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Multi-objective optimization for building retrofit strategies: A model and an application

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ABSTRACT

Due to growing limitations on land use and awareness of sustainability concerns, the building retrofit market has faced increasing opportunities worldwide. Several technological/constructive options are available to improve energy efficiency and indoor environmental quality in buildings. The identification of the most appropriate retrofitting options is a topic of outstanding importance given the potential costs and impacts involved.

This paper presents a multi-objective optimization model to assist stakeholders in the definition of intervention measures aimed at minimizing the energy use in the building in a cost effective manner, while satisfying the occupant needs and requirements. An existing house needing refurbishment is taken as a case study to demonstrate the feasibility of the proposed multi-objective model in a real-world situation. The results corroborate the practicability of this approach and highlight potential problems that may arise.

1. Introduction

The building sector is the largest user of energy and CO_2 emitter in the European Union (EU) and is responsible for about 40% of the EU's total final energy consumption and CO_2 emissions. Even if all future buildings were to be built so that their energy demands were very low, this would still only means that the increase in energy demands would be reduced and it would not reduce the present demands. For many years to come, only measures taken in existing buildings will have a significant effect on the total energy demands in the building stock. As a consequence, the cornerstone of the European energy policy has an explicit orientation to the conservation and rational use of energy in buildings as the energy performance of building directive (EPBD) 2002/91/EC and its recast (EPBD) 2010/31/EU indicate [1,2]. The EPBD's main objective is to promote the cost-effective improvement of the overall energy performance of buildings. One of the best opportunities to do so would be during building retrofit. Although a thorough building's retrofit evaluation is quite difficult to undertake, because a building and its environment are complex systems (since economical, technical, technological, ecological, social, comfort, and esthetical aspects, among others must be taken into account), in which all sub-systems influence the overall efficiency performance and the interdependence between sub-systems plays a significant role [3].

Furthermore, as innovative technologies and energy efficiency measures for buildings are well known, the main issue is to identify those that will prove to be the more effective and reliable in the long term. When choosing among a variety of proposed measures, the Decision Maker (DM) (the corresponding building expert) has to reconcile environmental, energy related, financial, legal regulation and social factors to reach the best possible compromise to satisfy the final occupant needs and requirements.

Several decision aid approaches (cost-benefit analysis [4], multi-criteria analysis [5–11], multi-objective optimization [12,13], energy rating systems [14,15], etc.) have been used for addressing the mentioned and other related problems.

Goodacre et al. [4] used a cost-benefit analysis framework to assess the potential scale of some of the benefits from upgrading heating and hot water energy efficiency in the English building stock.

Gero et al. [5] were among the first to propose a multi-criteria (MC) model to be used at the process of building design in order to explore the trade-offs between the building thermal

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performance and other criteria such as capital cost and usable area of the building. More recently, other researchers have also employed MC techniques to similar problems. Jaggs and Palmar [6], Flourentzou and Roulet [7], and Rey [8] proposed MC-based approaches for the evaluation of retrofitting scenarios. Blondeau et al. [7] used MC analysis to determine the most suitable ventilation strategy in a university building among a set of actions. Their aim was to ensure the best possible indoor air quality and thermal comfort of the occupants and the lowest energy consumption. Kaklauskas et al. [3] developed a multivariate design method and MC analysis for building refurbishment, by determining the significance, priorities and utility degree of building refurbishment alternatives and selecting the most recommended variant. Allane [10] used a MC knapsack model to select the most feasible actions in the conceptual phase of a renovation project. Kim et al. [11] developed a genetic algorithm-based decision support system for housing condition assessment that suggests optimal refurbishment actions considering the trade-off between cost and quality. Diakaki et al. [12] investigated the feasibility of applying multi-objective optimization techniques to the problem of improving energy efficiency in buildings.

These lines of research have allowed addressing many problems as far as buildings retrofit is concerned. However, most of them consider that a list of predefined and pre-evaluated intervention options/solutions is given. In case a small number of such solutions have been defined, there is no guarantee that the solution finally reached is the best one (from the DM's perspective). On the opposite, when a large number of solutions is defined the required evaluation and selection process may become extremely difficult to handle.

