Holistic Energy Upgrade of Dwellings. A Resource Management Optimization Approach

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Received: 30.06.2015 Accepted:03.09.2015

Abstract- Retrofit actions in buildings are optimized through a holistic approach, which investigates the interactions among the potential energy efficiency measures (EEMs) by considering financing limitations, leading in this way to the optimum allocation of the available budget. An approach is proposed to this aim, including pre-selection of the most promising EEMs, detailed cost estimations, design of experiments (DOE) and building simulations, analysis of the effects and interactions between the measures and a multi-variable optimization. Two objective functions are regarded, the energy performance of the dwelling and the cost of the applicable EEMs. In addition to the optimum resources allocation, a strategy to reach a target energy class is formulated, securing the effective exploitation of the available funds. The approach is demonstrated in a dwelling, and reveals the complications when a holistic optimization focusing on the envelope, the machinery and the use of renewables, is simultaneously attempted. Overlapping between the EEMs and reversals in their priorities, with increasing the available budget for the retrofit, are realized.

Keywords—Energy in buildings, Energy management, Design of experiment; retrofit, dwellings; holistic optimization.

1. Introduction

In the context of improving the energy performance of buildings (e.g. in the frame of the Energy Performance of Buildings Directive (EPBD) 31/2010/EC which is valid in the European Union), a stimulus to decrease energy consumption in buildings has been established. Regarding existing dwellings, the aim is their energy upgrade using conventional technologies and furthermore even going beyond cost-optimal solutions to renovate them into Nearly Zero-Energy Buildings. Indeed, a variety of energy efficiency measures (EEMs) is applicable in dwellings [1,2], at various cost and effectiveness. Quite usually, the effectiveness of an EEM decreases with its capacity (e.g. a first layer of insulation is much more effective than an additional one), while at the same time its cost increases, hence the need for economic optimization [3]. Numerous works in optimization were published during last ten years. As it is emphatically noticed in Ref.[4], "…*there are in excess of a hundred peer reviewed works dating back more than a decade*..". Some researchers optimized a variable at a time, while others limited the number of cases, considering only a set of predefined EEMs combination alternatives. Evins [5] reviewed the research works that applied common heuristic optimization algorithms to different fields of sustainable building design. Another review of optimization research efforts was attempted in Ref.[6]; besides, most papers in optimization include review of previous works (e.g. [7]).

The combined application of several measures stimulates interactions between each other and consequently affects their effectiveness (in most cases decreasing it). Due to these potential interactions, a holistic optimization seems to be more suitable, instead of optimizing one EEM at a time. Actually, there are very few works dealing with optimization through a holistic approach [8-11]. In [8] the researchers focused on optimum building design at an early stage however, integrating a non-linear optimization scheme with building modelling and aiming to find the economic optimum. In [9] the objectives were carbon emissions and construction cost, and the optimisation was performed using a multi-objective genetic algorithm. Variables covered solar and fabric properties as well as heating and cooling equipment, and assumed a hotel as a case study. In [10] a genetic algorithm was used to determine the cost minimal route to building-level CO_2 savings, considering as variables the envelope data (U-values, air-permeability), machinery data (boiler efficiency, heat recovery, fan capacity etc.) and the use of renewables (PVs), and assuming as a case study an office building. In [11] the objective functions were the energy savings and the investment cost. The researchers implemented Pareto-archive NSGA-II algorithm. The variables assumed were envelope characteristics, lighting control and night ventilation, and the building assumed was a shopping centre.

In the present work the scope is the energy upgrading of existing dwellings, focusing on a practical problem namely the maximization of primary energy savings with a given budget. Indeed, the owners are expected to upgrade their dwellings in order to achieve a better energy ranking (according to the concept of energy performance directives). In this context, a practical question arises, on how the owner may opt for the most effective EEMs for his dwelling, taking into consideration his probably limited budget, but also the option of adding other EEMs in the future (upgrade at stages). As a consequence, the present work attempts a holistic optimization to energy upgrade existing dwellings (retrofit), assuming two objective functions (energy performance and cost). The tool used to this aim is the design of experiment method [12,13]. The usefulness of this approach is demonstrated through a case study.

