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## Energy – Comfort – Environment: What matters most? A multi-criteria assessment of a residential apartment

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# Energy – Comfort – Environment: What matters most? A multi-criteria assessment of a residential apartment

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**Abstract.** In this study, a multi-criteria assessment approach is performed for a residential apartment located in Athens, for a combination of different energy systems, building envelope and shading systems. 24 alternative cases in total are fully simulated via EnergyPlus software aiming to the calculation Key Performance Indicators (KPIs) in terms of energy consumption for heating and cooling, thermal comfort, visual comfort and environmental impact. The results of KPIs are fed to a decision-making process that takes into consideration the preferences of stakeholders. The optimum solution is selected by the use of the Analytic Hierarchy Process (AHP). In the most optimum scenario, the potential of primary energy savings and CO<sub>2</sub> emissions are approximately 35% while the discomfort hours for thermal and visual comfort are respectively 17% and 67% less than the cases with the worst comfort conditions. The results suggest that such a multi-criteria assessment approach can be useful at an early stage of building design or renovation in order to better inform decisions and avoid sub optimizations.

**Keywords:** Residential building apartment, primary energy consumption, thermal comfort, visual comfort, carbon emissions, EnergyPlus software, analytic- hierarchy process, multi-criteria decision making.

## 1. Introduction

The residential sector, accounting for more than 25% of European Greenhouse gas emissions (GHG), needs novel technologies and systems to improve its environmental performance. Such systems include high-performance building envelopes and efficient, low emission, energy systems. In this way, the existent building sector needs to be improved, through renovation solutions, achieving energy saving goals, set by NZEBs policies, environmentally friendly approaches and economic affordability. Aside from environmental performance, indoor thermal comfort has to be at a high level. There are thus different aspects that need to be taken into account in order to characterize a construction project for its overall effectiveness and functionality. To address this strenuous task, a multi-criteria decision making process is necessary. The first step of this process is to measure the performance of the construction project across different aspects by use of appropriate Key Performance indicators (KPIs). As a second step, the assessment results are evaluated via multi-criteria analysis in order to conclude an optimal solution based on selected criteria.



Gero et al. were among the first to introduce a multi-criteria assessment in building design for enabling trade-offs between the building energy performance, capital cost and usable area. [1]. Similar approaches have been adopted since then, focusing on the assessment of energy, environmental impact and cost. Ciulla et al considered basic retrofit measures related to envelope insulation and glazing upgrade, investigating the primary energy saving and the cost impact for residential historical buildings in Italy [2]. Moreover, Tadeu et al examined several retrofit packages including envelope insulation, glazing and heating system upgrading, by using a cost-optimal method considering energy environmental and economic impacts [3]. Taking into consideration stakeholders' preferences, Xiangjie et. al have proposed a multi-criteria assessment approach, for a wide range of energy efficient measures and their combinations, applied for a residential building retrofit. A number of combination packages was simulated in a building simulation program, followed by comprehensive assessments of key retrofit priorities such as primary energy reduction, global costs, carbon emission reduction, and social assessments as to represent various stakeholders' views on the selected combinations cases [4].

In this study, 24 alternative scenarios of a residential apartment for a combination of different energy systems, building envelope and shading systems are investigated through the energy consumption, thermal and visual comfort and the environmental impact. The alternatives are fully simulated by means of EnergyPlus and the relative Key Performance Indicators (KPIs) are calculated. The optimum scenario is determined by means of AHP method taking into account the stakeholders preferences obtained by a questionnaire.

## 2. Methodology

### 2.1. Description of the building

The current study examines an apartment of a multi-family building located in Athens. The building is south-east oriented and composed of four stories (**Figure 1a**). Each storey has four apartments that are adjacent to an unconditioned space (floor corridors and staircases). Its load bearing structure (skeleton) is made of concrete; the external walls are constructed with double layered brick masonry, insulated with XPS, while the concrete horizontal structural components are insulated with EPS, leading to a U-value of  $0.40\text{W/m}^2\text{K}$ . Concerning the transparent elements, several types of windows are examined. The aluminium Frame to Window Ratio equals to 15% while the total Window to Wall Ratio (WWR) is approximately 33%. The main (initial) characteristics of the building's envelope are presented in **Table 1**.