The problem faced by the DM is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives for assessing the merits of the potential solutions according to different evaluation axes, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and constraints that should be taken into account to reach the best possible solution [12]. Accordingly, this paper presents a multi-objective optimization model to quantitatively assess technology choices in a building retrofit project. This model takes into account all feasible combinations of choices (concerning windows, insulation materials for roofs and walls, and solar collectors), without being confined to a small set of predefined scenarios in building retrofit. To this end, an illustrative real residential building is used to demonstrate the feasibility of the proposed approach and highlight potential problem that may arise. The DM is provided solutions corresponding to different trade-offs between energy savings and retrofit costs. A solution to obtain a desired efficiency label at minimum cost can also be identified.

The remainder of this paper is organized as follows. The proposed multi-objective optimization model is presented in the next section. It is followed by the application of the proposed model to a real-world case study. Finally Section 4 summarises conclusions and discusses issues for future works.

2. Theory and methodology

2.1. Multi-objective optimization problem

This study considers the multi-objective optimization (MOO) of buildings retrofit strategies. Therefore, it requires the definition of appropriate decision variables, objective functions and constraints, and finally the selection of appropriate solution techniques. The decision variables reflect the whole set of alternative measures that are available for the retrofitting of the building (e.g. windows, insulation material, etc.). The objectives to be achieved (minimum retrofit cost and maximum energy savings) are defined using the appropriate linear or non-linear mathematical formulations. Moreover, the set of feasible solutions is delimitated with respect to logical, physical and technical constraints concerning the decision variables and their intermediary relations.

2.2. Decision variables

The set of retrofit actions in this study concerns combinations of choices regarding windows, external wall insulation material, roof insulation material, and installation of solar collector to the existing building. Therefore, four types of decision variables are defined concerning the alternative choices regarding:

- the windows type;
- the external wall insulation materials;
- the roof insulation materials;
- the solar collector type.

For simplicity, it is assumed that only one retrofit action from each four set of actions may be selected for the building retrofit.

Assuming availability of I alternative types of windows, J alternative types of external wall insulation material, K alternative types of roof insulation material, and L alternative types of solar collector, binary variables x_i^{win} with $i = 1, \ldots, I$, x_j^{EWAL} with $j = 1, \ldots, J$, x_k^{ROF} with $k = 1, \ldots, K$, and x_l^{sc} with $l = 1, \ldots, L$ are defined as follows:

$$x_i^{win} = \begin{cases} 1, & \text{if window type } i \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \tag{2.1}$$

$$x_j^{EWAL} = \begin{cases} 1, & \text{if insulation material type } j \text{ is selected otherwise} \\ 0, & \text{otherwise} \end{cases} \tag{2.2}$$

$$x_k^{ROF} = \begin{cases} 1, & \text{insulation material type } k \text{ is selected otherwise} \\ 0, & \text{otherwise} \end{cases} \tag{2.3}$$

$$x_l^{sc} = \begin{cases} 1, & \text{if solar collector type } l \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \tag{2.4}$$

2.3. Objective function calculation procedures

2.3.1. Energy savings

The general procedure for estimating the energy savings, ES, from a retrofit project is based on the calculation of the difference between the pre-retrofit energy consumption predicted from a model and the post-retrofit energy consumption [15]:

$$ES = E_{pre} - E_{post} \tag{2.5}$$

where

- E_{pre} – the energy use predicted from a pre-retrofit model of the facility.
- E_{post} – the energy used in the facility after implementing the retrofit actions predicted from a model.

Therefore, it is important to develop a model for the building before estimating the retrofit energy savings. To limit the computational time, a simple thermal model of the building is developed based on the current methodology of the Portuguese building thermal code (RCCTE) [16], which is based on ISO-13790 [17].

Generally the energy sources in a building are used for space heating, cooling and domestic hot water (DHW) systems and for electric lighting (in this specific model electric lighting is not considered). The building energy needs ($E = E_{pre}$ or E_{post}) are calculated using Eq. (2.6):

$$E = Q_{ic} + Q_{vc} + Q_{ac} \tag{2.6}$$

where

- Q_{ic} – energy needed for space heating [kWh/year];
- Q_{vc} – energy needed for space cooling [kWh/year];
- Q_{ac} – energy needed for water heating [kWh/year].

