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A multi-objective decision model for the improvement of energy efficiency in buildings

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ABSTRACT

Improving energy efficiency in buildings is a major priority worldwide. The measures employed to save energy vary in nature, and the decision maker is required to establish an optimal solution, taking into account multiple and usually competitive objectives such as energy consumption, financial costs, environmental performance, etc. In other words, the decision maker is facing the challenge to solve a multi-objective optimization problem, although the common practice usually employs other methods like simulation and multiple criteria decision analysis techniques that exploit possibly many but in any case limited alternative options. The multi-objective decision model, presented herein, aims to overcome this limitation by allowing the examination of a potentially infinite number of alternative measures, evaluated according to a set of criteria, which include the annual primary energy consumption of the building, the annual carbon dioxide emissions and the initial investment cost. These criteria are adjusted to the decision maker's preferences and are optimized with the aid of compromise programming, which is a well-established multi-objective solution methodology. A simple case study is used to demonstrate the functionality of the proposed decision model. The results verify the feasibility of the approach, thus encouraging further improvements and extensions.

1. Introduction

The appreciation, within the European Union (EU) members, of the need for enhanced energy control and regulation in the building sector, which in fact accounts for approximately 40% of the total energy requirements, led to establishment of the Energy Performance in Buildings Directive (EPBD) 2002/91/EC [1] to improve building energy performance. The increasing energy consumption in buildings is accountable for the emission of considerable amounts of carbon dioxide (CO_2) in the environment, as well as for other macroeconomic or microeconomic implications such as the increase of the EU energy dependency, the high operational buildings' cost, etc. Amongst worldwide scale organizations, the International Organization for Standardization (ISO), the European Committee for Standardization (CEN) and the International Energy Agency (IEA) have complementary provided strategic and operational directions towards the implementation of energy efficiency improvements in buildings [2]. Additionally, due to the potential of reducing energy requirements in buildings, the EU is stepping up financial support to upgrade their energy performance, preparing at the same time the ground for new buildings producing at least as much energy as they consume on site by the end of 2018.

The "conventional" measures that can be employed to improve energy performance in buildings can be classified in those that immediately relate to the building envelope i.e., the constructional elements, and those that relate to the operation of energy systems used for heating, cooling, ventilation, hot water supply, etc. [3]. Apart from "conventional" type measures, energy management techniques combined with innovative environmental technologies and advanced materials and systems may, if properly applied, affect drastically the process of saving energy in the building sector.

A critical aspect in the design but also in the operational phase of a building, when renovation or retrofit actions are needed, is the evaluation and adjustment of the alternative measures based on a set of criteria such as energy consumption, environmental performance, investment cost, operational cost, indoor environment quality, security, social factors, etc. [3]. In some cases, the aforementioned criteria are competitive in nature, or interrelate in

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a non-linear way, making the problem of reaching a globally optimal solution generally infeasible. For this reason, a feasible intermediary solution is peered that will satisfy the specific requirements of the building's final user/occupant/owner. In practice, seeking such a solution is mainly attempted via two main approaches (see [3] for a complete review).

According to the first approach, an energy analysis of the building under study is carried out, and several alternative scenarios, predefined by a building expert, are developed and evaluated [4]. These specific scenarios, which may vary according to the buildings' characteristics, type, use, climatic conditions, etc., are pinpointed by the building expert and evaluated mainly through simulation (see e.g. [5–10]). The selection of the alternative scenarios, energy efficiency measures and actions is, thus, largely based on the building expert's experience.

The second approach includes decision supporting techniques, such as multicriteria-based decision making methods combined usually with simulation to assist the reaching of a final decision among a set of alternative actions predefined by the building expert (see e.g. [11–17]).

In both of the aforementioned approaches, therefore, the whole process as well as the final decisions are significantly affected by the experience and the knowledge of the corresponding building expert who, from now on, will be mentioned herein as "decision maker" (DM). Although this experience and knowledge are certainly significant and irreplaceable elements to the whole process, it is essential to develop practical tools that will assist the expert to address the problem in its full extend, and overcome the restrictions imposed by the predefined scenarios. To this end, new approaches evolved combining simulation with notions and concepts originating from the scientific area of multi-objective optimization (see e.g. [18–21]), which offers a wide variety of methods with great potential for the development of stand-alone tools assisting the solution of complicated decision problems ([22,23]).

Following the concepts of multi-objective optimization, Diakaki et al. [24] conducted some preliminary work, which indicated that indeed, it is feasible to develop a stand-alone decision tool for the improvement of the energy efficiency in buildings. The present paper aims to extend that initial and rather simplified modelling approach. The extended model is applicable to buildings that are in the design phase, and allows the DM to obtaining globally optimum solutions among practically infinite alternative measures according to the his/her preferences. This is accomplished with the aid of weight coefficients, which are set to define the relative importance of the criteria (objectives) according to the DM's preferences. The criteria concern energy consumption, investment cost and release of CO_2 emissions, and make use of decision variables which represent the selection of alternative materials for the building envelope and systems for space heating, cooling and hot water supply. The model is developed in a generic way so that it is not constrained to buildings of a particular type, size or use, and can be easily extended to complex building structures, as well as to buildings that are in the operational phase. A simple case study is used to demonstrate the functionality of the proposed model.

The paper is structured in three more sections. Section 2 presents the proposed multi-objective decision model, while Section 3 describes the model application to the simple case study. Finally, Section 4 summarises conclusions and discusses issues for future consideration, research and development.

2. The multi-objective decision model

2.1. Problem definition and basic principles

The proposed decision model focuses on the design phase of the buildings, although it could be easily extended to assist their energy performance improvement during their operational phase. Based on architectural plans, a decision model is developed to assist decisions concerning the structure of the building envelope and the acquisition and installation of systems for space heating, cooling and hot water supply.

Decisions are made so as to reduce the energy consumption and the release of CO_2 emissions foreseen for the operational phase of the building, at the most cost-effective way. These objectives are competitive in nature, since energy efficient and environmental friendly materials and equipment are usually more expensive than the corresponding conventional ones, while at the same time, energy efficient equipment may be less environmental friendly than other less efficient, due to the specific fuel of use. Addressing the problem requires careful design of the objectives, decision variables, criteria and constraints matched to the appropriate solution technique.

The decision variables, discrete and/or continuous, should reflect the total set of alternative measures that are available for the improvement of energy efficiency. The objectives to be achieved should be clearly defined and formulated into appropriate linear and/or non-linear mathematical expressions. The set of the feasible solutions should be delimitated through the identification of linear and/or non-linear constraints concerning either the decision variables and their intermediary relations or the objectives of the problem. Natural and logical constraints may also be considered as necessary. Finally, an appropriate solution method should be identified that will be able to handle the continuous as well as discrete decision variables and linear and non-linear objective functions and constraints. Following sub-sections describe the details of the proposed decision approach.

2.2. Decision variables and constraints

2.2.1. Building envelope-related decision variables and constraints

Building envelope comprises the boundary that separates the building from the outside environment, and greatly affects its thermal behaviour, since its construction defines actually the future energy requirements for heating and cooling. Building envelope is mainly composed of two different types of construction components [4]: *single-layer* components and *multi-layer* components. Single-layer components are these components that are considered to have one homogeneous construction layer with a unique thermal transmittance or *U*-value which defines their thermal behaviour. The doors and the windows of a building are normally assumed to be single-layer components of the building envelope. On the other hand, multi-layer components are composed of at least two homogeneous layer parts of different materials (e.g. concrete, insulation and gypsum board). In this case, the thermal transmittance of the whole construction, and subsequently its thermal behaviour, depends upon the thermal behaviour of each of the individual homogeneous layer parts that comprise the whole construction, which is defined by its thermal resistance or *R*-value.

The aforementioned *U* and *R*-values, determine therefore the thermal behaviour of the whole building, and depend upon the material or combination of materials (in the case of multi-layer constructions) being used and their corresponding thicknesses. Therefore, a decision model concerning the construction of the building envelope should include decision variables reflecting the choices on materials, as well as the choices on combinations of materials and materials thicknesses, when necessary. To this end, the following types of decision variables are defined:

- Decision variables to reflect the alternative choices regarding the doors type.
- Decision variables to reflect the alternative choices regarding the windows type.

- Decision variables to reflect the alternative choices regarding the structure of the multi-layer components such as walls, ceilings and floors.
- Decision variables to reflect the alternative choices regarding materials and corresponding thicknesses to be used in the multi-layer construction components such as walls, ceilings and floors.

For simplicity reasons, it is assumed that only one door type may be selected for all doors and only one window type for all windows of the considered building. It is also assumed that for all walls of the building under study, there is a common selection regarding its construction layers, materials and thicknesses. The same applies also for all the ceilings and the floors. These decision variables are described below.

