Energy Design and Multicriteria Decision Analysis in a New Residential Building - Study on the Application of Thermal Insulation

Abstract

In this study, an attempt was made to design and study a new two-storey house with energy planning criteria. At the theoretical level, the principles and systems used for building energy planning and the importance of multicriteria analysis in decision-making on this issue were analyzed.
The main criterion for the energy efficiency of the construction outside the bioclimatic design was the thermal insulation of the building where multi-criteria analysis was applied with the Visual Promethee application to select the most suitable thermal insulation material. Equal weights of criteria were analyzed, but also different weights calculated through personal interviews with civil engineers were applied. The results of the two analyses were compared. In the case of analysis with different criteria weights, the expanded polystyrene is followed by stone wool, while for the analysis with similar criteria weights expanded cork ICB is the best alternative.
Also, based on the case with similar weights, the two predominant thermal insulation materials (expanded polystyrene and rock wool) were introduced into the building's components and analyses were carried out showing the needs for cooling and heating of the new home in the four climate environments using Revit. Comparison and annotation of the analyses for the heating and cooling needs according to the peak loads for the two thermal insulation materials in the climate zones also took place.
In terms of peak load for cooling, rockwool in climatic zones B and D exhibits little difference in efficacy in comparison to expanded polystyrene. In the other two climate zones expanded polystyrene predominates. Polystyrene is particularly effective when applied to climatic zone A. On the other hand, for peak loads, rockwool in climatic zone B and D. performs better in climatic zone B than in climatic zone B compared to expanded polystyrene. while in zone D the largest difference is found in the two materials. In the other two zones, expanded polystyrene is superior to rock wool, with a significant difference being present in climate zone A. On the ground floor, climate zones A and C are more efficient, while for the other two, rock wool is the most efficient. On floor for climatic zones C and D the most effective is cotton wool, for climatic zone A expanded polystyrene while for B the insulating materials exhibit similar peak loads for cooling. Finally, the building is presented with proposed interventions such as the addition of passive and energy solar systems, addition of vegetation and devices that enhance natural cooling / lighting.

Keywords: Multi Criteria Analysis, Energy Design, Peak Loads, Visual PROMETHEE, Revit.

1. Introduction

In modern times the need for decision-making exists on a daily basis. There are many alternatives to choose from, and many interests appear, many times with antagonistic behaviour. The use of specific tools that help document the appropriate alternative action has proven absolutely essential.
The more complex an issue, the more necessary the standardization of the decision-making process. In addition, the criteria must be appropriately linked to the alternatives given that the factors that shape the opinion-solutions are likely to conflict. This reduces decision making to a Multi Objective Decision Making (MODM) or Multi Attribute Decision Making (MADM) problem, also known as Multi-Objective Decision Making (also known as Multi-Criteria Decision Making), Decision Analysis (MCDA) Multi-Attributes Decision Making (MADM). These methods give a new perspective where quantitative and qualitative considerations can be taken into account in formulating a decision issue. Meeting all the objectives of the decision is not possible because not all alternatives have the same performance across all criteria. In this way the alternatives are screened and some are selected with the highest performance.
Furthermore, in terms of the environment, energy needs are constantly increasing, so it is useful to save energy in every area of human activity. A large number of studies have been carried out internationally and nationally on energy consumption in buildings and at the same time regulations have defined specific energy saving objectives. A number of publications have addressed relevant issues. Initially, Nowak and Skłodkowski (2016) analyse the decision-making problem faced by a future house owner. The issue deals with the selection of the optimal solution of building thermal insulation in relation to the selected criteria, both related to costs and future benefits. The current study is based on the entropy method. In the same context Zagorskas et al. (2014) in their study focus on retrofitting the historical buildings, when due to the valuable façade or other heritage preservation requirements only the inside insulation is allowed. The study emphasizes on the method for selecting best insulation option. Five modern insulation materials are selected, then measurements are made and best alternative is identified using TOPSIS method.
Zigart et al (2018) produced an environmental impact comparison of four different building structural systems widely used that included: reinforced concrete, brick, cross-laminated timber, and timber-frame panel construction. Their study revealed that here is a significant potential for improving the environmental potential of low-rise buildings, by selecting suitable components and materials, sustaining the energy performance of the building.
Hart (2014) focuses his research on selecting thermal insulation. The criteria considered included: thermal conductivity, thermal expansion and contraction, combustion characteristics, compressive properties, water vapor permeability, wicking, susceptibility to water absorption, and corrosivity of the environment. Moreover, Centiner and Edis (2014) proposed an environmental and economic sustainability assessment method to evaluate the effectiveness of existing residential building retrofits. The aim was to reduce their space heating energy consumptions and the resulting emissions. The presented method is based on the life cycle assessment method, and measures the environmental and economic sustainability performance of building envelope retrofits. Nan et al (2020) examined the influence of external living wall systems (LWSs) on indoor thermal environments in winters with low temperatures and high humidity levels. Their study involved four containers with different