A steady-state yearly based calculation methodology is used here to estimate the heating and cooling needs of residential buildings, as well as the DHW needs. The heating needs are obtained applying a degree-days method and the envelope heat balance for the heating season. The cooling needs are obtained from the average difference between the indoor–outdoor temperature and the envelope heat balance during the cooling period. The DHW needs are obtained applying the average daily reference consumption and the annual number of days of DHW consumption.

2.3.1.1. Energy need for heating. For each building zone and each season, the building energy need for space heating, $Q_{ic}(x)$ (x denotes the vector of all decision variables defined in Section 2.2), for conditions of continuous heating, is calculated as given by Eqs. (2.7)–(2.14):

$$Q_{ic}(x) = Q_t(x) + Q_v - Q_{gu}(x) \text{ [kWh/year]} \tag{2.7}$$

$$Q_t(x) = Q_{ext}(x) + Q_{enu} - Q_{pt} \text{ [kWh/year]} \tag{2.8}$$

$$Q_{ext}(x) = 0.024 \cdot DD \cdot BLC_{ext} \text{ [kWh/year]} \tag{2.9}$$

$$BLC_{ext} = A_{win}\sum_{i=1}^{I} U_i \cdot x_i^{win} + \frac{A_{EWAL}}{\sum_{j=1}^{J} x_j^{EWAL} d_j/\lambda_j} + \frac{A_{ROF}}{\sum_{k=1}^{K} x_k^{ROF} d_k/\lambda_k} \tag{2.10}$$

$$Q_{enu} = 0.024 \cdot DD \cdot U \cdot A2 \text{ [kWh/year]} \tag{2.11}$$

$$Q_{pt} = 0.024 \cdot DD \cdot \sum_m \Psi_m \cdot B_m \text{ [kWh/year]} \tag{2.12}$$

$$Q_v = 0.024 \cdot (0.34 \cdot ACH \cdot A_p \cdot P_d) \cdot DD \text{ [kWh/year]} \tag{2.13}$$

$$Q_{gu}(x) = \eta[(0.720 \cdot A_p \cdot M \cdot q_i) + (M \cdot G_{south} \cdot \sum_i X_i \cdot A_{e,i} \cdot x_i^{win})] \text{ [kWh/year]} \tag{2.14}$$

where
Coefficients:

- τ – losses to non-heated spaces reduction coefficient [kWh/year];
- Ψ – linear heat flux transmission coefficient [W/m °C];
- X_i – orientation coefficient for the different facade orientations;

Parameters:

- U_i – window type i thermal transmission coefficient [W/m^2 °C];
- A_{win} – windows surface area [m^2];
- λ_j – thermal conductivity of external wall insulation material [W/m °C];
- d_j – thickness of the external wall insulation [m];
- A_{EWAL} – exterior wall surface area [m^2];
- λ_k – thermal conductivity of the roof insulation material [W/m °C];
- d_k – thickness of the roof insulation [m];
- A_{ROF} – roof surface area [m^2];
- ACH – air changes per hour [h^{-1}];
- DD – Degree-Days [°C/day];
- q_i – internal gains [W/m^2];
- M – heating season duration [months];
- G_{south} – average monthly solar energy that reaches a south oriented vertical surface [kWh/m^2 month];
- η – heat gains utilization factor;
- $Q_t(x)$ – conduction heat loss through building envelope [kWh/year];
- Q_v – heat loss due to fresh air flow [kWh/year];
- $Q_{gu}(x)$ – useful heat gains (internal + solar heat gains through glazing) [kWh/year];
- $Q_{ext}(x)$ – heat loss through zones in contact with outdoor (walls, glazing, roofs and pavements) [kWh/year];
- $Q_{enu}(x)$ – heat loss through zones in contact with non-useful spaces (walls, glazing, roofs and pavements) [kWh/year];
- $Q_{pt}(x)$ – heat loss through linear thermal bridges [kWh/year];
- BLC_{ext} – building load coefficient [W/°C];
- $A2$ – building envelope in contact with non-heated spaces [m^2];
- B – floor or wall interior linear perimeter for envelope in contact with the soil or thermal bridge interior length [m];
- A_p – net floor area [m^2];
- P_d – floor to ceiling height [m];
- A_e – effective glazing solar radiation collector area for the different windows orientations.