Assuming availability of V alternative types of doors and S alternative types of windows (e.g. single and double glazing windows), each including T_s with $s = 1,\ldots,S$, alternative sub-types (e.g. air-filled and argon filled double glazing windows), binary variables x_v^{DOR} with $v = 1,\ldots,V$ and x_{st}^{WIN} with $t = 1,\ldots,T_s$ are defined as follows:

$$x_v^{DOR} = \begin{cases} 1, & \text{if door type } v \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{1}$$

$$x_{st}^{WIN} = \begin{cases} 1, & \text{if window sub-type } t \text{ of type } s \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{2}$$

Since only one door and window type may be selected, the following constraints should hold for the previously defined decision variables:

$$\sum_{v=1}^{V} x_v^{DOR} = 1 \tag{3}$$

$$\sum_{s=1}^{S} \sum_{t=1}^{T_s} x_{st}^{WIN} = 1 \tag{4}$$

As far as the walls of the considered building are concerned, it is assumed that a choice among W alternative structures (e.g. brick-insulation, brick-insulation-brick) is possible. To this end, binary decision variables x_w^{WAL} with $w = 1,\ldots,W$ are defined as follows:

$$x_w^{WAL} = \begin{cases} 1, & \text{if wall structure } w \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{5}$$

Since only one structure may be selected for all the walls of the building, the following constraint should be obeyed:

$$\sum_{w=1}^{W} x_w^{WAL} = 1 \tag{6}$$

Each of the aforementioned wall structures w is further assumed to be comprised of a number KWL_w of layers for which both the materials and consequently their thermal conductivities $kk_{w,kwl}^{dWAL}$ (W/m °C) and the thicknesses $d_{w,kwl}^{dWAL}$ (m), with $kwl = 1,\ldots,KWL_w$, are predefined and therefore known, and a number Y_w of layers for which both the materials and thicknesses have to be decided. It is also assumed that for each of the unknown layer $y = 1,\ldots,Y_w$ of structure w, C_{wy} alternative materials are available one of which should be selected for the chosen wall structure, i.e., for that w for which $x_w^{WAL} = 1$ will hold. To this end, binary decision variables x_{wyc}^{mWAL} with $c = 1,\ldots,C_{wy}$ are defined as follows:

$$x_{wyc}^{mWAL} = \begin{cases} 1, & \text{if material } c \text{ is selected for layer } y \text{ of wall structure } w \\ 0, & \text{else} \end{cases} \tag{7}$$

for which, the constraint of Eq. (8) should hold:

$$\sum_{c=1}^{C_{wy}} x_{wyc}^{mWAL} = x_w^{WAL} \ \forall (y = 1,\ldots,Y_w \ \forall w = 1,\ldots,W) \tag{8}$$

since, as mentioned earlier, materials should be selected only for the chosen wall structure.

In addition, for each of the unknown layer y of wall structure w, the thickness (m) should be defined. To this end, corresponding decision variables x_{wy}^{dWAL} are defined. Thickness is a non-negative real number that is only constrained by the available space for the considered wall layer, i.e., $x_{wy}^{dWAL} \le d_{\max,wy}^{WAL}$ with $d_{\max,wy}^{WAL}$ the maximum permissible thickness (m) of layer y of wall structure w. Nevertheless, if this proves to be more beneficial (e.g. for the reduction of the initial investment cost), layers should be omitted from a particular wall structure by setting their thickness equal to 0. In simple words, it should be possible for some layers y to get $x_{wy}^{dWAL} = 0$, although the corresponding wall structure will have been selected. To reflect all these specifications for the decision variables expressing the thicknesses of the unknown construction layers of the building walls, the following constraint should apply:

$$x_{wy}^{dWAL} \in \left[0, d_{\max,wy}^{WAL}\right] \ \forall (y = 1,\ldots,Y_w \ \forall w = 1,\ldots,W) \tag{9}$$

In a similar way, decision variables are defined for the ceilings and the floors of the building. Assuming availability of D and H alternative ceiling and floor structures, respectively, binary decision variables x_d^{CEIL} with $d = 1,\ldots,D$ and x_h^{FLO} with $h = 1,\ldots,H$ are defined as follows:

$$x_d^{CEIL} = \begin{cases} 1, & \text{if ceiling structure } d \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{10}$$

$$x_h^{FLO} = \begin{cases} 1, & \text{if floor structure } h \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{11}$$

for which the following constraints should hold:

$$\sum_{d=1}^{D} x_d^{CEIL} = 1 \tag{12}$$

$$\sum_{h=1}^{H} x_h^{FLO} = 1 \tag{13}$$

Each of the aforementioned ceiling structures d is further assumed to be comprised of a number KCL_d of layers for which both the materials and consequently their thermal conductivities $kk_{d,kcl}^{dCEIL}$ (W/m °C) and the thicknesses $d_{d,kcl}^{dCEIL}$ (m), with $kcl = 1,\ldots,KCL_d$, are predefined and known, and a number F_d of layers for which both the materials and thicknesses have to be decided. It is also assumed that for each of the unknown layer $f = 1,\ldots,F_d$ of structure d, A_{df} alternative materials are available one of which should be selected for the chosen ceiling structure. To this end, binary decision variables x_{dfa}^{mCEIL} with $a = 1,\ldots,A_{df}$ are defined as follows:

$$x_{dfa}^{mCEIL} = \begin{cases} 1, & \text{if material } a \text{ is selected for layer } f \text{ of ceiling structure } d \\ 0, & \text{else} \end{cases} \tag{14}$$

for which the constraint of Eq. (15) should hold:

$$\sum_{a=1}^{A_{df}} x_{dfa}^{mCEIL} = x_d^{CEIL} \ \forall (f = 1,\ldots,F_d \ \forall d = 1,\ldots,D) \tag{15}$$

Moreover, each of the aforementioned floor structures h is assumed to be comprised of a number KFL_h of layers for which both the materials and consequently their thermal conductivities $kk_{h,kfl}^{dFLO}$ (W/m °C) and the thicknesses $d_{h,kfl}^{dFLO}$ (m), with $kfl = 1,\ldots,KFL_h$, are predefined and known, and a number E_h of layers for which both the materials and thicknesses have to be decided. It is also assumed that for each of the unknown layer $e = 1,\ldots,E_h$ of structure h, G_{he} alternative materials are available one of which should be selected for the chosen floor structure. To this end, binary decision variables x_{heg}^{mFLO} with $g = 1,\ldots,G_{he}$ are defined as follows:

$$x_{heg}^{mFLO} = \begin{cases} 1, & \text{if material } g \text{ is selected for layer } e \text{ of floor structure } h \\ 0, & \text{else} \end{cases} \tag{16}$$

for which the constraint of Eq. (17) should hold:

$$\sum_{g=1}^{G_{he}} x_{heg}^{mFLO} = x_h^{FLO} \ \forall (e = 1,\ldots,E_h \ \forall h = 1,\ldots,H) \tag{17}$$

Finally, decision variables x_{df}^{dCEIL} and x_{he}^{dFLO} are defined to reflect the thicknesses (m) of the unknown layer $f = 1,\ldots,F_d$ of ceiling structure d, and $e = 1,\ldots,E_h$ of floor structure h, respectively, for which the following constraints should apply:

$$x_{df}^{dCEIL} \in \left[0, d_{\max,df}^{CEIL}\right] \ \forall (f = 1,\ldots,F_d \ \forall d = 1,\ldots,D) \tag{18}$$

$$x_{he}^{dFLO} \in \left[0, d_{\max,he}^{FLO}\right] \ \forall (e = 1,\ldots,E_h \ \forall h = 1,\ldots,H) \tag{19}$$

where $d_{\max,df}^{CEIL}$ and $d_{\max,he}^{FLO}$ are the maximum permissible thicknesses (m) of layer f of ceiling structure d, and e of floor structure h, respectively.

2.2.2. Building systems-related decision variables and constraints

As far as heating, cooling and hot water supply are concerned, the systems available in the market are considered, for modelling purposes, to fall in one or more of the following categories:

- *Heating systems*: This category includes systems that will be considered only for heating purposes, although some of them may equally provide for space cooling or hot water supply. They are divided in electrical and non-electrical systems, and the non-electrical systems are further divided upon the specific fuel of use.
- *Cooling systems*: This category includes systems that will be considered only for cooling purposes, although they may also be used for heating purposes, as all known cooling systems can do. They operate only with electricity.
- *Domestic Hot Water* (*DHW*) *systems*: This category includes systems that will be considered only for hot water supply purposes, although some of them may equally provide for space heating. They are divided in electrical and non-electrical systems, and the non-electrical systems are further divided upon the specific fuel of use.
- *Heating–cooling systems*: This category includes systems that will be considered for the provision of both space heating and cooling. They operate only with electricity.
- *Heating–DHW systems*: This category includes systems that will be considered for the provision of both space heating and hot water supply. They are divided in electrical and non-electrical systems, and the non-electrical systems are further divided upon the specific fuel of use.
- *Solar collector systems*: The category includes systems that provide hot water supply via solar energy.

Within each of the aforementioned categories, a further division could be done, based on other characteristics that may be of interest to the DM. It should be noted, here, that the above categorisation is made so as to allow for the model to consider all possible combinations of systems for the provision of heating, cooling and hot water supply. As a result of this categorisation, it is possible for a particular system to appear in more than one category depending on its foreseen use. If, for example, a particular heating system should be considered either for the provision of space heating or for the provision of both space heating and cooling, it will be included in both the heating and the heating–cooling systems categories, while if it should be considered only for space heating, it will be included in the heating systems category only.

To allow for appropriate choices among the aforementioned systems, several decision variables and related constraints have to be defined as described below.

