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Environmental Assessment of Typical Construction Solutions in Residential Buildings in Greece

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Climatic change has been one of the most important issues that occupies the scientific community around the world for many years now and affects economic, environmental and social policies. A continuous effort is made in order to manage and reduce the demand and consumption of both energy and materials, with the further goal of reducing environmental impacts in all sectors of the constantly developing society. One of the most important sectors that are being developed, following the ongoing global urbanization and population growth, striving to meet the increasing demand is the construction sector. For the proper management of the demand and consumption legalization has been adopted and methodologies and tools have been created. In the European Union such an effort is the European Community Law 2002/91/EC which appears in the Greek legislation by the law 3661/2008 and the Regulation of the Energy Performance of Buildings (KENAK, 2010), aiming to upgrade the existing building stock and compliance the future construction to the new requirements (TOTEE20701−2, 2010). This is an effort to reduce the environmental impacts from the energy consumption in the building sector. Another important issue is the environmental impact from the materials and the stages of the construction of the building. In this scientific area efforts in Europe have been made such as the Environmental Product Declaration. A helpful tool for this analysis, which has not yet widely been used in Greece, is the LCA (Life Cycle Assessment), which is used to calculate the environmental impact throughout the life cycle of a material, a product or a process. The aim of this paper was to provide the ideal construction solution for the opaque elements of the building envelope of residential buildings in Greece and also create a database from which an engineer or a contractor, at the design stage of the building, can use to choose the solution with the least environmental impact depending on the climatic zone and its energy performance, according to the Regulation of Energy Performance in Buildings (KENAK, 2010), that is going to be constructed.

Keywords: *life cycle assessment, residential buildings, energy consumption, U value, TOPSIS.*

1. Introduction

Buildings are responsible for 40% of the energy consumption in the European Union. As indicated by the latest data of 2011 households are responsible for the 26.7% of the final energy consumption in Europe (Eurostat, 2013).

Greece from the year 2007 (the entrance year into the economic crisis) has launched a downward trend in gross domestic consumption of primary energy. The same trend is observed at the building activity. Since 2007 when the building sector began with 16,910,545 of constructed square meters building area there is a fall in 2012 to 2,641,200 square meters (EL.STAT., 2013). However from the year 1997 until 2007 the building activity was very intense and a significant building stock was constructed. As this is one of the most energy intensive parts of the Greek and European economy there is an urgent need to reduce the energy consumption and environmental impacts in this sector.

An effort for energy upgrading of buildings, in line with the Greek legislation in 2013, is the European Directive of the European Parliament 2012/31/EE. Its aim is to review periodically the provisions on energy performance of buildings, such as the Regulation of the Energy Performance in Buildings (KENAK, 2010), with the further goal all new buildings until the end of 2020 and new buildings occupied by public authorities until 2018 to become buildings with nearly zero energy consumption. Even encourages the conversion of the existing building stock in buildings with nearly zero energy consumption with funded programs for insulation installation, replacing windows and doors, upgrading HVAC systems etc.

However this effort only attempts to reduce the environmental impact of the consumption of energy during the operation stage of the building. The environmental impacts from the other stages of the life cycle of the building are ignored as they contribute with a small percentage at the total environmental impact of its life cycle.

The aim of this paper is to calculate the environmental impact of typical construction solutions of the building envelope in residential buildings and for a square meter cross section. Furthermore its aim is to provide the ideal solution, by using the multi-criteria analysis TOPSIS, for each building element and for each climatic zone according to KENAK. These results could be a helpful tool for a contractor or an engineer, in the design stage of a new building or in the design stage of an effort to upgrade the energy performance of the building stock, by choosing the ideal solution with the least environmental impact and also taking into account the energy performance of the building and the U value.

2. Methods

2.1. Typical construction solution of residential buildings in Greece

For this study, different construction solutions of building elements which constitute the building envelope of residential buildings in Greece were selected.