2.3.1.2. Energy need for cooling. The cooling needs are obtained applying the following equation:

$$Q_{vc}(x) = (1-\eta) \cdot (Q_1(x) + Q_{gu}(x) + Q_2 + Q_3) \text{ [kWh/year]} \tag{2.15}$$

$$Q_1(x) = 2.928 \cdot BLC_{ext} \cdot (\theta_m - 25) + BLC_{ext} \cdot [(a \cdot Ir/25)] \text{ [kWh/year]} \tag{2.16}$$

$$Q_2(x) = 2.928 \cdot (0.34 \cdot ACH \cdot A_p \cdot P_d)(\theta_m - 25) \text{ [kWh/year]} \tag{2.17}$$

$$Q_3 = 2.928 \cdot A_p \cdot q_i \text{ [kWh/year]} \tag{2.18}$$

where

- θ_m – average outdoor temperature in the cooling season;
- α– exterior envelope solar radiation absorption coefficient;
- Ir – solar radiation intensity for each orientation [W/m^2];
- Q_1 – heat gain through envelope [kWh/year];
- Q_2[1] – heat transfer due to infiltration [kWh/year];
- Q_3 – internal heat gains [kWh/year].

2.3.1.3. Energy needs for water heating. The DHW needs are obtained applying the following equations:

$$Q_{ac}(x) = \left(\frac{Q_a}{\eta} - E_{solar}(x) - E_{ren}\right) \text{ [kWh/year]} \tag{2.19}$$

$$Q_a = 0.081 \cdot M_{AQS} \cdot n_d \text{ [kWh/year]} \tag{2.20}$$

$$E_{solar}(x) = \sum_{l}^{L} E_l^{sol} \cdot x_l^{sc} \text{ [kWh/year]} \tag{2.21}$$

where
Coefficient:

- η_a – DHW system efficiency;

Parameters:

[1] This term is a negative heat gain, as the average outdoor temperature is always less than indoor air set-point temperature in cooling season (Annex III, RCCTE).

- M_{AQS} – average daily reference consumption;
- n_d – annual number of days with DHW consumption;
- $E_l^{sol}(x)$ – energy contribution from solar collector type l;
- E_{ren} – energy contribution from other renewable sources;
- Q_a – energy supplied with conventional systems for DHW [kWh/year].

2.3.2. Retrofit cost

The overall investment cost for the retrofit of the building is calculated by adding the retrofit costs corresponding to each action as follows:

$$ReCost(x) = A_{win}\sum_{i=1}^{I} C_i^{WIN}\cdot x_i^{win} + A_{EWAL}\sum_{j=1}^{J} C_j^{EWAL}\cdot x_j^{EWAL} + A_{EWAL}\sum_{k=1}^{K} C_k^{ROF}\cdot x_k^{ROF} + \sum_{l}^{L} C_l^{SC}\cdot x_l^{SC} \quad (2.22)$$

where

- C_i^{WIN} – cost in [€/m^2] for window type i;
- C_j^{EWAL} – cost in [€/m^2] for external wall insulation material type j;
- C_k^{ROF} – cost in [€/m^2] for roof insulation material type k;
- C_l^{SC} – cost for solar collector type l.

2.4. Solution techniques

The decision variables, objective functions and constraints developed above, lead to the formulation of the multi-objective programming problem:

$$\begin{aligned}
&Min\, Z_1(x) = ReCost(x)\\
&Max\, Z_2(x) = ES(x)\\
&S.t.\\
&x_i^{win} \in \{0,1\}\ \forall i \in \{1,2,\ldots,I\}\\
&x_j^{EWAL} \in \{0,1\}\ \forall j \in \{1,2,\ldots,J\}\\
&x_k^{ROF} \in \{0,1\}\ \forall k \in \{1,2,\ldots,K\}\\
&x_l^{sc} \in \{0,1\}\ \forall l \in \{1,2,\ldots,L\}\\
&\sum_{i=1}^{I} x_i^{win} = 1\\
&\sum_{j=1}^{J} x_j^{EWAL} = 1\\
&\sum_{k=1}^{K} x_K^{ROF} = 1\\
&\sum_{l=1}^{L} x_l^{sc} = 1
\end{aligned} \quad (2.23)$$

Problem (2.23) is a combinatorial bi-objective problem, in which the objective functions cost and energy savings are conflicting.

