Multi-Criteria Optimization for the Decision Making in Building Envelope Thermal Design

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Abstract. The increase of energy utilization reinforced the need of reducing the primary energy consumption based on fossil fuels and the limitation of carbon dioxide (CO_2) emissions to the atmosphere. Such goals aim at the provision of affordable and generally clean energy for the citizens. However, the final decision making is hard to be achieved, due not only to the multitude variety of such proposed technologies, but also to the consideration of different criteria and scenarios, that in many cases are conflicting with each other. This paper deals with the optimization of the building envelope design considering thermal insulation, economic, and environmental aspects. The Life Cycle Assessment perspective is implemented for the data of the environmental criterion, focusing on the CO_2 emissions and the cumulative energy demand. The decision making refers not only to the selection of the appropriate thermal insulation material and its width, but also to the choice of the window frame material. In that way, Mathematical Programming (MP) models for the optimization of such criteria were developed. The General Algebraic Modeling System (GAMS) was used to model these problems and the BARON solver was used to solve them. The respective MP models include mixed integer nonlinear programming problems, multiple objective functions, as well as multi-criteria techniques such as goal programming. According to the results, the increase of the envelope thermal protection implies that the economic and environmental costs are higher, displaying the importance of criteria compensation. For smoothing the conflicting criteria, a weighting sensitivity analysis was conducted, showing that reference optimal values are formed for certain ranges of weights, elaborating the framework of decision-making without having to precisely prescribe them beforehand. All in all, the use of the optimization models can improve and facilitate the building design process by analyzing the advantages and drawbacks of the various materials/technologies and allowing the comparative evaluation of the considered alternatives.

1. Introduction

The growth of the world's population and the rise of economy cause the increase in energy consumption worldwide, making it imperative to take repressive measures and decisions in order for this situation to be normalized. For these reasons, the European Union (EU) focused on the energy sector, as reflected in the official texts and directives (EU, 2018a; EU, 2018b). In particular, the European objectives focus on ensuring the supply of affordable and generally clean energy, with the perspective of reducing the primary energy consumption that is based on fossil fuels. In fact, such objectives concern the 40% limitation in greenhouse emission (from 1990 level), 27% improvement in energy efficiency and 27% share from renewable energy, according to '2030 climate and energy framework'. The energy consumption is evaluated on the basis of three main sectors: industry, transportation and building, with the latter one to contribute 40% of the energy use across EU and to be responsible for 1/3 of Carbon Dioxide (CO_2) emissions (Levine et al., 2007). The sustainability of the construction sector is essential for providing social, economic and environmental benefits, as it is related to the proper management of the energy consumed by the construction products. As a consequence, the ultimate purpose is the achieving of high energy efficiency, which is the result of the combination of different factors, including construction materials, orientation, heating and cooling systems etc. Such goals are reached easily when they are considered in the design phase (Asdrubali and Desideri, 2019). Therefore, it is vital to renew existing buildings in a proper manner so as to consume minimum energy and produce less adverse environmental impacts, all with reasonable renovation budgets and improving the aesthetic and indoor quality of the building facades.

As mentioned above, buildings are responsible for a significant amount of energy consumption resulting in a considerable negative environmental impact. So, the determination of the appropriate values that result from the optimization of the building parameters during the preliminary design stage leads to an optimized building envelope which directly improves the energy efficiency (Saikia et al., 2020) and affects the installed capacity of Heating Ventilation Air Conditioning (HVAC) systems (Kheiri, 2018). In this context, building design has major impact on final energy performance and costs (Sharif and Hammad, 2019), and the total building energy consumption, including any energized system or device, has a remarkable impact on the environment because of the CO_2 emissions to the atmosphere during the production and operation processes. For these reasons, choosing the appropriate solution options for a more efficient building is essential and decisions should be made at the early stage for achieving better performance improvement opportunities. Such options include the choices related to both the building envelope i.e., insulation materials, window frames, shading devices etc., and the energy systems installed to cover the energy demands of a building. The combination of different energy systems raises the issue of optimizing both their design and operation, in the sense of generalized energy hubs (Fabrizio et al., 2009; Kilis et al., 2021). However, despite the significant contribution of research on optimizing energy consumption, there is limited and conflicting research focusing on the renovation of existing buildings to minimize their Life Cycle Cost (LCC) and environmental impact using Life Cycle Assessment (LCA) (Sharif and Hammad, 2019).

