TÜBİTAK

**Turkish Journal of Electrical Engineering & Computer Sciences**

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2017) 25: 4172 – 4186

doi:10.3906/elk-1612-13

# Developing a model and software for energy efficiency optimization in the building design process: a case study in Turkey

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**Received:** 01.12.2016 • **Accepted/Published Online:** 18.05.2017 • **Final Version:** 05.10.2017

**Abstract:** Buildings are responsible for 40% of the primary energy consumption in the world. Recent studies have revealed that the energy efficiency and environmental impact of buildings are two very important criteria to consider during the process of building design for the future of our world. By considering the initial investment cost and its importance for investors, a problem with three objective functions has emerged with 16 building energy systems and 24 construction material alternatives. The aim of this work is to develop a methodology and software to solve multiobjective building optimization problems. Thus, two different software tools have been developed using MATLAB. The first tool, the Building Energy Consumption Calculation Program, is used to calculate the building's annual energy consumption according to the Turkish standard for thermal insulation requirements for buildings, initial investment costs, and $CO_2$ emissions. The second tool, the Building Energy Optimization Program, is a multiobjective optimization program that uses the NSGA-II genetic algorithm to minimize objectives. With the help of the programs in question, multiobjective optimization of a sample building has been conducted. The results demonstrate that the developed model and software tools are generic, feasible solutions that can be implemented in a reasonable timeframe; thus, they can be adapted to a large range of building optimization problems and will be useful for decision makers.

**Key words:** Building energy efficiency, multiobjective optimization, genetic algorithm

## 1. Introduction

The climate change that occurs as a result of the increase in primary energy consumption is one of the leading problems faced by humanity in history. Studies conducted in Europe and in the rest of the world have shown that buildings are responsible for 40% of total energy consumption [1]. Turkey imports about 70% of its energy resources; thus, a reduction of energy consumption is crucial for the country [2]. In this context, researchers try to build scientific methods and decision models to determine policies for Turkey [3]. The Turkish government has implemented some improvements in the Turkish standard for thermal insulation requirements for buildings (TS825) and prepared the "Energy Performance Directive in Buildings", based on the "EU Directive on the Energy Performance of Buildings", to reduce negative impacts on the environment and to provide energy efficiency in buildings. As a result of these advances, the number of academic studies related to building optimization problems (BOPs) has increased.

Problems aiming at various improvements in building performance are generally referred to as BOPs. The parametric method is used in the majority of studies about BOPs in Turkey. The parametric method is

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based on evaluation of the impact caused on the objective function by changing one of the decision variables. This method is time-consuming, since it changes variables one by one and evaluates impacts on the objective function, and inadequate, due to the complex structure of real-life problems. Conducted studies have shown that an average of 15.1 decision variables are used in BOPs, and the objective functions are single-objective in 60% of them [4]. In our study, 74 decision variables and 3 objective functions are used.

In addition, in real-life problems, decision makers have to evaluate a combination of many contradictory objectives together. With the introduction of multiobjective optimization, the complexity of BOPs increases so much that classical methods are incapable of dealing with them. The two most commonly used methods for solutions are the weighted sum and Pareto optimization methods. In this study, rather than using the weighted sum method, which is easy to apply, the Pareto optimization method, offering more detailed information for decision makers and providing flexibility in decision making, is used instead.

While objectives are multiplied by determined weights and the problem is transformed into a single-objective form in the weighted sum method, all objectives have equal weight and each objective is calculated individually in the Pareto optimization method [5]. Although this creates difficulty in computation, the Pareto set, consisting of feasible solutions, can be determined via algorithms providing the right amount of performance. If a solution cannot improve other objectives without corrupting at least one of the objective functions, it is called the Pareto optimal or nondominated solution [6]. Points forming the closest border to the optimal solution create the Pareto front (Figure 1) [7]. While the Pareto front consists of a curve for dual objective problems, for our problem comprising three objectives, it consists of surfaces called Pareto surfaces.

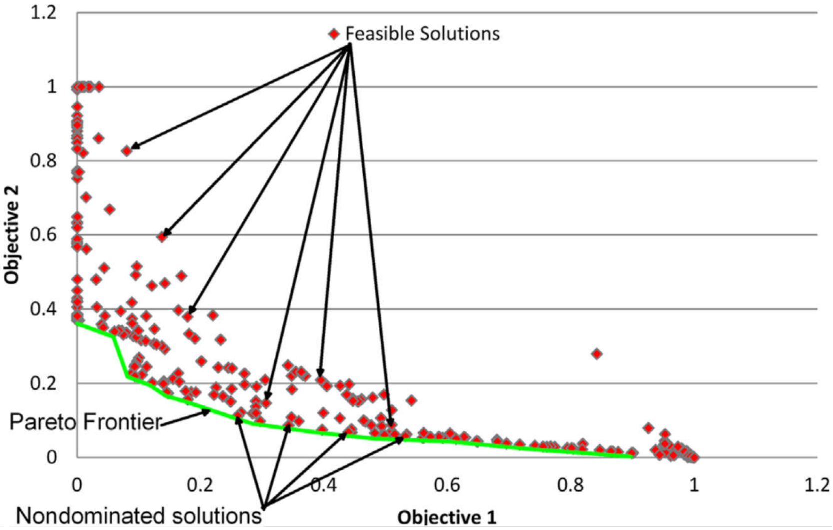


**Figure 1.** Pareto front.

In this context, for the solution of the BOP problem, BECCP software was initially developed to compute the objective functions. In the second stage, i.e. the genetic algorithm-based software, the Building Energy Optimization Program (BEOP) was developed with the aim of minimizing objective functions. Since it is very difficult and in some situations impossible to reach an optimum solution via classical methods, a fast and efficient multiobjective, nondominated sorting genetic algorithm (NSGA-II) is used [8]. For a sample building project in Ankara, Turkey, implementation of both software tools is conducted and the results are discussed.

## 2. Recent studies on building an optimization problem

In general, BOP-related studies vary according to the objectives that are chosen for optimization and the systems taken into consideration. These differences affect objective functions, decision variables, and the engineering calculations of the problem. Kolokotsa et al. [9] reviewed decision methodologies for energy efficiency in buildings and, as a result of this study, specified that it is possible to make evaluations in the following 6 different areas: a) energy-related: basic energy consumption, heating-cooling load, and electricity consumption; b) cost-related: initial investment cost, direct cost, net present value, and life cycle cost; c) environment-related: annual emissions, global warming, and lifelong environmental potential; d) comfort-related: internal ambient temperature and humidity, $CO_2$ rate, ventilation rate, and sunlight and noise levels; e) miscellaneous: construction time and safety. Diakaki et al. [1] developed a multiobjective optimization model by considering energy consumption and initial investment cost. In this model, window type, insulation material, and wall thickness were used as decision variables. Furthermore, in [10], they improved the model and added energy systems and heat layers to the model. In addition, they used energy consumption, initial investment cost, and $CO_2$ emissions in the objective function. Juan et al. [11] developed a genetic algorithm-based decision support system and researched the balance of cost and quality in home renovations. Chantrelle et al. [6] developed a software with an interface that employed the genetic algorithm for the renovation of buildings and contained energy consumption, thermal comfort, cost, and environmental impact. Hamdy et al. [12] developed a three-stage multiobjective optimization model based on simulation, seeking to minimize the cost and environmental effects of an air conditioning system and a house. Fesanghary et al. [13] used life cycle cost and $CO_2$ emissions in the objective function and reached a solution with the harmony search algorithm. Asadi et al. [14] used energy saving maximization and minimization of renovation cost as the objective function in their study. Evins [15] reviewed computational optimization methods used in building design and, as a result of the study, demonstrated that optimization methods, especially the use of multiobjective optimization methods, had increased noticeably. In addition, the study found that the most widely used method was the genetic algorithm, and that energy consumption and the cost of initial investment were included in the objective function most. Malatji et al. [16] studied the minimization of the payback period and maximization of energy saving by using the genetic algorithm and implemented a sensitivity analysis. Nguyen et al. [4] explored studies conducted that were related to building performance analysis in detail, and they specified that the biggest challenges experienced in simulation-based optimization studies used in building design were the complexity of problems, calculation difficulties, and parameter uncertainties. Karmellos et al. [17] developed a multiobjective nonlinear model to increase energy efficiency in new and existing buildings. They chose the minimization of energy consumption and cost of initial investment as the objective function. They also developed software for the solution of this problem and used it in two different case studies.

## 3. Multiobjective building optimization phases

BOPs can be divided into three phases: the preprocessing phase, optimization phase, and postprocessing phase [4]. In this study, the same phases were followed and two different software tools were developed for automation of the whole process (Figure 2).