The model has been implemented in MATLAB [18] and a Tchebycheff programming technique has been developed to tackle the multi-objective optimization.

To apply Tchebycheff programming, the decision model is rearranged to aggregate the two objective functions. In this method weighting vectors λ are used to define different weighted Tchebycheff metrics [19]. As a first step, the ideal objective function vector Z^* should be computed.

$$\begin{aligned}
Z_i^* &= \max\{Z_i(x)|x\in S\} \quad \text{if } Z_i \text{ to be maximized}\\
Z_i^* &= \min\{Z_i(x)|x\in S\} \quad \text{if } Z_i \text{ to be minimized}
\end{aligned} \quad (2.24)$$

The problem is then formulated in a way to compute the solutions closest to Z^*, according to those metrics. Therefore, the problem is formulated as follows:

$$\begin{aligned}
&Min\{\alpha\}\\
&s.t.\\
&\alpha \geq (Z_1(x) - Z_1^*)\left(\frac{\lambda_1}{Z_1^*}\right)\\
&\alpha \geq (Z_2^* - Z_2(x))\left(\frac{\lambda_2}{Z_2^*}\right)\\
&\alpha \geq 0\\
&x_i^{win} \in \{0,1\}\ \forall i \in \{1,2,\ldots,I\}\\
&x_j^{EWAL} \in \{0,1\}\ \forall j \in \{1,2,\ldots,J\}\\
&x_k^{ROF} \in \{0,1\}\ \forall k \in \{1,2,\ldots,K\}\\
&x_l^{sc} \in \{0,1\}\ \forall l \in \{1,2,\ldots,L\}\\
&\sum_{i=1}^{I} x_i^{win} = 1\\
&\sum_{j=1}^{J} x_j^{EWAL} = 1\\
&\sum_{k=1}^{K} x_K^{ROF} = 1\\
&\sum_{l=1}^{L} x_l^{sc} = 1
\end{aligned} \quad (2.25)$$

In this formulation, λ_1 and λ_2 are two constants representing the weight of each objective. These weights can be changed to obtain different compromise solutions. For strictly positive weight values this formulation yields solutions that are non-dominated (efficient, Pareto optimal): for each of these solutions there is no other solution able to improve one of the objectives without worsening the other objective.

3. An illustrative example

This section is aimed at illustrating how the approach described in Section 2 can be used to provide decision support for selecting a satisfactory compromise solution based on the MOO model. The building under study is a semi-detached house (one family) constructed in 1945, situated in central region of Portugal (Fig. 1). The number of degree-days, heating season duration, the average temperatures and the corresponding solar radiations have been extracted from the national regulation (RCCTE). The building has a ground floor and a basement. The two stories are connected by a staircase (Fig. 1). The gross floor area of the house is 97 m^2 and its average height is 2.47 m. The glazing area represents 10% of the floor area.

The building has a concrete structure. The walls are built in concrete with no thermal insulation (U = 2.37 W/m^2 K). The house has standard single glazing (U = 3.4 W/m^2 K) and window frames are in wood. Its main facade is toward south-east. The house is heated with electrical heaters, using a natural gas standard boiler for both space heating and sanitary hot water production.

According to the Portuguese regulations, internal temperatures for heating and cooling periods have been set to θ_{iH} = 20 °C and θ_{iC} = 25 °C, respectively. Temperature for heating water has been set to 45 °C. In addition, the internal heat gain per unit of floor area is set to 4 (W/m^2).

For heating, cooling and hot water supply, electricity is taken into account as the main source, while solar energy is only considered for hot water supply.