Decision-making for the improvement of both building envelope design and the operation of the involved energy systems is a high priority issue, that needs to take into consideration the dynamically developing field of the energy sector. Such decision-making constructs a multiparametric problem because of the complexity of the building and its environment, as well as the existence of several objectives that need to be achieved for the improvement of building efficiency and indoor quality. Such objectives are relative to the economic, energy, environmental, technical, social, aesthetic and thermal comfort fields (Kaklauskas et al., 2005). All above combined with the existence of numerous alternative investments, pose a multiparametric problem, where the final decisions require the development of reliable and relatively fast methods, that in literature are based on MP and Genetic Algorithms (GA), aiming at the development of a generalized Multi-Objective Optimization Problem (MOOP) for the building energy design (Ascione et al., 2015).

In the literature, about 60% of the building optimization studies used the single-objective approach, considering only one objective function, such as the minimization of cost, energy consumption or the maximization of energy efficiency, thermal comfort etc., (Evins, 2013). For instance, Kim and Park studied on the single-objective optimization problem in order to determine the optimum working conditions of the building systems that would reduce the energy consumption by coupling Energy Plus and MATLAB. Moreover, there are many single-objective approaches focusing on LCC and LCA perspectives, dealing with economic and environmental issues of the building sector (Bayer et al., 2010; Weerasinghe et al., 2021). However, in real-world building design problems, designers should deal with conflict design criteria simultaneously (Hamdy, 2011; Fesanghary, 2012), such as minimum energy consumption vs maximum thermal comfort or minimum construction cost, etc. Hence, in many cases, Multi-Objective Optimization (MOO) is more relevant than the single-objective approach. More specifically, new design methods primarily focus on developing both low-emission and energy-efficient building designs (Fesanghary, 2012). In fact, such research works mainly try to minimize energy consumption, and therefore the energy consumption costs, by altering building envelope materials including insulation types, roofing materials, finishing materials, window types, size, and glazing. Also, several studies have considered the effects of building shape, orientation, and size on energy consumption. The general results and conclusions show that considerable improvements can be made in case of the properly set of such parameters in the design stage (Gustavsson and Joelsson, 2010). One of the first attempts to develop a multi-criteria model was made by Gero et al., where optimal solutions were explored to improve the thermal function of a building in relation to both its cost and surface area during its design phase (Gero et al., 1983). Also, in Diakaki et al., the annual primary energy consumption of the building, CO_2 emissions and the initial investment cost were set as optimization criteria for a simple case study, where various multi-criteria optimization methodologies resulted in pluralistic solutions regarding different levels of significance of the criteria (Diakaki et al., 2008 and Diakaki et al., 2010). In Fesanghary et al., a MOO model based on harmony search algorithm was developed to find an optimal building envelope design that minimizes the life cycle costs and emissions (Fesanghary et al., 2012). In this context, Antipova et al. developed a systematic tool for the optimal retrofit of buildings, including insulation materials, windows and solar panels, that considers several economic and environmental criteria simultaneously at the design stage. The environmental criterion was implemented through the LCA methodology (Antipova et al., 2014).

In this paper, a MOO methodology was developed for optimizing the thermal behaviour of a typical residential building envelope of 240 m^2 floor area. The optimization techniques are based on MP principles considering three competitive criteria. These objectives are to minimize the thermal transmittance, taking under consideration the restrictions of the Greek EPBD (TEE, 2017), as well as the minimization of the economic and environmental costs. The decision variables considered for the optimal solution are the appropriate choice of insulation thickness and materials, as well as the selection of window frame materials. The economic criterion is related to the purchase and installation cost of the aforementioned parameters, while the environmental criterion examines the life cycle CO_2 emissions and the energy consumed during the production of the materials, and it is based on the LCA methodology. The proposed optimization methodology leads to optimal building envelope scenarios, resulting to the improvement of the building energy efficiency via the minimization of the heating and cooling energy demands. The rest of the paper is structured in three more sections. Section 2 introduces the proposed approach and the basic parameters of the examined case study, while Section 3 presents the results and findings. Section 4, finally, summarizes the conclusions of the study and highlights future research directions.

2. Materials and Methods

2.1. Basic Parameters

2.1.1. Building Envelope Components. The selection of building envelope materials is a laborious process where several issues, such as cost, implementation, performance, and environmental footprint, should be considered. In this context, several categories (i.e., insulation, glazing, fenestration, window frames, sealants, finishing, and cladding) should be taken into account throughout the renovation of the building envelope. In this study, five envelope components, with a specific structure of material amounts, construct the assumed building. These components refer to the masonry, that includes the outer wall brick construction, the structural frame elements (beams, columns, shear walls), the roof, the open-air floor (pilotis) and the windows.

The examined building is a typical apartment with a total floor area of 240 m^2 (A_{rf}=A_{fl}=240 m^2), consisting of the structural elements mentioned above. It is assumed that the building is located in four different Greek cities, which are representative to the four Climatic Zones, meeting the requirements of thermal insulation coverage. The main features of the building are shown in Table 1.

