% of energy from renewable sources by 2020 (Climate Action, 2007). In addition, the EU has made 'the recast of Energy Performance of Buildings Directive 2010/31/EU' (EPBD) to establish minimum requirements for buildings' energy performance (EU, 2010). Energy efficient retrofitting is as important as energy efficient design because many existing buildings do not meet energy performance standards.

Energy consumption of buildings affect building's carbon emission and energy cost significantly. Therefore, energy efficient building is an important issue for energy saving, carbon emission and cost reduction. Energy efficient building design depends on some criteria such as climate, building's orientation, distance between buildings, window-wall ratio and building envelope's thermo physical properties. As it is known, most of the energy efficient building design criteria such as orientation and distance between buildings couldn't be consider in built environment. Thus, building envelope design has important role in energy efficient building design. Increasing thermal mass and reduction heat loss from building envelope are major issues for energy efficiency in envelope design. Increasing thermal insulation is most common strategy for reducing heat losses especially in cold climates but thermal mass is an important approach for hot climates. Manioğlu and Yılmaz compare traditional house and modern house envelope from point of thermal mass' effect on comfort condition. (Manioğlu, Yılmaz 2008). Traditional house envelope, which is made with 1,2m. stone, have better surface temperature performance according to comfort zone than modern house envelope, which is made with 0,19m. brick. Increasing thermal mass related with solar gain but, increasing thermal mass couldn't be apply in built environment because of distance between buildings. Moreover, increasing thermal mass couldn't be done because of architectural restrictions such as constructing thick walls in high rise new buildings or existing buildings. Previous studies showed that adding or increasing thermal insulation thickness are most common or well-known strategy for energy efficiency in buildings (Boeck, 2015). Therefore, reduction heat loss from building become one of major strategy for energy efficient building design in built environment and retrofitting. Thick thermal insulation on building envelope reduce energy consumption and carbon emission in cold climate but it performs differently in Mediterranean climate. Hence, this study focus on thermal insulation in Mediterranean climate because of reasons as it is stated above.

Optimum insulation thickness has been studied using the number of heating and cooling days in different climates (Kürekçi, 2016; Bolattürk, 2008) and with respect to fuel type, glazing area and achieving low energy targets (Bolattürk, 2006; Uçar, Balo, 2009; Özkan, Onan, 2011; Özel, 2014; Kolaitis, 2013; Özel, Pıhtılı, 2007; Bojic, 2014; Al-Sanea, Zedan, 2011). Optimum position and material vary by climate, with different results based on thickness and fuel type (Uçar, Balo, 2010; Çomaklı, Yüksel, 2003, Özel 2001). Several studies have addressed the effect of thermal insulation on cooling and total energy consumption in buildings (Özel, 2013; Yu, 2009; Daouas, 2011). Specifically, energy performance standards in Northern European countries have low U values for building envelopes, towards increasing energy efficiency. However, thick insulation layers in warm climates increase primary energy consumption. Cooling set points and internal gains from equipment significantly increase cooling energy consumption in warm climates. Therefore Masoso and Grobler (2008) concluded that instead of 'the lower U value the better' it should be 'the higher U value the better'. Previous studies show that optimum thermal insulation thickness varies by climate. Optimization studies have generally focused on heating and cooling energy consumption but have not considered lighting and domestic water heating.

Optimum cost is another relevant factor, and is now obligatory in EPBD's declaration on energy efficiency in buildings (EU, 2010). Optimum cost of thermal insulation materials has been studied in different climates (Nematchoua, 2015; Kaynaklı, 2012; Hasan, 1999; Nyers, 2015). Jafari and Valentine (2017) proposed an optimization framework decision making focused on energy efficient measures. Optimal cost depends on climate, building typology, user behaviour and efficiency.

Environmental effects of different thermal insulation materials have also been studied throughout their life cycles with cradle to grave approach based on environmental, energy and cost performance in different climates (Pargana, 2014; Su, 2016; Shrestha et al, 2014; Sohn, et al, 2011; Lollini, et al, 2006; Papadopoulos and Giama, 2007; Dylewski and Adamczyk, 2011; Özel 2013; anastaselos, et al, 2009; Özel, 2012; Vilches, et al, 2017; Tingley, et al, 2015). These factors were the basis for Anastaselos et al.'s (2009) decision system for selecting thermal insulation materials. Different exterior wall types and insulation materials were compared. Heating and cooling energy consumption were included but not lighting, but lighting appliances can have a significant effect on a building's operational primary energy consumption and heat gain. Likewise, occupancy schedule, activity level and household appliances' schedule were not detailed. Barrau et al. (2014) affirm that insulation material life cycle performance, energy performance calculation methodology and assumptions affect optimum insulation thickness.

Generally, optimum thermal insulation thickness is calculated without considering building's life cycle energy, environmental and cost performance. However, several studies consider life cycle energy, environmental and cost performance of the building with undetailed calculations while determination thermal insulation thickness. But as it is known energy consumption level in operational period during building's life cycle affect energy consumption, environmental and cost performance significantly. For instance, occupancy and activity level, heat gains from lighting system and household equipment are not taken into account in the energy performance calculations. Therefore, energy performance in operational period should calculate with detailed assumptions. Occupancy, activity level and gains from lighting equipment significantly affect energy consumption of building. These factors' effect on building's energy consumption are noted by several studies (Ruellan, et al, 2016; Barthelmes, et al, 2016; Becchio, et al, 2016). Therefore an updated optimization approach is required that includes detailed energy performance calculations for a building's entire life cycle.