2. Methodology

Limited interventions can be applied to the envelope of an existing dwelling as compared to the early design possibilities. In addition, there are significant loads which are not accounted for the energy classification of the dwellings. For instance, the appliances do not constitute an integral part of the dwelling and its services, and there are no obligatory standards of illumination in domestic lighting. Hence, the potential EEMs are actually restricted to three groups relating with (i) the envelope of the dwelling (insulation, windows), (ii) the machinery (heating /cooling equipment) and (iii) the use of renewables. The optimization of the applicable EEMs could be elaborated stepwise by group. In Ref.[14] the envelope properties (construction, shading, glazing area and air tightness) are firstly optimized, and then the system properties (CHP, heat pump, storage and control); in Ref.[15], a three-stage optimization was applied, according to the afore-mentioned groups. This notwithstanding, there are EEMs that strongly interact to each other (e.g. the effectiveness of a high efficiency boiler is lower in highly insulated dwellings). Hence, by splitting the optimization problem, any synergies between the measures are missed out; for this reason, a holistic approach is more suitable [16].

Holistic optimization may be a tremendous work when processing simultaneously all potential EEMs. However, this task may become less tiresome when the potential measures are firstly screened (i) to discard some of them for which a bad economy, technical or administrative barriers restrict their application, and (ii) neglect others which present minor effect on the optimization process. Besides, some measures are alternative to each other, and a choice among them may be ex-ante specified by the user or the designer, before the optimization process. Evins et al. [4] for instance, developed a three-stage optimization process, allowing many inputs to de disregarded as non-significant at first, and then applying optimization at two steps, with increasing precision respectively.

Design of experiment (DOE) and detailed simulation of the building, including only the preselected EEMs, can be elaborated to this aim. An integrated holistic approach to the rational and effective renovation of existing buildings is formulated in this way, falling into the framework and the concept of EPBD. DOE is advantageous for this specific issue, as it allows obtaining the required information with a few simulations. In addition, it does not stick to local minima, while it provides adequately detailed results. Jaffal et al. [17] applied DOE to estimate heating demand in buildings. The authors realized the benefits of the method in giving information of what and how much may be improved, reducing at the same time the necessary number of dynamic simulations. Sadeghifam et al. [18] applied combined use of design of experiment and dynamic building simulation in assessment of energy efficiency in tropical residential buildings. Response Surface Methodology (RSM) is an evolution of DOE proceeding to optimization. Khalajzadeh et al. [19] applied RSM to optimize a vertical ground heat exchanger, applying a central composite design method. Ekren and Ekren [20] applied RSM to optimize an autonomous PV/WIND integrated hybrid with battery storage, by applying a Box–Behnken pattern.

Dynamic simulation software may be used for the "experiments". The application of building simulators like TRNSYS, ESP, EnergyPlus etc. is quite usual. In addition, combination with an optimizing tool, like GenOpt [11,21] facilitates the computational work. Other researchers applied codes used in energy certification, like SBEM [10], IDA-ICE which is accepted for LEED energy simulation [11], the Portuguese building thermal code RTCE, which is based on ISO 13790 [22] etc. The same practice is also followed here as well, as this work focuses on a better energy classification of a dwelling according to the prevailing regulations.

Multi-objective optimization is quite often restricted to two objectives, the energy consumption and the cost; more rarely, environmental impact minimization, or optimization of the energy and comfort performance is also elaborated. In general, the introduction of more objective functions introduces some subjectivity by the side of the researcher, attributing weighting factors to each single criterion. In the contrary, the optimization with a bounded-objective function, as it is attempted in this work, may simultaneously focus on both technical and economic criterions, without predefining their relative significance. Energy retrofit of dwellings is consequently examined here as a multi-variable two-objective optimization problem, with one of the objective functions bounded.