Table 1. Basic Building Envelope Features.

Building Envelope Dimensions				Building Envelope Components		
Length/Width	Height	Volume	Façade Surface	Window Surface (A_{wn})	Mansory Surface (A_{br})	Structural Element Surface (A_{be})
20/12 (m)	2.8 (m)	672 (m^3)	659.2 (m^2)	38.6 (m^2)	78.9 (m^2)	48.9 (m^2)

2.1.2. Building Thermal Insulation. Thermal comfort is essential for building stakeholders, and it could be achieved through multiple building envelope investments. In this study, the installation of five thermal insulation materials (TIM) and three frame window materials were examined, assuming that the thermal properties of all the other building envelope components are known. The proposed TIM are Glass Wool (GW), Rock Wool (RW), Expanded Polystyrene (EPS), Extruded Polystyrene (XPS) and Polyurethane (PU), which are representative in the building sector. Regarding the window type, a triple glazed with specific dimensions and Argon as insulation gas was considered and three window frame materials (Aluminium, PVC and Timber) were examined. The thermal properties of the proposed TIM and window frames are presented in Tables 2 and 3, respectively.

2.1.3. Building Economic and Environmental Cost. Sustainable buildings usually have higher initial capital investment costs than conventional ones. However, during the life cycle of a building, the extra spending incurred in the original capital cost of sustainable buildings can be recovered within a relatively short period because of several factors, such as the reduction in the energy consumption (Kibert, 2008). As a result, the choice of the appropriate components and materials for a building is essential for the design budget. However, when it comes to improving environmental sustainability, finding a balance is crucial for improving building energy performance (Sharif and Hammad, 2019). LCA is a useful approach to evaluate the environmental impacts of a product or process during its entire life cycle, especially for the building envelope components and materials. In LCA, the environmental impacts of the building, such as CO_2 emissions, are analyzed in all steps of its life cycle. These steps are grouped into pre-use (product) phase, construction and installation phase, use phase, and End-of-Life phase.
For this case study, the economic cost includes the capital purchase and installation costs of the examined window frame materials and of the TIM. Regarding the environmental footprint, CO_2 equivalent emissions, as well as the Non-Renewable Primary Energy (NRPE) consumption were considered, according to the LCA principles. NRPE accounts for the cumulative energy based on fossil fuels, consumed during the construction of a system or material. The boundaries of the LCA methodology include the raw material extraction, the raw material processing, and the production of the final product. In TIM LCA the functional unit (FU) is the amount of the material required to present thermal resistance of 1 m^2K/W from a surface area of 1 m^2 of the TIM, but in Window LCA, the FU is the triple glazed window. The Life Cycle Inventory was based on the Environmental Product Declaration (EPD) and literature data for several European countries, while the environmental impacts were calculated according to CML 2001 and CED methods (Teenou, 2012; Saadatian, 2014). Tables 2 and 3 present the economic and environmental data for the examined materials.

Table 2. Database for Thermal Insulation Materials.

	Density (kg/m^3)	**Thermal conductivity** **λ (W/mK)**	**Mass** **(kg)**	**Env_{ins} (CO_2 eq.)** **(kg/FU)**	**$NRPE_{ins}$** **(MJ/FU)**	**Capital Cost (C_{ins})** **(€/m^3)**
RW	70	0.033	2.31	3.02	18	287
GW	22	0.033	0.726	1.49	25.8	149
EPS	25	0.034	0.85	2	67	223.5
XPS	32	0.035	1.12	4.95	112	464
PU	40	0.023	0.92	3.6	80	765

Table 3. Database for Window Frame Materials.

	U_f (W/m^{2}K)	U_g (W/m^{2}K)	U_{wn} (W/m^{2}K)	Env_{wn} (CO_2 eq.) (kg/FU)	$NRPE_{wn}$ (MJ/FU)	Capital Cost (C_{wn}) (€/m^2)
Timber	2.5	0.65	1.35	108	1769.2	393.4
Aluminium	4.5	0.65	1.85	502	9322.1	525.6
PVC	2	0.65	1.225	205	4443.5	205.4

2.2. Formulation of Building Optimization Model

The development of a decision-making methodology for optimizing single or multiple criteria for problems related to improving the performance of buildings requires the forming of mathematical models. The formulation of such models could be based on the principles of MP and includes the following basic aspects:

1. Determination of decision variables.
2. Definition of constraints.
3. Definition of objective functions, i.e., the criteria of optimization.
4. Determination of mathematical techniques solving the problem.