The first phase involves the determination of building characteristics, materials, and system alternatives to be used in the model. At this stage, building characteristics belonging to the building, construction, and insulation material alternatives, along with energy system alternatives such as heating, hot water, and cooling,

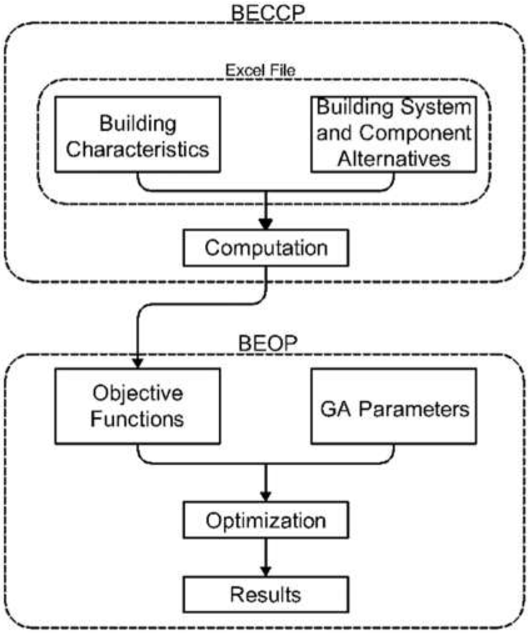


**Figure 2.** Schematic structure of the proposed methodology.

must be entered into an Excel file to form the decision variables. After completion of data entry, the BECCP is executed. The software calculates the energy values consumed by heating, cooling, hot water, lighting, and devices by reading data in the Excel file. Here, calculation of heating energy is carried out according to the TS825. Similarly, the software gives the initial investment cost and $CO_2$ emission values. The BECCP software automatically calculates the three objective functions together with the decision variables.

The second phase is referred to as the optimization process. This is the process involving minimization of the objective functions obtained in the first process. Classical calculation methods are insufficient due to the complexity of BOP problems. For a BOP, optimization does not always mean finding the global optimum point, since this might be inappropriate in relation to the definition of the problem [18]. Even in some related studies, optimization is defined as iterations that help find suboptimal solutions [19–21]. Therefore, in general, the term "convergence" is used in the optimization stage of such studies. This is because in many problems, rather than finding the global optimum point, only an algorithm's termination conditions can be reached. Performance of the algorithm is always measured in terms of not being caught by local optimums and by how fast it converges to the global optimum. In this study, the NSGA-II algorithm is used because recent studies show that it is one of the genetic algorithms that produces the best performance in optimization problems [4,8].

In the third phase, results obtained during the optimization process are presented by converting them into graphics, tables, and diagrams that can be easily reviewed by the decision maker. The most commonly used presentation method in this respect, the scatter plot, is used in the BEOP [22]. The software saves information required for each generation in the Excel file.

## 4. Multiobjective building optimization model

General explanations for the proposed model are made in this section. For detailed information on the proposed model, see Appendix A.

### 4.1. Decision variables

The building envelope and energy systems are the cause of most of the energy consumption in building construction. The decision variables used in our model basically consist of the building envelope, building energy systems, lighting systems, and electrical appliances [17].

Components that make up the building envelope include building walls, floors, ceilings, windows, and doors. These components are among those affecting the heating and cooling loads of buildings, mainly due to their heat transfer coefficient. The heat transfer coefficients of doors and windows are specific to their types, but walls, ceilings, and floors constitute various layers. According to the materials and thickness of layers, their heat transmission coefficient varies. While the thickness of floor layers for some materials are predetermined, the thickness of the insulation layer is specifically determined in the model as another decision variable. The BEOP software determines the building components together with the optimum thickness of insulation layers.

The energy systems of buildings, the second source of primary energy consumption, are classified as follows:

- Heating systems: electrical and nonelectrical system used only for heating.
- Cooling systems: electrical systems only used for cooling.
- Hot water systems: electrical or nonelectrical systems used only for hot water production.
- Heating–cooling systems: electrical systems used only for heating–cooling objectives.
- Heating–hot water systems: electrical or nonelectrical systems used for heating and hot water production.
- Solar energy systems: solar systems used for hot water production.

Lighting and electrical appliances are used in the model as the third and fourth energy consumption systems.

### 4.2. Objective functions

By considering the environmental and economic effects in the model, three objective functions are determined. These include:

Objective 1: minimization of building energy consumption (kWh).

Objective 2: minimization of initial investment costs (USD, $).

Objective 3: minimization of $CO_2$ emission (kg $CO_2$ eq.).

### 4.3. Constraints

It is necessary to select only one decision variable from similar types of variables. For example, there could be N types of doors for our model, but only one type should be selected. Constraints are established for all decision variables to determine this status.

## 5. Case study

The BECCP and BEOP software programs are implemented on a sample building project in Ankara, the capital of Turkey.

### 5.1. Entering the building characteristic data

To calculate the objective functions belonging to the sample building by BECCP software, it is necessary to enter the characteristic data of the building. The BECCP software calculates objective function values by reading data entered in an Excel file for the sample building provided in Figure 3. Characteristic values belonging to the building in question are provided in Table 1. Area and volume values are calculated from the building design. Inner temperature values can be determined by technical specialists; however, in this study, these values are determined by the authors. $CO_2$ emissions can differ from region to region. In this study, $CO_2$ emission values are referenced from [23] and [24], respectively.

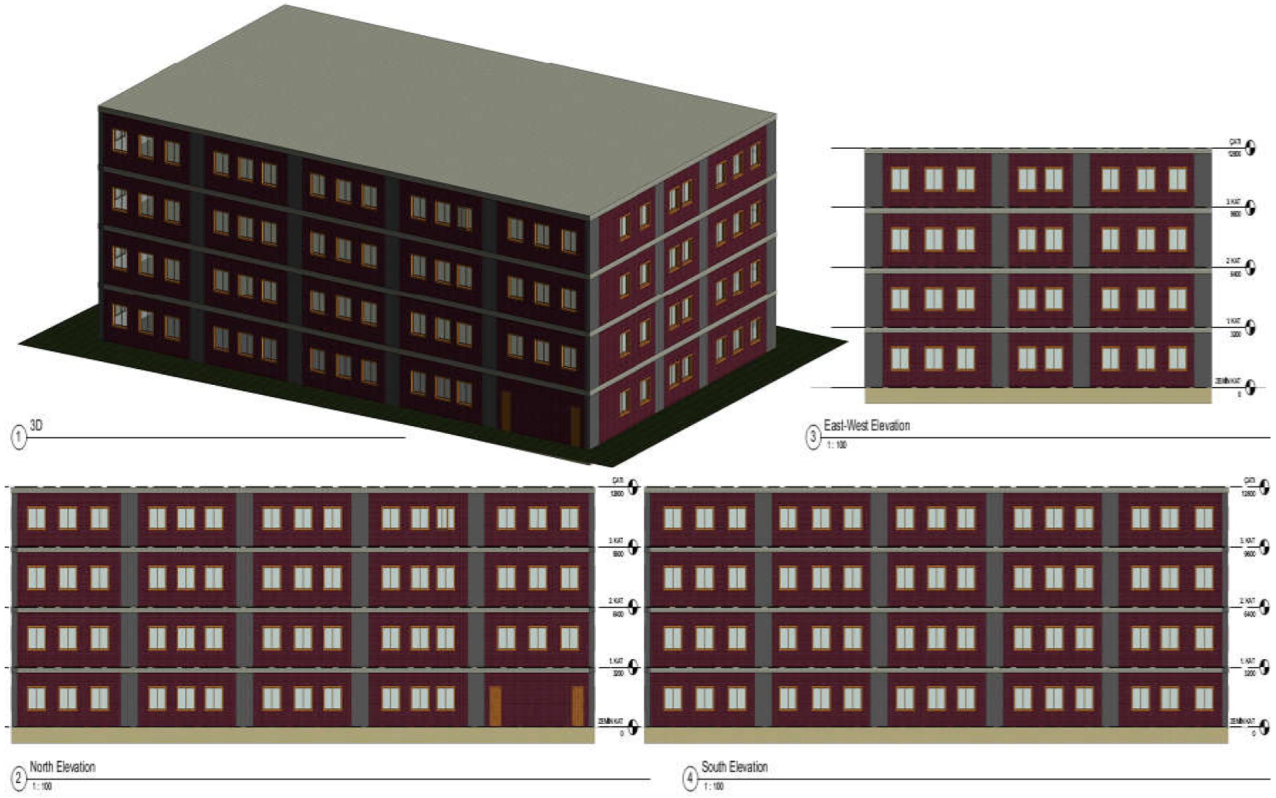


**Figure 3.** Sample building.

### 5.2. Entering decision variables belonging to the building

As explained in Section 4, decision variables affecting energy consumption, initial investment cost, and $CO_2$ emissions consist of the building envelope, building energy systems, lighting systems, and electrical appliances. Material and system alternates used in the sample building are given in Tables 2–5. The number of decision variables is 74, and there are 15 constraints and 3 objective functions. Among these, the insulation thickness can vary between 0 and 10 cm, and other variables have a value of 0–1.

### 5.3. Running BECCP software

The BECCP software calculates three objective functions according to our model. These objective functions are annual energy consumption, initial investment cost, and $CO_2$ emissions. Using BECCP software, heating

**Table 1.** Building characteristic values.

| Wall areas | Quantity | Unit |
|---|---|---|
| 1. Wall area | 1128.5 | $m^2$ |
| 2. Concrete wall area | 494 | $m^2$ |
| Flooring area | Quantity | Unit |
| 1. Floor area | 1511 | $m^2$ |
| Roof area | Quantity | Unit |
| 1. Ceiling | 1511 | $m^2$ |
| Window fields | Quantity | Unit |
| 1. Southern facade | 131.1 | $m^2$ |
| 2. Northern facade | 124.5 | $m^2$ |
| 3. Eastern facade | 87.4 | $m^2$ |
| 4. Western facade | 87.4 | $m^2$ |
| Total window area | 430.4 | $m^2$ |
| Door area | Quantity | Unit |
| 1. Outer door area | 4.7 | $m^2$ |
| Total area losing heat | 5079.6 | $m^2$ |
| Heated volume | 19340.8 | $m^3$ |
| Internal design temperature (winter) | 20 | Celsius |
| Internal design temperature (summer) | 26 | Celsius |
| $CO_2$ emissions (electricity) | 0.446 | kg $CO_2$ eq./kWh |
| $CO_2$ emissions (natural gas) | 0.374 | kg $CO_2$ eq./kWh |

energy consumption, cooling energy consumption, hot water energy consumption, lighting energy consumption, and electrical appliance energy consumption are calculated as the first objective function and submitted to the user in a text file. At the same time, the initial investment cost as the second objective function and $CO_2$ emissions as the third objective function are calculated. A multiobjective mixed integer nonlinear optimization problem with 74 decision variables, 15 constraints, and 3 objective functions emerges [17]. This problem is included in the category of NP-hard problems [18]. At this stage, the calculated values are entered into the BEOP software to conduct optimization calculations.