**Table 1.** Thermal Transmittance of the building envelope surfaces

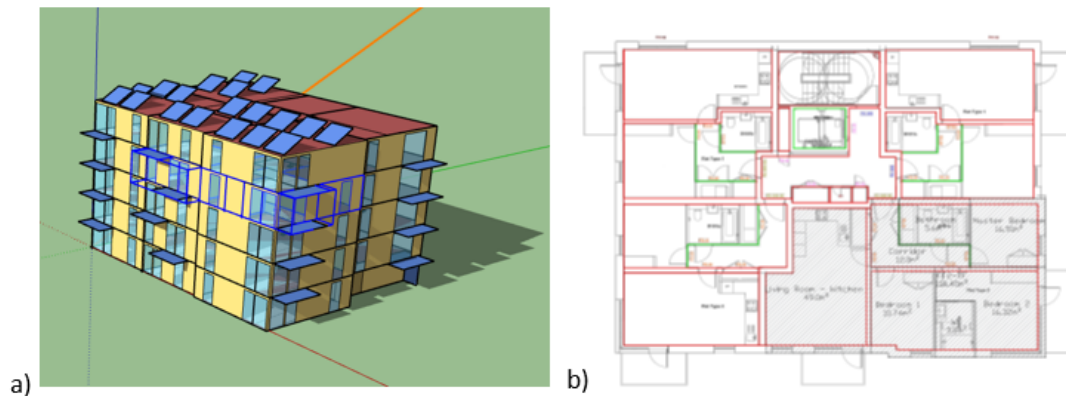
Surface	U-value ( $\text{Wm}^{-2}\text{K}^{-1}$ )
Floor	0.40
Roof	0.40
Ceilings	0.40
Internal walls	2.4

Energy simulation is performed independently for the south-east oriented third storey apartment, but also the whole building is simulated. The examined apartment, with conditioned area of  $114.40\text{m}^2$ , is analytically simulated, divided into seven thermal zones, considering each room as a separate zone. An independent energy system for heating, cooling and DHW is installed to this apartment (**Figure 1b**). The rest of the building is simulated as one thermal zone per apartment with ideal energy systems. For all conditioned spaces, indoor temperature is set to  $20^\circ\text{C}$  for heating and  $26^\circ\text{C}$  for cooling mode. Further assumptions of the building model, such as the internal loads from lighting, electric equipment and people's presence, infiltration and natural ventilation, are based on Greek National Energy legislation (KENAK), summarized in **Table 2** [5].

**Table 2.** The building's internal thermal loads

Thermal load	Assumption	Value
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People	5 people/100m <sup>2</sup>	4W/m <sup>2</sup>
Artificial lighting	6.4 W/m <sup>2</sup>	200lux
Electric equipment	4 W/m <sup>2</sup>	Normalized factor 0.5
Ventilation	0.75m <sup>3</sup> /h/m <sup>2</sup>	
Infiltration	5.5m <sup>3</sup> /h/m <sup>2</sup>	



**Figure 1.** The examined building and apartment: a) view in Sketch-Up model and b) the plan of the third storey.

## 2.2. Alternative cases

24 different alternative cases in total are examined, with different combinations of heating and cooling systems, insulation thickness, window types, and shading systems. The combinations of all the different scenarios are summarized in **Table 3**. All cases are simulated by means of EnergyPlus software.

**Table 3.** The examined alternative cases.

Case	Energy System	Fuel type	$U_{wall}$	Window Type	Shading Type
BAC01	Boiler + AC unit	Natural Gas-Electricity	0.45	Double low-e	Exterior Shading
BAC02	Boiler + AC unit	Natural Gas-Electricity	0.45	Triple low-e	Exterior Shading
BAC03	Boiler + AC unit	Natural Gas-Electricity	0.45	Double EC low-e	No Shading
BAC04	Boiler + AC unit	Natural Gas-Electricity	0.45	Triple EC low-e	No Shading
BAC05	Boiler + AC unit	Natural Gas-Electricity	0.30	Double low-e	Exterior Shading
BAC06	Boiler + AC unit	Natural Gas-Electricity	0.30	Triple low-e	Exterior Shading
BAC07	Boiler + AC unit	Natural Gas-Electricity	0.30	Double EC low-e	No Shading
BAC08	Boiler + AC unit	Natural Gas-Electricity	0.30	Triple EC low-e	No Shading
BAC09	Boiler + AC unit	Natural Gas-Electricity	0.15	Double low-e	Exterior Shading
BAC10	Boiler + AC unit	Natural Gas-Electricity	0.15	Triple low-e	Exterior Shading
BAC11	Boiler + AC unit	Natural Gas-Electricity	0.15	Double EC low-e	No Shading
BAC12	Boiler + AC unit	Natural Gas-Electricity	0.15	Triple EC low-e	No Shading
HP01	Heat Pump +fan coil	Electricity	0.45	Double low-e	Exterior Shading
HP02	Heat Pump +fan coil	Electricity	0.45	Triple low-e	Exterior Shading
HP03	Heat Pump +fan coil	Electricity	0.45	Double EC low-e	No Shading
HP04	Heat Pump +fan coil	Electricity	0.45	Triple EC low-e	No Shading
HP05	Heat Pump +fan coil	Electricity	0.30	Double low-e	Exterior Shading
HP06	Heat Pump +fan coil	Electricity	0.30	Triple low-e	Exterior Shading
HP07	Heat Pump +fan coil	Electricity	0.30	Double EC low-e	No Shading
HP08	Heat Pump +fan coil	Electricity	0.30	Triple EC low-e	No Shading
HP09	Heat Pump +fan coil	Electricity	0.15	Double low-e	Exterior Shading
HP10	Heat Pump +fan coil	Electricity	0.15	Triple low-e	Exterior Shading
HP11	Heat Pump +fan coil	Electricity	0.15	Double EC low-e	No Shading
HP12	Heat Pump +fan coil	Electricity	0.15	Triple EC low-e	No Shading