For the construction solutions of column are considered a cross section of reinforced concrete 30 cm thick, insulating material (polyurethane, extruded polystyrene (XPS) and expanded polystyrene (EPS)) and coating with plaster internally 2 cm thick and lime plaster externally 2.5 cm thick. A final covering with color is considered to the internal and external surface of the element. For construction solutions of beam and wall with reinforced concrete there is the same configuration as the column with the thickness difference of the concrete which is 25 cm and the amount of the reinforcing steel. As regards masonry is constructed with bricks of 18 cm thick (two layers of 9 cm thick), adhesive mortar for their connection, insulating material (rock wool, glass wool, extruded polystyrene (XPS) and expanded polystyrene (EPS)) coated with plaster internally 2 cm thick and lime plaster 2.5 cm thick externally and final covering with color in the internal and external surface. The variants differ in the use of an air layer, in the form of air gap, and its position and the mounting position of the insulating material. The flat roof construction solutions include accessible and inverted (with the insulation layer on the outside in order to protect the underlying layers), with variation in the thermal insulation material (polyurethane or extruded polystyrene (XPS)). Includes materials such as bitumen sheets, PVC sheet, HDPE sheet, reinforced concrete slab of 15 cm thick, gravel-concrete 8cm thick, lined with plaster in the internal surface 2 cm thick and exterior topcoat with gravel or stone slabs etc. The inclined roof construction includes solutions which differ in the use of thermal insulation material (expanded polystyrene (EPS) or glass wool) and the use of concrete slab of 15cm or wood for the case of wooden roof with ceramic tiles. The construction solutions for flooring over pilotis differ in the type of insulation (extruded polystyrene (XPS) and glass wool) with an outer covering (lime plaster and cement board respectively). And a final covering with wood, marble or ceramic tiles is considered in the internal surface. The main layer is the reinforced concrete slab 15 cm thick.

2.2. Thickness of insulating material and U value

As observed the main difference in the cross sections of the construction solutions of a building element is located in the choice of the insulating material. For the final configuration of the thickness of the insulating layer the thermal transmittance (U value) was calculated (Eq.1).

$$U = \frac{1}{R_{si} + \sum_1^n \frac{d_i}{\lambda_i} + R_{se} + R_{al}}, \tag{1}$$

where: R_{si} – thermal resistance of internal surface (m^2.K/ W); d_i – layer thickness (m); λ_i – thermal conductivity coefficient (W/m.K); R_{se} – thermal resistance of external surface (m^2.K/W); R_{al} – thermal resistance of the air layer of the air gap (m^2.K/W).

The calculated U value was compared with the maximum U value per climatic zone as defined in the Regulation of Energy Performance of Buildings (table 1).

$$U_{calculated} \le U_{\max}, \tag{2}$$

where: $U_{calculated}$ – thermal transmittance of the element as it is calculated (W/m^2.K) (Eq. 1); $U_{\max}$ – maximum thermal transmittance of the element (W/m^2.K) (table 1);

The thickness of the insulating material was chosen in order to fulfill the conditions of (Eq. 2) according to the maximum U values (table 1) and follows integer values as they appear in the Greek market.

Table 1. *Maximum value of thermal transmittance (W/m^2.K) per climatic zone in Greece according to the Regulation of Energy Performance in Buildings (TOTEE20701−2, 2010)*

Building elements	Climatic zone A	Climatic zone B	Climatic zone Γ	Climatic zone Δ
External flat or inclined roof	0,50	0,45	0,40	0,35
External vertical building elements	0,60	0,50	0,45	0,40
Flooring over pilotis	0,50	0,45	0,40	0,35

Climatic zones of Greece according to the Regulation of Energy Performance in Buildings

According to KENAK Greece is divided into four climatic zones depending on the heating degree days of each region. The schematic depiction (Fig. 1) defines the regions located in the four climatic zones, from the warmer (climatic zone A) to the coldest (climatic zone Δ). In each region of a climatic zone that is located in an altitude over 500 meter, is considered to be in the next colder climatic zone than the one they are originally located. All regions located in climatic zone Δ regardless of altitude are included in this zone (TOTEE20701−3, 2010).