Assuming availability of

- EHI electrical heating systems categories each of which includes EHJ_{ehi} different systems with $ehi = 1,\ldots,EHI$, and $NEHI$ non-electrical heating systems categories each of which includes $NEHJ_{nehi}$ different systems with $nehi = 1,\ldots,NEHI$,
- ECI electrical cooling systems categories each of which includes ECJ_{eci} different systems with $eci = 1,\ldots,ECI$,
- EWI electrical DHW systems categories each of which includes EWJ_{ewi} different systems with $ewi = 1,\ldots,EWI$, and $NEWI$ non-electrical DHW systems categories each of which includes $NEWJ_{newi}$ different systems with $newi = 1,\ldots,NEWI$,
- $EHCI$ electrical heating–cooling systems categories each of which includes $EHCJ_{ehci}$ different systems with $ehci = 1,\ldots,EHCI$,
- EHW electrical heating–DHW systems categories each of which includes $EHWJ_{ehwi}$ different systems with $ehwi = 1,\ldots,EHWI$, and $NEHWI$ non-electrical heating–DHW systems categories each of which includes $NEHWJ_{nehwi}$ different systems with $nehwi = 1,\ldots,NEHWI$,

binary variables $x_{ehi,ehj}^{EH}$ with $ehj = 1,\ldots,EHJ_{ehi}$, $x_{nehi,nehj}^{NEH}$ with $nehj = 1,\ldots,NEHJ_{nehi}$, $x_{eci,ecj}^{EC}$ with $ecj = 1,\ldots,ECJ_{eci}$, $x_{ewi,ewj}^{EW}$ with $ewj = 1,\ldots,EWJ_{ewi}$, $x_{newi,newj}^{NEW}$ with $newj = 1,\ldots,NEWJ_{newi}$, $x_{ehci,ehcj}^{EHC}$ with $ehcj = 1,\ldots,EHCJ_{ehci}$, $x_{ehwi,ehwj}^{EHW}$ with $ehwj = 1,\ldots,EHWJ_{ehwi}$, and $x_{nehwi,nehwj}^{NEHW}$ with $nehwj = 1,\ldots,NEHWJ_{nehwi}$ are defined as follows:

$$x_{ehi,ehj}^{EH} = \begin{cases} 1, & \text{if electrical heating system } ehj \text{ of category } ehi \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{20}$$

$$x_{nehi,nehj}^{NEH} = \begin{cases} 1, & \text{if non-electrical heating system } nehj \text{ of category } nehi \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{21}$$

$$x_{eci,ecj}^{EC} = \begin{cases} 1, & \text{if electrical cooling system } ecj \text{ of category } eci \text{ is selected} \\ 0, & \text{else} \end{cases} \tag{22}$$

$$x^{EW}_{ewi,ewj} = \begin{cases} 1, & \text{if electrical DHW system } ewj \text{ of category } ewi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (23)$$

$$x^{NEW}_{newi,newj} = \begin{cases} 1, & \text{if non – electrical DHW system } newj \text{ of category } newi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (24)$$

$$x^{EHC}_{ehci,ehcj} = \begin{cases} 1, & \text{if electrical heating–cooling system } ehcj \text{ of category } ehci \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (25)$$

$$x^{EHW}_{ehwi,ehwj} = \begin{cases} 1, & \text{if electrical heating–DHW system } ehwj \text{ of category } ehwi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (26)$$

$$x^{NEHW}_{nehwi,nehwj} = \begin{cases} 1, & \text{if non – electrical heating–DHW system } nehwj \text{ of category } nehwi \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (27)$$

For simplicity purposes, it is assumed that only one from all available systems providing heating, is selected. The same applies for all systems providing cooling, as well as for the DHW systems. Moreover, in case that a system is chosen to provide both space heating and cooling or space heating and hot water supply, no further system will be selected for that same purpose. To apply this rationale, the following constraints should hold for the decision variables defined by Eqs. (20)–(27):

- For the selection of only one system to provide space heating among all available heating, heating–cooling and heating–DHW systems:

$$\sum_{ehi=1}^{EHI}\sum_{ehj=1}^{EHJ_{ehi}} x^{EH}_{ehi,ehj} + \sum_{ehci=1}^{EHCI}\sum_{ehcj=1}^{EHCJ_{ehci}} x^{EHC}_{ehci,ehcj} + \sum_{ehwi=1}^{EHWI}\sum_{ehwj=1}^{EHWJ_{ehwi}} x^{EHW}_{ehwi,ehwj} + \sum_{nehi=1}^{NEHI}\sum_{nehj=1}^{NEHJ_{nehi}} x^{NEH}_{nehi,nehj} + \sum_{nehwi=1}^{NEHWI}\sum_{nehwj=1}^{NEHWJ_{nehwi}} x^{NEHW}_{nehwi,nehwj} = 1 \quad (28)$$

- For the selection of only one system to provide space cooling among all available cooling and heating–cooling systems:

$$\sum_{eci=1}^{ECI}\sum_{ecj=1}^{ECJ_{eci}} x^{EC}_{eci,ecj} + \sum_{ehci=1}^{EHCI}\sum_{ehcj=1}^{EHCJ_{ehci}} x^{EHC}_{ehci,ehcj} = 1 \quad (29)$$

- For the selection of only one DHW system among all available DHW and heating–DHW systems:

$$\sum_{ewi=1}^{EWI}\sum_{ewj=1}^{EWJ_{ewi}} x^{EW}_{ewi,ewj} + \sum_{ehwi=1}^{EHWI}\sum_{ehwj=1}^{EHWJ_{ehwi}} x^{EHW}_{ehwi,ehwj} + \sum_{newi=1}^{NEWI} \times \sum_{newj=1}^{NEWJ_{newi}} x^{NEW}_{newi,newj} + \sum_{nehwi=1}^{NEHWI}\sum_{nehwj=1}^{NEHWJ_{nehwi}} x^{NEHW}_{nehwi,nehwj} = 1 \quad (30)$$

Finally, assuming availability of U solar collector systems categories each of which includes B_u different solar collector systems with $u = 1,\ldots,U$, binary variables x^{SLC}_{ub} with $b = 1,\ldots,B_u$ are defined as follows:

$$x^{SLC}_{ub} = \begin{cases} 1, & \text{if solar collector } b \text{ of category } u \text{ is selected} \\ 0, & \text{else} \end{cases} \quad (31)$$

for which the constraint of Eq. (32) should apply:

$$\sum_{u=1}^{U}\sum_{b=1}^{B_u} x^{SLC}_{ub} \le 1 \quad (32)$$

to allow for the model to choose one or even no solar collector, if this proves to be more beneficial (e.g. for the reduction of the initial investment cost).

2.3. Decision criteria

2.3.1. Energy consumption

The primary energy sources in a building are consumed for space heating, cooling and DHW systems and for electric lighting. While in this specific model electric lighting is not considered, the formula that reflects building's primary energy needs, and consequently, the corresponding operational costs, reads:

$$Q_T = Q_H + Q_C + Q_{DHW} \quad (33)$$

where Q_T is the total annual primary energy consumption (MJ/year), and Q_H, Q_C and $Q_{DHW}$are the total annual primary energy consumption (MJ/year) by the space heating, cooling and DHW systems, respectively.

The total annual primary energy consumption for space heating depends upon the particular source of energy that the heating system uses and may be calculated according to the following equation [25]:

$$Q_H = \frac{Q^H_{el}}{n_{el}} + \sum_{fuel=1}^{FUEL} Q^H_{nel,fuel} \quad (34)$$

where, Q^H_{el} represents the annual energy (MJ/year) consumed by an electrical system and n_{el} is the return rate (%) of the electricity power plant, while $Q^H_{nel,fuel}$ represents the annual energy consumed (MJ/year) by a non-electrical system that uses a particular fuel $fuel = 1,\ldots,FUEL$, with $FUEL$ the total number of available fuels that may be used alternatively to electricity (e.g. gas or oil).

The energy consumption of a particular system may be calculated taking into account the energy demand and the generation efficiency of the system. To this end, the following equations may be used:

$$Q^{H}_{el} = Q^{HD} SEH_{el} \tag{35}$$

$$Q^{H}_{nel,fuel} = Q^{HD} SEH_{nel,fuel} \quad \forall fuel \in \{1, \dots, FUEL\} \tag{36}$$

where Q^{HD} is the total annual energy demand (MJ/year) for space heating purposes, while SEH_{el} and $SEH_{nel,fuel}$ represent the generation efficiency of the system that will be finally selected for the provision of the required heating energy. To this end, taking into account the decision variables, which correspond to all available systems that provide space heating, as defined in Section 2.2.2, and their corresponding efficiencies, SEH_{el} and $SEH_{nel,fuel}$ are calculated according to the following equations:

$$SEH_{el} = \sum_{ehi=1}^{EHI} \sum_{ehj=1}^{EHJ_{ehi}} \left(\frac{x^{EH}_{ehi,ehj}}{e^{EH}_{ehi,ehj}} \right) + \sum_{ehci=1}^{EHCI} \sum_{ehcj=1}^{EHCJ_{ehci}} \left(\frac{x^{EHC}_{ehci,ehcj}}{e^{EHC}_{ehci,ehcj}} \right) + \sum_{ehwi=1}^{EHWI} \sum_{ehwj=1}^{EHWJ_{ehwi}} \left(\frac{x^{EHW}_{ehwi,ehwj}}{e^{EHW}_{ehwi,ehwj}} \right) \tag{37}$$

$$SEH_{nel,fuel} = \sum_{nehi=1}^{NEHI} \sum_{nehj=1}^{NEHJ_{nehi}} \left(\frac{x^{NEH}_{nehi,nehj} FU^{NEH}_{nehi,nehj,fuel}}{e^{NEH}_{nehi,nehj}} \right) + \sum_{nehwi=1}^{NEHWI} \sum_{nehwj=1}^{NEHWJ_{nehwi}} \left(\frac{x^{NEHW}_{nehwi,nehwj} FU^{NEHW}_{nehwi,nehwj,fuel}}{e^{NEHW}_{nehwi,nehwj}} \right) \quad \forall fuel \in \{1, \dots, FUEL\} \tag{38}$$

where $e^{EH}_{ehi,ehj}$, $e^{EHC}_{ehci,ehcj}$ and $e^{EHW}_{ehwi,ehwj}$ denote the generation efficiencies (%) of the electrical heating system ehj of category ehi, the electrical heating–cooling system $ehcj$ of category $ehci$ and the electrical heating–DHW system $ehwj$ of category $ehwi$, respectively, and $e^{NEH}_{nehi,nehj}$ and $e^{NEHW}_{nehwi,nehwj}$ denote the generation efficiencies (%) of the non-electrical heating system $nehj$ of category $nehi$ and the non-electrical heating–DHW system $nehwj$ of category $nehwi$, respectively. In addition $FU^{NEH}_{nehi,nehj,fuel}$ and $FU^{NEHW}_{nehwi,nehwj,fuel}$ are parameters indicating whether a particular non-electrical heating system $nehj$ of category $nehi$ and a non-electrical heating–DHW system $nehwj$ of category $nehwi$, respectively, utilise a particular fuel $fuel = 1,\dots,FUEL$. Each of these latter parameters gets the value 1, if the corresponding system uses a specific fuel type else, it becomes equal to 0. Obviously, the activation of the constraint of Eq. (28) in combination with Eqs. (35)–(38) will lead to the selection of only one system for the provision of space heating, the generation efficiency of which will finally determine the energy consumption for heating purposes, according to Eq. (34).