1.2. Aim of the study

Thermal insulation have significant effect on building's life cycle energy consumption, carbon emission and cost performance according to climate zone and building typology. Hence, primary aim of this study is to determine thermal insulation thickness and material from life cycle energy, carbon emission and cost perspective. As it is known operational stage in building's life cycle cause nearly 85% energy consumption of entire life cycle. Therefore, energy performance calculations are done with detailed assumptions on occupancy, activity level, and gains from lighting system and household equipment. Comprehensive calculations were done for a multi-storey residential building in İzmir, Turkey, which has a Mediterranean climate. Different insulation materials and thickness are compared towards optimum solutions based on life cycle energy consumption, carbon emission, and cost in a Mediterranean climate. Energy performance and thermal insulation standards in Northern Europe focus on low U values for building envelopes to save energy. But thermal insulation's effect on energy saving and carbon emission reduction change according to climate and building type. Therefore, results compared with cold climate (Erzurum, Turkey) show the effect of low U values on energy consumption and carbon emission in Mediterranean climate. The secondary aim of the study is to demonstrate the need to revise standards on energy efficiency to include life cycle energy and environmental performance while considering climate and building typology.

2. Approach

The approach, which determine optimum thermal insulation thickness and material, are formed of six steps as follows,

1. determining thermal insulation material alternatives,
2. selecting a case study building and getting architectural data,
3. making life cycle energy analysis (LCEA) calculations,
4. making life cycle carbon emission analysis (LCCA) calculations,
5. making life cycle cost (LCC) calculations and
6. getting results and optimum solutions.

2.1. Determining thermal insulation material alternatives

Thermal insulation materials alternatives were selected based on usage intensity and application possibilities in the construction sector. Expanded polystyrene (EPS), extruded polystyrene (XPS) , rock wool (RW) and glass wool (GW) were chosen and compared for thicknesses of 0 (no insulation), 3, 5, 7, 9 and 10 cm. Insulation thickness are chosen from market's most used thickness.

2.2. Selecting a case study building and getting architectural data

A multi-storey residential building was selected, which is a typical housing block built by the Turkish Housing Development Administration (TOKİ, 2016). The building has one basement, 12 floors and 48 individual housing units. Architectural plans and measurements are presented in Figure 1 and Tables 1–2.

Table 1. Architectural measures o f the case study building.

Floors	1 basement, 12 floors	Housing units quantity	4 per floor, total=48
Floor area	26 × 23 m, total=576 m²	Housing unit size	130 m²
Floor height	279 cm	Building height	37.5 m

Table 2. Construction details of the case study building (TOKI, 2016).

Building element	Layers
External wall	External paint, cement plaster (2 cm), brick (19 cm), plaster (2 cm); U=1.57 W/m²K
Roof	Gravel (5 cm), water insulation (1 cm), screed (3 cm), thermal insulation (EPS 8 cm), reinforce concrete slab (20 cm), plaster (1 cm); U=0.55 W/m²K
Floor (internal)	Ceramic tiles (1 cm), screed (1 cm), reinforce concrete slab (20 cm), plaster (1 cm). U=3.44 W/m²K
Floor (on the ground)	Ceramic tiles (1 cm), screed (3 cm), thermal insulation (EPS 8 cm), reinforce concrete foundation (20 cm), water insulation (1 cm), gravel (5 cm); U=0.6 W/m²K
Interior wall	Plaster (1 cm), brick (8.5 cm), plaster (1 cm) U: 2 W/m²K
Window	Air filled clear double glass PVC window (3 × 13 × 3 mm); U=2.8 W/m²K
Window to wall ratio	25%

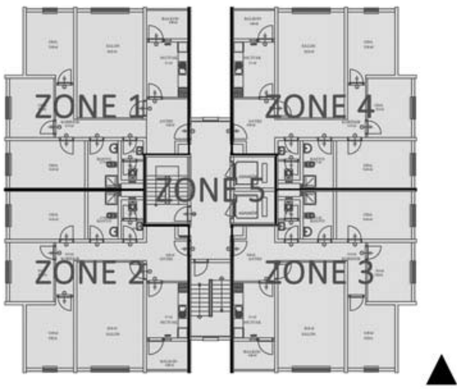


Figure 1. Architectural plan and thermal zones of the case study building.

2.3. Making life cycle energy analysis (LCEA) calculations

LCEA is derived from the life cycle assessment approach, which considers energy consumption of products or services for their entire life cycle. Life cycle has two different approach which are cradle to grave and cradle to cradle. Cradle to grave approach identified as the entire life of a material or product up to the point of disposal, is used in this study. According to the European Committee for Standardization (CEN) TC 350 (2008) standards, the life cycle of a building comprises the production, construction, use and end of building life stages. Life cycle energy consumption of the case study building were calculated with the method developed by Adalberth (1997). Energy consumption is calculated as primary energy in all stages. Limitations on life cycle stage of the case study building can be seen in Table 3. Construction and demolition were not included be-

Table 3. Limitations on building's life cycle.