After introducing the required data into an excel spreadsheet, the program developed imports the data into MATLAB

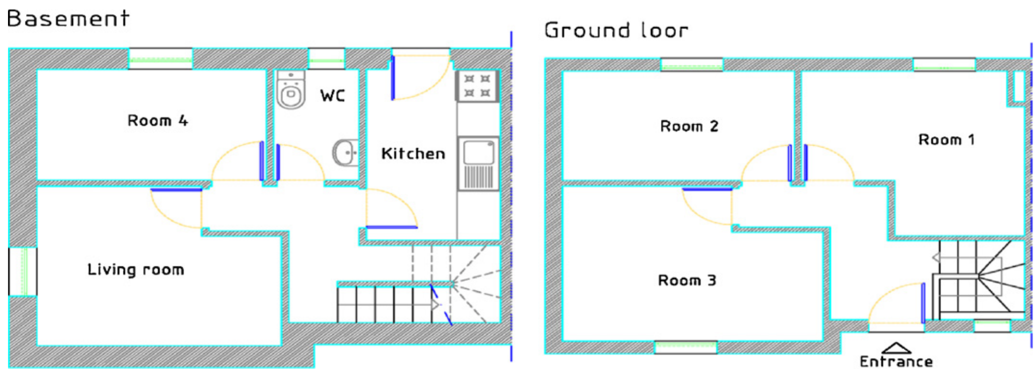

Fig. 1. Schematic plan of basement and ground floor of case study.

Table 1
Building energy analysis before retrofit.

Building performance indicators	
Estimated global annual primary energy for heating, cooling and water heating	12.89 [kgoe/m^2 year]
Existing building total energy consumption	31641.58 [kWh/year]
Existing building Energetic Classification	C
Existing building CO_2 emission	1.4945 [TCO_2/year]

automatically for further analysis, including prediction of the building energy use before retrofit.

The summary of results from the energy analysis of the building before retrofit is reported in Table 1.

A list of alternative retrofit actions applied in this study is based on a CYPE rehabilitation price generator database [20] extracted by the authors. Typical retrofit actions including different window types, external wall insulation materials, roof insulation materials, and solar collectors have been introduced on the list aiming at improving the building energy saving by decreasing energy consumption and retrofit cost. Tables 2–5 present the retrofit actions that will be referred to in the results (these are a subset of the 101 retrofit actions considered).

After the energy analysis of the building, the non-dominated solutions to the MOO problem that individually optimize each objective function are computed (solutions S1 and S2 in Table 6) using the function *bintprog* in MATLAB's optimization toolbox. The components of the ideal solution, which is the initial reference point, are displayed in bold italic. Table 6 also indicates the row numbers of corresponding retrofit actions leading to the S1 and S2

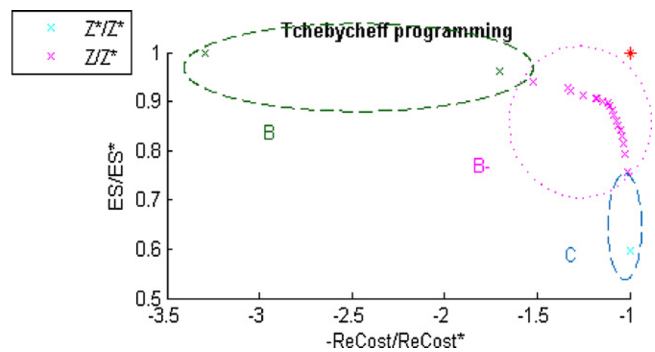

Fig. 2. Normalized multi objective solutions for the building retrofit strategies.

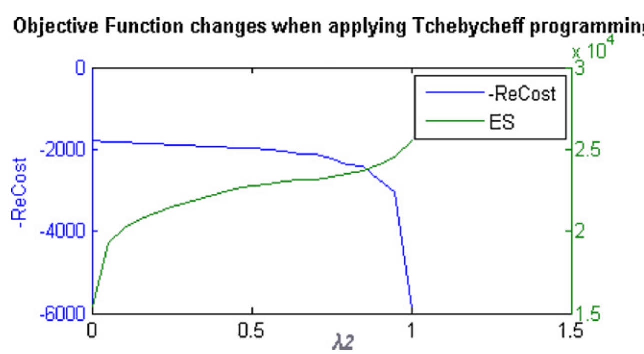

Fig. 3. Objective functions change when the corresponding weights in the Thebycheff formulation change.