The calculation of the annual primary energy consumption via Eqs. (34)–(38) requires also the estimation of the annual energy heating demand, which is obtained by the sum of the heating demand Q^{HD}_{n} (MJ/month) for each month $n = 1,\dots,12$ of a year:

$$Q^{HD} = \sum_{n=1}^{12} Q^{HD}_{n} \tag{39}$$

The monthly heat demand Q^{HD}_{n} is a result of many factors [26]. It increases due to the monthly transmission $Q_{T,n}$ and ventilation $Q_{VEN,n}$ heat losses (MJ/year) and decreases due to the internal heat gains $Q_{INHG,n}$ and the solar gains $Q_{SL,n}$ (MJ/month) via the openings, i.e., the windows, of the building. According to these, the monthly heat demand may be calculated as follows:

$$Q^{HD}_{n} = \begin{cases} HS_{n}\left(Q_{T,n} + Q_{VEN,n} - Q_{INHG,n} - Q_{SL,n}\right), & \text{if positive} \\ 0, & \text{else} \end{cases}$$

$$Q^{HD}_{n} = \begin{cases} HS_{n}\left(BLC(\theta_{IH} - \theta_{E,n})T_{n} + \rho_{air} c_{air} V_{air}(\theta_{IH} - \theta_{E,n}) - Q_{AINHG} T_{n} - \sum_{wn=1}^{WN}\left(A^{WIN}_{wn} F_{F,wn} F_{S,wn} F_{CM,wn} I_{SL,wn,n} \sum_{s=1}^{S} \sum_{t=1}^{T_{s}} \left(x^{WIN}_{st} g^{WIN}_{st}\right)\right)\right), & \text{if positive} \\ 0, & \text{else} \end{cases} \tag{40}$$

where HS_{n} is a parameter indicating whether heating is required for month n (when $HS_{n} = 1$) or not (when $HS_{n} = 0$), BLC is the building load coefficient (W/°C), θ_{IH} and $\theta_{E,n}$ are the internal design temperature (°C) during the heating season and the average external temperature (°C) during month n, respectively, and T_{n} is the duration (s) of month n. In addition ρ_{air}, c_{air} and V_{air} are the air density (kg/m^3), specific heat (J/kg °C) and volume (m^3), respectively, while Q_{AINHG} are the average monthly internal heat gains (W/month) foreseen for the operational phase of the building. Finally, A^{WIN}_{wn} is the area (m^2) of window $wn = 1,\dots,WN$ with WN the total number of windows of the considered building, $F_{F,wn}$, $F_{S,wn}$ and $F_{CM,wn}$ are the frame factor (%), the correction factor (%) for shading and the correction factor (%) for movable devices of window wn, respectively, $I_{SL,wn,n}$ is the solar radiation on window wn, having a certain orientation and tilt angle, during month n (MJ/m^{2}month), and g^{WIN}_{st} is the effective total solar energy transmittance (%) of window sub-type t of type s.

Generally, the building load coefficient BLC is calculated according to the equation $BLC = \sum_{com} A_{com} U_{com} b_{com}$ [4], where com is a building envelope component (with one unique U-value), and A_{com} and U_{com} are the surface area (m^2) and the thermal transmittance (W/m^2 °C) of the component, respectively. Moreover, b_{com} is a temperature correction factor that is equal to 1 for components facing the outside air such as doors, windows, outside walls and roofs, and lowers, down to 0, for surfaces facing earth or unheated spaces such as ground, floors and cellar of crawl spaces [26]. Introducing in the aforementioned BLC equation the decision variables defined in Section 2.2.1 and taking into account for multi-layer construction components [4] that:

- the thermal transmittance U equals to the reverse of the thermal resistance R (i.e., $U = 1/R$),
- the thermal resistance R equals to the sum of the thermal resistances R_{layer} of all considered layers (i.e., $R = \sum R_{layer}$), and
- the thermal resistance of a layer R_{layer} equals to its thickness d_{layer} divided by the thermal conductivity k_{layer} of the layer's material (i.e., $R_{layer} = d_{layer}/k_{layer}$)

the following equation results:

$$
\begin{aligned}
BLC = {} & \sum_{dr=1}^{DR}\left(A_{dr}^{DOR}b_{dr}^{DOR}\right)\sum_{v=1}^{V}\left(x_{v}^{DOR}U_{v}^{DOR}\right)+\sum_{wn=1}^{WN}\left(A_{wn}^{WIN}b_{wn}^{WIN}\right)\sum_{s=1}^{S}\sum_{t=1}^{T_s}\left(x_{st}^{WIN}U_{st}^{WIN}\right)\\
& +\frac{\sum_{wl=1}^{WL}\left(A_{wl}^{WAL}b_{wl}^{WAL}\right)}{\sum_{w=1}^{W}\left(x_{w}^{WAL}\left(\sum_{kwl=1}^{KWL_w}\left(\frac{d_{w,kwl}^{dWAL}}{kk_{w,kwl}^{mWAL}}\right)+\sum_{y=1}^{Y_w}\left(x_{wy}^{dWAL}\sum_{c=1}^{C_{wy}}\left(\frac{x_{wyc}^{mWAL}}{k_{wyc}^{mWAL}}\right)\right)\right)\right)}\\
& +\frac{\sum_{ce=1}^{CE}\left(A_{ce}^{CEIL}b_{ce}^{CEIL}\right)}{\sum_{d=1}^{D}\left(x_{d}^{CEIL}\left(\sum_{kcl=1}^{KCL_d}\left(\frac{d_{d,kcl}^{dCEIL}}{kk_{d,kcl}^{mCEIL}}\right)+\sum_{f=1}^{F_d}\left(x_{df}^{dCEIL}\sum_{a=1}^{A_{df}}\left(\frac{x_{dfa}^{mCEIL}}{k_{dfa}^{mCEIL}}\right)\right)\right)\right)}\\
& +\frac{\sum_{fl=1}^{FL}\left(A_{fl}^{FLO}b_{fl}^{FLO}\right)}{\sum_{h=1}^{H}\left(x_{h}^{FLO}\left(\sum_{kfl=1}^{KFL_h}\left(\frac{d_{h,kfl}^{dFLO}}{kk_{h,kfl}^{mFLO}}\right)+\sum_{e=1}^{E_h}\left(x_{he}^{dFLO}\sum_{g=1}^{G_{he}}\left(\frac{x_{heg}^{mFLO}}{k_{heg}^{mFLO}}\right)\right)\right)\right)}
\end{aligned}
\tag{41}
$$

allowing for the calculation of the building load coefficient. In Eq. (41), A_{dr}^{DOR}, A_{wn}^{WIN}, A_{wl}^{WAL}, A_{ce}^{CEIL} and A_{fl}^{FLO} are the areas (m^2) of the building's door $dr = 1,\ldots,DR$, window $wn = 1,\ldots,WN$, wall $wl = 1,\ldots,WL$, ceiling $ce = 1,\ldots,CE$ and floor $fl = 1,\ldots,FL$, respectively, with DR, WN, WL, CE and FL the total number of doors, windows,

$$Q_{el}^{C} = Q^{CD}SEC_{el} \tag{43}$$

$$Q^{CD} = \sum_{n=1}^{12} Q_n^{CD} \tag{44}$$

$$Q_n^{CD} = \begin{cases} CS_n\left(Q_{SL,n}+Q_{AINHG,n}-Q_{T,n}-Q_{VEN,n}\right), & \text{if positive}\\ 0, & \text{else}\end{cases}$$

$$Q_n^{CD} = \begin{cases} CS_n\left(\sum_{wn=1}^{WN}\left(A_{wn}^{WIN}F_{F,wn}F_{S,wn}F_{CM,wn}I_{SL,wn,n}\sum_{s=1}^{S}\sum_{t=1}^{T_s}\left(x_{st}^{WIN}g_{st}^{WIN}\right)+Q_{AINHG}T_n-BLC\left(\theta_{IC}-\theta_{E,n}\right)T_n-\rho_{air}c_{air}V_{air}\left(\theta_{IC}-\theta_{E,n}\right)\right)\right), \\ \qquad\qquad \text{if positive}\\ 0, \quad \text{else}\end{cases} \tag{45}$$

walls, ceilings and floors of the building, respectively. Moreover, b_{dr}^{DOR}, b_{wn}^{WIN}, b_{wl}^{WAL}, b_{ce}^{CEIL} and b_{fl}^{FLO} comprise the temperature correction factors (%) for the construction parts dr, wn, wl, ce and fl, respectively. In addition, U_v^{DOR} and U_{st}^{WIN} constitute the thermal transmittances (W/m^2 °C) of a door of type v and a window of subtype t of type s, respectively, and k_{wyc}^{mWAL},k_{dfa}^{mCEIL} and k_{heg}^{mFLO} form the corresponding thermal conductivities (W/m °C) of the material c available for the unknown layer y of wall structure w, material a available for the unknown layer f of ceiling structure d and material g available for the unknown layer e of floor structure h.

The first two terms at the right-hand side of Eq. (41) reflect the load coefficient of the doors and windows of the building, while the latter three terms correspond to the multi-layer construction components namely the walls, the ceilings and the floors. Obviously, the activation of the constraints of Eq. (3) for the doors, Eq. (4) for the windows, Eqs. (6)–(8) for the walls, Eqs. (12), (15) and (18) for the ceilings and Eqs. (13), (17) and (19) for the floors will lead to the selection of only one door type, one window type and one wall, one ceiling and one floor structure with specific layers, materials, thicknesses and thermal conductivities that will ultimately define the building load coefficient, a measure of the thermal behaviour of the construction as a whole.