3. Case Study

An apartment was selected as a typical dwelling, according to the Greek dwellings topology [23,24]. The apartment belongs to a seven-storey building (Fig. 1); it has a floor-area of 110m^2 and a plan as depicted in Fig. 2. The building is in Athens (Latitude 37.97^o, Longitude 23.75^o), and is insufficiently insulated (e.g. U-value of walls 1.1 W/m^2-K). It is centrally heated by an oil-fired boiler; a hydronic system with radiators is used to this aim, allowing independent heating of each apartment and allocation of heating costs according to elapsed time meter indications. In the assumed apartment, domestic hot water (DHW) is produced by an electric heater.

3.1. Screening of EEMs

Potential energy efficiency measures are depicted in Fig. 3, arranged according to their cost and effectiveness in a two-dimensional matrix [25]. A preliminary screening of EEMs is attempted, to find which of them should be accounted for the optimization. The low cost measures are firstly assumed. Weather compensation and use of a variable speed driven (VSD) circulating pump refers to the whole heating system and in this way does not regard the apartment alone. Besides, the addition of thermostatic regulating valves (TRVs) does not make sense, due to the use of elapsed time meters in heating costs allocation. As a consequence, the applicable low cost measures are restricted to:

- Heating: Application of a digital thermostat, and balancing between the loops of the hydronic distribution network within the apartment
- Cooling: Installation of ceiling fans, application of night ventilation
- Envelope: Application of weather proofing, wherever necessary.

Since the above measures are low cost but also of medium to high cost-effectiveness, they are assumed as first priority measures to be anyway applied, and in this sense they are not included in the optimization.

Regarding the medium cost measures (middle column in the matrix of Fig. 3), roof insulation is not applicable (the apartment is at the 3rd floor); replacement of Air-conditioners (AC) is not needed as they are not old units; at last, the existing frames are not wooden to allow the addition of glazing. In addition, a comprehensive energy management system (like KNX or Dupline etc.) to monitor consumption and to control heating, cooling, lighting, the awnings and natural ventilation, is preferably installed at the construction phase. Furthermore, insulation of heating network refers to the whole heating system; the same is valid with the replacement of elapsed time meters with heat-meters [26], while independent heating option is already available to the occupants. As an outcome of above analysis, the applicable measures are finally restricted to:

Fig. 1. The block of flats (building in the middle) where the apartment of the case study belongs