*2.2.1. Energy systems.* Two different energy systems for heating and cooling are investigated as alternative scenarios for the examined apartment. The first energy system, based on a Boiler and Air Condition system (BAC) consists of a condensing natural gas boiler with 95% thermal efficiency, along with baseboards as terminal units for heating. As it concerns the cooling system, Air Conditioning spilt units are installed in all the examined thermal zones, except from the Bathroom and WC. The coefficient of performance (COP) for the cooling efficiency of the A/C system is set to 4.5.

The second system, based on a Heat Pump (HP) is a low temperature heat pump with fan coils as terminal units for both heating and cooling. The Energy Efficiency Ratio (EER) for heating and the COP for cooling efficiency are considered equal to 5.0 and 4.5, respectively. The cooling system is operated in all examined thermal zones, except the bathroom and WC.

For the Domestic Hot Water (DHW), all the alternative scenarios utilize solar thermal system with 4 m<sup>2</sup> of solar panels and a storing tank linked with an auxiliary natural gas boiler with total efficiency equal to 95%, including the distribution losses. Both systems are designed in Openstudio software tool and linked with EnergyPlus models.

*2.2.2. Envelope.* The insulation thickness at the external walls and the window systems are also examined at the alternative cases. The maximum acceptable wall U-value for Athens is 0.45 W/(m<sup>2</sup>K), according to Hellenic regulations [5] that is achieved using 11 cm insulation thickness, with thermal conductivity equal to 0.035 W/(mK), at a typical brick wall. Besides, the maximum acceptable U-value for windows is 2.60 W/(m<sup>2</sup>K), corresponding to a double pane low-e window system [5]. In the current study, three different alternatives regarding the insulation thickness, i.e. the wall U-value, are investigated: 5cm, 10cm and 20cm XPS insulation corresponding to U-values of 0.45, 0.30 and 0.15 W/(m<sup>2</sup>K), respectively. As it concerns the window systems, four different alternatives are examined: a) conventional double pane windows with low-e coatings linked with external shading devices, b) double electrochromic window (EC), c) conventional triple pane low-e windows with external shading and d) triple electrochromic window. The conventional solutions are combined with external shading, that closes when the incident radiation exceeds 60 W/m<sup>2</sup>. The EC glazing systems are combined with a switching strategy that dynamically adjust their transmittance to meet the desirable daylight illuminance level of 200 lux for the residential zones [5].

### 2.3. Key Performance Indicators (KPIs)

*2.3.1. Energy Performance.* One of the most crucial KPIs regarding the energy assessment of buildings' scenarios is the primary energy consumption per floor area, meaning the energy that has not been subjected to any conversion or transformation process [6]. For residential cases, as the examined study, this indicator is a major metric within the Energy Performance of Buildings Directive (EPBD – Directive 2010/31/EU) and concerns the total energy that consumed annually for heating, cooling, and domestic hot water (DHW). The primary energy is normalized per unit floor area [kWh/(m<sup>2</sup>yr)] and defined by the following equation:

$$PE = \frac{\sum_i E_{d,i} \cdot PEF_i}{A} \quad (1)$$

where, PE is the primary energy consumption, A the apartment area, E<sub>d</sub> is the delivered energy required to meet the energy demands of considered end-uses of the building for heating, cooling and DHW from each fuel source i and PEF<sub>i</sub> is the primary energy factor that converts the energy use of fuel i to primary. For the energy performance calculation, the default primary energy factor for natural gas is 1.05 while the primary energy factor for electricity in Greece is 2.50 [7].