outer facades that were arranged in Hangzhou and a comparative analysis was conducted on changes in the internal and external thermal environments of these containers.
The current study examines three diferent insulation materials for a residential house in Greece. The paper is highlighting the methodological approach and PROMETHEE methodology. The next section includes analyses findings and a detailed discussion on the results. Finally, the last but not least section includes conlcusions, limitations of research, ideas for further research and proposals for improvement of the current context.

2. Methodological Approach

The purpose of multicriteria analysis is to select the appropriate thermal insulation material according to various parameters that characterize it for the vertical elements of a new residential building. The thermal insulation materials available on the market today are varied, but after a bibliographical investigation the following three (alternatives) have been selected and used for comparison:

- Expanded Polystyrene EPS
- Stonewool/ Rockwool
- Expanded Cork ICB

The problem was formulated with evenly distributed criteria weights and unequal criteria weights, and comparisons were made between the two approaches. The considered criteria included both quantitative and qualitative criteria.

Table 1 - Criteria and units of measurement

CRITERIA	**MEASUREMENT UNITS**
QUANTITATIVE	
Thermal conductivity coefficient λ	W/m·K
Lifetime	years
Special heat capacity cp	J/kg·K
Cost C.	€/m2
Temperature range	°C
Primary energy content contained	kWh/m3
Vapor diffusion resistance coefficient m	-
QUALITATIVE	**CATEGORIZATION**
Fire resistance	Very Low / Low / Moderate / High / Very High
Resistance to solar radiation	Yes No
Soundproofing	Very Low / Low / Moderate / High / Very High

Table 2 Actions, criteria and performance of actions against each criterion

Thermal insulation materials	**CRITERIA**									
	Thermal conductivity coefficient λ (W/m·K)	**Special heat capacity c_p (J/kg·K)**	**Vapor diffusion resistance coefficient m**	**Lifetime (years)**	**Cost C (€/m²)**	**Temperature range (°C)**	**Primary energy content contained (kWh/m³)**	**Resistance to solar radiation**	**Soundproofing**	**Fire resistance**
Expanded Polystyrene EPS	0.031-0.041	1450-1550	20-100	50	2.04-12.5	-50 to 75	250	NO	GOOD	B
Stonewool / Rockwool	0.033-0.041	840	1- 1.5	30	2.25-13.7	-100 to 750	650	YES	VERY GOOD	A1
Expanded Cork ICB	0.042-0.065	1500-1560	10-40	50	12-25	-200 to 130	15	YES	EXCELLENT	D

3. Visual PROMETHEE

The overall objective of all Multicriteria methods is to enrich the dominance graph to substantially reduce the number of weaknesses of comparison. This methodology is not always the most correct as it is based on fairly strong assumptions and changes the structure of the original issue. Methods belonging to the PROMETHEE family are considered relatively simple methods of Multicriteria Analysis and belong to the Methods of Excellence. PROMETHEE follows a transparent computational process and can be easily understood by the decision maker. In general, the application of PROMETHEE is useful in complex problems for choosing between alternatives, where multiple decision criteria are involved, for setting priorities, for ranking alternatives, and for conflict resolution (if incompatible objectives exist). PROMETHEE methods require that a certain preference function be defined for each criterion. They calculate positive preference flows, which express whether one alternative is predominant over the other and negative preference flows which express whether one alternative is predominant. The method is divided into five versions (PROMETHEE I, II, III, IV, V, VI) that have been developed over time to address decision issues. These versions have important similarities but are used in different types of issues. The PROMETHEE methods are methods of comparing the alternatives bilaterally. Specifically, alternatives result in partial ranking through PROMETHEE I or complete ranking through PROMETHEE II. PROMETHEE III ends up arranging the alternatives at intervals. PROMETHEE IV generalizes to PROMETHEE II if the set is not finite. PROMETHEE V seeks to construct a subset of alternatives in the presence of constraints. PROMETHEE VI represents the human brain. (http://www.promethee-gaia.net) The PROMETHEE method used in the present work belongs to the family of methods of excellence relationships. Visual PROMETHEE software contains many tools that can analyze the data and rank it. The most important analyses offered are the following (Visual PROMETHEE Manual): PROMETHEE Rankings, Diamond, Table, Rainbow, Visual Stability Intervals, GAIA Visual Analysis.