In this study, the mathematical model is related to the optimization of the building envelope during the design phase, determining the optimum decisions that concern the choice of the appropriate window frame materials, the selection of the thermal insulation materials, as well as the thickness of the insulation. The insulation material and their thickness could differ towards the building envelope components. These parameters constitute the decision variables to the optimization problem. Moreover, the optimum decisions were made considering three criteria; economic, environmental and thermal insulation, which construct the objective functions (Figure 1). Feasible mathematical constraints, as well as limitations relative to thermal insulation covering were included. The formulation and resolution of the proposed optimization problem developed through coding in GAMS environment, which is specialized in the formulation, analysis and solution of optimization problems, according to the principles of MP. The problem is characterized as a Mixed Integer Nonlinear Programming (MINLP) problem, due to the nonlinear relationships developed between the decision variables in the objective functions. For this reason, the BARON solver (Kilinc and Sahinidis, 2018) under GAMS is used, which finds guaranteed global optimal solutions to general nonlinear problems with continuous and/or discrete variables and supports most mathematical functions, including functions that are non-smooth.

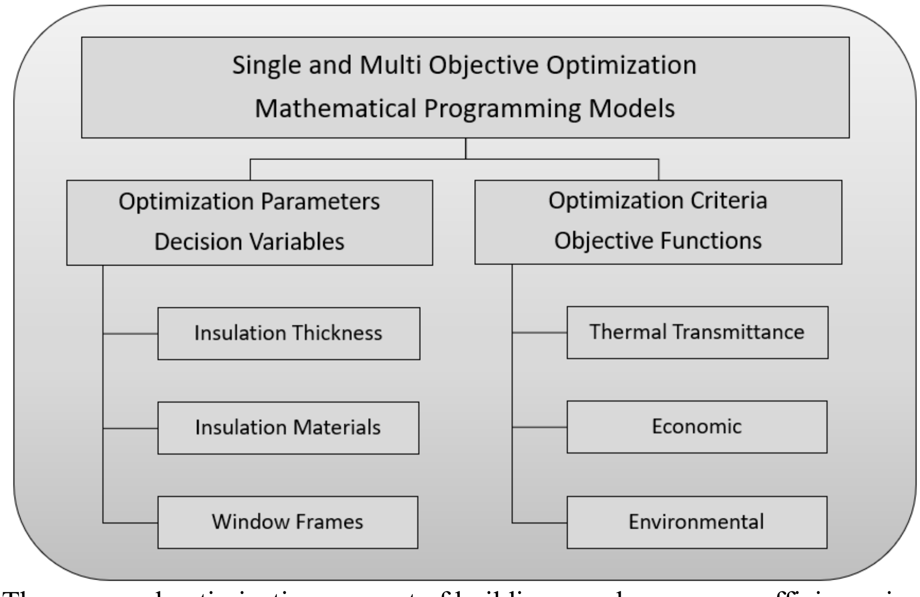

Figure 1. The proposed optimization concept of building envelope energy efficiency improvement.

2.2.1. Design Variables. For the decision of choosing the appropriate window frame material, a binary variable ($x_{wn,i}$) was introduced. The choice is made between the three materials (Aluminum, PVC, Timber), according to the data presented in Table 3 and depending on the optimization criterion.

$$x_{wn,i} = \begin{cases} 1, \text{when the i window frame material is chosen} \\ 0, \text{when anotherwindow frame material is chosen} \end{cases}$$

where, $i = 1,2, \ldots, I$: The different window frame materials (I=3, thus Aluminum, PVC, Timber).

The decision related to the choice of the appropriate insulation material is separated into four binary variables ($x_{ins,k,j}$), due to the four building envelope components examined (Mansory, Structural frame elements, Roof, Floor). The choice is made between the five insulation materials (RW, GW, EPS, XPS, PU), according to the data presented in Table 2 and depending on the optimization criterion.

$$x_{ins,k,j} = \begin{cases} 1, \text{when the j insulation material is chosen for component k} \\ 0, \text{when another insulation material is chosen for component k} \end{cases}$$

where,

- $j = 1,2, \ldots, J$: The different insulation materials (I=5, thus RW, GW, EPS, XPS, PU).
- $k = 1,2, \ldots, K$: The different building envelope components (K=4, thus Mansory, Structural frame elements, Roof, Floor).

Also, regarding the selection of the insulation material thickness, it is considered that there are specific thicknesses available on the market per 1cm. Therefore, four integer decision variables were introduced, with respect to the four building envelope components examined (x_{br}, x_{be}, x_{rf}, x_{fl}). These variables define the number of such ds=1cm layers of insulation material to be installed.