Stage	Module	Stages Included
Production	Raw material supply	Yes
	Transportation	Yes
	Manufacturing	Yes
Construction	Transportation	Yes
	Erection	No
Use	Operational energy use: Heating, cooling, lighting and domestic hot water need	Yes
	Maintenance and repair	No
End of life	Demolition	No
	Transportation	No
	Recycling	No
	Disposal	No

Table 4. Assumptions for case study building (TS 825, 2008; ÇŞB-BEP, 2010; Yılmaz, Z. et al. ,2016).

CASE STUDY BUILDING	
Occupancy Data	**Assumptions**
People per residential unit	4
Occupancy schedule	Table 5
Internal gains from users	Table 5
Lighting	**Assumptions**
Lighting instrument	Fluorescent lamp
Lighting instrument power	20 W fluorescent lamp
Lighting system occupancy schedule	Table 6
Automatic control	Stepped control
Thermal Comfort Level and Heating System	**Assumptions**
Heating set point temperature	20°C Reference
Cooling set point temperature	26°C Reference
Infiltration rate (ach)	0.5 Reference
Internal gains from equipment and schedule	Table 7
Heating system and efficiency	Natural gas central heating with condensing boiler; efficiency=0.85
Cooling system and EER	Chiller (electric); EER=3

cause of lack of information and their negligible effects on the overall life cycle (Sartori and Hestnes, 2006).

Production stage: Energy consumption at the production stage is calculated by multiplying the material quantity and embodied energy of material (equation 1) (Adalberth, 1997). Necessary data for embodied energy calculations are from a well-known database (ICE, 2008; GreenSpec, 2015; GABI, 2015). Embodied energy consumption of all thermal insulation materials were calculated but the embodied energy consumption of other building elements were not included.

$$Q_{product} = \sum_{i=1}^{n} m_i \cdot (1 + \frac{wi}{100}) \cdot M_i \quad (1)$$

$Q_{product}$: Energy requirement for producing all the building materials (kWh)
n: Number of building materials
i: Material of concern
m_i: Amount of the building material (tons)
w_i: Waste factor for the building material (%)
M_i: Energy required to manufacture the building material (kWh/ton)

Transportation stage: Energy consumption in the transportation stage was calculated with equation 2 (Adalberth, 1997). It is assumed that all thermal insulation materials are supplied from nearest factory to the case study building.

$$Q_{transportation} = \sum_{i=1}^{n} m_i \cdot (1 + \frac{wi}{100}) \cdot d_i . T_c \quad (2)$$

$Q_{transportation}$: energy requirement for transportation of the building materials (kWh)
n: Number of building material
i: Material of concern
m_i: Amount of the building material (tons)
w_i: Waste factor of the building material (%)
d_i: Distance between factory and construction site (km)
T_c: Energy consumption of the transportation vehicle (kWh/ton/km)

Use stage: Energy consumption during the use stage includes the amount of energy consumed by the mechanical systems in order to provide comfort conditions in the building. Energy consumption by equipments for heating, cooling, lighting and domestic hot water were included in primary energy consumption in this study. Energy consumption was calculated with a dynamic calculation method, as suggested by the EPBD, using the Design Builder energy performance simulation software (EPBD, 2010; Design Builder 2016). The case study building was assumed to have five individual thermal zones (Figure 1). Thermal conditioned zones 1–4 are residential and zone 5 is the building core used for circulating, which is unconditioned by an HVAC system and is lighted with an automatic control system.

Detailed usage assumptions about the case study building can be seen in Tables 4–7. These assumptions are from based on national standards, regulations and previous studies (TS 825, 2008; ÇŞB-BEP, 2010; Yılmaz at al, 2016). Activity values are from the ASHRAE 55 standard (ASHRAE, 2010). Occupancy and activity level assumptions for each individual housing unit are in Table 5 (ÇŞB-BEP, 2010; Yılmaz et al, 2016). Heat gain from home appliances and their operating time for each housing unit are in Table 6 (Yılmaz, et al, 2016). Lighting power density of interior spaces were calculated with DIALux evo software (DIALUX 2016). Illumination levels are assumed to be 200 lux for kitchens, 300 lux for childrens' bedrooms and 100 lux for living rooms, bedrooms, corridors and bathrooms. The lighting system's operating time and power density are in Table 7.

2.4. Making life cycle carbon emission analysis (LCCA) calculations

Life cycle carbon emissions are the accumulated carbon emission in all building stages. Carbon emissions are calculated with the Tier-2 methodology developed by the International Panel on Climate Change (IPCC) (IPCC, 2016). The amount of carbon emission is calculated with equation 3. National carbon emission conversion factors were 0.21 for natural gas and 0.63 for electricity (ÇŞB-BEP, 2010).

$$C = \sum_{i=1}^{n} E_{i\,fuel} \cdot f_{CO_2} \quad (3)$$

C: Carbon emission during a life cycle stage (CO_2 tons)
n: life cycle stage
i: Number of life cycle stages
$E_{i\ fuel}$: Energy consumption per fuel type during life cycle stage (kWh)
f_{CO2}: Carbon emission conversion factor per fuel type