*2.3.2. Thermal comfort.* Indoor environment (temperature, humidity, air velocity) affects not only the energy consumption of buildings, but also the health, productivity and comfort of the occupants. ISO 7730 defines the thermal comfort as the condition of mind which expresses satisfaction with the thermal

environment [8]. According to ASHRAE standard 55, the comfort zone is defined by the combination of major variables of indoor thermal environmental factors and personal factors, that produce acceptable conditions for the majority of the occupants within a space. These factors are: a) Metabolic rate -  $M$  [ $W/m^2$ ], b) the effective mechanical power -  $W$  [ $W/m^2$ ], c) clothing insulation -  $I_{cl}$  [ $(m^2.K)/W$ ],  $t_{cl}$  [ $^{\circ}C$ ] and  $f_{cl}$  [-], d) air temperature -  $t_a$  [ $^{\circ}C$ ], e) mean radiant temperature -  $t_r$  [ $^{\circ}C$ ], f) relative air velocity -  $v_a$  [ $m/s$ ] and g) relative humidity -  $RH$  [%].

The thermal comfort model uses heat balance principles of the above key factors defining the Predicted Mean Vote (PMV) according to the following equation [9]:

$$\begin{aligned} PMV = & [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] \\ & - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ & - 3.96 \cdot 10^{-8} \cdot f_{cl} [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \end{aligned} \quad (2)$$

The EnergyPlus model of each case provides the air temperature  $t_a$ , the mean radiant temperature  $t_r$  and the relative humidity  $RH$ . The metabolic rate and the effective mechanical power are assumed for seated occupants equal to  $58 W/m^2$  and  $0$ , respectively, according to ISO 7730, while the clothing insulation ( $clo$ ) is based on the ASHRAE clothing model. The air velocity is determined taking into account the maximum acceptable air velocity ( $0.15 m/sec$ ) and the operation of fans for HVAC systems [10].

In this direction, a Thermal Discomfort index is introduced the evaluation of the thermal comfort, described by the following equation:

$$TD = \frac{\sum_i \tau_i A_i}{A_t} \quad (3)$$

where  $\tau_i$  is the number of hours when PMV is out of this range  $[-0.5, 0.5]$  in an area  $A_i$ , meaning that the comfort conditions are in category B, according to ISO 7730

**2.3.3. Visual comfort.** Visual comfort is evaluated by means of the Daylight Glare Index (DGI), which indicates whether a glare situation is acceptable or intolerable. The maximum acceptable value of DGI is 22 corresponding to an "acceptable" glare [11]. In the current study, the evaluation of different cases in terms of visual comfort is performed via the Visual Discomfort (VD) index, which is calculated using the following equation:

$$VD = \frac{\sum_i v_i A_i}{A_t} \quad (4)$$

where  $v_i$  is the number of hours that the DGI exceeds the value of 22 in an area  $A_i$ .

**2.3.4. Environmental impact.** Greenhouse Gas emissions (GHG), particulate matter  $NO_x$  and  $SO_2$ , are the emissions caused due the operation of energy systems for heating cooling and DHW. For the comparability of different systems, emissions can be related by the size of the system (e.g. gross floor area), and the considered interval of time (e.g. year). Greenhouse gases are considered as unit of mass (e.g. kg) of  $CO_2$  or  $CO_2$  equivalents.

The KPI of the environmental impact is the Greenhouse Gas emissions, translated into  $CO_2$  equivalent emissions over a period of time (annual) by using the following equation with the use of conversion emission factors

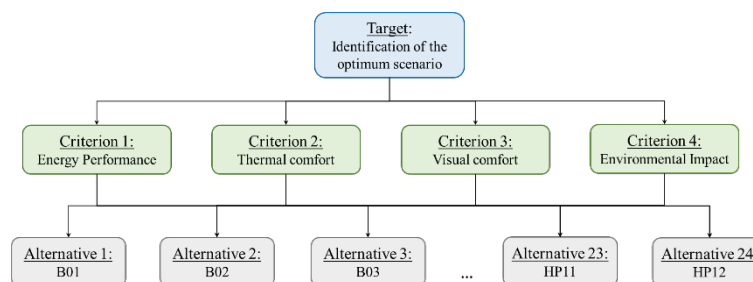
$$\text{GHG} = \frac{\text{TE}_c \cdot \text{GEF}_T}{A} \quad (5)$$