2.2.2. Constraints. Constraints for selecting one window frame material and one insulating material for each building envelope component.

$$\sum_{i=1}^{I} x_{ins,i} = 1 \quad (1) \qquad \sum_{j=1}^{J} x_{ins,k,j} = 1, \text{for each k.} \quad (2)$$

Constraints for thermal insulation adequacy, which were defined by the Greek EPBD for each Climatic Zone. Such constraints limit the upper bound for the U-values of each building envelope component, as well as the average thermal transmittance coefficient (U_m).

$$U \leq U_{max} \quad (3) \qquad U_m \leq U_{m,max} \quad (4)$$

Constraints for selecting the appropriate insulation thickness, which were defined by the thermal principles of the Passive House ($U \leq 0.15$ W/m^{2}K). Such U-values correspond to a maximum insulation thickness (d_{max}).

$$(x_{br}, x_{be}, x_{rf}, x_{fl}) \cdot d_s \leq d_{max}, \text{where } d_s = 1\text{cm} \quad (5)$$

2.2.3. Objective Functions of Single Criteria Optimization.

Thermal Insulation Optimization

The minimization of the Building Load Coefficient (BLC) brings the same results as that of U_m, aiming to increase the thermal resistance and to achieve the thermal insulation adequacy of the building envelope. Equation 6 shows the general form of BLC, while Equation 7 presents the objective function for optimizing BLC in the proposed case study.

$$BLC = \sum_{z=1}^{Z} (A_z \cdot U_z \cdot b_z) \quad (6)$$

where,

- A_z: the surface area of each building envelope component.
- U_z: the thermal transmittance coefficient of each building envelope component.
- b_z: reducing rate (=1, for surfaces in contact with ambient air).
- z: the number of building envelope components.

$$\text{Min BLC} = A_{wn} \cdot b_{wn} \cdot \sum_{i=1}^{I} (U_{wn,i} \cdot x_{wn,i}) + A_{br} \cdot b_{br} \cdot \frac{1}{R_{in} + \sum_{nbr} \left(\frac{d_{nbr}}{\lambda_{nbr}}\right) + \frac{x_{br} \cdot d_s}{\sum_{j=1}^{J} (\lambda_{ins,j} \cdot x_{ins,br,j})} + R_{out}} +$$

$$A_{be} \cdot b_{be} \cdot \frac{1}{R_{in} + \sum_{nbe}\left(\frac{d_{nbe}}{\lambda_{nbe}}\right) + \frac{x_{be} \cdot d_s}{\sum_{j=1}^{J}\left(\lambda_{ins,j} \cdot x_{ins,be,j}\right)} + R_{out}} +$$
$$A_{fl} \cdot b_{fl} \cdot \frac{1}{R_{in} + \sum_{nfl}\left(\frac{d_{nfl}}{\lambda_{nfl}}\right) + \frac{x_{fl} \cdot d_s}{\sum_{j=1}^{J}\left(\lambda_{ins,j} \cdot x_{ins,fl,j}\right)} + R_{out}} +$$
$$A_{rf} \cdot b_{rf} \cdot \frac{1}{R_{in} + \sum_{nrf}\left(\frac{d_{nrf}}{\lambda_{nrf}}\right) + \frac{x_{rf} \cdot d_s}{\sum_{j=1}^{J}\left(\lambda_{ins,j} \cdot x_{ins,rf,j}\right)} + R_{out}} \quad (7)$$

where,

- R_{in} (m^2 K/W): thermal resistance due to indoor air convection (=0.13 m^2 K/W).
- R_{out} (m^2 K/W): thermal resistance due to outdoor air convection (=0.04 m^2 K/W).

Economic and Environmental Optimization

Cost optimization is associated with minimizing the cost of purchasing both insulation materials and window frames. Therefore, the binary decision variables choose the appropriate value of the cost, while the integer ones choose the thickness of the insulating material. In the same logic, the environmental optimization model was developed. This optimization is conducted by minimizing not only the emitted pollutants, CO_2 emissions (Env), but also the energy consumed (NRPE) for the construction of insulation materials and window frames. Equation 8 describes the general formula of the economic and environmental objective functions, where Y illustrates the cost (C_{ins}, C_{wn}) and environmental (Env_{ins}, Env_{wn}, $NRPE_{ins}$, $NRPE_{wn}$) data.

$$\text{Min Cost or Env or NRPE} = A_{wn} \cdot \sum_{i=1}^{I}\left(Y_{wn,i} \cdot x_{wn,i}\right) + A_{br} \cdot x_{br} \cdot d_s \cdot \sum_{j=1}^{J}\left(Y_{ins,j} \cdot x_{ins,br,j}\right) +$$
$$A_{be} \cdot x_{be} \cdot d_s \cdot \sum_{j=1}^{J}\left(Y_{ins,j} \cdot x_{ins,be,j}\right) + A_{fl} \cdot x_{fl} \cdot d_s \cdot \sum_{j=1}^{J}\left(Y_{ins,j} \cdot x_{ins,fl,j}\right) + A_{rf} \cdot x_{rf} \cdot d_s \cdot \sum_{j=1}^{J}\left(Y_{ins,j} \cdot x_{ins,rf,j}\right) \quad (8)$$