### 5.4. Running BEOP software

BEOP is a multiobjective optimization program that uses the NSGA-II genetic algorithm to minimize objectives. An m-objective minimization problem is described as follows [25]:

$Minimize\ F(x) = (f_1(x), f_2(x), \ldots f_m(x))\ ,\ S.T.\ x \in X\ ,$

where $F(x)$ is the m-dimensional objective vector, $f_i(x)$ is the $i$th objective to be minimized, and $x$ is the decision vectors belonging to feasible region $X$ of the solution space.

Let $A$ and $B$ be two feasible solutions of the m-objective minimization problem. If the following conditions hold, $A$ can be viewed as being better than $B$ and $A$ dominates $()B$ or $B$ is dominated by $A$:

$A\ \ B \leftrightarrow \forall i \in \{1, \ldots m\} : f_i(A) \leq f_i(B)\ and\ \exists j f_j(A) < f_j(B).$

When $A$ is not dominated by any other feasible solutions, we can say that $A$ is a nondominated solution. The set of all nondominated solutions in a decision space, called the Pareto(-optimal) set (PS), and the set of all nondominated solution in objective space, called the Pareto(-optimal) front (PF), are mathematically described as follows:

**Table 2.** Building envelope alternatives.

| Recommended wall structure | Layer | Material |
|---|---|---|
| Wall structure 1 | 1 | Plaster |
| | 2 | Bricks |
| | 3 | Plaster |
| | 4 | Insulation |
| | 5 | Plaster |
| Wall structure 2 | 1 | Plaster |
| | 2 | Bricks |
| | 3 | Insulation |
| | 4 | Bricks |
| | 5 | Plaster |
| Suggested concrete wall Structure | Layer | Material |
| Concrete wall structure 1 | 1 | Plaster |
| | 2 | Concrete |
| | 3 | Plaster |
| | 4 | Insulation |
| | 5 | Plaster |
| Concrete wall structure 2 | 1 | Plaster |
| | 2 | Concrete |
| | 3 | Insulation |
| | 4 | Plaster |
| Recommended floor structure | Layer | Material |
| Floor structure 1 | 1 | PVC flooring |
| | 2 | Alum |
| | 3 | Insulation |
| | 4 | Alum |
| | 5 | Concrete |
| Floor structure 2 | 1 | Ceramic |
| | 2 | Alum |
| | 3 | Insulation |
| | 4 | Alum |
| | 5 | Concrete |
| Recommended ceiling Structure | Layer | Material |
| Roof structure 1 | 1 | Plaster |
| | 2 | Concrete |
| | 3 | Insulation |
| | 4 | Plaster |
| Roof structure 2 | 1 | Plaster |
| | 2 | Concrete |
| | 3 | Insulation |
| | 4 | Plaster |
| | 5 | Mosaic |
| Recommended insulation materials | | |
| 1 (extruded polystyrene foam) (XPS) | | |
| 2 (expanded polystyrene foam) (EPS) | | |
| 3 (polyurethane rigid foam) (PUR) | | |
| The recommended window Types | Subtypes | |
| 1 Woodwork | Single glazed windows | |
| | Double glazed windows (Interstitial Space 9 mm) | |
| | Low-e coated double glazed windows (interstitial space 9 mm) | |
| 2 Plastic joinery | Single glazed windows | |
| | Double glazed windows (interstitial space 9 mm) | |
| | Low-e coated double glazed windows (interstitial space 9 mm) | |
| 3 Aluminum joinery | Single Glazed Windows | |
| | Double glazed windows (interstitial space 9 mm) | |
| | Low-e coated double glazed windows (interstitial space 9 mm) | |
| Recommended door types | | |
| 1 Wooden door | | |
| 2 Plastic door | | |
| 3 Metal (insulated) door | | |
| 4 Metal (noninsulated) door | | |

**Table 3.** Building energy systems alternatives.

| Recommended heating systems |
|---|
| Electronic systems |
| 1 Electric boiler A |
| 2 Electric boiler B |
| Nonelectric systems |
| 1 Natural gas boiler A |
| 2 Natural gas boiler B |
| Recommended cooling systems |
| Electronic systems |
| 1 Air cooled chiller A |
| 2 Air cooled chiller B |
| Recommended heating–cooling systems |
| Electronic systems |
| 1 Heat pump |
| 2 VRF air conditioner |
| Recommended hot water systems |
| Electronic systems |
| 1 Electric boiler A |
| 2 Electric boiler B |
| Recommended heating–hot water systems |
| Electronic systems |
| 1 Electric boiler A |
| 2 Electric boiler B |
| Nonelectric systems |
| 1 Natural gas boiler A |
| 2 Natural gas boiler B |
| Recommended solar collectors |
| 1 Copper collector |
| 2 Aluminum collector |
| 3 Selective surface collector |

**Table 4.** Building lighting alternatives.

| Recommended lamp types |
|---|
| 1 Fluorescent lamp A |
| 2 Fluorescent lamp B |
| 3 LED lamp |

**Table 5.** Electrical appliance alternatives.

| Refrigerator alternatives | Washing machine alternatives | Dishwasher alternatives |
|---|---|---|
| Recommended refrigerator types | Recommended washing machine types | Recommended dishwasher types |
| 1 Refrigerator A | 1 Washing mach. A | 1 Dishwasher A |
| 2 Refrigerator B | 2 Washing mach. B | 2 Dishwasher B |

$$\textit{Pareto Set (PS)} = \{\ x\ \in X | y \in X : y\ \ x\ \}\ ,$$

$$\textit{Pareto Front (PF)} = \{\ \textit{F(x)}\ |x \in\ PS\ \}\ .$$

The main loop of the NSGA-II algorithm is given in Figure 4, and the procedure is shown in Figure 5 [8]. The complexity of the NSGA-II is $O(MN^2)$, where M is the number of objectives and N is the population size [8].

```
$R_t = P_t \cup Q_t$                              combine parent and offspring population
$F$ = fast-nondominated-sort ($R_t$)              $F = (F_1, F_2 \ldots)$, all nondominated fronts of $R_t$
$P_{t+1} = \varnothing$ ve $i = 1$
Until $|P_{t+1}| + |F_i| \leq N$                  until the parent population is filled
          crowding-distance-assignment ($F_i$)              calculate crowding-distance in $F_i$
          $P_{t+1} = P_{t+1} \cup F_i$              include ith nondominated front in the parent
                                                            pop
          $i = i + 1$                              check the next front for inclusion
Sort ($F_i$, $\prec_n$)                            sort in descending order using $\prec_n$ (Crowded-
                                                  Comparison Operator)
$P_{t+1} = P_{t+1} \cup F_i[1: (N - |P_{t+1}|)]$  choose the first $(N - |P_{t+1}|)$ elements of $F_i$
$Q_{t+1}$ = make-new-pop ($P_{t+1}$)              use selection, crossover and mutation to
                                                  create a new population $Q_{t+1}$
$t = t+1$                                         increment the generation counter
```