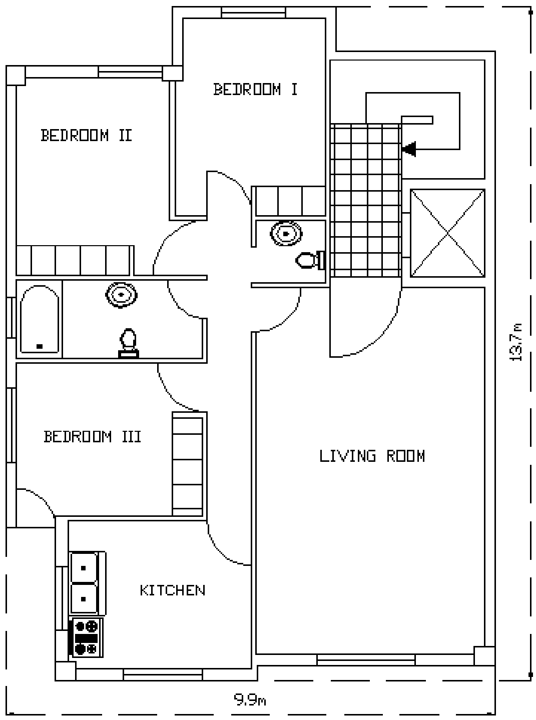

Fig. 2. Floor plan of the apartment of the case study

	LOW COST	MEDIUM COST	HIGH COST
HIGH COST-EFFECTIVENESS	• Weather proofing • Pumps/fans with VSDs • Ceiling fans	• Roof insulation • Repair of envelope • Replacement of old AC units	• Replacement of old boilers • Use of a biomass boiler
MEDIUM COST EFFECTIVENESS	• Balancing network • Weather compensation • TRVs in radiators • Night ventilation	• Switch to NG • Solar water heating • Energy management • Awnings • Double glazing • Heat-meters	• Insulation of external walls • Use of heat-pumps • Solar space heating • PV panels
LOW OR MARGINAL COST-EFFECTIVENESS	• Digital thermostats	• Insulation of pipes • Independent heating in old buildings	• Resizing boiler • Windows/frames • Use of CHP • Green roofs

Fig. 3. Energy efficiency measures, distinguished according to the required capital and cost-effectiveness (source: [25]).

- Installation of awnings.

while the following measures need further optimization:

- Switch to natural gas (to optimize the efficiency of the boiler)
- Solar collectors for DHW production (to optimize the area of the collectors).

In the third group (right column in the matrix of Fig. 3) there are measures which may not be affordable, due to their high cost and their marginal economy. This is the case with the green-roofs, but also with CHP, where the required capacity is smaller than the threshold economical size [27,28]. Resizing the boiler or use of a biomass boiler refer to the central heating system as a whole. On the other hand, replacement of the windows constitutes a quite expensive measure, but may become necessary when upgrading the whole envelope. In the same group there are also competitive measures between each other, like the replacement of the boiler (e.g. by using a wall-mounted NG boiler to separately serve the apartment) and the installation of a heat pump. Bonaros et al. [29] compared these two alternatives from the cost and energy points of view. The final choice between them can be based on a multi-criterion decision, and in this context it strongly depends on the owner's preferences. Here, we consider the installation of a wall-mounted gas boiler. Photovoltaics (PV) and solar thermal are also competitive, as sharing the same available roof surface area. In Ref.[30] it was demonstrated that PV panels installed on south facing vertical fabric elements and combined with sufficient reflecting surfaces may perform almost equally to their roof installation, but this cannot be the case with this specific apartment due to space limitations. As a consequence, the applicable high cost measures (and the respective optimization variables) are restricted to:

- Insulation on external walls: an optimum insulation thickness of 10 cm is assumed [31], and the walls area to be insulated is set as an optimization variable.
- Replacement of windows: Highly insulating windows are assumed (double glazed with argon and frame with a thermal break); the area (number) of windows to be replaced is set as an optimization variable.
- Solar space heating: the area of the solar collectors is set as an optimization variable.

3.2. Design of Experiments

The next step of the proposed approach is to apply DOE to find out the variables that have the most significant effect on the performance of the dwelling, and reveal any interactions between them. The optimization variables are presented in Table 1, as arisen from the preceded analysis. In the same table, the lower and upper limits of their values are also included. The values in the shaded cells correspond to the existing situation, which is also included among the considered alternatives.

A two-level factorial is assumed, which is in most cases sufficient [13]. The results of the simulations are shown in Table 2, together with the assumed values for the variables. The software package Design Expert® was used in the analysis of the results.

The effects are presented in a normal probability diagram (Fig. 4). It is obvious that the main effects are A, B, C, D and the interaction $C*D$. A model is assumed based on these variables, and the relevant analysis of variance is shown in Table 3. According to the data of Table 2 and the analysis of Table 3, the following equation arises, giving the response in terms of coded factors:

$$R_1 = + 67.76 + 9.54*A + 7.75*B - 10.96*C - 19.39*D + 6.83*C*D \quad (1)$$

The normal plot of residuals R_1 is given in Fig. 5; obviously, they follow satisfactorily the normal distribution. The other response, R_2, is the total cost of the applied EEMs; response R_2 is assumed to be a linear function of factors A

Table 1. Variables lower and upper values, as used in the factorial analysis

Factor	Unit	Lower value	Upper value
A=Mean thermal transmissivity of walls	W/m^2-K	0.26	1.10
B=Mean U-value of Windows	W/m^2-K	2.6	5.0
C=Natural gas combi boiler efficiency	%	85	96
D=Solar collectors for space heating and DHW	m^2	0.0	10.8

and *B*, and a second degree function of factors *C* and *D*, as it is explained in the next paragraph.