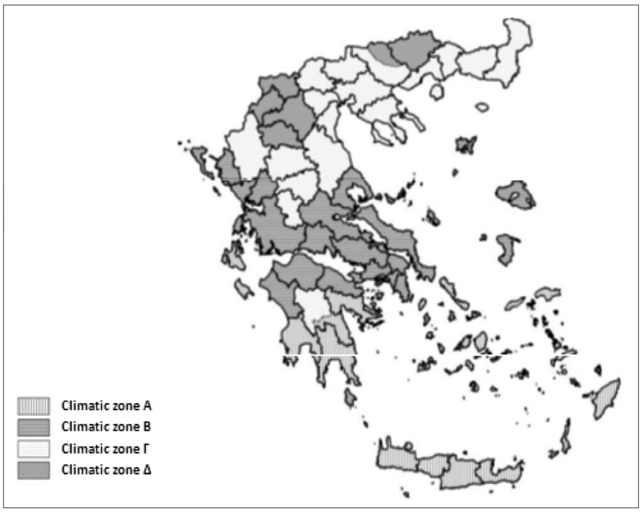

Fig. 1. *Climatic zones of Greece (TOTEE20701−3, 2010)*

2.3. Life Cycle Assessment

The goal and scope of this LCA is to calculate the environmental impact of the typical constructions solutions of the opaque building elements and for a square meter cross section.

This LCA includes environmental impacts from the extraction and production of the material until the material reaches door of the factory and is ready for sale. Also includes the transportation from the factory to the construction site which is considered 100 km. The energy that is required for the construction of the building element in mega joules (MJ) is also taken into account (Αραϊλόπουλος & Χαστάς, 2009). The maintenance stage of the building element is included. The life cycle of the building element is considered 75 years. For the insulation 35–40 years, so it participates in the life cycle of the building element with two life cycles. The same assumption is done for the layers that need to be replaced along with the insulation to complete the maintenance stage. The color covering of the internal surface participates with six life cycles and the external with two in the life cycle of the building element. The LCA also includes environmental impacts from the energy that is required for the demolition of the construction in mega joules (MJ). Furthermore the transportation from the construction site after the demolition to the place for the final disposal of the materials which is considered 100 km. And at last the environmental impacts from the final disposal of the materials of the building element at the end of its life cycle.

The materials and transportation vehicles of Life Cycle Inventory are secondary data from libraries (Ecoinvent system and unit processes, IDEMAT 2001, ETH-ESU system and unit processes). The energy that is required for the demolition and construction of the building elements was calculated and the production energy mix of Greece is also secondary data that was adapted to the latest data from the Energy Regulatory Authority and the Hellenic Transmission System Operator.

The method that was used for the life cycle assessment of the construction solutions is CML Baseline (Preconsultants, 2008). It is a classification method for LCA analysis that is based on the method and database of the CML University of Leiden (CML, 2013). For this LCA were chosen six of the ten impact categories of this method (table 2).

Table 2. *Environmental impact categories*

Environmental impact categories	Units
Ozone layer depletion (ODP)	kg CFC_{-11} equal
Photochemical oxidation (POCP)	kg C_2H_4 equal
Global warming (GWP100)	kg CO_2 equal
Acidification (AP)	kg SO_2 equal
Abiotic depletion (ADP)	kg Sb equal
Eutrophication (EP)	kg PO_4 equal

2.4. Multi-criteria decision analysis method TOPSIS

The TOPSIS (Technique for Order or Preference by Similarity to Ideal Solution) is a method for multi-criteria analysis developed by Hwang and Yoon. It is based on the logic that the chosen alternative has the shortest distance from the positive ideal solution and the greater distance from the negative ideal solution. It is a method that compares a set of options by determining the weights for each criterion, normalizing the values for each criterion and calculating the geometrical distance of each alternative and the ideal alternative, which is also the best value for each criterion (Hwang & Yoon, 1981).

In our case the alternatives are the different construction solutions for each building element of the building envelope. The criteria are the calculated environmental impact of the life cycle of the construction solutions in the six impact categories of CML Baseline method.

For determining the weights for each criterion it was considered the weighting set of the method CML Baseline (table 3) in order to maintain the objectivity of this analysis.

Table 3. *Weighting set of method CML Baseline used in TOPSIS analysis*

Environmental impact categories	Weighting set
Ozone layer depletion (ODP)	6.74 E-11
Photochemical oxidation (POCP)	3.66 E-11
Global warming (GWP100)	8.02 E-11
Acidification (AP)	2.08 E-13
Abiotic depletion (ADP)	1.20 E-7
Eutrophication (EP)	1.21 E-10

For the identification of the positive and negative ideal solution because the criteria are environmental impacts were considered to be cost criteria.