where  $\text{TE}_c$  is the thermal consumption [kWh/year], meaning the sum of heating and cooling consumption of the energy systems and  $\text{GEF}_T$  is the greenhouse gas emission factor for the weighted average based on thermal energy production source/fuel mix [ $\text{kgCO}_{2\text{eq}}/\text{kWh}$ ] [13]. The electricity  $\text{GEF}_T$  is calculated using the data provided by the latest energy balance of the Greek grid by the Independent Power Transmission Operator (IPTO or ADMIE). Accounting for both Greek generation and imports for May 2020, the corresponding contributions were as follows: Lignite 6%, wind and solar production 32% (18.6% assumed for wind and 13.4% for solar generation), Natural Gas 35%, Hydroelectric power 7%, imports from Italy 8%, imports from North Macedonia 6%, imports from Bulgaria 1.6% and from Albania and Turkey 4.2%. The carbon load for the electricity production (plus imports) mix is considered  $0.462\text{kg}_{\text{eq}}/\text{kWh}_{\text{el}}$  via SimaPro v8.1 software. The natural gas GEF is calculated equal to  $0.237\text{kg}_{\text{eq}}/\text{kWh}$ , based on data from Intergovernmental Panel on Climate Change (IPCC) report (AR5) and U.S. environmental Protection Agency (EPA). [12].

#### 2.4. Analytic Hierarchy Process

In this study, the multi-criteria decision making (MCDM) support is carried out by means of the Analytic Hierarchy Process (AHP), a protocol developed by the mathematician Thomas L. Saaty in 1970s. This method identifies the optimum case evaluating the most preferable alternatives, including also the uncertainty information, taking into account the crucial KPIs for the examined impacts meaning the primary energy consumption, the TD, VD and GHG indexes. AHP method was selected through other MCDM support tools, because of its flexibility, as it provides the criteria ranking, depending on their importance. Moreover, AHP method can be able to translate the evaluations of stakeholders' opinion, into quantitative and qualitative values, which can then be easily transformed into multi- criteria ranking. [14]

The AHP process decomposes the decision-making problem and makes a hierarchical structure by developing the ratings for each decision alternative for each criterion (**Figure 2**). Then, the weight factor of each criterion is calculated determining its relative importance.



**Figure 2.** The goal of the analysis, the criteria and the alternative choices.

The relative weights ( $w_{ij}$ ) are assigned through the construction of the pair comparisons matrix, where all the criteria are compared in pairs resulting in an  $a_{ij}$  dominance coefficient that expresses the relative importance between criteria  $i$  and criteria  $j$ . through the Saaty scale of comparison, in term of integer values from 1 (equal importance) to 9 (extreme importance) [15]. The final step is to calculate the consistency ratio (CR), as a common method to judge whether the comparison approach is consistent or not. In the current study, a questionnaire was used in perspective of the examined criteria (energy consumption, thermal/visual comfort and environmental impact). The questionnaire was intended for four stakeholders: occupants, constructors, designers and researchers, collecting more than 30 responses. Due to the lack of significant responses for all stakeholders, current analysis was performed by grouping the questionnaire answers. The AHP method is applied for the calculation of weight factors for all the stakeholder's preferences, as shown in **Table 4**.

**Table 4.** The weight factors and the consistency index based on AHP method

Energy	Thermal Comfort	Visual Comfort	<i>Environmental</i>	<i>CR</i>
34.2%	37.5%	5.2%	23.1%	9.7%

Just as done with the initial criteria, the same process is executed for the alternative solutions, through the logic of AHP, by means of comparison matrices in pairs of alternatives, with respect to each criterion. The optimum case is identified by the minimization of the following cost function.

$$\text{Score} = wf_{en} \cdot Pr_{en} + wf_{tc} \cdot TC + wf_{vc} \cdot VC + wf_{env} \cdot GGE \quad (6)$$

where  $wf_{en}$ ,  $wf_{tc}$ ,  $wf_{vc}$  and  $wf_{env}$  are the weight factors of energy consumption, thermal and visual comfort and environmental impact respectively, as presented in **Table 4**, while PE, TD, VD and GGE are the dimensionless values of primary energy consumption, discomfort hours for thermal and visual comfort, and Greenhouse gas emissions, respectively, of each case. The dimensionless values were calculated based on AHP method, by the relative importance between the simulation results alternatives and not the Saaty 1 to 9 scale, so as to approach to a distinct result between all the alternative cases.