2.5. Making life cycle cost calculations (LCC)

LCC is a cost analysis tool that includes all building stages. Global cost calculation methodology, which is suggested by EPBD and the EN 15459 standard, was used in this study (EC, 2012; CEN, 2007). Global cost calculations were based on the 'Net Present Value' (NPV) methodology, using equation 4.

$$C_g(\tau) = C_I + \sum_{j}^{\square} \left(\sum_{i=1}^{\tau} (C_{a,i}\ (j)\ x\ R_d\ (i)) - V_{f,\tau}\ (j) \right) \quad (4)$$

where τ is the calculation period; Cg(τ) is global cost (referred to starting year τ_0) over the calculation period; C_1 is initial investment cost for a measure or set of measures j; C_a,i (j) is the annual cost during year i for measure or set of measures j; $V_{f,\tau}$ (j) is the residual value of a measure or set of measures j at the end of the calculation period. R_d(i) is the discount factor for year i based on discount rate r, calculated as follows:

$$R_d(\mathrm{p}) = \left(\frac{1}{1+r/100}\right)^p$$

where p is the number of years from the starting period and r is the real discount rate. Global cost calculations

Table 5. *Occupancy and activity level schedules (Yılmaz, Z. et al., 2016; ASHRAE 55, 2010).*

	Hours	Number of people	Activity	Activity level (W/m²)	Space
WEEKDAYS	00:00–07:00	4	Sleeping	40	Bedrooms
	07:00–07:30	4	Breakfast	60	Kitchen
	07:30–12:30	1	House work	115	All spaces
	12:30–15:30	1	Rest	45	Living room
	15:30–16:30	1	House work	115	All spaces
	16:30–19:00	3	1 Person: House work 2 People: Rest	115 45	All spaces
	19:00–20:00	4	1 Person: House work 3 People: Light work	115 60	Kitchen Living room
	20:00–20:30	4	Dinner	60	Kitchen
	20:30–23:00	4	Reclining, Light work	60	Living room, bedrooms
	23:00–24:00	4	Sleeping	40	Bedrooms
WEEKEND	Hours	Number of people	Activity	Activity Level (W/m²)	Name of the Space
	00:00-00:30	4	Reclining, Light work	60	Living room, bedrooms
	00:30-08:00	4	Sleeping	40	Bedrooms
	08:30-12:30	4	Reclining, Light work	60	Living room, bedrooms
	12:30-15:30	0	-	-	-
	15:30-18:30	2	Reclining, Light work	60	Living room, bedrooms
	18:30-22:30	3	Reclining, Light work	60	Living room, bedrooms
	22:30-24:00	4	Rest	45	Living room, bedrooms

Table 6. *Power and operating time of the electrical equipment (Yılmaz, Z. et al. ,2016).*

Home Appliance	Power (W)	Operating Time
Refrigerator	38	All day (24 hours)
Oven	2600	4 hours per week
Dishwasher	1030	5 hours per week
Washing machine	851	4 hours per week
Electric Kettle	1650	Weekdays: 3 hours per day Weekends: 2 hours per day
Iron	2300	2 hours for 2 days per week
Vacuum Cleaner	200	2 hours for 2 days per week
Television	105	Weekdays: 5 hours per day Weekends: 4 hours per day
Notebook	120	3 hours per day
Stove	1800	2.5 hours per day
Cooker hood	290	1.5 hours per day

Table 7. Lighting power densities (Yılmaz, Z. et al. ,2016).

Room	Area (m²)	Lighting power density (W/m²)	Operating time
Bedroom	12.8	9.6	2 hours per day
Children's bedroom	12.5	17.4	Manually controlled depending on illumination during occupied hours
Children's bedroom	14.0	20.0	
Living room	28.0	5.7	
Kitchen	9.0	10.7	2 hours per day
Bathroom	6.0	7.4	2 hours per day
Bathroom	3.6	8.3	
WC	2.1	10.0	
Corridor	9.0	8.9	
Entrance	8.0	10.0	

Table 8. Case study building's primary energy consumption (kWh/m2 per year).

	Mediterranean Climate (Izmir)		Cold Climate (Erzurum)	
	End use energy consumption kWh/m² year	Primary energy consumption kWh/m² year	End use energy consumption kWh/m² year	Primary energy consumption kWh/m² year
Heating kWh/m² year	15.37	15.37	72.43	72.43
Cooling kWh/m² year	22.79	53.80	2.17	5.14
Lighting kWh/m² year	9.72	22.95	10.75	25.38
Domestic hot water kWh/m² year	17.12	17.12	17.12	17.12
Total kWh/m² year	**65.00**	**109.23**	**102.47**	**120.06**

Table 9. Case study building life cycle energy consumption and carbon emission for 50 year life span.

		Mediterranean climate (İzmir)	Cold climate (Erzurum)
Energy Consumption	Embodied energy	4.83	4.83
	Transportation energy	0.45	0.45
	Operational energy (year)	5461.55	6003.11
	Total (kWh/m² 50 years)	**5466.78**	**6008.39**
Carbon Emissions	Embodied carbon	0.59	0.59
	Transportation carbon	0.01	0.01
	Operational carbon (year)	2714.50	1960.50
	Total (kg CO_2/m² 50 years)	**2715.10**	**1961.10**

were made for 30 years, as suggested by the EPBD (EC 2012). Therefore the case study building life's span is assumed to be 30 years for life cycle cost calculations. Costs that have effects on energy consumption were included and other costs were ignored. Macroeconomic data, which are necessary for global cost calculation, are from the Central Bank of the Republic of Turkey (TCMB, 2016). The costs of insulation materials and construction are from the annual unit price book, published by the Turkish Ministry of Public Works and Settlement (ÇŞB, 2015). Energy prices by fuel type for energy costs were provided by local energy supply companies (Gediz, Izgaz, Palen, Arasedas 2016).