The TOPSIS analysis was used for the ranking of the construction solutions of each building element of the building envelope, in order to provide the ideal one, and for each one of the four climatic zones (KENAK, 2010).

2.5. The influence of U value in the identification of the ideal solution

The calculation of the thickness of the insulation layer was carried out for integer values as they appear in the Greek market. It was noticed that for a construction solution, in order to fulfil the conditions of the U value (Eq. 2), when the thickness of the insulation layer was high the calculated U value of the building element had significant deviation from the maximum U value. The construction solution with the greater thickness of insulation materials, as the LCA analysis and the environmental impacts are based on the quantities of the materials (kg) that compose the construction solution, appears to have the greater environmental impact. This was noticed mainly in the comparison between construction solutions that differ only at the kind of the insulation material.

As a result the construction solution with the greater thickness and the lower U value would have more environmental impacts and would be far from the ideal solution at the final ranking of the construction solutions with TOPSIS. However this solution, with considerable distance from the maximum U value, would probably appear to have high improved energy performance during the life cycle of the building element and the building envelope. And probably would be one of the factors that could reduce the energy consumption of a building.

From this consideration it was decided after running the first LCA and TOPSIS analysis to carry out a second one where the effect of the U value in each construction solution and its environmental impact will be taken into account.

In order to take into account the effect of the U value it was necessary to provide one more weight at the weighting set of TOPSIS analysis for this criterion. However as in the first place it was decided to use the weighting set of the CML Baseline method, in order to preserve the objectivity of this analysis, the use of an extra weight would undermine this effort.

So it was decided to use a typical construction that is provided by ISO 13790/2008 for tests, in order to quantify the effect of the U value in terms of energy and to be imported in the life cycle analysis, without providing an extra weight and criterion in the TOPSIS analysis.

2.6. The influence of U value in the energy performance of the building elements

The software that was used for this analysis is TEE KENAK, the software that is used for the inspections of energy performance of buildings in Greece. The method that is used by the software is the monthly method of energy simulations in buildings. For the completeness of this analysis it was considered a theoretical heating and cooling system according to Regulation of Energy Performance of Buildings.

The typical construction that is examined is provided for tests by ISO 13790/2008 (table 4) and takes no account of thermal bridges.

Table 4. *Dimensions of construction* (ISO13790, 2008)

Building element	Area (m^2)
West wall	10.08
Window glazing	7.00
North wall	15.40
South wall	15.40
East wall	10.08
Floor	19.80
Roof-ceiling	19.80

In order to calculate the influence of the U value in the consumption of the primary energy by end use the maximum U value (table 1), depending on the climatic zone, of all building elements is defined. Then the U value of the examined element is changing with a descending step 0.05 W/m^2.K while all the other building elements keep their original maximum U value. The procedure is carried out for all the opaque building elements and for the four climatic zones of Greece. Then from the analysis and the linear trends of the results, the reduction in the primary energy consumption by end use of the building is calculated for a reduction of 0.01 W/m^2.K of the U value of each building element and for the four climatic zones.

2.7. Quantification of the effect of the U value in the life cycle of the building element

In order to quantify the effect of the reduction of U value and to import it in the life cycle of each construction solution is taken into account the numerical distance of the calculated U value of the construction solution from the maximum U value of the climatic zone:

$$DU = U_{max} - U_{calculated}, \tag{3}$$

where: $U_{calculated}$ – thermal transmittance of the element as it is calculated (W/m^2.K) (Eq. 1); U_{max} – maximum thermal transmittance of the element (W/m^2.K) (table 1).

Then it is multiplied by the change in the consumption of primary energy by end use for a reduction of 0.01 W/m^2.K of the U value:

$$E_U = DU \times DE \times 100\%, \tag{4}$$

where: E_U – the contribution of U value of the element to the reduction of annual primary energy consumption by end use (kWh/m^2 ×year); DU – the numerical distance of the maximum and calculated U value of the building element (Eq. 3); DE – the reduction in the primary energy consumption by end use of the building for a reduction of 0.01 W/m^2.K of the U value.