### 3. Results and Discussion

#### 3.1. Energy Performance

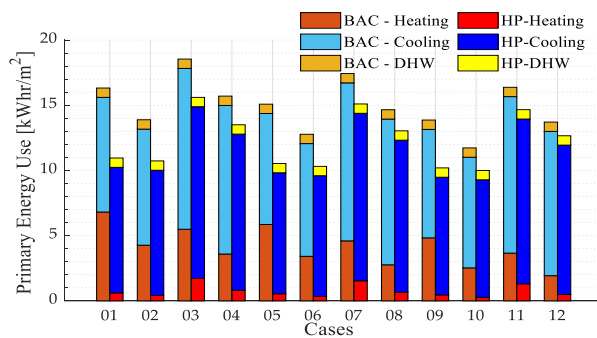
**Figure 3** presents the primary energy use for heating, cooling and domestic hot water (DHW) for all examined cases. As it is presented, for cases with boiler - baseboards and AC units (BAC) the cooling loads corresponds to the 70%, the heating loads the 25% and the DHW the 5% of the total energy consumption, while for the cases with heat pump and fan coil (HP), the cooling, heating and DHW loads corresponds to 90%, 5% and 5%, respectively.

The HP cases present lower primary energy use than the corresponding BAC cases. This occurs due to the better efficiency of the heat pump system for heating loads, despite the higher value of primary energy factor of electricity compared with natural gas. The simple triple pane low-e windows provide reduced primary energy by 15% for the BAC cases and 4-7% for the HP cases, compared to double pane low-e windows. On the other hand, installation of triple EC windows leads to a primary energy reduction by 13-16%, in relation to double EC windows for all the alternatives scenarios. Additionally, the presence of EC foil on the windows increases the total primary energy consumption by 9-13% for the BAC cases and 15-28% for the HP cases (for the same number of panes and similar U-values). This can be supported by the argument that the exterior shading of simple windows blocks the high solar gains reducing the cooling loads of the building. On the other hand, for the same reason, a slight reduction of heating loads is presented with the presence of EC foils. However, the high contribution of cooling loads to the whole energy use, results the negative impact of EC windows to the energy efficiency of building.

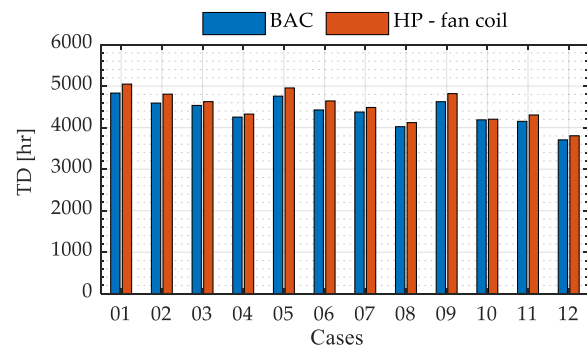
Another substantial output from the primary energy analysis is that the reduction of the U-value from 0.45 W/(m<sup>2</sup>K) to 0.30 W/(m<sup>2</sup>K), with additional 4cm insulation thickness results ca. 7% and 3% reduction of primary energy consumption, for BAC and HP cases, respectively. Further reduction of U-value (from 0.30 W/(m<sup>2</sup>K) to 0.15 W/(m<sup>2</sup>K)) adding 12cm of insulation thickness, results almost the same reduction of primary energy consumption (7 and 3%).

Among all examined cases, the case HP10, representing the building with U=0.15 W/(m<sup>2</sup>K), simple triple low-e windows, and a heat pump- energy system, provides the lowest primary energy consumption of all the alternative cases.





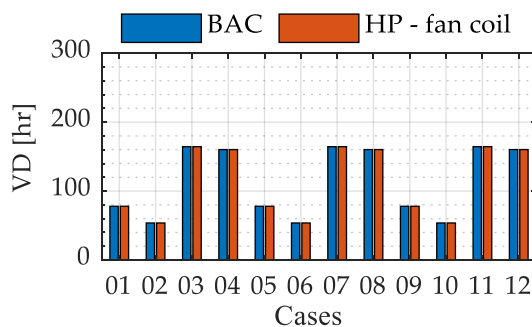
**Figure 3.** Primary energy use for alternative cases.