4. Analysis Findings and Discussion

Initially the implimentation of the analysis for different weights highlighted that the expanded polystyrene is exceptional, followed by the stone wool, while the last position is occupied by the Expanded Cork.

On the contrary in the case that similar criteria weights are considered, the rock wool is the last one, and Expanded Cork is slightly ahead of the expanded polystyrene based on the outcomes of PROMETHEE Rankings.

It is noteworthy that in the case of different weights, the cost and thermal conductivity factor play an important role since they increase the positive flow of expanded polystyrene and at the same time increase the negative flow of the expanded cork. Rock wool and expanded polystyrene have the same behavior in response to the temperature range. Fire resistance helps to increase the net flow of rock wool and at the same time reduces the net flow of expanded cork. The specific heat capacity and the primary energy content of the two latter materials play influence the outcome in an opposite manner. Finally, the materials' life expectancy seems to negatively affect the alternative choice of rockwool. The other criteria do not play a particularly important role in qualifying some of the alternatives according to PROMETHEE Rainbow.

In the case of similar weights, all criteria give a negative and positive direction to the alternatives at similarly significant rates. However, material life expectancy has little effect on the yield of expanded cork and expanded polystyrene, and the resistance to sunlight has little effect on the yield of expanded cork and rock wool.

The criteria of primary energy / sound insulation / fire resistance have little effect on the performance of the expanded polystyrene. Also, the performance of the expanded cork scores negatively against the specific criteria heat capacity, the primary energy content and the fire resistance. Finally, the net flow of rock wool seems to have no impact on sound insulation and cost according to PROMETHEE Rainbow.

Comparing the two PROMETHEE Rainbow charts for equal and unequal weights the order of preference changes. It is reasonable to assume that all criteria play a major role in the net flows of alternatives in the case of unequal weights.

In the case of equal weights, it appears that half the net flows of the same thermal insulation materials are affected. Also, while in the first analysis (unequal weights) the water vapor diffusion coefficient and solar radiation resistance in the second analysis (similar weights) do not play a significant role in the net flow of expanded polystyrene, the first criterion significantly increases the positive flow while the second criterion increases similarly the negative flow according to PROMETHEE Rainbow.

5. Conclusions and Future Research

Initially, the Visual Promethee program where the multi-criteria analysis was done had a very user - friendly and simple graphical interface and made the presentation of a multi-solution issue easy. The user can even make comparisons between different scenarios, which was not considered necessary in the present work. Other scenarios could be created to reduce the demand for energy in buildings and compare with each other to select the best one. The optimal solution may at any time be different if other evaluation criteria are taken into consideration, especially when the criteria are conflicting.

The approach to an issue has a strong element of subjectivity. The limitations identified in the study are therefore the weights assigned to the criteria. Accurate weight assignment is not easy because it involves the personal opinion of the participants. Other population groups, such as home users, could also be asked. The three thermal insulation materials compared had specific performance against each criterion. The object of research may be to improve the parameters of each material so that its application would be considered a good solution.

The multicriateria analysis identified a number of significant findings. For analysis with different criteria weights, the expanded polystyrene is followed by the stone wool and in the last place resides expanded cork while in the analysis with the equal criteria weights the best alternative is the expanded cork and the worst is the rock wool.