2.2.4. Objective Functions of Multi Criteria Optimization. Multi-criteria decision analysis (MCDA) methods have become increasingly popular in decision-making for sustainable energy because of the multi-dimensionality of the sustainability goal and the complexity of the examined systems. In this study, two MOO methods were employed (Global Criterion and Goal Programming), combining the economic, environmental and thermal insulation criteria. All factors have their internal impact normalized to a common scale, so that it is necessary to determine each criteria's relative impact in the sustainable energy decision-making problem. In this context, the objective functions were normalized, and weights were introduced to indicate their relative importance. A sensitivity analysis with different combinations of weights was conducted, in order to present a wide range of results that influence the final decision-making.

Global Criterion (GC)

In this method, the criteria of the baseline optimization problem are integrated into one single objective function, so that the optimal solution leads to decision choices as close as possible to those that would have been achieved in single criteria optimization. Equation 9 shows the objective function.

$$\min f_{GC} = w_1 \cdot \frac{BLC - BLC_{opt}}{BLC_{opt}} + w_2 \cdot \frac{Cost - Cost_{opt}}{Cost_{opt}} + w_3 \cdot \frac{Env - Env_{opt}}{Env_{opt}} \quad (9)$$

where,

- BLC, Cost, Env: The objective functions of single criteria optimization.
- BLC_{opt}, $Cost_{opt}$, Env_{opt}: The optimum values from single criteria optimization.
- w_1, w_2, w_3: Weights of each criterion ($w_1 + w_2 + w_3 = 1$).

Goal Programming (GP)

This method seeks the optimal solution, in order to achieve specific goals for each criterion; these refer to the upper limits of the optimization problem. The objective function (Equation 10) aims to minimize the deviations of the goals set from single criteria optimization.

$$\min f_{GP} = w_1 \cdot \frac{n_1^- + p_1^+}{\mathrm{BLC_{opt}}} + w_2 \cdot \frac{n_2^- + p_2^+}{\mathrm{Cost_{opt}}} + w_3 \cdot \frac{n_3^- + p_3^+}{\mathrm{Env_{opt}}} \quad (10)$$

Subject to:

$$\mathrm{BLC} + \mathrm{n_1^-} - \mathrm{p_1^+} = \mathrm{BLC_{opt}} \quad (11)$$

$$\mathrm{Cost} + \mathrm{n_2^-} - \mathrm{p_2^+} = \mathrm{Cost_{opt}} \quad (12)$$

$$\mathrm{Env} + \mathrm{n_3^-} - \mathrm{p_3^+} = \mathrm{Env_{opt}} \quad (13)$$

$$\mathrm{n_1^-}, \mathrm{p_1^+}, \mathrm{n_2^-}, \mathrm{p_2^+}, \mathrm{n_3^-}, \mathrm{p_3^+} \geq 0 \quad (14)$$

where

- $\mathrm{n_1^-}, \mathrm{n_2^-}, \mathrm{n_3^-}$: Negative deviation variable from BLC, Cost and Env goals respectively.
- $\mathrm{p_1^+}, \mathrm{p_2^+}, \mathrm{p_3^+}$: Positive deviation variable BLC, Cost and Env goals respectively.

3. Results

3.1. Results of Single Criteria Optimization

3.1.1. Thermal Insulation Optimization. In the case of minimizing BLC to increase the thermal resistance of the building envelope, Polyurethane is chosen as the appropriate insulating material, due to its low thermal conductivity. The thickness of the insulation selected is the maximum one for all structural elements, directing the solution to the specifications of the Passive House. Also, the PVC window frame material is considered the optimal decision, because of its low U-value. It is important to mention that in this case, the thermal insulation coverage is clearly oversupplied, meeting all the limitations set by the technical instruction of the Greek EPBD for each Climatic Zone.

3.1.2. Economic Optimization. In this case, the cheapest type of window frame material is chosen, namely PVC, which happens to have the lowest U-value too. Also, regarding the insulation material, cost minimization requires the choice of Glass Wool, which has higher thermal conductivity compared to Polyurethane, alternating the solution of the Passive House (BLC Criterion). The choice of thermal insulation thickness is the minimum one that covers the restrictions of U-values for each Climate Zone. The optimization results show that the thickness of the insulation increases from warmer regions (Climatic Zone A) to colder ones (Climatic Zone D), as the U-value restrictions become stricter.