In a similar way, the total annual primary energy consumption for space cooling purposes may be estimated according to the following equation [25]:

$$Q_C = \frac{Q_{el}^{C}}{n_{el}} \tag{42}$$

where Q_{el}^{C} is the total annual energy (MJ/year) consumed by an electrical system providing space cooling that may be calculated through the following equations:

$$SEC_{el} = \sum_{eci=1}^{ECI}\sum_{ecj=1}^{ECJ_{eci}}\left(\frac{x_{eci,ecj}^{EC}}{e_{eci,ecj}^{EC}}\right)+\sum_{ehci=1}^{EHCI}\sum_{ehcj=1}^{EHCJ_{ehci}}\left(\frac{x_{ehci,ehcj}^{EHC}}{e_{ehci,ehcj}^{EHC}}\right) \tag{46}$$

where Q^{CD} and Q_n^{CD} are the total annual energy demand (MJ/year) for space cooling purposes and the average monthly cooling demand (MJ/month), respectively. In addition SEC_{el} represents the generation efficiency of the system that will be finally selected for the provision of the necessary cooling energy, and $e_{eci,ecj}^{EC}$ and $e_{ehci,ehcj}^{EHC}$ denote the generation efficiencies (%) of the electrical cooling system ecj of category eci and the electrical heating–cooling system $ehcj$ of category $ehci$, respectively. Moreover, CS_n is a parameter indicating whether cooling is required for month n (when $CS_n = 1$) or not (when $CS_n = 0$), while θ_{IC} is the internal design temperature (°C) during the cooling season. Obviously, the activation of the constraint of Eq. (29) in combination with Eqs. (43)–(46) will lead to the selection of only one system for the provision of space cooling, the generation efficiency of which will finally determine the energy consumption for cooling purposes according to Eq. (42).

Finally, the total annual energy consumption by a DHW system for hot water supply may be calculated according to the following equation [25]:

$$Q_{DHW} = \frac{Q_{el}^{W}}{n_{el}} + \sum_{fuel=1}^{FUEL} Q_{nel,fuel}^{W} \tag{47}$$

where, Q_{el}^{W} represents the annual energy (MJ/year) consumed by an electrical system delivering hot water supply and $Q_{nel,fuel}^{W}$ represents the annual energy (MJ/year) consumed by a non-electrical system using a particular fuel type.

The calculation of the energy consumed by an electrical or a non-electrical DHW system is accomplished with the aid of the following equations:

$$Q_{el}^{W} = Q^{WD} SEW_{el} \tag{48}$$

$$Q_{nel,fuel}^{W} = Q^{WD} SEW_{nel,fuel} \ \forall fuel \in \{1, \ldots, FUEL\} \tag{49}$$

where QWD is the total annual DHW energy demand (MJ/year), and SEW_{el} and $SEW_{nel,fuel}$ represent the generation efficiency of the alternative systems for the provision of the required DHW energy, which may be calculated as follows:

$$SEW_{el} = \sum_{ewi=1}^{EWI} \sum_{ewj=1}^{EWJ_{ewi}} \left(\frac{x_{ewi,ewj}^{EW}}{e_{ewi,ewj}^{EW}} \right) + \sum_{ehwi=1}^{EHWI} \sum_{ehwj=1}^{EHWJ_{ehwi}} \left(\frac{x_{ehwi,ehwj}^{EHW}}{e_{ehwi,ehwj}^{EHW}} \right) \tag{50}$$

$$\begin{aligned} SEW_{nel,fuel} = & \sum_{newi=1}^{NEWI} \sum_{newj=1}^{NEWJ_{newi}} \left(\frac{x_{newi,newj}^{NEW} FU_{newi,newj,fuel}^{NEW}}{e_{newi,newj}^{NEW}} \right) \\ & + \sum_{nehwi=1}^{NEHWI} \sum_{nehwj=1}^{NEHWJ_{nehwi}} \left(\frac{x_{nehwi,nehwj}^{NEHW} FU_{nehwi,nehwj,fuel}^{NEHW}}{e_{nehwi,nehwj}^{NEHW}} \right) \\ & \forall fuel \in \{1, \ldots, FUEL\} \end{aligned} \tag{51}$$

where $e_{ewi,ewj}^{EW}$ and $e_{ehwi,ehwj}^{EHW}$ denote the generation efficiencies (%) of the electrical DHW system ewj of category ewi and the electrical heating–DHW system $ehwj$ of category $ehwi$, respectively, and $e_{newi,newj}^{NEW}$ and $e_{nehwi,nehwj}^{NEHW}$ denote the generation efficiencies (%) of the non-electrical DHW system $newj$ of category $newi$ and the non-electrical heating–DHW system $nehwj$ of category $nehwi$, respectively. Obviously, the activation of the constraint of Eq. (30) in combination with Eqs. (48)–(51) will lead to the selection of only one DHW system, the generation efficiency of which will finally determine the energy consumption for hot water supply purposes according to Eq. (47).

To calculate the energy consumption of the DHW systems, their total annual DHW energy demand Q^{WD} should also be calculated. The calculation may be performed by simply adding the corresponding monthly energy demands (MJ) $DQ_{dDHW,n}$ as follows:

$$Q^{WD} = \sum_{n=1}^{12} (WS_n DQ_{dDHW,n}) \tag{52}$$

where WS_n is a parameter indicating whether hot water supply is required for month n (when $WS_n = 1$) or not (when $WS_n = 0$).

The monthly energy demand of the DHW systems $DQ_{dDHW,n}$ comprises actually, the average monthly energy demand (MJ/month) for hot water supply Q_{dhwu}, reduced by the energy (MJ/month) $Q_{dSLC,n}$ provided by a solar collector system, in case such a system has also been installed and used:

$$DQ_{DHW,n} = \begin{cases} Q_{dhwu} - Q_{dSLC,n}, & \text{if } Q_{dhwu} \geq Q_{dSLC,n} \\ 0, & \text{else} \end{cases} \tag{53}$$

The average monthly energy demand for hot water supply Q_{dhwu}, as well as the monthly energy demand covered by a solar collector system $Q_{dSLC,n}$ may be calculated according to the following equations [26]:

$$Q_{dhwu} = \frac{V_{water} \rho_{water} c_{water} (\theta_{DHW} - \theta_{DCW})}{10^6 \sum_{n=1}^{12} SW_n} \tag{54}$$

$$Q_{dSLC,n} = \frac{A_{SLC} I_{SL,SLC,n} F_{S,SLC} \sum_{u=1}^{U} \sum_{b=1}^{B_u} \left(x_{ub}^{SLC} e_{ub}^{SLC} \right)}{10^6} \tag{55}$$

where V_{water}, ρ_{water} and c_{water} correspond to the water volume (m^3), density (kg/m^3) and specific heat, (J/kg °C), respectively, and θ_{DCW} and θ_{DHW} are the domestic cold water temperature (°C) and the temperature (°C) set for the DHW system's boiler, respectively. In addition, A_{SLC}, $I_{SL,SLC,n}$ and $F_{S,SLC}$ are the area (m^2) of the solar collector, the solar radiation on the solar collector, having a certain orientation and tilt angle, during month n (MJ/m^2month) and a correction factor for shading (%), respectively, while e_{ub}^{SLC} is the generation efficiency (%) of a solar collector type $b$of category u. Obviously, the activation of the constraint of Eq. (32) will lead to the selection of at most one (or even none, if this proves to be more beneficial according to the decision criteria) solar collector system for complementary use to a DHW system.

2.3.2. CO_2 emissions

The CO_2 emissions (kg CO_2/year) released to the environment by the operation of heating, cooling and/or DHW systems depend upon the energy consumption level and the specific fuels of the systems in use and may be estimated according to the following equation [25]:

$$\begin{aligned} EM_{CO_2} = & \left(Q_{el}^{H} + Q_{el}^{C} + Q_{el}^{W} \right) F_{station} + \sum_{fuel=1}^{FUEL} \Big(Q_{nel,fuel}^{H} \\ & + Q_{nel,fuel}^{W} \Big) \frac{F_{fuel}}{LHP_{fuel}} \end{aligned} \tag{56}$$

where $F_{station}$ is the emissions factor (kg CO_2/MJ) of the electricity power plant, F_{fuel} is the conversion factor (kg CO_2/kg fuel) of fuel $fuel$ to CO_2 emissions, and LHP_{fuel} is the conversion factor (MJ/kg fuel) of fuel $fuel$ to energy. Moreover, Q_{el}^{H}, Q_{el}^{C}, Q_{el}^{W}, $Q_{nel,fuel}^{H}$ and $Q_{nel,fuel}^{W}$ are the total annual energy consumed by the electrical heating systems, the electrical cooling systems, the electrical DHW systems, the non-electrical heating systems and the non-electrical DHW systems, respectively, which are calculated according to Eqs. (35), (43), (48), (36) and (49), respectively.

Obviously, the activation of all the constraints that apply to the decision variables entered in Eqs. (35), (43), (48), (36) and (49), and consequently in Eq. (56), will limit the amount of released CO_2 emissions to the emissions released by the systems that will be finally selected by the decision model.

2.3.3. Initial investment cost

The investment cost for the construction of the building envelope and the acquisition and installation of heating, cooling, DHW and solar collector systems may be simply calculated, by adding the corresponding costs as follows:

$$\begin{aligned} INCOST = & COST_{DOR} + COST_{WIN} + COST_{WAL} + COST_{CEIL} \\ & + COST_{FLO} + COST_{HS} + COST_{CS} + COST_{WS} + COST_{HCS} \\ & + COST_{HWS} + COST_{SLC} \end{aligned} \tag{57}$$

where $COST_{DOR}$, $COST_{WIN}$, $COST_{WAL}$, $COST_{CEIL}$, and $COST_{FLO}$ are the costs (€) for the materials of the doors, windows, walls, ceilings, and floors of the considered building, respectively, while $COST_{HS}$, $COST_{WS}$, $COST_{HCS}$, $COST_{HWS}$ and $COST_{SLC}$ are the costs for the acquisition and installation of a heating, a cooling, a DHW, a heating–cooling, a heating–DHW and a solar collector system, respectively.