Table 2
Characteristics of alternative windows.

N	Type	Thermal transmittance (W/m^2 °C)	Effective solar energy transmittance (%)	Cost (€/m^2)
1	Single glazing Typical glazing	5.10	85.00	34.08
2	2bl glazing Without thermal break Uncoated air-filled metallic frame 4-12-4	2.80	75.00	39.42
3	2bl glazing Without thermal break Uncoated air-filled metallic frame 4-16-4	2.70	75.00	40.31
4	2bl glazing Low-e window (with thermal break) coated air-filled metallic frame 4-12-4 NEUTRALUX	1.60	62.00	55.72
5	2bl glazing Window air-filled metallic frame 6-12-4 SOLARLUX Supernatural 70/40 Temprado	1.60	44.00	135.53

Table 3
Characteristics of alternative external wall insulation materials.

N	Insulation types	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m²)
1	Stone wool	0.03	0.034	11.25
2	Glass wool	0.05	0.038	12.67
3	EPS (expanded polystyren)	0.03	0.036	7.64
4		0.07	0.036	10.44
5		0.08	0.036	11.15
6		0.08	0.033	16.38
7		0.04	0.036	8.1
8		0.06	0.036	9.56
9	Sprayed polyurethane	0.02	0.042	6.39
10	Cork	0.01	0.04	3.05
11		0.10	0.04	17.95
12		0.15	0.04	26.93
13		0.30	0.04	53.85

Table 4
Characteristics of alternative roof insulation materials.

N	Insulation types	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m²)
1	Sprayed polyurethane	0.02	0.042	6.39
2	EPS (expanded polystyren)	0.03	0.033	4.32
3		0.04	0.033	5.6
4		0.05	0.033	6.87
5		0.06	0.033	8.14
6		0.07	0.033	9.43
7		0.08	0.033	10.7
8	XPS (extruded polystyren)	0.04	0.034	11.64
9	Stone wool	0.065	0.037	24.67
10		0.105	0.037	34.8

solutions, as well as the building energy classification after implementing the associated retrofit action package.

The non-dominated solution that minimizes the Tchebycheff distance (that is, minimizes the largest deviation) to the ideal solution is then computed for different combinations of objective function weight coefficients using a modified version of the *bintprog* function in MATLAB, which makes the construction of the non-dominated frontier possible. Table 7 shows the objective function values at an equally spaced finite number of λ values. As the weight coefficient of the energy saving objective increases, the solution to problem (2.25) approaches the optimum solution when only the second objective is optimized and finally reaches it (when $\lambda_1 = 0$, $\lambda_2 = 1$). As the weight coefficient of the retrofit cost objective function increases, the solution approaches the optimum solution when the first objective is optimized individually. The values in Table 7 were used to construct the graph shown in Fig. 2, displaying some of the points that lie on the non-dominated solution frontier. Choosing each solution from this frontier will lead to different retrofit cost/energy saving trade-offs, possibly leading to distinct energy classification of the building according to Portuguese code (RCCTE). The location of the ideal solution is also shown (red star). In terms of retrofit actions, we can note that in the right hand side of the curve a small increase of retrofit cost can lead to an improvement of the energy classification of the building from C to B⁻. In the left hand side, the situation is more difficult, and a large amount of investment is required to improve the energy classification of the building from B⁻ to B. This case highlights the major advantage of a multi-objective formulation, which is to provide a thorough understanding of the trade-offs between the competing objectives, and bring the potentiality of each investment into focus. In the current case the building owner could be easily convinced to slightly increase the amount of investment from €1791 to €1814 in order to improve energy classification of the building by one level.

Table 5
Characteristics of alternative solar collector systems.