3.3. Optimization

The cost data used in the optimization, are presented in Table 4, and are based on detailed quotations by suppliers.

Factors *A* and *B* present linear behaviour regarding both their cost and effectiveness, hence a single cost datum is sufficient. On the other hand, factors *C* and *D* succeed economy of scale. For this reason a middle point was additionally introduced among the runs; the cost of the non-linear terms at the mid-point was duly estimated, based also on detailed quotations.

According to the cost data of Table 4, the response function R_2 gets the following analytical form:

$$R_2 = + 1675\bullet(-A) + 3300\bullet(-B) - 605\bullet C^2 + 1225\bullet C - 380\bullet D^2 + 2570\bullet D + 9755 \quad (2)$$

The minus signs were introduced for factors *A* and *B* because the existing situation, usually attributed the value of (-1) corresponds to their upper value. The optimization problem gets now the form:

- Minimize objective function R_1
- when the objective function R_2 is bounded
- and the coded values of variables *A*, *B*, *C* and *D* are within the range [-1, +1].

After solving this optimization problem, an optimum set of (-*A*), (-*B*), *C*, *D* and the respective response R_1 arise for each specific value of R_2, as it depicted in Fig. 6. The curve of primary energy consumption (*PE*) in Fig. 6, does constitute the Pareto front for the two objective-functions.

Table 2. Assumed values for the variables and results of the runs

Run	*A* Walls U-value (W/m^2-K)	*B* Windows U-value (W/m^2-K)	*C* Boiler efficiency (%)	*D* Solar collectors (m^2)	R_1 Response (kWh/m^2-yr)
1	0.26	2.60	85.00	0.00	84.0
2	1.10	2.60	85.00	0.00	107.5
3	0.26	5.00	85.00	0.00	106.6
4	1.10	5.00	85.00	0.00	125.9
5	0.26	2.60	96.00	0.00	52.8
6	1.10	2.60	96.00	0.00	72.8
7	0.26	5.00	96.00	0.00	67.3
8	1.10	5.00	96.00	0.00	88.8
9	0.26	2.60	85.00	10.80	37.6
10	1.10	2.60	85.00	10.80	55.5
11	0.26	5.00	85.00	10.80	51.1
12	1.10	5.00	85.00	10.80	70.1
13	0.26	2.60	96.00	10.80	31.6
14	1.10	2.60	96.00	10.80	46.8
15	0.26	5.00	96.00	10.80	43.3
16	1.10	5.00	96.00	10.80	59.5
17	0.68	3.80	90.50	5.40	50.8

Table 3. Analysis of variance for the selected factorial model

Source	Sum of Squares	df	Mean square	F value	p-value Probability>F
Model	11098.54	5	2219.71	66.11	< 0.0001 significant
***A*-INSULATION**	1455.42	1	1455.42	43.34	< 0.0001
***B*-WINDOWS**	961.00	1	961.00	28.62	0.0002
***C*-BOILER**	1922.82	1	1922.82	57.26	< 0.0001
***D*-SOLAR**	6014.00	1	6014.00	179.10	< 0.0001
C·D	745.29	1	745.29	22.20	0.0006
Residual	369.36	11	33.58		
Cor. Total	11467.90	16			