Taking into account the decision variables and the corresponding costs for all materials and systems, the aforementioned costs may be calculated according to the following equations:

Table 1
Types and characteristics of alternative door types.

Type		Thermal transmittance (W/m^2 °C)	Cost (€/m^2)
1	Hollow-core flush door	2.7	800
2	Solid-core flush door with single glazing (17% glass)	2.1	1000

Table 2
Types and characteristics of alternative window types.

Type		Sub-type		Thermal transmittance (W/m^2 °C)	Effective total solar energy transmittance (%)	Cost (€/m^2)
1	Single glazing	1	Typical glazing	5.0	80	40
2	Double glazing	1	4-20-4, uncoated, air-filled	2.6	72	55
		2	4-12-4, coated, argon filled	1.6	76	65

$$COST_{DOR} = \sum_{dr=1}^{DR}\left(A_{dr}^{DOR}\right)\sum_{v=1}^{V}\left(x_v^{DOR}C_v^{DOR}\right) \tag{58}$$

$$COST_{WIN} = \sum_{wn=1}^{WN}\left(A_{st}^{WIN}\right)\sum_{s=1}^{S}\sum_{t=1}^{T_s}\left(x_{st}^{WIN}C_{st}^{WIN}\right) \tag{59}$$

$$COST_{WAL} = \sum_{wl=1}^{WL}\left(A_{wl}^{WAL}\right)\sum_{w=1}^{W}\left(x_w^{WAL}\left(\sum_{kwl=1}^{KWL_w}\left(d_{w,kwl}^{dWAL}CK_{w,kwl}^{mWAL}\right)\right.\right.$$
$$\left.\left.+\sum_{y=1}^{Y_w}\left(x_{wy}^{dWAL}\sum_{c=1}^{C_{wy}}\left(x_{wyc}^{mWAL}C_{wyc}^{mWAL}\right)\right)\right)\right) \tag{60}$$

$$COST_{CEIL} = \sum_{ce=1}^{CE}\left(A_{ce}^{CEIL}\right)\sum_{d=1}^{D}\left(x_d^{CEIL}\left(\sum_{kcl=1}^{KCL_d}\left(d_{d,kcl}^{dCEIL}CK_{d,kcl}^{mCEIL}\right)\right.\right.$$
$$\left.\left.+\sum_{f=1}^{F_d}\left(x_{df}^{dCEIL}\sum_{a=1}^{A_{df}}\left(x_{dfa}^{mCEIL}C_{dfa}^{mCEIL}\right)\right)\right)\right) \tag{61}$$

$$COST_{FLO} = \sum_{fl=1}^{FL}\left(A_{fl}^{FLO}\right)\sum_{h=1}^{H}\left(x_h^{FLO}\left(\sum_{kfl=1}^{KFL_h}\left(d_{h,kfl}^{dFLO}CK_{h,kfl}^{mFLO}\right)\right.\right.$$
$$\left.\left.+\sum_{e=1}^{E_h}\left(x_{he}^{dFLO}\sum_{g=1}^{G_{he}}\left(x_{heg}^{mFLO}C_{heg}^{mFLO}\right)\right)\right)\right) \tag{62}$$

$$COST_{HS} = \sum_{ehi=1}^{EHI}\sum_{ehj=1}^{EHJ_{ehi}}\left(x_{ehi,ehj}^{EH}CST_{ehi,ehj}^{EH}\right) + \sum_{nehi=1}^{NEHI}$$
$$\times\sum_{nehj=1}^{NEHJ_{nehi}}\left(x_{nehi,nehj}^{NEH}CST_{nehi,nehj}^{NEH}\right) \tag{63}$$

$$COST_{CS} = \sum_{eci=1}^{ECI}\sum_{ecj=1}^{ECJ_{eci}}\left(x_{eci,ecj}^{EC}CST_{eci,ecj}^{EC}\right) \tag{64}$$

Table 3
Types and characteristics of alternative wall structures.

Structure	Layer	Material	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m^3)
1	1	Plaster	0.025	0.87	10
	2	Brick (complex)	0.150	0.72	23
	3	Plaster	0.025	0.87	10
2	1	Plaster	0.025	0.87	10
	2	Brick (simple)	0.060	0.72	6.2
	3	Brick (simple)	0.060	0.72	6.2
	4	Plaster	0.025	0.87	10

Table 4
Types and characteristics of alternative ceiling structures.

Structure	Layer	Material	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m^3)
1	1	Tiles	0.02	1.00	55
	2	Concrete	0.15	0.72	55
2	1	Tiles	0.02	1.00	55
	2	Wood	0.03	0.17	70

$$COST_{WS} = \sum_{ewi=1}^{EWI}\sum_{ewj=1}^{EWJ_{ewi}}\left(x_{ewi,ewj}^{EW}CST_{ewi,ewj}^{EW}\right) + \sum_{newi=1}^{NEWI}$$
$$\times\sum_{newj=1}^{NEWJ_{newi}}\left(x_{newi,newj}^{NEW}CST_{newi,newj}^{NEW}\right) \tag{65}$$

$$COST_{HCS} = \sum_{ehci=1}^{EHCI}\sum_{ehcj=1}^{EHCJ_{ehci}}\left(x_{ehci,ehcj}^{EHC}CST_{ehci,ehcj}^{EHC}\right) \tag{66}$$

$$COST_{HWS} = \sum_{ehwi=1}^{EHWI}\sum_{ehwj=1}^{EHWJ_{ehwi}}\left(x_{ehwi,ehwj}^{EHW}CST_{ehwi,ehwj}^{EHW}\right) + \sum_{nehwi=1}^{NEHWI}$$
$$\times\sum_{nehwj=1}^{NEHWJ_{nehwi}}\left(x_{nehwi,nehwj}^{NEHW}CST_{nehwi,nehwj}^{NEHW}\right) \tag{67}$$

$$COST_{SLC} = A_{SLC}\sum_{u=1}^{U}\sum_{b=1}^{B_u}\left(x_{ub}^{SLC}CST_{ub}^{SLC}\right) \tag{68}$$

where C_v^{DOR} and C_{st}^{WIN} are the costs (€/m^2) for a door of type v and a window of sub-type t of type s,respectively, $CK_{w,kwl}^{mWAL}$, $CK_{d,kcl}^{mCEIL}$ and $CK_{h,kfl}^{mFLO}$ are the costs (€/m3) for the material to be used in the known layer kwl of wall structure w, kcl of ceiling structure d and kfl of floor structure h, respectively, and C_{wyc}^{mWAL}, C_{dfa}^{mCEIL} and C_{heg}^{mFLO} are the costs (€/m^3) of material c available for unknown layer y of wall structure w, material a available for unknown layer f of ceiling structure d and material g available for unknown layer e of floor structure h, respectively. Moreover, $CST_{ehi,ehj}^{EH}$ and $CST_{nehi,nehj}^{NEH}$ are the acquisition and installation costs (€) for the electrical heating system ehj of category ehi and the non-electrical heating system $nehj$ of category $nehi$, respectively, $CST_{eci,ecj}^{C}$ is the acquisition and installation cost (€) for an electrical cooling system ecj of category eci, $CST_{ewi,ewj}^{EW}$ and $CST_{newi,newj}^{NEW}$ are the acquisition and installation costs (€) for the electrical DHW system ewj of category ewi and the non-electrical DHW system $newj$ of category $newi$, respectively, $CST_{ehci,ehcj}^{HC}$ is the acquisition and installation cost (€) for an electrical heating–cooling system $ehcj$ of category $ehci$, $CST_{ehwi,ehwj}^{EHW}$ and $CST_{nehwi,nehwj}^{NEHW}$ are the acquisition and installation costs (€) for the electrical heating–DHW system $ehwj$ of category $ehwi$ and the non-electrical heating–DHW system $nehwj$ of category $nehwi$, respectively, and CST_{ub}^{SLC} is the acquisition and installation cost (€/m^2) for a solar collector system b of category u.

Table 5
Types and characteristics of alternative floor structures.

Structure	Layer	Material	Thickness (m)	Thermal conductivity (W/m °C)	Cost (€/m^3)
1	1	Tiles	0.01	1.00	55
	2	Concrete	0.15	0.72	55
2	1	Wood	0.02	0.17	85
	2	Concrete	0.15	0.72	55

Table 6
Characteristics of alternative insulation materials.

Material		Thermal conductivity (W/m °C)	Cost (€/m^3)
1	Polysterene	0.036	200
2	Mineral fiber	0.042	180
3	Plastic fiber	0.020	300

Obviously, the activation of all the constraints that apply to the decision variables (see Section 2.2) will limit the initial investment cost to the costs of the materials and systems that will be finally selected by the decision model.

2.4. Decision model and solution process

The decision variables and criteria developed in Sections 2.2 and 2.3, lead to the formulation of the following decision problem:

$$\begin{aligned} &[\min]\, g_1(\mathbf{x}) = Q_T \\ &[\min]\, g_2(\mathbf{x}) = EM_{CO_2} \\ &[\min]\, g_3(\mathbf{x}) = INCOST \\ &s.t. \\ &\text{constraints of Eqs.}(1)-(68) \end{aligned} \tag{69}$$

The decision problem of Eq. (69) is a mixed-integer multi-objective combinatorial optimization problem, for the solution of which, severable techniques such as compromise programming, goal programming, etc. are available. The efficiency of these approaches had been demonstrated during preliminary past investigations of a smaller-scale's similar problem [24], and they constitute a good starting point for the solution of the decision problem of Eq. (69). Nevertheless, in case that such traditional methods do not allow for the solution of the described decision problem, other, more sophisticated approaches like ([22,23]) aggregated approaches (ε-constraint method, Tchecebyshev scalarisation, etc.), interactive techniques (interactive surrogate worth trade-off method, GDF method, STEM, Light Beam Search, etc.) or other methods (GUESS, NIMBUS, reference point approach, etc.) should be exploited.