3.1.3. Environmental Optimization. Environmental optimization includes the minimization of CO_2 emissions and energy consumption during the manufacturing of the examined materials. For both of them, the Timber window frame material is chosen, as it includes the minimum environmental footprint. Also, regarding the thickness of the insulation installed, the results are the same as the economic optimization, because of the EPBD restrictions. However, in the case of CO_2 minimization, the Glass Wool is selected as the insulation material, while Rock Wool is chosen in NRPE minimization. Here it is important to mention that GW and RW have the same thermal conductivity, which leads to the same U-values and BLC, but the economic and environmental costs are different.

Table 4 presents the optimum results for the three single criteria for all climatic zones, while Figure 2 shows the optimum BLC, Cost and Environmental values for Climatic Zone A. The results prove that the three criteria are contradictory to each other. More specifically, the improvement of thermal insulation properties (BLC Criterion) causes an obvious increase in economic and environmental costs, while when the criterion is the minimization of the environmental footprint, costs increase, and the thermal insulation gets worsen. As a result, such conflicting results between the criteria highlight the problem of multi-criteria optimization, seeking balanced solutions.

Table 4. Optimum Thickness (cm) and Materials from Single Criteria Optimization.

Criteria	BLC	Economic	Environmental (CO_2)	Environmental (NRPE)
Insulation Material	PU	GW	GW	RW
Frame Material	PVC	PVC	Timber	Timber
Cl Zone A	$15^{br}/14^{be}/15^{rf}/15^{fl}$	5/4/5/6	5/4/5/6	5/4/5/6
Cl Zone B	15/14/15/15	6/5/6/7	6/5/6/7	6/5/6/7
Cl Zone C	15/14/15/15	7/6/7/8	7/6/7/8	7/6/7/8
Cl Zone D	15/14/15/15	7/7//8/9	7/7//8/9	7/7//8/9

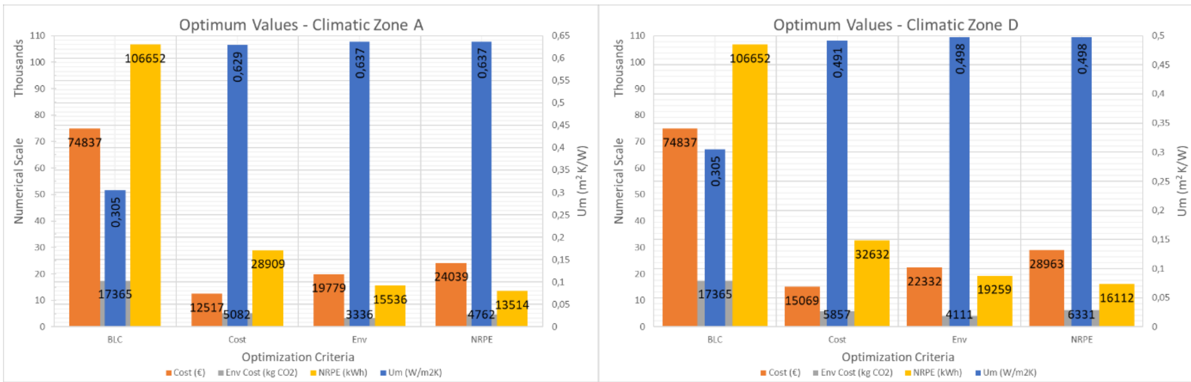

Figure 2. Optimal BLC, Cost, Env and NRPE values of each optimization criteria for Climate Zone A.

3.2. Results of Multi Criteria Optimization

In this section, the results of Global Criterion and Goal Programming methods were presented, considering the constraints of Climatic Zone A. Figure 3 shows the evolution of the optimum U_m-values for different weighting combinations of the three optimization criteria. The increase in both the economic and environmental criteria causes a sharp increase in U_m, which explains the contradiction between these criteria. In the case of GC model, maximum U_m-values have already been approached by small percentages of the environmental and economic weights. This is due to the extreme values obtained by the objective function, since it simultaneously considers the influence of all three criteria, leading to separated solutions. While, the U_m-values distribution is smoother in WGP, as the objective is to minimize the deviations from the goals.