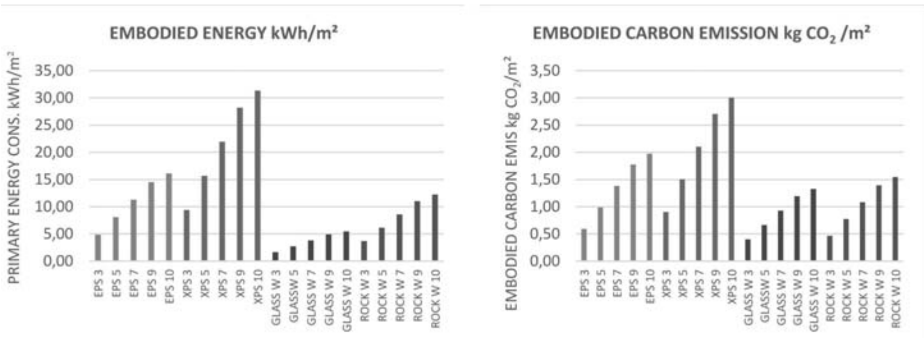
2.6. Getting results and optimum solutions

Following the approach described above and the energy consumption calculations, the case study building was divided into end use energy and primary energy (table 8). Cooling energy consumption accounts for nearly half of primary energy consumption and end use energy consumption is nearly 35% lower than primary energy consumption in the Mediterranean climate. Primary energy conversion factors are 1 for natural gas and 2.36 for electricity (ÇŞB-BEP, 2010). Therefore, cooling energy consumption dominates annual primary energy consumption in the Mediterranean climate region (İzmir). Energy performance analysis should be done as primary energy consumption to obtain accurate results.

Table 9 compares the case study building's life cycle energy consumption and carbon emission performance in Mediterranean (İzmir) and cold climates (Erzurum). As seen in the table, there is a remarkable difference in life cycle energy and carbon emission performance. Although life cycle energy performance in the Mediterranean climate is better than in the cold climate, carbon emission is nearly 50% higher. High levels of cooling energy consumption in the Mediterranean climate significantly affect life cycle energy consumption and carbon emission. Cooling provided by electricity causes a large amount of carbon emission, due to carbon emission conversion factors of 0.21 for natural gas and 0.63 for electricity (ÇŞB-BEP, 2010). Therefore, cooling energy consumption in hot or hot and humid climate regions such as Mediterranean climates is important for reducing primary energy consumption saving and carbon emissions.

Embodied energy consumption and carbon emissions of different insulation materials with different thicknesses can be seen in Figure 2. Three-centimetre thick glass wool has the lowest embodied energy consumption, 1.63 kWh/m², while the same thickness of XPS has the highest, 9.40 kWh/m². There is a linear relationship between insulation thickness and embodied energy. For instance, the embodied energy of glass wool increases from 1.63 to

Figure 2. *Comparison of thermal insulation materials' embodied energy and carbon emissions.*



5.44 kWh/m^2 as its thickness increases from 3 to 10 cm. Embodied carbon emissions also vary by material and thickness such as glass wool's carbon emission increase of 0.73 kg CO_2/m^2 with an increase from 3 to 10 cm thickness. There is a 7.77 kWh/m^2 energy saving potential, which is nearly equal to annual end use energy consumption for lighting, and a 0.50 kg CO_2/m^2 carbon emission reduction from thermal insulation material selection. Most of the thermal insulation standards and regulations focus on the U value of the building envelope. However, as seen in Figure 2, insulation material and thickness affect life cycle energy consumption and carbon emissions. Thus, insulation thickness should be determined according to a material's life cycle performance.

Figure 3 shows the effect of thermal insulation thickness on primary energy consumption during the case study building's use stage for Mediterranean and cold climates. Increasing insulation from 0 to 10 cm saves 5.53 kWh/m^2 energy in the Mediterranean climate and 22.06 kWh/m^2 in the cold climate. Thick insulation prevents night cooling, which is important for reducing cooling energy consumption in the Mediterranean climate. Moreover, cooling equipment powered by electricity increases cooling energy consumption due to its high conversion factor of 2.36 Thermal insulation standards focus on U value and heating energy consumption, so they suggest low U values for building envelopes for greater energy efficiency, especially in Northern European countries. But as Figure 3 shows, increasing thermal insulation thickness provides less energy savings in the Mediterranean climate than the cold climate. Therefore, determining insulation thickness should consider cooling, lighting, heating, building type and climate. Otherwise, energy savings expected from increasing thermal insulation thickness could be unexpectedly low, for example in Mediterranean climates.