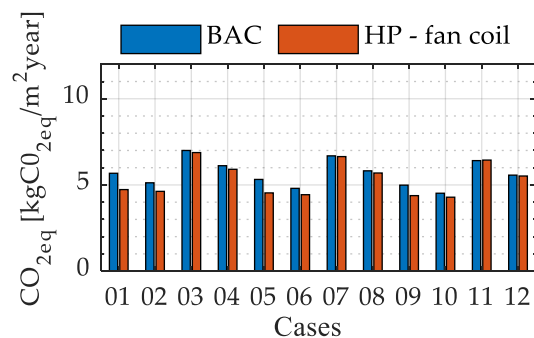
**Figure 4.** The thermal discomfort index for all alternative cases.

### 3.2. Thermal Comfort

**Figure 4** presents the discomfort hours (TD) for all examined alternative cases. It is obvious that the BAC-cases introduce less thermal discomfort hours, which is translated in better thermal comfort conditions than the HP cases. This occurs due to the forced and unsteady airflow from fan coils, resulting in higher values of air velocity for the winter and summer period, while for the BAC cases this is noted only during the cooling months as a result of the AC-split units' operation. Additionally, the operation of baseboards increases the radiative temperature into the conditioned zones, improving the thermal comfort conditions during the heating period. It is also illustrated that the presence of EC windows and the reduction of walls' U-value improve the thermal comfort conditions inside the building by 6-12% and 2-9%, respectively.



**Figure 5.** The visual discomfort index for all alternative cases.



**Figure 6.** The environmental index for all alternative cases.

### 3.3. Visual Comfort

**Fehler! Verweisquelle konnte nicht gefunden werden.** illustrates the Visual Discomfort index (VD) for all cases. It is obvious that the visual comfort depends on only the windows and shading system regardless of the heating/cooling energy system and the wall U-value. As it is shown, the optimum solution for the visual comfort point of view is the use of triple windows with external shading. The cases with EC windows provide ca. 100 hours more than simple windows with non-acceptable daylight glare index. However, this may be negligible due to the benefit of EC windows that the occupants have visual contact with the external surroundings.

### 3.4. Environmental

Greenhouse gas emissions are depicted for all the alternative cases in **Fehler! Verweisquelle konnte nicht gefunden werden.** The cases with triple pane and lowest U-value (BAC10 and HP10) appear to have the lower environmental impact due to the low values of primary energy consumption. The installation of triple low-e windows leads to a CO<sub>2</sub> emission reduction from 29.5% and 33.4% compared

with the scenarios with double low-e EC windows. In general, the cases with double low-e windows and triple low-e windows are more environmentally friendly than the alternatives with EC-low-e windows.

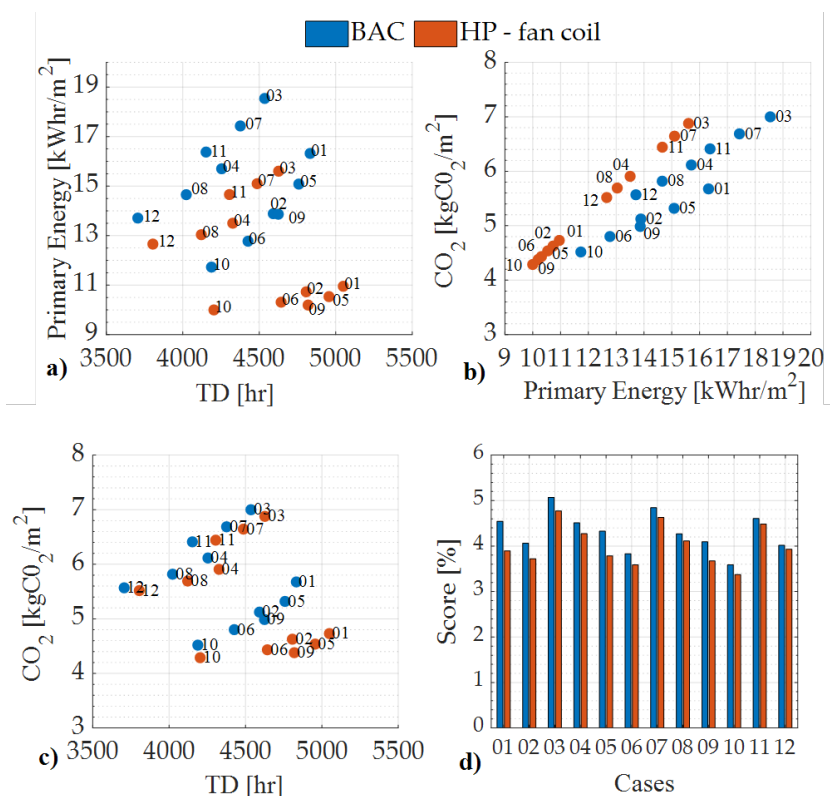
### 3.5. Multi-criteria assessment

The comparison of all examined cases, related the energy consumption and the thermal comfort is presented in **Figure 7a**. The cases with the lowest U-value and the triple pane windows (EC and simple) appear to be the optimum solution for energy and thermal comfort index, regardless of the energy system.