In the case of different criteria weights the cost, thermal conductivity, temperature range and fire resistance are the criteria that occupy the highest percentages for evaluating alternatives. In addition, the specific heat capacity, the primary energy content, and the life span affect the performance of some thermal insulation materials to a lesser extent. The influence of the other criteria is negligible.

On the other hand, in the case of analysis with equal criteria weights, almost all the criteria equally affect the performance of the thermal insulation materials, either negatively or positively. Life expectancy has little effect on the performance of expanded cork and expanded polystyrene.

The resistance to sunlight has little effect on the yield of expanded cork and rock wool. Primary energy content, sound insulation and fire resistance have little effect on the net flow of expanded polystyrene. The performance of the cork has little influence on the specific heat capacity, the primary energy content and the fire resistance. The performance of rock wool does not appear to be affected by the sound insulation and cost of the material.

The shorter stability interval for both cases is found in the resistance to solar radiation. A marginal identification of stability intervals between the two cases shows the sound insulation with a difference of only 1.75% between the two cases. Regarding the future research the following are some considerations for the futrther development of multicriteria decision-making research, both in the context of this paper and in more general directions:

- Considering additonal criteria for comparing alternative actions taking into account, for example, installation costs
- Addition of other thermal insulation materials as alternatives
- Multi-criteria analysis with another method for comparing results

A number of suggestions could be taken into consideration. In Greece, there is a large volume of buildings that show high energy consumption without providing users with the necessary thermal comfort conditions. In recent years, the renovation of the existing building stock has been promoted with the appropriate legislative and financial incentives to bring the country in line with European directives requiring a reduction in energy consumption. Despite today's difficult economic environment, reducing the energy needs of the buildings is a key pillar of growth. Therefore, new buildings should be studied and constructed with the basic principles of energy planning and sustainability. For the sustainability of construction, an effort is made to find solutions that are environmentally friendly and user-friendly. The complexity of the issues requires a systematic presentation of the objectives and strategies needed to achieve the sustainability of the constructions.

Citizens need to realize that reducing energy consumption and protecting the environment is not a hindrance to comfort, cost and aesthetics. There are a number of simple interventions available in buildings to optimize construction. Such an investment usually has a depreciation in the short term and then generates a profit if the amount of energy wasted decreases. More complex operations can then be performed, but expert advice and careful techno-economic study is needed.

The general public has incomplete information regarding energy management. Relevant events organized in municipalities are needed to identify the benefits of building energy planning locally. The information should also refer to the existing institutional / financial incentives for the implementation of energy technologies. It is also useful to implement energy planning applications in public buildings. Promotion is important because it has been made clear that no legislation can be fully implemented unless it is first assimilated by the public. Generally speaking, it is good for public buildings to develop a system of grading their energy requirements based on Multi-criteria analysis. The most important principle for achieving sustainability in buildings is the awareness of both experts and users that each building is a living organism that interacts with the environment and is directly linked to quality of life and health.

6. References

Cetiner, I., & Edis, E. (2014). An environmental and economic sustainability assessment method for the retrofitting of residential buildings. *Energy and Buildings*, *74*, 132-140. doi:10.1016/j.enbuild.2014.01.020

Hart, G. H. (2014). Selecting thermal insulation. *Chemical Engineering Progress*, *110*(6), 22-27. Retrieved from www.scopus.com

Nowak, P., & Skłodkowski, M. (2016). Multicriteria analysis of selected building thermal insulation solutions. Archives of Civil Engineering, 62(3), 137-148. doi:10.1515/ace-2015-0088

Zagorskas, J., Zavadskas, E. K., Turskis, Z., Burinskiene, M., Blumberga, A., & Blumberga, D. (2014). Thermal insulation alternatives of historic brick buildings in baltic sea region. Energy and Buildings, 78, 35-42. doi:10.1016/j.enbuild.2014.04.010

Žigart, M., Kovačič Lukman, R., Premrov, M., & Žegarac Leskovar, V. (2018). Environmental impact assessment of building envelope components for low-rise buildings. *Energy*, *163*, 501-512. doi:10.1016/j.energy.2018.08.149

Nan, X., Yan, H., Wu, R., Shi, Y., & Bao, Z. (2020). Assessing the thermal performance of living wall systems in wet and cold climates during the winter. *Energy and Buildings, 208* doi:10.1016/j.enbuild.2019.109680