This contribution is multiplied by the duration of the life cycle of the building elements which was considered to be seventy five years.

$$E'_{U-total} = E_U \times 75, \tag{5}$$

where: $E'_{U-total}$ – the contribution of U value of the element to the reduction of primary energy consumption by end use during the life cycle of the building element (kWh/m^2); E_U – the contribution of the U value of the element to the reduction of annual primary energy consumption by end use (kWh/m^2×year); 75 – the duration of the life cycle of the building element (years).

Finally this contribution is converted from kWh/m^2 to MJ/m^2 in order to be imported in the life cycle of the building element.

$$E_{U-total} = E'_{U-total} \times 3.6, \tag{6}$$

where: $E_{U-total}$ – the contribution of U value of the building element to the reduction of primary energy consumption by end use during the life cycle of the building element (MJ/m^2); $E'_{U-total}$ – the contribution of U value of the building element to the reduction of primary energy consumption by end use during its life cycle (kWh/m^2); 3.6–1.0 kWh equals to 3.6 MJ.

For each construction solution this contribution is imported as a benefit during its life cycle in the sector of energy. It is added with a minus sign to the total energy that is required for the stages of the construction and demolition of the building element.

$$E_{final} = E_{calculated} - E_{U-total}, \quad (7)$$

where: E_{final} – the final energy that is imported in the life cycle of the building element (MJ/m^2); $E_{calculated}$ – the total energy that is required for the construction and demolition of the building element (MJ/m^2); $E_{U-total}$ – the contribution of U value of the building element to the reduction of primary energy consumption by end use during its life cycle of (MJ/m^2).

Then the LCA and TOPSIS analysis were carried out again with the modified data in the sector of energy.

3. Results

3.1. Ideal solutions from the LCA and TOSIS analysis

The construction solutions of the building element inclined roof show a significant difference as the optimal solutions are those with the use of wood than concrete for as the main material for its construction (table 5).

For the same construction solution of inclined roof with the only difference the insulating material glass wool overrides the use of extruded polystyrene (XPS).

Table 5. *Optimal solutions for the building element of sloping roof*

Climatic zones	**Inclined Roof**
A	Roof with wood, ceramic tiles and insulation glass wool (2 cm)
B	Roof with wood, ceramic tiles and insulation glass wool (2 cm)
Γ	Roof with wood, ceramic tiles and insulation glass wool (3 cm)
Δ	Roof with wood, ceramic tiles and insulation glass wool (4 cm)

For the construction solutions of masonry in bricks the optimal solutions for all climatic zones, with the same ranking, are the walls with an air layer (air gap) and rock wool for insulation in the middle of the section, the ventilated walls with rock wool for insulation in the external surface and the masonry with rock wool for insulation in the internal surface and final coating with plasterboard (table 6).

Between the four remaining similar profiles of masonry that were examined, with unique variation the insulating material, is observed as better solution the use glass wool rather than rock wool, expanded polystyrene and extruded polystyrene without observed differences between the four climatic zones.

Table 6. *Optimal solutions for the building element masonry in bricks*

Climatic zones	**Masonry in bricks**
A	Air gap (5 cm) with no contact with the external air and insulation rock wool (5 cm) in the middle
	Ventilated wall with insulation rock wool (4 cm) in the external surface
	Insulation rock wool (4 cm) in the internal surface and final covering with plasterboard
B	Air gap (5 cm) with no contact with the external air and insulation rock wool (6 cm) in the middle
	Ventilated wall with insulation rock wool (5 cm) in the external surface
	Insulation rock wool (6 cm) in the internal surface and final covering with plasterboard
Γ	Air gap (5 cm) with no contact with the external air and insulation rock wool (7 cm) in the middle
	Ventilated wall with insulation rock wool (6 cm) in the external surface
	Insulation rock wool (6 cm) in the internal surface and final covering with plasterboard
Δ	Air gap (5 cm) with no contact with the external air and insulation rock wool (7 cm) in the middle
	Ventilated wall with insulation rock wool (7 cm) in the external surface
	Insulation rock wool (7 cm) in the internal surface and final covering with plasterboard

Regarding construction solutions of the flat roof the inverted roof appears to be better solution than the compatible one (table 7).