Figure 4 shows the effect of different thermal insulation thicknesses on carbon emissions during the use stage. There is a 0.64 kg CO_2/m^2/year carbon emission reduction potential in the Mediterranean climate and 4.21 kg CO_2/m^2/year in the cold climate. Cooling with electricity significantly increases carbon emission because of electricity's carbon emission conversion factor value of 0.63 Strategies to decrease cooling energy consumption and carbon emission should focus on energy efficiency in the Mediterranean climate. Therefore, optimization of thermal insulation thickness based on multiple factors primary energy saving and carbon emission are important for countries with Mediterranean climates in order to save energy and meet carbon emission targets.

Figures 5 and 6 show the effects of increasing insulation thickness on life cycle energy consumption and carbon emissions. As it is stated before building life span assumed as 50 years but in LCEA and LCC cost results comparison building life span assumed as 30 years because of life span suggestion in LCC methodology in EPBD. In the Mediterranean climate, increasing thermal insulation over 3 cm for EPS insulation increases carbon emissions while life cycle energy consumption decreases. On the other hand, life cy-

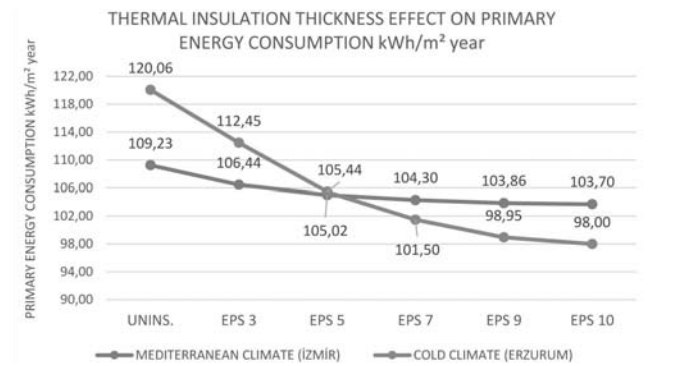


Figure 3. *The effect of thermal insulation thickness on heating and cooling energy consumption for the case study building.*

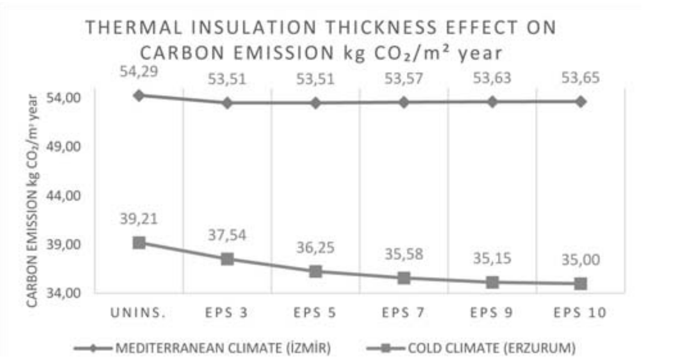


Figure 4. *The effect of thermal insulation thickness on carbon emissions.*

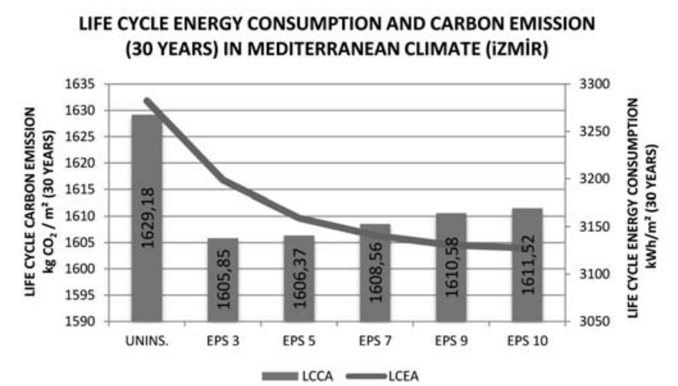


Figure 5. *The effects of EPS with different thicknesses on life cycle energy consumption and carbon emissions in the Mediterranean climate region.*

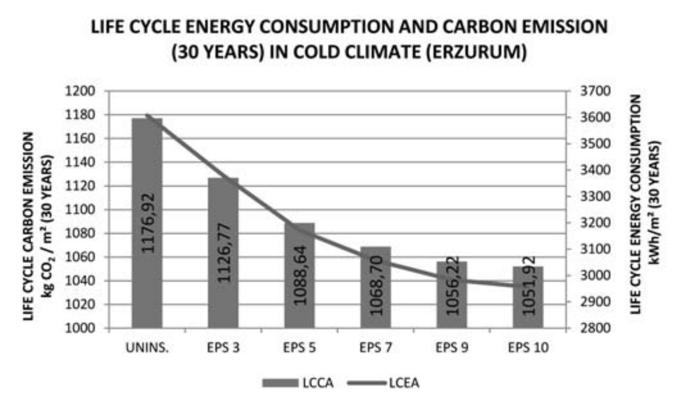


Figure 6. *The effects of EPS of different thicknesses on life cycle energy consumption and carbon emissions in the cold climate.*

cle energy consumption and carbon emissions decrease with increasing insulation thickness in the cold climate. The energy performance of buildings during the use stage dominates life cycle energy performance. High cooling energy consumption in the Mediterranean climate affects primary energy consumption and carbon emission. Therefore, determining optimum insulation thickness based on life cycle performance is important for saving energy and reducing carbon emissions, especially in Mediterranean climates. However, standards and regulations such as EPBD and Building Energy Performance regulation for Turkey (BEP) do not consider life cycle energy consumption and carbon emissions.