**Figure 4.** NSGA-II algorithm pseudocode.

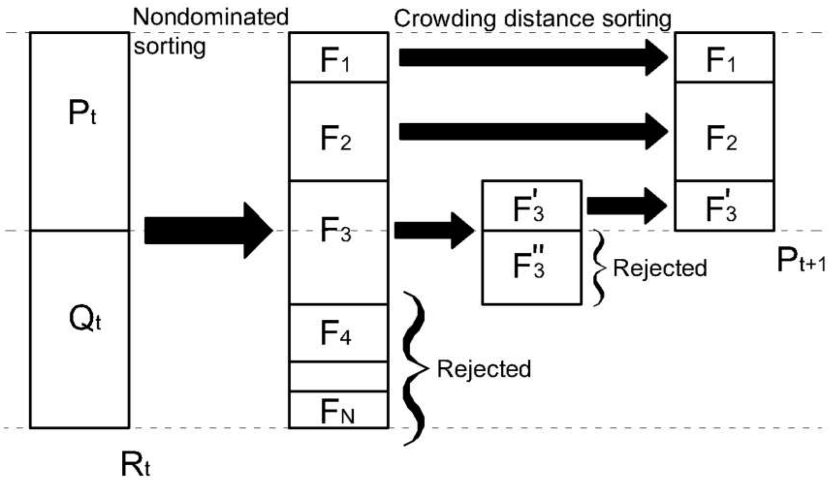
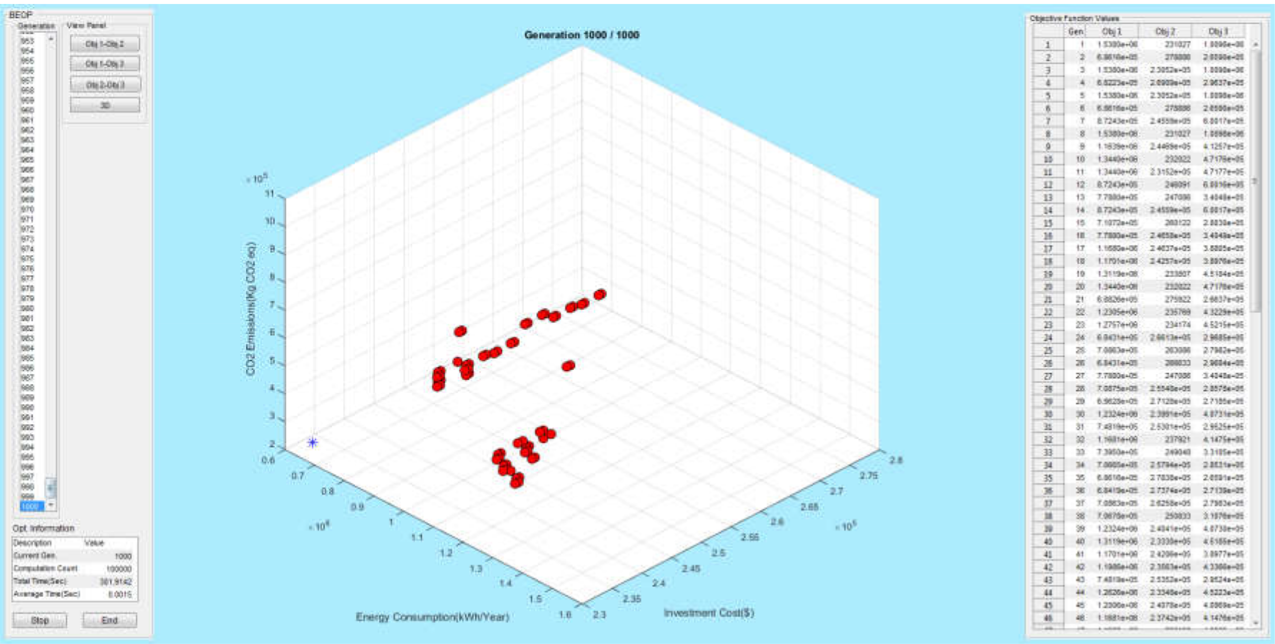


**Figure 5**. NSGA-II procedure.

By entering the objective function and constraints in the BEOP software, the solution process begins. Here, the software allows for the setting of the parameters of the genetic algorithm. While calculation processes are in progress in the background in the BEOP, as can be seen in Figure 6, it is possible to monitor the number of generations, objective function values, calculation time, and average calculation time. While the software implements solutions, at the same time, it saves all of the data in the Excel file.



Opt. Information

| Description | Value |
|---|---|
| Current Gen. | 1000 |
| Computation Count | 100000 |
| Total Time(Sec) | 301.9142 |
| Average Time(Sec) | 0.0015 |

**Figure 6.** BEOP interface.

## 6. Results and discussion

Objective functions can be reviewed by clicking on one of the feasible solutions shown in the BEOP interface, as can be seen in Figure 6. The decision maker can choose among the suitable solutions on the interface. Additionally, the selection of equipment to be used for each objective function and optimum insulation thickness is determined in the Excel file.

It takes 301.91 s to reach a maximum generation number of 1000 in a computer with an Intel Zeon E5-1660@3.30 GHz CPU and 32 GB of RAM. Two of the feasible solutions are selected in consideration of the results. One of them is average and the other one is better in energy consumption, as shown in Figures 7–10. The selected system and insulation thicknesses are given in Table 6 for the suitable solutions in question.

It can be easily seen in Figure 8 that Objective 1 increases and Objective 2 decreases, as investment cost and energy consumption values are inversely proportional. In Figure 9, it can be observed that the increase in energy consumption also increases $CO_2$ emissions. In Figure 10, with an increase in the investment cost, $CO_2$ emissions slowly decrease. It is possible to explain this situation with the fact that environmentally sensitive materials are more expensive.

Material and system types chosen by the BEOP for the sample building are listed in Table 6. The software has determined the wall, concrete, window, door, ceiling, and floor structures to be used in the building envelope. The software also provides the optimum insulation thickness and necessary insulation materials to be used in these structures. In addition, appropriate systems among many heating, cooling, and hot water systems are selected. Electrical appliances such as refrigerators, washing machines, and lamps to be used in the building are also determined.

Analyzing Table 6, it can be seen that small changes made in the selection of the heating, cooling, and lighting systems brings approximately $19,547 in additional costs, 94.488 kWh of energy savings, and 43.648 kg $CO_2$ eq. less emissions annually.

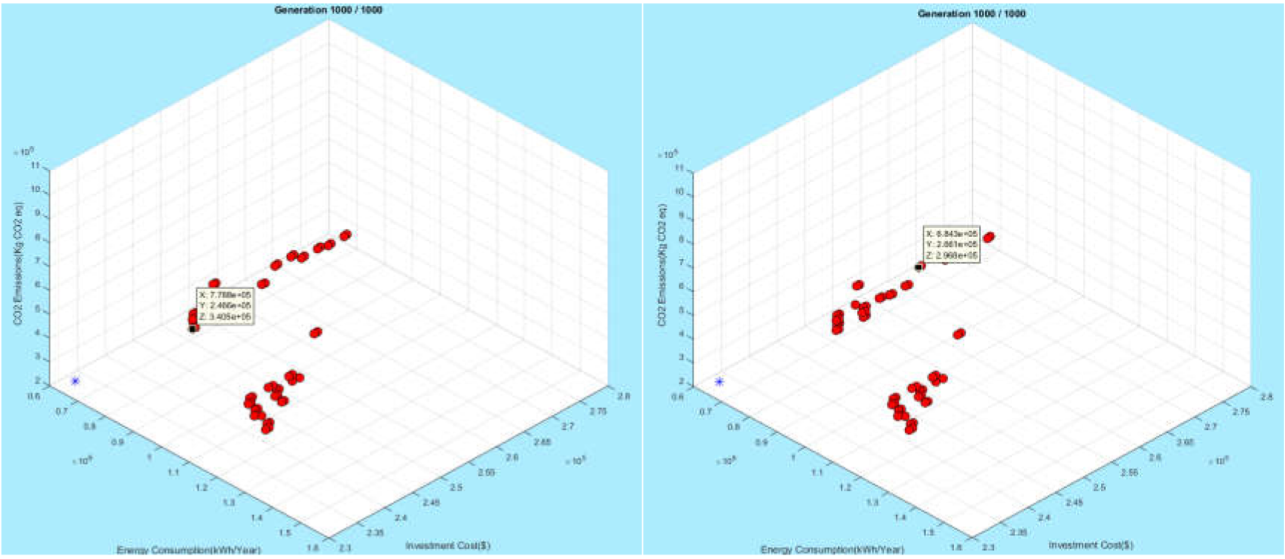


**Figure 7.** Chosen feasible solutions.

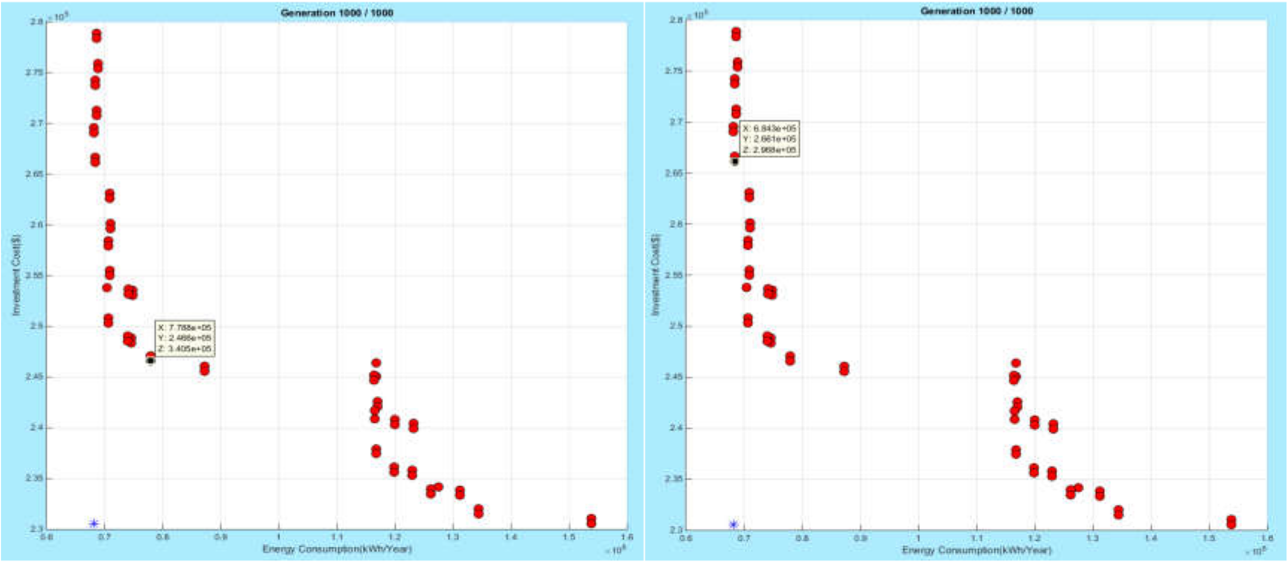


**Figure 8.** Chosen feasible solution values for Objective 1 and Objective 2.

## 7. Conclusion and perspectives for future work

Today, energy consumption and related environmental effects have gained great importance. As a result, the minimization of energy consumption, environmental effects, and investment costs has become more of an issue. In this context, in accordance with measures recently taken by the Turkish government, a method and software have been developed taking into account various building materials and energy systems used in the market. It is observed that, after implementation in a real project, the software reached Pareto solutions in a short time and provided clear guidance for the decision maker.