3. Example case study

3.1. Problem description

To study the efficiency of the decision model of Eq. (69), a simple building has been examined as a case study.

The dimensions of the considered building envelope assume a floor and ceiling area of 100 m^2, 2 walls of area 24 m^2, 2 walls of area 30 m^2, and a door and window area both of 6 m^2. Moreover, all door, window, wall, ceiling and floor surfaces are assumed to face the outside air, thus, the corresponding temperature correction factors (b_{dr}^{DOR}, b_{wn}^{WIN}, b_{wl}^{WAL}, b_{ce}^{CEIL} and b_{fl}^{FLO}) are all set equal to 1. Especially for the window, a frame factor ($F_{F,wn}$) 0.7 has been assumed according to suggestions of local manufacturers, while the shading factors ($F_{S,wn}$ and $F_{CM,wn}$) have been set equal to 1, for simplicity reasons.

The building is further assumed to be located in the wider area of Athens, Greece, for which, the average monthly temperatures and the corresponding solar radiations were extracted by the METEONORM software [27]. In addition, the internal design temperatures for heating and cooling periods, have been set to $\theta_{IH} = 20$ °C and $\theta_{IC} = 25$ °C, respectively, according to the preferences assumed for the DM, while the domestic hot and cold water temperatures have been set to $\theta_{DHW} = 55$ °C and $\theta_{DCW} = 13$ °C, respectively, so as to lay within the health and comfort range prescribed by Neufert and Neufert [28].

The annual internal heat gain has been calculated on the assumption that 4 inhabitants in the building dissipate 70 W of heat a day each, while for the ventilation rate, a complete air space renewal has been assumed per hour (300 m^3/h) according to Kreider et al [29] typical values. In addition, the monthly energy requirements for hot water supply are assumed to be 425 MJ, according to a rough estimate of the needs of a 4-person family in Greece [30]. Furthermore, concerning the air and water density, and the air and water specific heat, the values $\rho_{air} = 1.2$ kg/m^3 and $\rho_{water} = 1000$ kg/m^3, $c_{air} = 1.0035$ J/kg °C and $c_{water} = 4.2$ J/kg °C have been assumed, respectively.

For heating, cooling and hot water supply purposes, electricity, oil and gas are taken into account, while solar energy is only considered in the case of hot water supply. As far as electricity is concerned, the emissions factor and the return rate of the electricity power plant are considered to be $F_{station} = 0.295$ kgCO$_2$/MJ and $n_{el} = 0.35$, respectively [25]. As far as the alternative fuels are concerned, the conversion factors to CO$_2$ emissions and energy are considered $F_1 = 3.142$ kgCO$_2$/kg of oil and $F_2 = 2.715$ kgCO$_2$/kg of gas, and $LHP_1 = 42.912$ MJ/kg of oil and $LHP_2 = 49.788$ MJ/kg of gas, respectively [25].

The decisions regarding the building under study concern appropriate choices for:

- the type of the building's door and window;
- the structure of the building's walls, ceiling and floor;

Table 7
Characteristics of alternative heating only systems.

Category		Type		Generation efficiency (%)	Cost (€)
Electrical systems					
1	Resistance-based	1	Dry core storage boiler type 1	100	5000
		2	Dry core storage boiler type 2	85	4200
Non-electrical systems					
1	Oil-based	1	Condensing	83	5300
		2	Standard oil boiler	62	4700
2	Natural-gas based	1	Condensing	85	5800
		2	Floor mounted boiler	55	4500

Table 8
Characteristics of alternative heating/cooling systems.

Category		Type		Generation efficiency (%)	Cost (€)
1	Water cooled electric	1	<12 000 BTU	200	500
		2	<18 000 BTU	230	800
		3	<24 000 BTU	250	1200

Table 9
Characteristics of alternative heating/DHW systems.

Category		Type		Generation efficiency (%)	Cost (€)
Electrical systems					
1	Resistance-based	1	Electric CPSU	100	7200
		2	Water storage boiler	85	5800
Non-electrical systems					
1	Oil-based	1	Condensing combi	81	6200
		2	Combi	70	5800
2	Natural-gas based	1	Condensing combi	84	7200
		2	Combi	65	5700

Table 10
Characteristics of alternative DHW systems.

Category		Type		Generation efficiency (%)	Cost (€)
Electrical systems					
1	Resistance-based	1	Electric immersion	100	1200
		2	Electric instantaneous at point of use	85	1000
Non-electrical systems					
1	Oil-based	1	Oil boiler/circulator	80	1000
		2	Oil single burner	60	800
2	Natural-gas based	1	From a circulator built into a gas warm air system type 1	73	850
		2	From a circulator built into a gas warm air system type 2	60	650

- the thicknesses and corresponding materials to be used in the building's walls, ceiling and floor insulation layers;
- the space heating system;
- the space cooling system;
- the hot water supply system(s).

More specifically, as far as the door and the window of the building are concerned, choices have to be made between the alternative types displayed in Tables 1 and 2, respectively. Considering the walls, the ceiling and the floor of the building, choices have to be made among the alternative structures displayed in Tables 3–5, respectively. Moreover, for each of the aforementioned wall, ceiling and floor structures, a choice has to be further made on whether to add or not an insulation layer of maximum permissible thickness 0.10 m and material selected among the three alternative materials displayed in Table 6. The values of the thermal and solar transmittance, and the thermal conductivity of construction materials and components in Tables 1–6 have been taken from the ASHRAE database [29], while the cost values have been obtained through a short unofficial market survey.

Finally, for the space heating, cooling and hot water supply, choices have to be made as follows:

- For heating purposes, a system has to be selected among those, which provide space heating only, space heating and cooling and space heating and DHW, displayed in Tables 7–9, respectively.
- For cooling purposes, a system has to be selected among those, which provide space cooling, displayed in Table 8.
- For hot water supply purposes, a system has to be selected among those, which provide space heating and DHW and DHW only, displayed in Tables 9 and 10, respectively. In addition, the installation of a solar collector system for hot water supply via solar energy has also to be considered. In this case, alternative solutions include the systems displayed in Table 11.

The values in Tables 7–11 have been obtained through a short unofficial market survey.

Table 11
Characteristics of alternative solar collector systems.

Category		Type		Generation efficiency (%)	Cost (€/m^2)
1	Flat collector	1	Type 1	90	900
		2	Type 2	80	600
2	Vacuum heat pipe	1	Type 1	72	780
	CPC collector	2	Type 2	67	500

Table 12
Payoff matrix.

Type of solution	Q_T (MJ/year)	EM_{CO_2} (kg CO_2/year)	$INCOST$ (€)
$[min]g_1$ ($\boldsymbol{x}$)	**15 078.49**	1553.729	21 986.60
$[min]g_2$ ($\boldsymbol{x}$)	15 406.44	**1042.961**	27 636.60
$[min]g_3$ ($\boldsymbol{x}$)	355 605.30	36 302.140	**7524.35**

3.2. Model development and solution

The application of the decision model of Eq. (69) requires the definition of appropriate decision variables to reflect the choices available to the DM for the construction of the building envelope and the acquisition and installation of heating, cooling, DHW and solar collector systems.

Table 13
Building envelope and systems-related decisions.

Type of solution	Door and window		
	Door type	Window	
		Type	Sub-type
$[min]g_1$ ($\boldsymbol{x}$)	2	2	2
$[min]g_2$ ($\boldsymbol{x}$)	2	2	2
$[min]g_3$ ($\boldsymbol{x}$)	1	1	1
Type of solution	Walls		
	Structure	Insulation thickness (m)	Insulation material
$[min]g_1$ ($\boldsymbol{x}$)	1	0.10	3
$[min]g_2$ ($\boldsymbol{x}$)	1	0.10	3
$[min]g_3$ ($\boldsymbol{x}$)	2	0.00	none
Type of solution	Ceiling		
	Structure	Insulation thickness (m)	Insulation material
$[min]g_1$ ($\boldsymbol{x}$)	1	0.10	3
$[min]g_2$ ($\boldsymbol{x}$)	1	0.10	3
$[min]g_3$ ($\boldsymbol{x}$)	2	0.00	none
Type of solution	Floor		
	Structure	Insulation thickness (m)	Insulation material
$[min]g_1$ ($\boldsymbol{x}$)	2	0.10	3
$[min]g_2$ ($\boldsymbol{x}$)	2	0.10	3
$[min]g_3$ ($\boldsymbol{x}$)	1	0.00	none
Type of solution	Heating system		
	Type of system	Category	Type
$[min]g_1$ ($\boldsymbol{x}$)	Electrical heating/ cooling system	1	3
$[min]g_2$ ($\boldsymbol{x}$)	Non-electrical heating system	2	1
$[min]g_3$ ($\boldsymbol{x}$)	Electrical heating/ cooling system	1	1
Type of solution	Cooling system		
	Type of system	Category	Type
$[min]g_1$ ($\boldsymbol{x}$)	Electrical heating/ cooling system	1	3
$[min]g_2$ ($\boldsymbol{x}$)	Electrical heating/ cooling system	1	3
$[min]g_3$ ($\boldsymbol{x}$)	Electrical heating/ cooling system	1	1
Type of solution	DHW system		
	Type of system	Category	Type
$[min]g_1$ ($\boldsymbol{x}$)	Non-electrical DHW system	1	1
$[min]g_2$ ($\boldsymbol{x}$)	Non-electrical DHW system	2	1
$[min]g_3$ ($\boldsymbol{x}$)	Non-electrical DHW system	2	2
Type of solution	Solar collector system		
	Category	Type	
$[min]g_1$ ($\boldsymbol{x}$)	1	1	
$[min]g_2$ ($\boldsymbol{x}$)	1	1	
$[min]g_3$ ($\boldsymbol{x}$)	none		