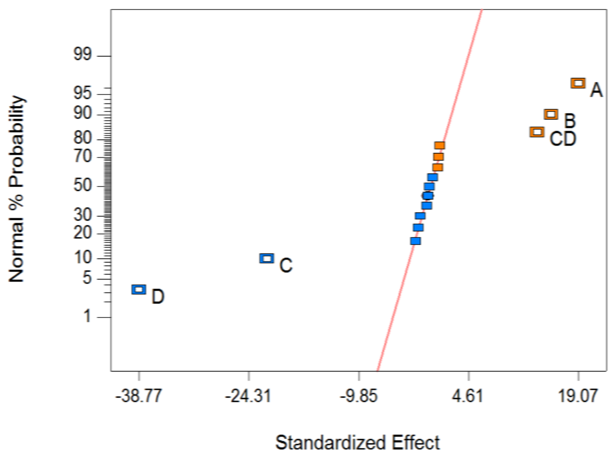

Fig. 4. Normal plot of the effects

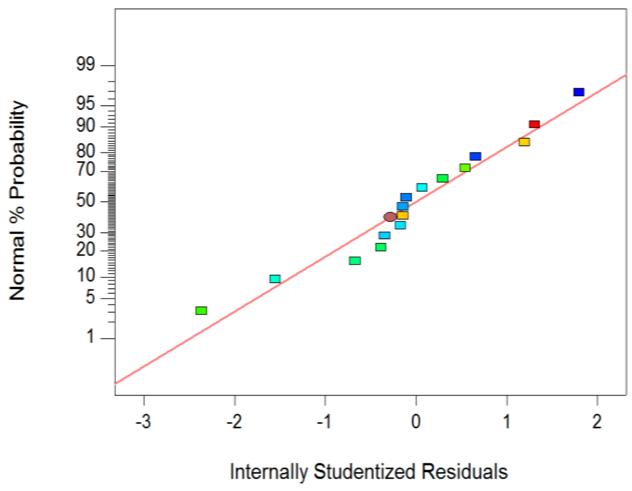

Fig. 5. Normal plot of residuals for response R_1

4. Analysis of Results - Discussion

The situation regarding envelope upgrade is quite straightforward. There is insignificant interaction between the two EEMs (walls insulation and replacement of windows) and in this way the measures are applied sequentially, according to their energy effectiveness (determined as the primary energy decrease per capital invested). In this sense, the walls are firstly insulated, and the windows are replaced afterwards. In the holistic energy upgrade however, the situation becomes complicated, since (i) there are measures start getting applied before the previously applied measure have acquired their maximum value and (ii) there may arise reversals in the sequence the EEMs are applied, revealing in this sense that their relevant priorities depend actually on the available budget.

Switch to natural gas proved to be the first priority measure (when the available budget is relatively low). The main advantage of this EEM however, is attributed to its capability to be simultaneously used for DHW production, succeeding in this way the substitution of electrical energy by natural gas and leading to remarkable primary energy

Table 4. Cost data used in the calculations

EEM, installed	Cost
External thermal insulation of walls (10cm, k=0.034W/m-K)	3350 €
Aluminum framed windows with thermal brake, double glazing with argon	6600 €
Natural gas combi condensing boiler (96% efficiency)	2450 €
Natural gas combi conventional boiler (90.5% efficiency)	1830 €
Solar system with 10.8m^2 collectors for space heating and DHW production	5140 €
Solar system with 5.4m^2 collectors for space heating and DHW production	2950 €