The developed method is quite general and can be applied for all types of buildings, materials, and systems. Besides the 74 decision variables, 3 objective functions, and 15 constraints calculated as per TS825 for the first time, a large variety of materials and systems are used in the model. In accordance with construction

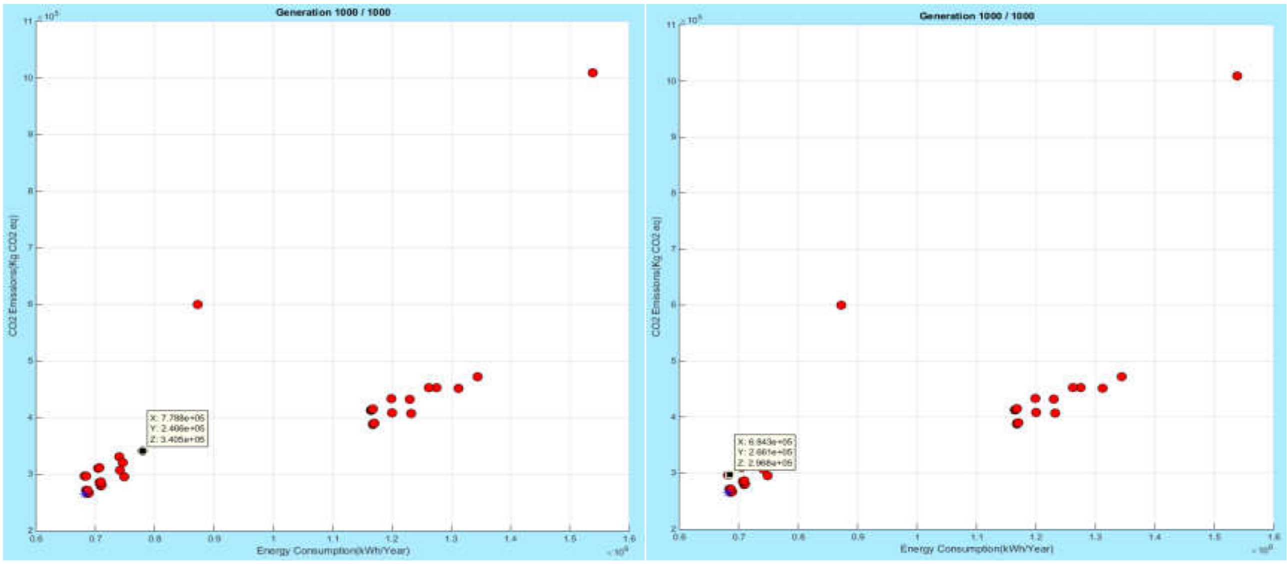


**Figure 9.** Chosen feasible solution values for Objective 1 and Objective 3.

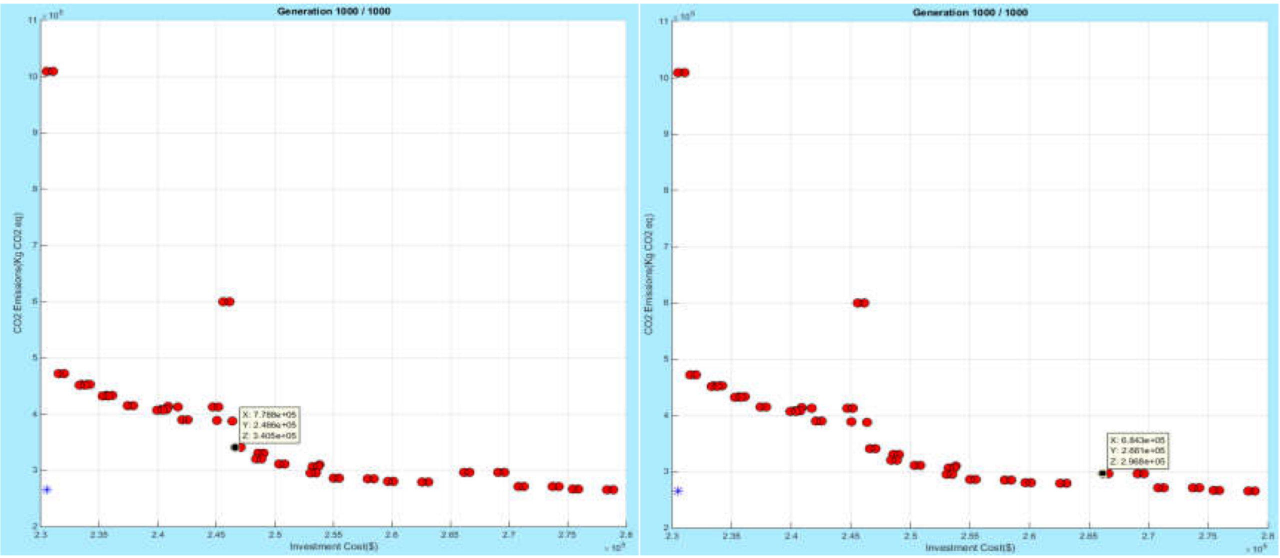


**Figure 10.** Chosen feasible solution values for Objective 2 and Objective 3.

sector guidelines, the minimization of investment cost, energy consumption, and $CO_2$ emissions is intended. The two developed software tools are intended to be guidance for decision makers in the construction sector.

In future studies, it is planned to extend the variety of used materials and system types in the building and to include different objective functions in the model. A performance comparison with different building designs and computational analysis can also be conducted.

**Table 6.** Comparison of decision variables and objective functions for selected solutions.

| Alternatives | Chosen solution 1 | Chosen solution 2 |
|---|---|---|
| | Materials and systems | Materials and systems |
| Wall | Wall structure 1 | Wall structure 1 |
| Concrete wall | Concrete wall structure 2 | Concrete wall structure 2 |
| Base | Floor structure 2 | Floor structure 2 |
| Ceiling | Roof structure 2 | Roof structure 2 |
| Insulation | (Extruded polystyrene foam) (XPS) | (Extruded polystyrene foam) (XPS) |
| Window | Aluminum joinery/single glazed Windows | Aluminum joinery/single glazed Windows |
| Door | Plastic door | Plastic door |
| Lighting | Fluorescent lamp B | LED lamp |
| Refrigerator | Refrigerator A | Refrigerator A |
| Washing machine | Washing machine A | Washing machine A |
| Dishwasher | Dishwasher B | Dishwasher B |
| Heating–hot water Sys. | Natural gas boiler B | Natural gas boiler A |
| Cooling systems | Air cooled chiller B | Air Cooled chiller A |
| Solar collectors | Aluminum collector | Aluminum collector |
| Wall insulation Thickness | 10 cm | 10 cm |
| Concrete wall ins. Thick. | 10 cm | 10 cm |
| Insulation thickness | 10 cm | 10 cm |
| Ceiling insulation Thickness | 10 cm | 10 cm |
| Objective function 1 | 778.802 kWh | 684.314 kWh |
| Objective function 2 | $246,583 | $266,130 |
| Objective function 3 | 340,495 kg $CO_2$ eq. | 296,847 kg $CO_2$ eq. |

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## Appendix A. Equations of the proposed model

### A1. Decision variables

Decision variables used in our model are divided into four parts: building envelope, building energy systems, lighting systems, and electrical appliances.

### A1.1. Building envelope

a) Doors:

If K is the number of door alternatives, then the $x_k^{Kapı}$ decision variable is defined as follows: $x_k^{Kapı} = \begin{cases} 1, \; if\, door\, type\, k\, is\, selected \\ 0, \; else \end{cases}$

$$k = 1, \ldots, K$$

b) Windows:

If P is the number of window alternatives (aluminum frame, wooden frame, or PVC frame) and Z is the subtype of each alternative (monoglazed, double-glazed, or low-e), then the $x_{pz}^{Pen}$ decision variable is defined as follows:

$$x_{pz}^{Pen} = \begin{cases} 1, \; if\, window\, sub-type\, z\, of\, type\, p\, is\, selected \\ 0, \; else \end{cases}$$

$$p = 1, \ldots, P\, z = 1, \ldots, Z$$

c) Insulation:

If Y is the number of insulation alternatives, then the $x_y^{Yalıtım}$ decision variable is defined as follows:

$$x_y^{Yal} = \begin{cases} 1, \; if\, insulation\, type\, y\, is\, selected \\ 0, \; else \end{cases}$$

$$y = 1, \ldots, Y$$

d) Walls:

If D is the number of wall structure alternatives, then the $x_d^{Duvar}$ decision variable is defined as follows:

$$x_d^{Duvar} = \begin{cases} 1, \; if\, wall\, structure\, type\, d\, is\, selected \\ 0, \; else \end{cases}$$

$$d = 1, \ldots, D$$

Each wall structure consists of different layers. The number of known layers can be defined as $bk_{duvar} = 1, \ldots, BK_{duvar}$. Their thickness can be defined as $(d_{d,bk}^{Duvar})$, and their specific thermal conductivities can be defined as $(\lambda_{d,bk}^{Duvar})$.