N	Type	E_Solar (kWh)	Cost (€/m²)
1	AZIMUT145P1 (1plain collector with Thermosyphon)	1061	1645.1
2	AZIMUT192P2 (2plain collector with Thermosyphon)	1865	2402.27
3	JUNKERS (1plain collector with Thermosyphon) A1/TS150/FKB	1048	1900.9
4	DANOSA SOLAR TDS150/CIS (1plain collector with Thermosyphon)	1048	1465.47
5	DANOSA SOLAR TDS200/CIS (2plain collector with Thermosyphon)	1900	2113.5
6	JUNKERS (2plain collector with Thermosyphon) A1/TS150/FKB Inclination39	1920	3135.54

Note: E_Solar (kWh) that is the energy production from solar collector has been calculated by SOLTERM software [21] which is developed by the Portuguese National Laboratory for Energy and Geology (LNEG).

Table 6
Non-dominated solutions.

Solution	*ReCost* (€)	*ES* (kWh/year)	Window type	*EWAL* insulation	*ROF* insulation	Solar collector	Energy classification
S1	***1791***	15263	1	10	1	4	C
S2	5901	***25539***	4	13	10	6	B

Table 7
Problem solution applying Tchebycheff programming.

Z	λ_1	λ_2	*ReCost* (€)	*ES* (kWh/year)	Window type	*EWAL* insulation	*ROF* insulation	Solar collector	Energy classification
0.00	1.00	0.00	1791.12	15263.06	1	10	1	4	C
0.02	0.90	0.10	1834.12	20229.46	1	7	3	4	B⁻
0.03	0.80	0.20	1865.05	21165.40	1	8	3	4	B⁻
0.04	0.70	0.30	1902.73	21765.78	1	4	5	4	B⁻
0.05	0.60	0.40	1941.81	22306.88	2	4	4	4	B⁻
0.05	0.50	0.50	1983.58	22769.88	2	5	6	4	B⁻
0.06	0.40	0.60	2057.09	23025.45	3	6	7	4	B⁻
0.07	0.30	0.70	2117.15	23158.30	3	11	7	4	B⁻
0.06	0.20	0.80	2361.89	23511.42	2	12	5	4	B⁻
0.05	0.10	0.90	2729.42	24047.54	4	12	10	4	B⁻
0.00	0.00	1.00	5901.16	25539.47	4	13	10	6	B

Fig. 3 demonstrates how the objective values change in relation with the specific value of the weights. This figure clearly shows the competitive nature of objective functions. As the weight on energy saving (λ_2) increases, the set of actions leading to higher energy savings and at the same time higher cost have been selected.

4. Conclusions and future work

Technological advances and new construction methods and techniques mean that in the very near future all new buildings can be nearly zero energy buildings. The big challenge is therefore existing buildings as these represent such a high proportion of world energy consumption and they will be with us for many decades to come. One of the best opportunities to improve energy efficiency of the buildings would be during building retrofit. One of the key steps in building retrofit is the selection of retrofit actions among a large number of possibilities. The problem is in fact a multi-objective optimization problem, characterized by the existence of multiple and competing objectives, a set of feasible solutions that are not predefined but are implicitly defined by a set of parameters and a set of constraints that should be taken into account to reach the best possible solution. However, the problem is usually approached through simulation that focuses on particular aspects of the problem rather than a global confrontation. Accordingly, the aim of this paper was to develop a multi-objective mathematical model to provide decision support in the evaluation of technology choices for the building retrofit strategies. The model allows explicitly for the simultaneous consideration of all available combinations of alternative retrofit actions. It also allows for the consideration of logical, physical and technical constraints. The result of the application of a Tchebycheff programming technique to compute solutions to the model shows the feasibility of this methodology to find well balanced strategies for retrofitting of buildings to be presented to a DM in the framework of a decision support process.

As stated earlier, to limit the computational time, a simple thermal model of the building has been developed based on the current methodology of the Portuguese building thermal code (RCCTE). It would be interesting to include more objective functions related to the building behaviour such as an indoor thermal comfort or indoor air quality [22] that need a monthly or even hourly simulation. Unfortunately, this model is not able to perform such a detailed analysis of buildings. Therefore it remains to incorporate in the future more detailed thermal simulation such as an equivalent resistance–capacitance (R–C) model, which uses an hourly time step. The mentioned model makes a distinction between the internal air temperature and mean temperature of the internal surfaces (mean radiant temperature) that enables its use for thermal comfort considerations and increases the accuracy of building thermal model.

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