Table 7. *Optimal solutions for the building element flat roof*

Climatic zones	**Flat roof**
A	Inverted flat roof with XPS (6 cm)
B	Inverted flat roof with XPS (7 cm)
Γ	Inverted flat roof with XPS (8 cm)
Δ	Inverted flat roof with XPS (9 cm)

For the same construction solution of flat roof, with the only difference the insulating material, XPS appears to be a better solution than polyurethane.

As seen from the results for the building element flooring over pilotis a significant contribution to the final classification of the sections is the use of wood and then the ceramic and marble floor (table 8).

In construction solutions beam, wall and column of reinforced concrete is observed that for all four climatic zones as the optimal solution in terms of environmental impact appears to be the one with expanded polystyrene (table 9, table 10 and table 11). The similarity between the results of these building elements can be explained by the fact that the differences between them are minor and located in small varying in the thickness of the concrete and the amount of reinforcing steel that is used for their construction.

Table 8. Optimal solutions for the building element flooring over pilotis

Climatic zones	Flooring over pilotis
A	With external insulation glass wool (4 cm), external coating with plasterboard and internal final covering with wood
B	With external insulation glass wool (5 cm), external coating with plasterboard and internal final covering with wood
Γ	With external insulation glass wool (6 cm), external coating with plasterboard and internal final covering with wood
Δ	With external insulation glass wool (7 cm), external coating with plasterboard and internal final covering with wood

Table 9. Optimal solutions for the building element beam of reinforced concrete

Climatic zones	Beam of reinforced concrete
A	With external insulation EPS (5 cm)
B	With external insulation EPS (6 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

Table 10. Optimal solutions for the building element wall of reinforced concrete

Climatic zones	Wall of reinforced concrete
A	With external insulation EPS (5 cm)
B	With external insulation EPS (6 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

Table 11. Optimal solutions for the building element column of reinforced concrete

Climatic zones	Column of reinforced concrete
A	With external insulation EPS (5 cm)
B	With external insulation EPS (6 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

Evaluation

From the results of the LCA and TOPSIS analysis it is observed that the use of wood as a material in a construction solution is suggested as an optimal solution, according to environmental impact, than materials such as concrete (in inclined roof) and ceramic or marble (in flooring over pilotis). For the horizontal construction solutions of the building envelope the use of glass wool is preferred, for the vertical construction solutions of reinforced concrete the use of EPS and for the masonry in bricks the use of rock wool. The use of air gap in the construction solutions appears to have a positive contribution in their final ranking as optimal solutions. There is no diversity of the ideal construction solutions of the building elements between the four climatic zones. In the majority of the ideal solutions, as it was expected, the U value is higher than the other solutions that have a greater distance between the ideal and negative ideal solution. However this contradicts with the improved energy performance that these not ideal solutions would probably provide in the life cycle of a building and will reduce the environmental impacts in terms of energy during its life cycle.

3.2. The influence of the reduction of the U value in the energy performance of the building elements

The results in this section are representative of the typical construction that was examined in this study.

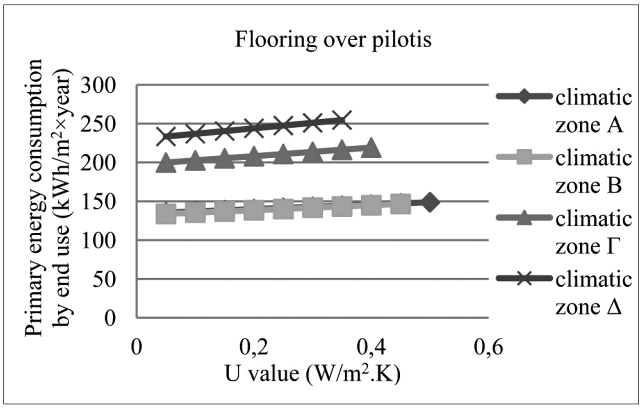

Fig. 2. *Reduction of annual primary energy consumption by end use for the change of U value of the building element flooring over pilotis for the four climatic zones*

As seen from the results of the building element flooring over pilotis, the reduction of the U value by 0.01 $W/m^2.K$, as calculated from the linear trends (Fig. 2), leads to a decrease in annual primary energy consumption by end use 0.29333 kWh/m^2 in climatic zone A, 0.31967 kWh/m^2 in climatic zone B, 0.55 kWh/m^2 in climatic zone Γ and 0.70643 kWh/m^2 in climatic zone Δ.