The thickness of the insulation layer is unknown and is defined as $d_{d,y}^{DYal}$. The specific thermal conductivities can be defined as $(\lambda_{d,y}^{Yal})$. Thus, the heat transfer coefficient of each wall $(U_d^{duvar})$ can be calculated as:

$$U_d^{duvar} = \left( \frac{1}{R_i} + \sum_{bk_{duvar}=1}^{BK_{duvar}} \frac{d_{d,bk}^{Duvar}}{\lambda_{d,bk}^{Duvar}} + \sum_{y=1}^{Y} x_y^{Yal} \left( \frac{d_{d,y}^{DYal}}{\lambda_{d,y}^{Yal}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$d_{d,min}^{thickness} \le d_{d,y}^{DYal} \le d_{d,max}^{thickness}$$

where:

$\lambda$ : specific thermal conductivity (W/mK)

U: overall heat transfer coefficient (W/m$^2$K)

R$_i$: indoors combined convection-radiation coefficient (W/m$^2$K)

R$_e$: outdoors combined convection-radiation coefficient (W/m$^2$K)

$d_{d,min}^{thickness}$, $d_{d,max}^{thickness}$ : min and max isolation thickness for walls

e) Structural walls:

Two different wall types are defined in our model. Structural walls are used for carrying building loads. If YD is the number of structural wall alternatives, then the $x_{yd}^{YDuvar}$ decision variable is defined as follows:

$$x_{yd}^{YDuvar} = \begin{cases} 1, \, if \, structural \, wall \, type \, yd \, is \, selected \\ 0, \, else \end{cases}$$

$$yd = 1, \ldots, YD$$

Each structural wall consists of different layers. The number of known layers can be defined as $bk_{Yduvar} = 1, \ldots, BK_{Yduvar}$ , and their thickness can be defined as ($d_{yd,bk}^{YDuvar}$). Their specific thermal conductivities can be defined as ($\lambda_{yd,bk}^{YDuvar}$).

The thickness of the insulation layer is unknown and is defined as $d_{yd,y}^{YYal}$. Specific thermal conductivities can be defined as ($\lambda_{yd,y}^{Yal}$). Thus, the heat transfer coefficient of each wall ($U_{yd}^{Yduvar}$) can be calculated as:

$$U_{yd}^{Yduvar} = \left( \frac{1}{R_i} + \sum_{bk_{Yduvar}=1}^{BK_{Yduvar}} \frac{d_{yd,bk}^{YDuvar}}{\lambda_{yd,bk}^{YDuvar}} + \sum_{y=1}^{Y} x_y^{Yal} \left( \frac{d_{yd,y}^{YYal}}{\lambda_{yd,y}^{Yal}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$d_{yd,min}^{thickness} \le d_{yd,y}^{YYal} \le d_{yd,max}^{thickness}$$

$d_{yd,min}^{thickness}$, $d_{yd,max}^{thickness}$ : min and max isolation thickness for structural walls

f) Ceilings:

If TAV is the number of ceiling structure alternatives, then the $x_{tav}^{Tavan}$ decision variable is defined as follows:

$$x_{tav}^{Tavan} = \begin{cases} 1, \, if \, ceiling \, structure \, type \, tav \, is \, selected \\ 0, \, else \end{cases}$$

$$tav = 1, \ldots, TAV$$

Each ceiling structure consists of different layers. The number of known layers can be defined as $bk_{tav} = 1, \ldots, BK_{tav}$. Their thickness can be defined as $(d^{Tavan}_{tav,bk})$, and their specific thermal conductivities can be defined as $(\lambda^{Tavan}_{tav,bk})$.

The thickness of the insulation layer is unknown and is defined as $d^{TavYal}_{tav,y}$. Specific thermal conductivities can be defined as $(\lambda^{Yal}_{tav,y})$. Thus, the heat transfer coefficient of each wall $(U^{Tavan}_{tav})$ can be calculated as:

$$U^{Tavan}_{tav} = \left( \frac{1}{R_i} + \sum_{bk_{tav}=1}^{BK_{tav}} \frac{d^{Tavan}_{tav,bk}}{\lambda^{Tavan}_{tav,bk}} + \sum_{y=1}^{Y} x^{Yal}_{y} \left( \frac{d^{TavYal}_{tav,y}}{\lambda^{Yal}_{tav,y}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$d^{thickness}_{tav,min} \leq d^{TavYal}_{tav,y} \leq d^{thickness}_{tav,max}$$

$d^{thickness}_{tav,min}$, $d^{thickness}_{tav,max}$ : min and max isolation thickness for ceiling

g) Floors:

If TAB is the number of floor structure alternatives, then the $x^{Taban}_{tab}$ decision variable is defined as follows:

$$x^{Taban}_{tab} = \begin{cases} 1, \, if\, floor\, structure\, type\, tab\, is\, selected \\ 0, \, else \end{cases}$$

$$tab = 1, \ldots, TAB$$

Each floor structure consists of different layers. The number of known layers can be defined as $bk_{tab} = 1, \ldots, BK_{tab}$. Their thickness can be defined as $(d^{Taban}_{tab,bk})$, and their specific thermal conductivities can be defined as $(\lambda^{Taban}_{tab,bk})$.

The thickness of the insulation layer is unknown and is defined as $d^{TabYal}_{tab,y}$. Specific thermal conductivities can be defined as $(\lambda^{Yal}_{tab,y})$. Thus, the heat transfer coefficient of each wall $(U^{Taban}_{tab})$ can be calculated as:

$$U^{Taban}_{tab} = \left( \frac{1}{R_i} + \sum_{bk_{tab}=1}^{BK_{tab}} \frac{d^{Taban}_{tab,bk}}{\lambda^{Taban}_{tab,bk}} + \sum_{y=1}^{Y} x^{Yalıtım}_{y} \left( \frac{d^{TabYal}_{tab,y}}{\lambda^{Yal}_{tab,y}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$d^{thickness}_{tab,min} \leq d^{TabYal}_{tab,y} \leq d^{thickness}_{tab,max}$$

$d^{thickness}_{tab,min}$, $d^{thickness}_{tab,max}$ : min and max isolation thickness for floors.

### A1.2. Buildings energy systems

a) Heating systems:

EISi is a category of electrical heating systems that includes EISj electrical heating systems. If eısi=1, …, EISi and eısj=1, …, EISj, then:

$$x^{EIS}_{eısi,eısj} = \begin{cases} 1, \text{ if an electrical heating system eısj of category eısi is selected} \\ 0, \; else \end{cases}$$

EOISi is a category of nonelectrical heating systems that includes EOISj nonelectrical heating systems. If eoisi = 1, . . . , EOISi and eoisj = 1, . . . , EOISj, then:

$$x^{EOIS}_{eo\imath si,eo\imath sj} = \begin{cases} \text{1, if a nonelectrical heating system eoisj of category eoisi is} \\ \text{selected} \\ 0, \ else \end{cases}$$

b) Cooling systems:

SSi is a category of electrical cooling systems that includes SSj electrical cooling systems. If ssi = 1, . . . , SSi and ssj = 1, . . . , SSj then:

$$x^{SS}_{ssi,ssj} = \begin{cases} 1, \textit{if an electrical cooling system ssj of category ssi is selected} \\ 0, \ else \end{cases}$$

c) Domestic hot water systems:

ESSi is a category of electrical domestic hot water systems that includes ESSj electrical domestic hot water systems. If essi = 1, . . . , ESSi and essj = 1, . . . , ESSj , then:

$$x^{ESS}_{essi,essj} = \begin{cases} 1, \textit{ if an electrical domestic hot water system essj of category} \\ \textit{essi is selected} \\ 0, \ else \end{cases}$$

d) Heating–cooling systems:

ISSi is a category of electrical heating cooling systems that includes ISSj electrical heating cooling systems. If issi = 1, . . . , ISSi and issj = 1, . . . , ISSj, then:

$$x^{ISS}_{\imath ssi,\imath ssj} = \begin{cases} \text{1, if an electrical heating cooling system issj of category issi is} \\ \text{selected} \\ 0, \ else \end{cases}$$

e) Heating–domestic hot water systems:

EISSSi is a category of electrical heating–domestic hot water systems that includes EISSSj electrical heating–domestic hot water systems. If eisssi = 1, . . . , EISSSi and eisssj = 1, . . . , EISSSj, then:

$$x^{EISSS}_{e\imath sssi,e\imath sssj} = \begin{cases} \text{1, if an electrical heating} - \text{domestic hot water system } eisssj \\ \textit{of category} \text{ eisssi is selected} \\ 0, \ else \end{cases}$$

EOISSSi is a category of nonelectrical heating–domestic hot water systems that includes EOISSSj nonelectrical heating–domestic hot water systems. If eoisssi = 1, . . . , EOISSSi and eoisssj = 1, . . . , EOISSSj, then:

$$x^{EOISSS}_{eo\imath sssi,eo\imath sssj} = \begin{cases} \text{1, if a nonelectrical heating} - \text{domestic hot water system} \\ \text{eoisssj of category eoisssi is selected} \\ 0, \ else \end{cases}$$

f) Solar collector systems:

GKi is the number of solar collector system alternatives. If gki = 1, . . . , GKi, then:

$$x_{gk}^{GK} = \begin{cases} 1, \, if\, gki\, solar\, collector\, system\, altenative\, is\, selected \\ 0, \;\; else \end{cases}$$

### A1.3. Lighting systems

L is the number of lighting systems alternatives. If l = 1, . . . , L, then:

$$x_{l}^{Ayd} = \begin{cases} 1, \, if\, l\, lighting\, system\, alternative\, is\, selected \\ 0, \;\; else \end{cases}$$