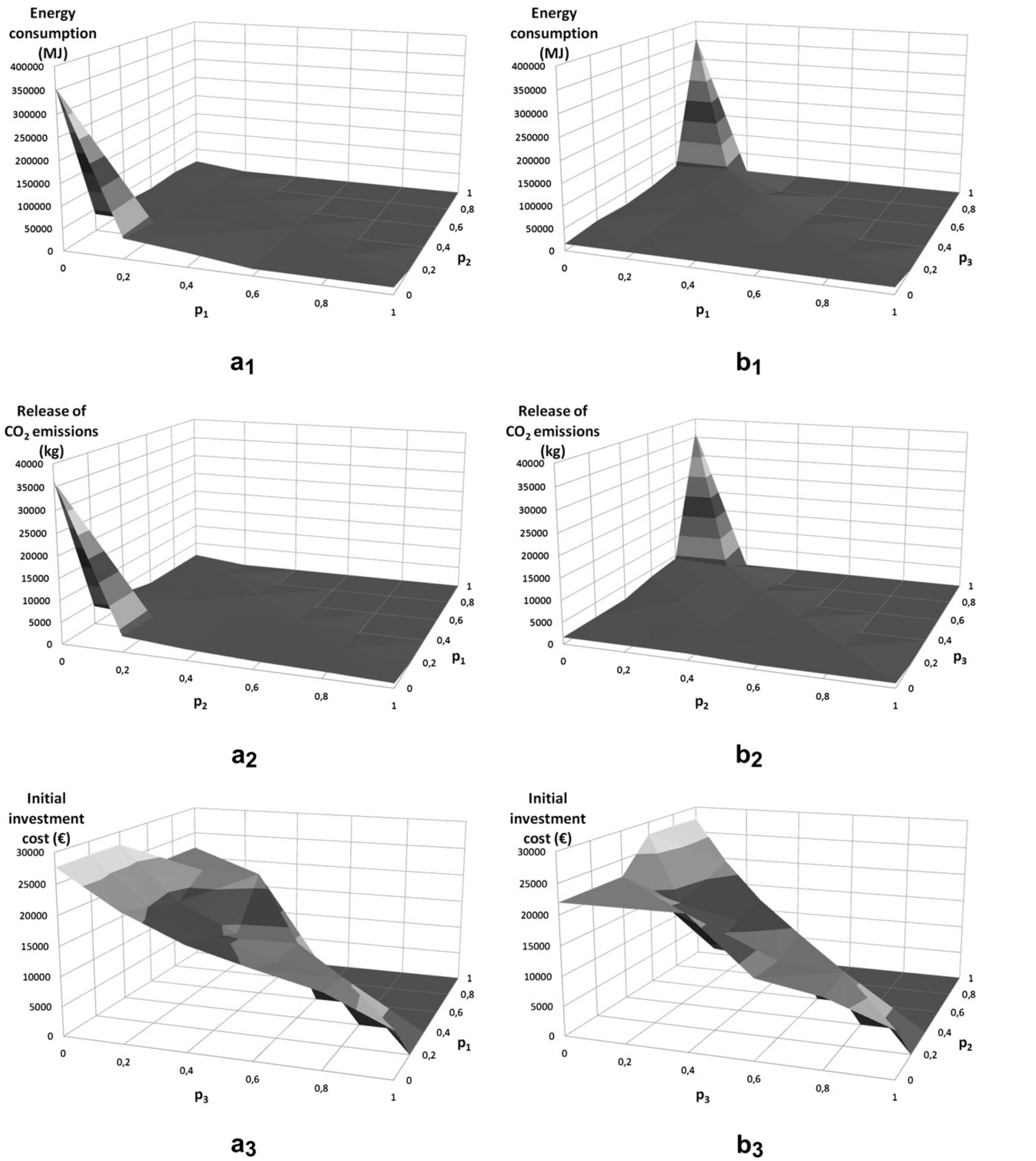

Fig. 1. Energy consumption vs release of CO_2 emissions (a_1) and initial investment cost (b_1), release of CO_2 emissions vs energy consumption (a_2) and initial investment cost (b_2), and initial investment cost vs energy consumption (a_3) and release of CO_2 emissions (b_3)

Given the data described in Section 3.1, the particular decision problem is formulated according to Eq. (69). The formulated decision problem includes 18 continuous and 57 binary (0-1) variables in 68 linear and non-linear constraints, with 3 competitive decision criteria.

The decision criteria are competitive, since any decrease of the one, leads to an increase of the others. Table 12, which displays the payoff matrix when each criterion is optimized independently from the others, demonstrates this competitiveness.

When, the energy consumption criterion is optimized independently of the others, the doors and windows with the minimum thermal and solar transmittances are selected. At the same time, the wall, ceiling and floor structures with the lowest resulting building load coefficient are selected. This means that the structures with the higher layer thermal resistances (i.e., thickness/thermal conductivity of material) are selected, all with additional insulation layers using the material of the lower thermal conductivity at the maximum permissible thickness. In addition, a combination of heating, cooling, DHW and solar collector systems is made, choosing the systems with the highest generation efficiency. Especially as far as hot water supply is concerned, the solar collector system with the maximum generation efficiency is selected, and the DHW system with the maximum generation efficiency is selected too, to be used, however, complementary to the operation of the solar collector that should be the prime source for this particular energy requirement. However, the aforementioned choices, the details of which are displayed in Table 13, result in the significant increase of the initial investment cost, since they are the most expensive choices. At the same time, the emissions criterion gets a value higher than the one obtained when it is optimized in isolation of the others, since the release of CO_2 emissions also depends on the particular fuel that a system uses and not solely on its generation efficiency. As a consequence, a system that utilises e.g. electricity is expected to lead to a higher release of emissions in the environment than another system with potentially lower generation efficiency, which uses, however, an alternative fuel such as gas or oil.

When the CO_2 emissions criterion is optimized independently of the others, reduced energy consumption choices are also made, in a different, however, way. As far as the building envelope is concerned, the choices are the same with these made under the optimization of the energy criterion so as to result to a building with low energy requirements. However, as far as the systems for space heating, cooling and hot water supply are concerned, choices are not made based on their generation efficiencies (as in the case of the energy consumption criterion) but on the foreseen release of CO_2 emissions. As a consequence, the categories of systems with lower release of CO_2 emissions are preferred, and from these categories, the systems with the maximum generation efficiencies are then selected. Therefore, the choices in this case, which are also displayed in Table 13, result to increased values in both the energy consumption and the initial investment cost criteria.

Finally, when the cost criterion is optimized independently of the others, choices of low cost are made (see Table 13), resulting, however, in maximum energy consumption and release of CO_2 emissions.

To optimize simultaneously all three aforementioned decision criteria, the compromise programming approach has been considered. The efficiency of this approach to handle a similar, although significantly smaller, decision problem had been investigated during preliminary past investigations [24].

The aim of the compromise programming approach is to minimise the distance of the criterion values from their optimum values. To apply this particular technique, the decision model has to be modified so as to include one only criterion. Considering this, the decision problem of Eq. (69) is structured as follows ([21,22]):

$$
\begin{aligned}
&[\min]\; z = \lambda \\
&s.t. \\
&\text{all constraints of multiobjective problem of Eq.(69)} \\
&\lambda \geq (g_1(\mathbf{x}) - g_{1\min})(p_1/g_{1\min}) \\
&\lambda \geq (g_2(\mathbf{x}) - g_{2\min})(p_2/g_{2\min}) \\
&\lambda \geq (g_3(\mathbf{x}) - g_{3\min})(p_3/g_{3\min}) \\
&\lambda \geq 0
\end{aligned}
\qquad (70)
$$

where, λ corresponds to the Tchebyshev distance, g_{1min}, g_{2min} and g_{3min} are the optimum (minimum) values of the three criteria when optimized independently (see Table 12), and p_1, p_2 and p_3 are corresponding weight coefficients reflecting the relative importance of the three criteria. The weight coefficients allow the DM to express his/her preferences regarding the criteria, and must sum up to 1.

The solution of the resulting problem for different values of the weight coefficients, leads to several different solutions. Obviously, as the weight coefficient of any criterion increases from 0 to 1, its corresponding values decrease and finally reach its optimum value when only this criterion is optimized independently of the others. For intermediary values of the weight coefficients, several solutions may be obtained that favour each criterion at a higher or lower level depending upon the specific values that have been selected. This behaviour is demonstrated through Fig. 1 that displays graphically the changes of the criteria values in relation to the weight coefficient values, indicating that the more a criterion is considered important by the DM, the more the final decision is in favour of this criterion.

The results of the application of the compromise programming technique, employed for the solution of the problem under study, demonstrate the feasibility as well as the strengths of applying such techniques to the problem of energy efficiency improvement. The application of this systematic approach allows for the simultaneous consideration (without having to prescribe any particular set of choices) of all available combinations of alternative actions. It also allows for the consideration of any logical, physical, technical or other constraints that may apply and permits the DM to guide the solution according to his/her own preferences.

4. Conclusions and future work

The improvement of energy efficiency of buildings is among the first priorities of the energy policy in the EU and worldwide as indicated by the published directives and the promotion of ISO and other related standards.

For the improvement of the energy efficiency of the buildings, several measures are available, and the DM has to compensate environmental, energy, financial and social factors in order to make an optimal selection.

The problem of the DM is characterized by the existence of multiple and in several cases competitive objectives, each of which should be optimized against a set of feasible and available solutions that is prescribed by a set of parameters and constraints, all of which should be taken into account. In simple words, the DM is facing a multi-objective optimization problem that is usually, however, approached through simulation and/or multicriteria decision making techniques that focus on particular aspects of the problem rather than deal with the problem to its global dimension.

In contrast to the aforementioned state-of-practice approaches, the decision model developed in this paper allows for the consideration of many available options, without the need to be combined and/or complemented by any other method, such as simulation, multicriteria decision analysis techniques, etc.

The model was applied to a simple case study, and the results demonstrated the feasibility of the approach, thus encouraging further extensions and/or improvements such as consideration of more complex building constructions and decision criteria (like indoor comfort, operational costs, etc.), and application to existing buildings for renovation and/or retrofit purposes.

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