LCC is an important tool for making decisions about energy efficiency measures in buildings. Life cycle energy and cost performance of EPS insulation material for Mediterranean and cold climates are shown in Figures 7 and 8. Climate affects energy consumption, which is affected by energy prices. Prices for energy are €0.12/kWh for electricity and €0.035/kWh for natural gas in İzmir. High levels of cooling energy consumption, which is done with electricity, increase global cost significantly. Increasing thermal insulation thickness decreases global cost and energy consumption in all thickness in the cold climate, but in the Mediterranean climate, global cost increases for increasing insulation thickness from 9 to 10 cm. Cooling energy consumption in the Mediterranean climate is important for energy efficiency and cost. Therefore, energy efficiency measures should be optimized with multiple criteria such as energy, carbon emission and cost. Determining insulation thickness without considering annual energy consumption and cost would give ineffective results for Mediterranean climates. In addition to global cost, lighting energy consumption, which increases cooling energy consumption by heat gain from lighting instruments, should be considered in energy performance and global cost calculations.

After getting life cycle energy, carbon emission and cost performance from life cycle perspective optimum solutions are given in this section. Optimum solutions are getting with comparison of all results. Optimum solutions present alternatives with low energy consumption, carbon emission and cost in life cycle period. Thermal insulation material alternative's life cycle energy consumption and carbon emission performance can be seen in figure 9. According to alternatives' performance, optimum life cycle energy consumption is between 3120.00 and 3140.00 kWh/m^2/year and life cycle carbon emissions range from 1606.00 to 1608.00 kg CO_2/m^2/year. EPS, XPS and glass wool with 5 or 7 cm thickness alternatives provide optimum solutions for the Mediterranean climate. Figure 10 shows all alternatives' life cycle energy consumption and costs. Optimum solutions for life cycle energy consumption are between 3110.00 and 3140.00 kWh/m^2 over 30 years and cost between €94.50 and 95.50/m^2 over 30 years. Thermal insulation materials with optimum performance are EPS, XPS and glass wool with thicknesses of 7, 9 and 10 cm.

As it is seen from figure 9 and 10 optimum insulation thickness change according to life cycle energy, carbon and cost performance. Optimum thickness for both LCEA and LCCA is 5 or 7 cm and materials are EPS, XPS and glass wool for the Mediterranean climate. However, for LCEA and LCC, the optimum materials are EPS, XPS and glass wool with 7, 9 or 10 cm thickness. EPS and XPS with 7 cm thickness have optimum performance from LCEA, LCCA and LCC points for the Mediterranean climate (İzmir).Rock wool and glass wool with 9 or 10 cm thickness have optimum solutions from LCEA, LCCA and LCC point of view for the cold climate (Erzurum). As seen from the findings, even if insulation thickness and thermal conductivity are the same life cycle energy, carbon emissions and cost performance are significantly different. Therefore choosing the optimal material and thickness should consider the entire life cycle. Determining optimum insulation thickness based on a single criterion or without considering life cycle performance gives ineffective results.

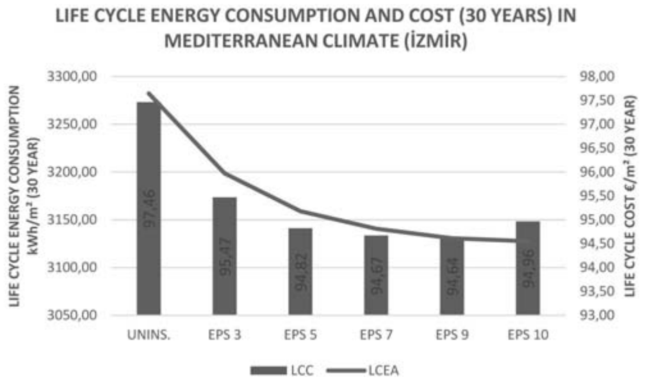


Figure 7. Life cycle energy consumption and cost of EPS with different thicknesses in the Mediterranean climateregion (İzmir).

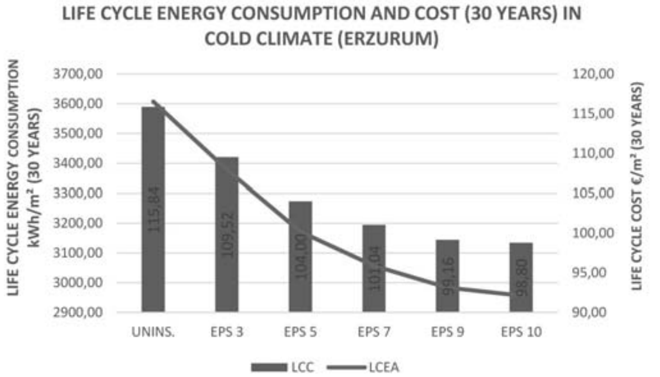


Figure 8. Life cycle energy consumption and cost of EPS with different thicknesses in the Mediterranean climateregion (İzmir).