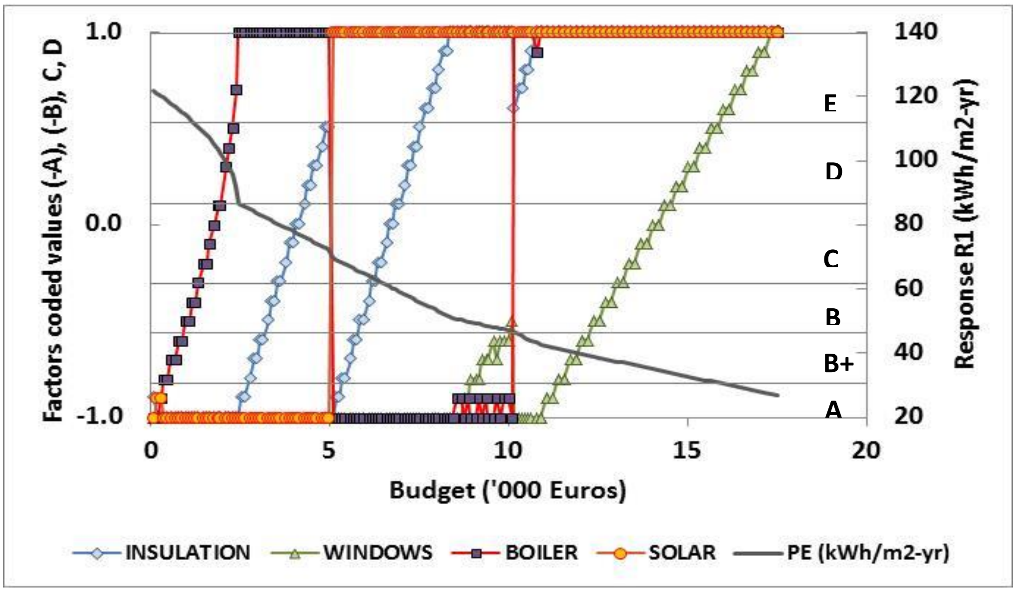

Fig. 6. Optimization of applicable EEMs, as a function of the available budget. The limits between the energy classes from **E** (upper) to **A**, are also depicted.

savings. The measure keeps its first priority until it gets its maximum value (C=+1, value that corresponds to a condensing boiler). In this sense, the owner should not install a conventional NG wall-mounted boiler, if he intends to invest again in the future in further energy upgrade of his dwelling. For instance, he could make the necessary arrangements (e.g. loan, payment in instalments) and opt for the installation of a condensing boiler from the beginning. Indeed, the installation of a conventional wall-mounted NG combi boiler (factor coded value for Boiler C=0) leads to only a single class energy upgrade (from class **E** to class **D**), while the installation of a condensing boiler (factor coded value for Boiler C=+1) leads to two classes energy upgrade (performance falls into class **C** zone).

The second most important EEM proved to be the walls insulation. Surprisingly this measure does not reach its maximum value at its first stage of application (for budgets 2500-5000€). This is explained by the fact that solar heating starts becoming more effective, with increasing the available budget, due to scale economies. It is remarkable that this measure becomes even more advantageous than switching to natural gas, for which the effectiveness decreases remarkably with insulating the walls. In this sense, if the owner disposes about 5000€ then he could only install a solar thermal system. If he further intends to invest more, then he may insulate some of the walls (starting e.g. from the North facing walls).

After the addition of insulation and the installation of a solar thermal system, upgrade of the boiler is hardly competitive due to the restricted heating energy demand and the already substitution of electrical energy (for DHW) with solar energy. Hence, even the replacement of the windows seems initially to be more advantageous. Taking into consideration the fixed expenses of the installation of an NG boiler and the respective scale economy, this measure becomes preferable again soon (at a budget value of 10,000€ approx.), leaving finally the replacement of windows as the last priority measure. In this sense, replacement of all windows is only suggested after the installation of an NG boiler; noticeably, the dwelling becomes class **A** before the replacement of all the windows.

In conclusion, all considered EEMs should be applied to upgrade the specific dwelling to class **A**. For such a high cost upgrade, it does not make any difference what measure will be applied first. On the other hand, targeting to a lower upgrade requires more careful planning, especially when the measures are planned to be applied stepwise. Again, although an NG-boiler was the most competitive EEM for low budget interventions, it was finally excluded from an upgrade to class **B**. In this sense, the diagram of Fig. 6 may be used as a guide to plan energy upgrade interventions, taking as granted either the available budget or the desired energy class.

The upgrade options are concisely presented in Fig. 7. Actually, Fig. 7 results from Fig. 6, although the former gives more information about the selection of the measures. Nevertheless, interpretation of Fig.7 is more straightforward to the owners and end users. In this sense, such kind of a diagram could be included in the energy audits and certificates addressed to the general public.