From the results of the vertical building elements (beam, wall, column of reinforced concrete and masonry in bricks), the reduction of the U value by 0.01 $W/m^2.K$, as calculated from the linear trends (Fig. 3), leads to a decrease in annual primary energy consumption by end use 0.73266 kWh/m^2 in climatic zone A, 0.79297 kWh/m^2 in climatic zone B, 1.3313 kWh/m^2 in climatic zone Γ and 1.7252 kWh/m^2 in climatic zone Δ.

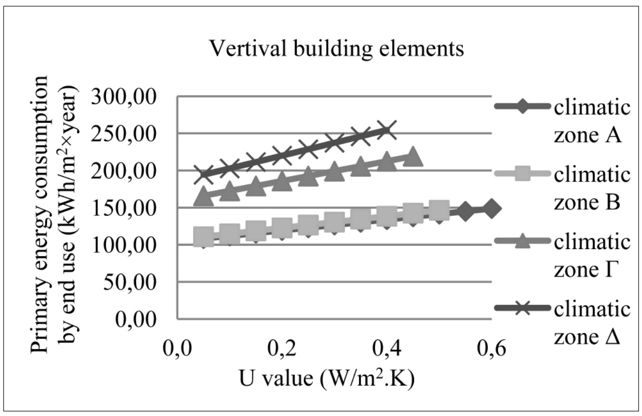

Fig. 3. *Reduction of annual primary energy consumption by end use for the change of U value of the vertical building elements for the four climatic zones*

From the results of building element of roof (inclined or flat) the reduction of the U value by 0.01 W/m^2.K, as calculated from the linear trends (Fig. 4), leads to a decrease in annual primary energy consumption by end use 0.30048 kWh/m^2 in climatic zone A, 0.32333 kWh/m^2 in climatic zone B, 0.50833 kWh/m^2 in climatic zone Γ and 0.67143 kWh/m^2 in climatic zone Δ.

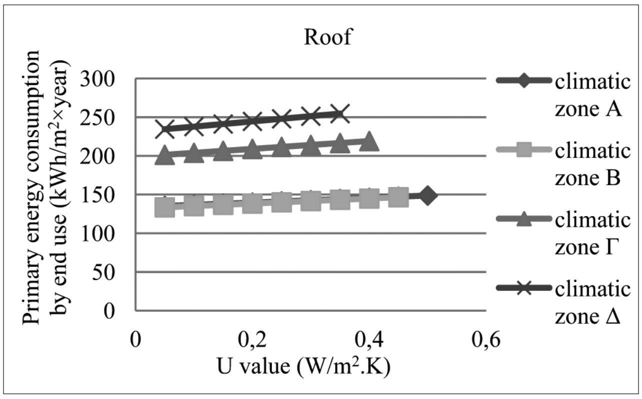

Fig. 4. *Reduction of annual primary energy consumption by end use for the change of U value of building element of roof for the four climatic zones*

Evaluation

From the results it can be observed that in the transaction from climatic zone A to climatic zone Δ for all the building elements the reduction in final annual primary energy consumption by end use increases to 100%–150%. This can be explained from the fact that in this transaction the heating requirements of the building increase from zone A to Δ and so the influence of the U value to the reduction of energy consumption increases.

3.3. The influence of the reduction of the U value in the environmental impact of the LCA and the final classification of the construction solutions

The results in this section are representative of the typical construction that was examined in this study. In this analysis the quantification of the distance of the calculated U values from the maximum U values was considered in the calculation of the environmental impacts.

In the building elements of masonry in bricks, flat roof, inclined roof and flooring over pilotis the ideal solution is the same with the results of the first analysis (table 5, table 6, table 7 and table 8).