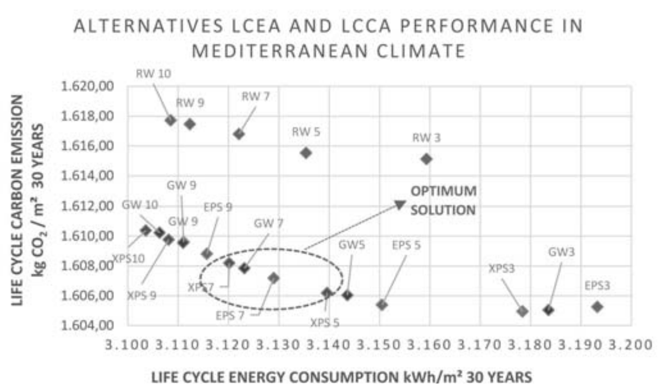


Figure 9. Life cycle energy consumption and carbon emission performance of all alternatives in the Mediterranean climate region (İzmir).

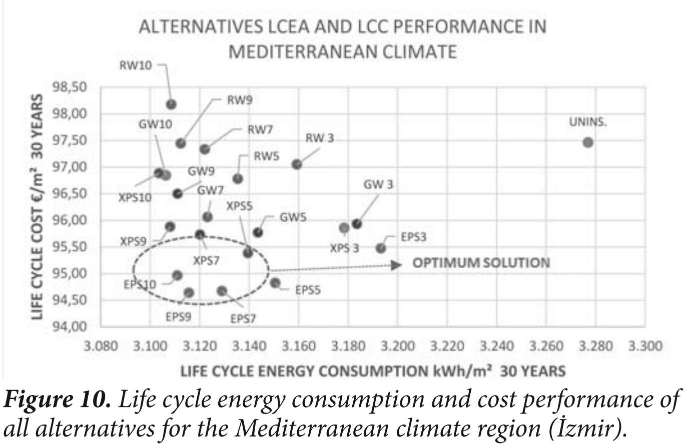


Figure 10. Life cycle energy consumption and cost performance of all alternatives for the Mediterranean climate region (İzmir).

3. Conclusion

This study has presented and demonstrated a new approach to selecting insulation material and thickness though a case study of a multi-storey residential building that optimizes energy efficiency, carbon emission reduction and cost over the building's life cycle. Detailed energy performance calculations included occupancy, activity level, equipment and lighting system. The results were compared to the same building in a cold climate to highlight the effect of climate on energy efficiency and carbon emissions. Using a life cycle perspective is important for countries working toward reduced energy consumption, carbon emission targets and cost in buildings.

Energy efficiency in buildings depends on some parameters such as building form, orientation, distance between buildings, but most of these parameters couldn't be consider while building design in built environment. Therefore design of building envelope is a key factor for energy efficiency and carbon emission reduction. Thermal mass and using thermal insulation are important strategies for energy efficiency in buildings. But providing thermal mass in building envelope couldn't be apply in built environment because of getting solar gain and architectural restrictions such as constructing thick walls. Therefore, adding thermal insulation to building envelope or increasing thermal insulation thickness become most common energy efficiency strategy in envelope for buildings. Adding a thick insulation layer has a significantly different impact on carbon emissions and energy consumption in Mediterranean and cold climates. Cooling energy consumption in Mediterranean climates significantly increases energy consumption, carbon emission and cost because of the electricity conversion factor. Therefore, reducing cooling energy consumption is an important strategy for saving energy and reducing carbon emissions in Mediterranean climate. Other strategies include using thermal mass, natural ventilation, effective central cooling systems, shading devices and renewable energy sources. However, applying these strategies can be inefficiency, expensive or limiting to architectural design. For instance, using thermal mass couldn't be applied in built environment because of solar gain amount and architectural restrictions, using an efficient central cooling system decreases cooling energy consumption but investment and maintenance costs are high; it can also be difficult to integrate into the architectural design. Thermal insulation material and various thickness' performance could change according to climate and building typology significantly. Thus, as seen from results of this study, optimum thermal insulation material and thickness should be determined according to multiple criteria such as energy, carbon emission and cost from life cycle perspective.

Many standards and regulations on energy efficiency or thermal insulation focus energy consumption, carbon emission and cost without considering material's life cycle performance. This study's results show that determining insulation thickness without considering life cycle performance results in unexpected performance, especially in Mediterranean climates. Therefore optimization with multiple criteria such as LCEA, LCCA and LCC should be done to determine insulation material and thickness. Many standards and regulations generally focus on heating energy consumption or energy performance for end use. This study's results show that energy consumption of buildings' primary energy consumption should be calculated to determine optimum efficiency measures. Occupancy, activity level, heat gain from house appliances and lighting systems should be taken into account in calculations because these parameters directly affect energy consumption. Standards and regulation should be revised to include life cycle calculations, including the details of different building types. Such a revision would be significant for countries targeting energy efficiency and carbon emission reduction.

In sum, multiple criteria are required to optimize insulation thickness and material based on life cycle energy, carbon emission and cost. Determining insulation thickness from a single criterion or without considering insulation material's life cycle performance may result in unexpected results. The study focuses on life cycle energy consumption, carbon emission and cost. Future research may incorporate other parameters such as fire resistance, durability and effect on air quality. Future research may also consider details of specific cooling systems, operational schedules and different building types, which may modify and improve the results of this study.

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