The proposed approach does not present any draw-backs or side-effects when used for planning energy upgrade initiatives. From the case study it has been revealed that the independent selection of effective EEMs does not guarantee that these may necessarily constitute part of the optimum route to the achievement of a desired energy class, as this optimum route can be formulated by the present approach. The proposed approach does not have any limitations, since both linear and non-linear terms can be simultaneously processed. In addition, the application of DOE minimizes the required calculations and simulations and allows the designer to acquire a sound knowledge on the effect of the various

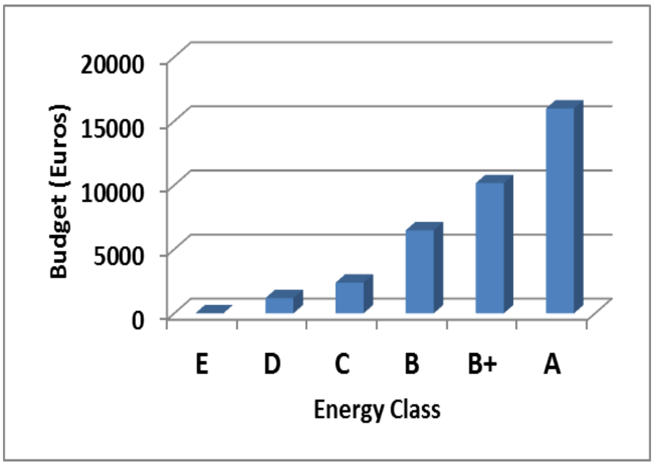

Fig. 7. Minimum necessary funds to upgrade the apartment of the Case Study, as a function of the targeted energy-class. Suggested EEMs: Class **E**=No EEMs, existing situation (*ES*). Class **D**=*ES* + Conventional NG boiler. Class **C**=*ES* + Condensing boiler. Class **B**=*ES* + Solar heating/DHW + Insulation of Northern wall. Class **B plus**=The same as for class-**B**, + Insulation of the rest walls + Use of NG condensing boiler. Class **A**=The same as for class-**B plus** + Replacement of windows.

EEMs and their potential interactions. Lastly, the presentation of the results of the present approach in a convenient diagram (like that of Fig. 7) allows the owner of the dwelling (and end user) to get an integrated proposal regarding the feasibility and effectiveness of the several EEMs, and based on this to further plan his/her energy upgrade investment initiatives in a short but -more importantly- in a long term, too.

5. Conclusion

An approach is proposed that can be used for the optimum energy upgrading of existing dwellings. The approach applies holistic optimization considering at the same time the envelope, the machinery and the exploitation of renewables. A multi-variable and two-objective functions optimization proved to be suitable to this aim, in combination with DOE; emphasis is given to the better classification of the dwelling, according to the prevailing regulations. Cost data used are based on actual quotations; introduction of simplifications in cost estimations is avoided in this way, while any scale economies are also considered. Total cost of EEMs is processed as a bounded-objective function, and the issue takes the form of a resource allocation and management problem.

The application of the proposed approach was demonstrated in a dwelling. An energy upgrade path was formulated, improving the performance of the dwelling up to class **A**. The arisen **A**-class optimum scenario consists of a duly insulated envelope with double glazed windows, heated by an autonomous heating system based on a combi NG condensing boiler and assisted by solar thermal system. Obviously, this is not necessarily the global minimum and the only solution among all potential EEMs combinations; for instance, the application of a central heat pump and photovoltaics to drive it, could have been alternatively considered. Actually, some major choices may still depend on the owner preferences, the designer/engineer concept and the principal and side benefits each solution may present by case. In any circumstance, the proposed approach will attribute relevant priorities to the pre-selected EEMs, and reveal the strategy to reach the ultimately desired energy class.

Acknowledgements

This work was co-financed by the European Union and the Greek Government under the framework of the Education and Initial Vocational Training Program - ARCHIMEDES III.

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