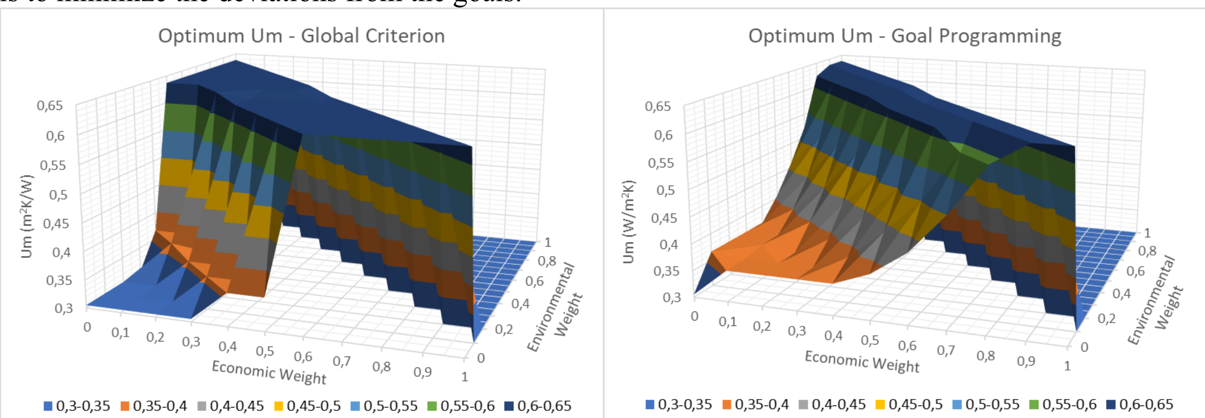

Figure 3. Optimum distribution of U_m-values with Global Criterion and Goal Programming methods.

To further investigate these phenomena, it was deemed necessary to implement the optimization model for two criteria, with a shorter weighting step of 1%. BLC and Cost criteria were selected because of their extreme contradictory. Figure 4 presents the distribution of the optimum U_m-values and costs through different combinations of weights. It is obvious that the increase in economic criterion causes a reduction in total costs and an increase in U_m-values. However, in the GP method, these changes are smoother than in GC. In particular, at 32% economic weight, the TIM changes from PU to GW in GC optimization, while in GP such a change occurs earlier at 6%. The next transitions are at 51% for GC and 45% for GP, and they are due to the change of TIM thickness. However, this change is sharp for the GC method, while in GP there is a gradual transition with multiple thickness combinations. As a result, the GP method is more flexible.

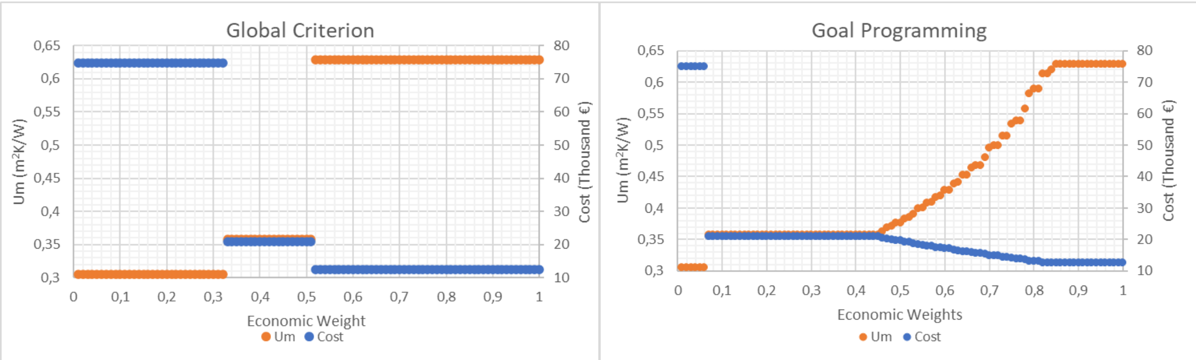

Figure 4. Optimum distribution of Costs and U_m-values in BLC-Cost optimization with Global Criterion and Goal Programming methods.

4. Conclusion

In this paper a decision-making tool was presented for the improvement of the building envelope, during the design or retrofitting phase. The proposed approach is based on the formulation of MINLP models for the single and multi-criteria optimization, under the principles of MP. The decisions for improving the building envelope design, and as a consequence space heating and cooling, include the selection of window frame material, as well as the thickness and materials for thermal insulation. Such choices were made considering three basic criteria; economic, environmental (based on LCA) and thermal insulation.

In single criteria optimization, it is proven that the three objectives are conflicting with each other. In particular, when building thermal resistance is maximized, an increase of about 322% up to 421% in CO_2 emissions (562% up to 689% in NRPE) and 397% up to 498% in costs is presented, in comparison to the optimum results of environmental and economic optimization, respectively. Also, the use of environmentally friendlier materials leads to higher economic costs. As a result, the development of multi objective optimization models seems to be crucial, in order to balance the conflicting criteria. The results of Global Criterion method follow a defined pattern, which separates the optimum decisions. In this case, the goal of minimum cost has already been approached at 40% BLC weights (in 3 criteria optimization), which is due to the fact that the results do not include different combinations of thermal insulation thickness. However, Goal Programming is more flexible, forming more choices for the decision-making. These findings, as well as the proposed methodology, may be helpful in the design of more effective regulations for improving the environmental and economic performance of buildings. Last but not least, an extension of such techniques during the operation stage of the building, through energy system optimization, would provide a more comprehensive tool for building energy design.

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