Regarding the comparison between primary energy consumption and CO<sub>2</sub> emissions (**Figure 7b**), cases HP10, HP09, HP06, HP05, HP02 and HP01, meaning cases with heat pumps as energy systems for heating and cooling, and low-e window types, have the less energy consumption and less environmental impact than the BAC cases. The small difference of the CO<sub>2</sub> equivalent emission factors for consumed electricity and natural gas, due to the updated energy balance of the Greek electricity grid, in combination with the high energy efficiency of the heat pumps, makes the HP cases more environmentally friendly in contrary with fossil fuels energy systems. (BAC).

Comparing all the examined cases related thermal comfort and the CO<sub>2</sub> emissions, as depicted in **Figure 7c**, both BAC10 and HP10 cases, with triple pane low-e windows installed, are the most preferable alternatives depending environmental aspect. Also, cases BAC12 and HP12 as well, lead to less discomfort hours than the other cases, with affordable CO<sub>2</sub> emissions comparing the rest of the cases.

Finally, **Figure 7d** presents the final scores of all scenarios, taking into account the criteria weights as calculated based on AHP methodology. Alternative cases BAC03 and HP03 (highest U-value and double EC) have the bigger scores while BAC10 and HP10 (lowest U-value and triple low-e) seem to be the most preferable alternative cases, with the lowest scores. This is mainly because of the low energy consumption and the relative less thermal discomfort hours of these cases caused by the installation of the triple pane low-e windows, regarding also the higher values of the weight factors for the criteria of energy consumption and thermal comfort.



**Figure 7.** The variations of a) primary energy with respect to thermal comfort, b) CO<sub>2</sub> emissions with respect to the primary energy, c) CO<sub>2</sub> emissions with respect to thermal comfort.

### 3.6. Conclusions

The current study analyzed crucial parameters that affect a decision-making process during a building construction or a retrofit project. Up-to-date, most studies focus on energy consumption overlooking other important factors such thermal comfort, visual comfort, and environmental impacts. By setting different aspects with the use of KPIs, and evaluating the simulation results via multi-criteria analysis, this study manages to select an optimal solution via 24 alternative cases with different energy systems for heating and cooling, different envelope insulation thickness and different window system types. Using the AHP method as a MCDM support tool, stakeholders' preferences are obtained through a questionnaire, translated into quantitative and qualitative multi-criteria ranking. This strengthens the selection of the package combination for construction or retrofit, by providing useful reference regarding affective parameters.

Taking into consideration as a decision criterion each KPI separately, the case with the heat pump as energy system, wall thermal transmittance of 0.15 W/(m<sup>2</sup>K), triple pane low-e windows and exterior shadings is the optimum scenario based on the minimization of the energy consumption with approximately 10 kWh/m<sup>2</sup>year. The case with condensing natural gas heating boiler, AC split units, wall thermal transmittance of 0.15 W/(m<sup>2</sup>K), triple pane low-e electrochromic windows with no shadings has fewer thermal discomfort hours than the other alternative cases, with 3705 hours out of the comfort range (-0.5 < PMV < +0.5). All the cases with conventional triple pane low-e windows appear to have the advantage of the less discomfort hours according to the visual comfort index. The most environmentally friendly approach case is HP10, with 4.29 kgCO<sub>2eq</sub>/m<sup>2</sup>year of greenhouse gas emissions. Regarding all the four KPIs, using the cost function for the alternative cases total score, the most preferable scenario is the HP10, with 10 kWh/m<sup>2</sup>year primary energy consumption, 4203 hours out of the desired thermal comfort range, 54 of visual discomfort hours, and 4.29 kgCO<sub>2</sub>/m<sup>2</sup>year of CO<sub>2</sub> emissions, resulting the smaller final score, comparing the other alternative examined cases.

In conclusion, the approach implemented in the current study, highlights the importance of a multi-criteria assessment during an early stage of building design or renovation, taking into consideration a multitude of parameters, such as thermal comfort, visual comfort, and environmental impacts. The method can be further generalized in the future to take into account additional criteria and parameters. Financial aspects should be added into the cost function as a crucial KPI, while in respect of the decarbonization of the building stock, life cycle assessment of the alternative cases should be taken also into consideration.

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