### A1.4. Electrical appliances

ECSi is a category of electrical appliances that includes ECSj electrical appliances. If ecsi = 1, . . . , ECSi and ecsj = 1, . . . , ECSj, then:

$$x_{ecsi,ecsj}^{ECS} = \begin{cases} 1, \, if\, an\, electrical\, appliance\, ecsj\, of\, category\, ecsi\, is\, selected \\ 0, \;\; else \end{cases}$$

### A2. Objective functions

Objective functions are a minimization of building energy consumption, the initial investment cost, and $CO_2$ emissions. They can be defined as:

$Min[g_1(x)] = Q_T$ (minimization of building energy consumption)

$Min[g_2(x)] = Y_T$ (minimization of initial investment cost)

$Min[g_3(x)] = CO_2^T$ (minimization of $CO_2$ emissions)

### A2.1. Building energy consumption

The total annual energy consumption of a building is the sum of energy used for heating, cooling, domestic hot water, lighting, and electrical appliances can. It can be defined as:

$Q_T = Q_{Is\imath} + Q_{So\breve{g}} + Q_{S\imath cSu} + Q_{Ayd} + Q_{Cih}$

Energy consumption for heating ($Q_{Is\imath}$):

$$Q_{Is\imath} = Q_e^{Is\imath} + Q_{eo}^{Is\imath}$$

$Q_e^{Is\imath}$ : annual energy consumption for the electrical heating system

$Q_{eo}^{Is\imath}$ : annual energy consumption for the nonelectrical heating system

$$Q_e^{Is\imath} = Q_{y\imath l}^{Is\imath} v_e^{Is\imath}$$

$$Q_{eo}^{Is\imath} = Q_{y\imath l}^{Is\imath} v_{eo}^{Is\imath}$$

$$v_e^{Isi} = \sum_{eisi=1}^{EISi} \sum_{eisj=1}^{EISj} \frac{x_{eisi,eisj}^{EIS}}{v_{eisi,eisj}^{EIS}} + \sum_{issi=1}^{ISSi} \sum_{issj=1}^{ISSj} \frac{x_{issi,issj}^{ISS}}{v_{issi,issj}^{ISS}} + \sum_{eisssi=1}^{EISSSi} \sum_{eisssj=1}^{EISSSj} \frac{x_{eisssi,eisssj}^{EISSS}}{v_{eisssi,eisssj}^{EISSS}}$$

$$v_{eo}^{Isi} = \sum_{eoisi=1}^{EOISi} \sum_{eoisj=1}^{EOISj} \frac{x_{eoisi,eoisj}^{EOIS}}{v_{eoisi,eoisj}^{EOIS}} + \sum_{eoisssi=1}^{EOISSSi} \sum_{eoisssj=1}^{EOISSSj} \frac{x_{eoisssi,eoisssj}^{EOISSS}}{v_{eoisssi,eoisssj}^{EOISSS}}$$

$v_{e}^{Isi}$, $v_{eo}^{Isi}$ : efficiency of the selected electrical and nonelectrical systems for heating

$v_{eisi,eisj}^{EIS}$, $v_{issi,issj}^{ISS}$, $v_{eisssi,eisssj}^{EISSS}$, $v_{eoisi,eoisj}^{EOIS}$, $v_{eoisssi,eoisssj}^{EOISSS}$ : efficiency of the electrical and nonelectrical systems of the related categories.

$Q_{y\imath l}^{Isi}$ : building's total annual energy demand for heating (W)

Calculation method:

$$Q_{y\imath l}^{Isi} = \sum_{1}^{12} Q_{ay}^{Isi}$$

$$Q_{ay}^{Isi} = \begin{cases} \left[H\left(\theta_i - \theta_e\right) - \eta_{ay}\left(\emptyset_{i,ay} + \emptyset_{s,ay}\right)\right], & if\, positive \\ 0, & else \end{cases}$$

$Q_{ay}^{Isi}$ : building's monthly energy demand for heating (W)

$H$ : building's specific heat loss (W/K)

$\theta_i$ ,$\theta_e$: average internal and external temperature in a month (°C)

$\eta_{ay}$: correction factor for heat gains

$\emptyset_{i,ay}$ : average internal heat gains per month (W)

$\emptyset_{s,ay}$ : average solar heat gains per month (W)

1. Building-specific heat loss (H)

$$H = H_T + H_V$$

$H_T$ : transmission heat loss (W/K)

$H_V$ : ventilation heat loss (W/K)

2. Transmission heat loss (H$_T$)

$$H_T = \sum AU + IU_I$$

$$\begin{aligned} H_T \;=\; & A_{Kap\imath} \sum_{k=1}^{K} \left(x_k^{Kap\imath} U_k^{Kap\imath}\right) + A_{Pen} \sum_{p=1}^{P} \sum_{z=1}^{Z} \left(x_{pz}^{Pen} U_{pz}^{Pen}\right) + A_{Duv} \sum_{d=1}^{D} \left(x_d^{Duvar} U_d^{Duvar}\right) \\ & + A_{YDuv} \sum_{yd=1}^{YD} \left(x_{yd}^{YDuvar} U_{yd}^{YDuvar}\right) + 0.8\, A_{Tav} \sum_{tav=1}^{TAV} \left(x_{tav}^{Tavan} U_{tav}^{Tavan}\right) + 0.5\, A_{Tab} \sum_{tab=1}^{TAB} \left(x_{tab}^{Taban} U_{tab}^{Taban}\right) \end{aligned}$$

$U_k^{Kap\imath}$, $U_{pz}^{Pen}$, $U_d^{Duvar}$, $U_{yd}^{YDuvar}$, $U_{tav}^{Tavan}$, $U_{tab}^{Taban}$ : heat transfer coefficient of the related categories (W/m$^2$K)

$A_{Kap\imath}$, $A_{Pen}$, $A_{Duv}$, $A_{YDuv}$, $A_{Tav}$, $A_{Tab}$ : area of the related categories (m$^2$)

The thermal bridge ($IU_I$) value is insignificant because of insulation, so it is not taken into consideration.

- Calculation of the heat transfer coefficient (U):

$$U_{d}^{duvar} = \left( \frac{1}{R_i} + \sum_{bk_{duvar}=1}^{BK_{duvar}} \frac{d_{d,bk}^{Duvar}}{\lambda_{d,bk}^{Duvar}} + \sum_{y=1}^{Y} x_y^{Yal\imath t\imath m} \left( \frac{d_{d,y}^{Duvar}}{\lambda_{d,y}^{Duvar}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$U_{yd}^{Yduvar} = \left( \frac{1}{R_i} + \sum_{bk_{Yduvar}=1}^{BK_{Yduvar}} \frac{d_{yd,bk}^{YDuvar}}{\lambda_{yd,bk}^{YDuvar}} + \sum_{y=1}^{Y} x_y^{Yal\imath t\imath m} \left( \frac{d_{yd,y}^{YDuvar}}{\lambda_{yd,y}^{YDuvar}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$U_{tav}^{Tavan} = \left( \frac{1}{R_i} + \sum_{bk_{tav}=1}^{BK_{tav}} \frac{d_{tav,bk}^{Tavan}}{\lambda_{tav,bk}^{Tavan}} + \sum_{y=1}^{Y} x_y^{Yal\imath t\imath m} \left( \frac{d_{tav,y}^{Tavan}}{\lambda_{tav,y}^{Tavan}} \right) + \frac{1}{R_e} \right)^{-1}$$

$$U_{tab}^{Taban} = \left( \frac{1}{R_i} + \sum_{bk_{tab}=1}^{BK_{tab}} \frac{d_{tab,bk}^{Taban}}{\lambda_{tab,bk}^{Taban}} + \sum_{y=1}^{Y} x_y^{Yal\imath t\imath m} \left( \frac{d_{tab,y}^{Taban}}{\lambda_{tab,y}^{Taban}} \right) + \frac{1}{R_e} \right)^{-1}$$

$d_{d,bk}^{Duvar}$, $d_{yd,bk}^{YDuvar}$, $d_{tav,bk}^{Tavan}$, $d_{tab,bk}^{Taban}$ : thickness of the related categories of known layers (m)

$d_{d,y}^{Duvar}$, $d_{yd,y}^{YDuvar}$, $d_{tav,y}^{Tavan}$, $d_{tab,y}^{Taban}$ : thickness of the related categories of unknown layers (m)

$\lambda_{d,bk}^{Duvar}$, $\lambda_{yd,bk}^{YDuvar}$, $\lambda_{tav,bk}^{Tavan}$, $\lambda_{tab,bk}^{Taban}$: specific thermal conductivity of the related categories of known layers (W/mK)

$\lambda_{d,y}^{Duvar}$, $\lambda_{yd,y}^{YDuvar}$, $\lambda_{tav,y}^{Tavan}$, $\lambda_{tab,y}^{Taban}$: specific thermal conductivity of the related categories of unknown layers (W/mK)

3. Ventilation heat loss ($H_v$)

$$H_V = 0.33 n_h V_h$$

$n_h$ : air change ratio $(h^{-1})$

$V_h$ : ventilated volume (0.8 × $V_{Brüt}$) (m$^3$)

$V_{Brüt}$ : ventilated gross volume (m$^3$)

4. Average internal heat gains in a month ($\O_{i,ay}$)

$\O_{i,ay} = 10 \times A_n$ (W)

$A_n$: building usage area (m$^2$)

$A_n = 0.32 \times V_{brüt}$

5. Average solar heat gains per month ($\O_{s,ay}$)

$$\O_{s,ay} = \sum_{ay}^{AY} \sum_{yon}^{YON} \left( r_{ay,yon} I_{ay,yon} A_{yon} \sum_{p=1}^{P} \sum_{z=1}^{Z} \left( x_{pz}^{Pen} g_{pz}^{Pen} \right) \right)$$

$r_{ay,yon}$ : monthly shading factor for “yon” direction

$I_{ay,yon}$ : monthly solar radiation for “yon” direction (W/m$^2$)

$A_{yon}$ : total window area for “yon” direction (m$^2$)

$g_{pz}^{Pen}$ : effective total solar energy transmittance factor of window subtype z of type p

$$g_{pz}^{Pen} = F_W g$$

F$_w$: correction factor for windows

$g$ : effective total solar energy transmittance factor in laboratory conditions

6. Gain utilization factor ($\eta_{ay}$)

   $\eta_{ay} = 1 - e^{(-1/KKO_{ay})}$

   $KKO_{ay}$ : monthly gain utilization ratio

   $KKO_{ay} = \frac{(\text{Ø}_{i,ay}+\text{Ø}_{s,ay})}{H(\theta_i-\theta_e)}$

   For reasons of simplicity, it is assumed to be 0.9 in our model.