Table 12. *Optimal solutions for the building element beam of reinforced concrete*

Climatic zones	Beam of reinforced concrete
A	With external insulation polyurethane (4 cm)
B	With external insulation polyurethane (5 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

In construction solutions beam, wall and column of reinforced concrete is observed that in climatic zone A and B the optimal solution in terms of environmental impact appears to be the one with polyurethane (table 12, table 13 and table 14). In climatic zone Γ and Δ the optimal solution appears to be expanded polystyrene (EPS).

Table 13. *Optimal solutions for the building element wall of reinforced concrete*

Climatic zones	Wall of reinforced concrete
A	With external insulation polyurethane (5 cm)
B	With external insulation polyurethane (6 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

Table 14. *Optimal solutions for the building element column of reinforced concrete*

Climatic zones	Column of reinforced concrete
A	With external insulation polyurethane (4 cm)
B	With external insulation polyurethane (5 cm)
Γ	With external insulation EPS (7 cm)
Δ	With external insulation EPS (8 cm)

Evaluation

From this analysis is observed that there is more diversity in the optimal solutions between the four climatic zones. The use of wood instead of materials like concrete, ceramics and marble appears to be a better solution as it also was in the first analysis. In construction solutions that only differ in the type of the insulating material, the one with the lower U value appears to be the optimal solution. The use of rock wool and air gap in masonry in bricks and glass wool in flat roof and flooring over pilotis appear to be optimal solutions such as in the first LCA and TOPSIS analysis.

4. Discussion

In this study the LCA takes into account quantities of materials that are used for the construction of a building element. As a result from the first and second LCA and TOPSIS analysis, an important issue that determines an ideal construction solution is the number of layers and the type of materials that it consists of, as they affect the quantities and the environmental impacts of its life cycle.

A second important issue is that the U value affects the energy performance of a building and the energy consumption by end use. It is a parameter that should be considered when a selection of a construction choice depends both on the environmental impacts and its energy performance during its life cycle. When the construction solutions have the same number of layers and materials and they only differ in the type of the insulating material is suggested that the preferable solution is the one with the lower U value.

The use of wood as material is an optimal solution, when the criteria for this choice are environmental impacts, as in some categories of environmental impacts it has nearly zero or maybe negative values.

The use of air gap in construction is suggested either if the air layer is isolated in the middle of the construction or in a ventilated solution because it improves the energy performance of a building element by decreasing the U value without increasing the environmental impacts.

5. Conclusions

Continuous efforts in Europe aim to reduce the environmental impact from the energy consumption and to decrease the use of non renewable sources of energy. This occurs from the fact that in a life cycle of buildings the majority of environmental impacts come from the energy consumption from the use stage of the building. The environmental impact from the materials and the other stages amount a small percentage of the total environmental impact of its life cycle. However even it is a small percentage it is something that cannot be ignored. All these interventions for upgrading the energy performance of a building should be examined for their environmental impacts. Also in the choice of the materials and the construction solutions for upgrading an existing building or designing a new one, should be taken into account the environmental impact during their whole life cycle and not only in the operation stage.

Furthermore in the choice of an insulating material or a construction solution that affects the energy performance of a building should be considered not only the U value that it provides but also if the benefit from this choice overrides the environmental impacts during its life cycle.

This study shows the optimal construction solutions of building elements in residential buildings in Greece and provides suggestions for the materials that should be used. Its aim is to provide a helpful guide to the designers in order to choose a construction solution, depending on the climatic zone that is going to be constructed, considering its energy performance and its environmental impact during its life cycle.

In conclusion this study shows that the influence of the U value in the energy performance of the building elements and the choice of the insulating material are significant factors to the environmental impacts of their life cycle. For the masonry in bricks the use of rock wool with the use of air gap is suggested rather than EPS or XPS in all climatic zones. In the construction solution of flat roof the use of XPS appears to be an optimal solution in all climatic zones rather than polyurethane. For the inclined roof the use of wood and glass wool appear to be optimal solutions rather than concrete and EPS in all climatic zones. In the construction solution of flooring over pilotis the use of glass wool is suggested rather than XPS in all climatic zones. For the vertical construction solutions of reinforced concrete (beam, column and wall) the use of polyurethane in climatic zones A and B is suggested rather than EPS and XPS. In climatic zones Γ and Δ the use of EPS appear to be an optimal solution rather than polyurethane and XPS.

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