Energy consumption for cooling (Q$_{Soğ}$):

$$Q_{Soğ} = Q_e^{Soğ}$$

$Q_e^{Soğ}$ : annual energy consumption for the electrical cooling system

$$Q_e^{Soğ} = Q_{yıl}^{Soğ} v_e^{Soğ}$$

$$v_e^{Soğ} = \sum_{ssi=1}^{SSi}\sum_{ssj=1}^{SSj}\frac{x_{ssi,ssj}^{SS}}{v_{ssi,ssj}^{SS}} + \sum_{issi=1}^{ISSi}\sum_{issj=1}^{ISSj}\frac{x_{issi,issj}^{ISS}}{v_{issi,issj}^{ISS}}$$

$v_e^{Soğ}$ : efficiency of the selected electrical systems for cooling

$v_{ssi,ssj}^{SS}$, $v_{issi,issj}^{ISS}$ : efficiency of the electrical systems of the related categories

$Q_{yıl}^{Soğ}$ : building's total annual energy demand for cooling (W)

Calculation method:

$$Q_{yıl}^{Soğ} = \sum_{1}^{12} Q_{ay}^{Soğ}$$

$$Q_{ay}^{Soğ} = \begin{cases} Q_i + Q_h + Q_{ik} + Q_{g,ay}\,, & if\,positive \\ 0, & else \end{cases}$$

$Q_{ay}^{Soğ}$ : building's monthly energy demand for cooling (W)

$Q_i$ : transmission heat gain (W)

$Q_h$ : ventilation heat gain (W)

$Q_{ik}$ : internal heat gain (W)

$Q_{g,ay}$ : solar heat gain (W)

7. Transmission heat gain ($Q_i$)

   $Q_i = H_S\left(\theta_e - \theta_i\right)$

$$\begin{aligned} H_s \quad = \quad & A_{Kapı}\sum_{k=1}^{K}\left(x_k^{Kapı}U_k^{Kapı}\right) + A_{Pen}\sum_{p=1}^{P}\sum_{z=1}^{Z}\left(x_{pz}^{Pen}U_{pz}^{Pen}\right) + A_{Duv}\sum_{d=1}^{D}\left(x_d^{Duvar}U_d^{Duvar}\right) \\ & + A_{YDuv}\sum_{yd=1}^{YD}\left(x_{yd}^{YDuvar}U_{yd}^{YDuvar}\right) + A_{Tav}\sum_{tav=1}^{TAV}\left(x_{tav}^{Tavan}U_{tav}^{Tavan}\right) + A_{Tab}\sum_{tab=1}^{TAB}\left(x_{tab}^{Taban}U_{tab}^{Taban}\right) \end{aligned}$$

   $H_s$ : building's specific heat gain (W/K)

   $\theta_i, \theta_e$: average internal and external temperature of month ($^\circ$C)

   $U_k^{Kapı}$, $U_{pz}^{Pen}$, $U_d^{Duvar}$, $U_{yd}^{YDuvar}$, $U_{tav}^{Tavan}$, $U_{tab}^{Taban}$ : heat transfer coefficient of the related categories (W/m$^2$K)

   $A_{Kapı}$, $A_{Pen}$, $A_{Duv}$, $A_{YDuv}$, $A_{Tav}$, $A_{Tab}$ : area of the related categories (m$^2$)

8. Ventilation heat gain ($Q_h$)

   $Q_h = n_h V_h \left(h_e - h_i\right)\rho_h$

   $n_h$ : air change ratio ($h^{-1}$)

   $V_h$ : ventilated volume (0.8 × $V_{Brüt}$) (m$^3$)

   $V_{Brüt}$ : ventilated gross volume (m$^3$)

   $h_e, h_i$ : enthalpy of the internal and external air (kJ/kg)

   $\rho_h$: air density (kg/m$^3$)

9. Internal heat gain ($Q_{ik}$)

$$Q_{ik} = \sum_{i}^{n} n_i W_i Z_i$$

   $n$ : number of heat gain sources (humans, machines, etc.)

   $W$ : heat load of related source (W)

   $Z =$ daily working hours of respective source (h)

10. Solar heat gains ($Ø_{g,ay}$)

$$Ø_{s,ay} = \sum_{ay}^{AY}\sum_{yon}^{YON}\left(r_{ay,yon}I_{ay,yon}A_{yon}\sum_{p=1}^{P}\sum_{z=1}^{Z}\left(x_{pz}^{Pen}g_{pz}^{Pen}\right)\right)$$

   $r_{ay,yon}$ : monthly shading factor for “yon” direction

   $I_{ay,yon}$ : monthly solar radiation for “yon” direction (W/m$^2$)

$A_{yon}$ : total window area for "yon" direction (m$^2$)

$g_{pz}^{Pen}$ : effective total solar energy transmittance factor of window subtype z of type p

$$g_{pz}^{Pen} = F_W g$$

F$_w$: correction factor for windows

$g$ : effective total solar energy transmittance factor in laboratory conditions

Energy consumption for domestic hot water (Q$_{S\imath cSu}$):

$$Q_{S\imath csu} = Q_e^{S\imath csu} + Q_{eo}^{S\imath csu} - Q_{y\imath l}^{Gk}$$

$Q_e^{S\imath csu}$ : annual energy consumption for electrical domestic hot water system

$Q_{eo}^{S\imath csu}$ : annual energy consumption for nonelectrical domestic hot water system

$Q_{y\imath l}^{Gk}$ : annual energy gains from solar collector system

$$Q_e^{S\imath csu} = Q_{y\imath l}^{S\imath csu} v_e^{S\imath csu}$$

$$Q_{eo}^{S\imath csu} = Q_{y\imath l}^{S\imath csu} v_{eo}^{S\imath csu}$$

$$v_e^{S\imath csu} = \sum_{essi=1}^{ESSi} \sum_{essj=1}^{ESSj} \frac{x_{essi,essj}^{ESS}}{v_{essi,essj}^{ESS}} + \sum_{eisssi=1}^{EISSSi} \sum_{eisssj=1}^{EISSSj} \frac{x_{eisssi,eisssj}^{EISSS}}{v_{eisssi,eisssj}^{EISSS}}$$

$$v_{eo}^{S\imath csu} = \sum_{eoisssi=1}^{EOISSSi} \sum_{eoisssj=1}^{EOISSSj} \frac{x_{eoisssi,eoisssj}^{EOISSS}}{v_{eoisssi,eoisssj}^{EOISSS}}$$

$v_e^{S\imath csu}$, $v_{eo}^{S\imath csu}$ : efficiency of the selected electrical and nonelectrical systems for domestic hot water

$v_{essi,essj}^{ESS}$, $v_{eisssi,eisssj}^{EISSS}$, $v_{eoisssi,eoisssj}^{EOISSS}$ : efficiency of the electrical and nonelectrical systems of the related categories

Calculation method:

$Q_{y\imath l}^{S\imath csu} = m_{ss} c_{su} \left(\theta_{\c{c}\imath k\imath \c{s}}^{su} - \theta_{giri\c{s}}^{su}\right) t_{y\imath l}$

$Q_{y\imath l}^{S\imath csu}$ : annual energy consumption for domestic hot water (kcal)

$m_{ss}$ : rate of consumption of hot water per hour (L/h)

$c_{su}$ : specific heat of water (1 kcal/kg °C)

$\theta_{\c{c}\imath k\imath \c{s}}^{su}$, $\theta_{giri\c{s}}^{su}$: water inlet and outlet temperatures (°C)

$t_{y\imath l}$ : annual operating hours (h)

$$Q_{y\imath l}^{Gk} = \sum_{1}^{12} Q_{ay}^{Gk}$$

$$Q_{ay}^{Gk} = A_{gk} I_{gk,ay} \sum_{gk}^{GK} x_{gk}^{GK} v_{gk}^{GK}$$

$Q_{ay}^{Gk}$ : annual energy gains from solar collector (kWh)

$A_{gk}$ : area of the solar collector (m$^2$)

$I_{gk,ay}$ : monthly collector gains (kcal/m$^2$ month)

$v_{gk}^{GK}$ : efficiency of the related solar collector

<u>Energy consumption for lighting (Q$_{Ayd}$):</u>

$$Q_{Ayd} = t_{yıl} \sum_{l=1}^{L} n_{Ayd,l} P_{Ayd,l} x_l^{Ayd}$$

$Q_{Ayd}$ : annual energy consumption for lighting (kWh)

$n_{Ayd,l}$ : number of lighting appliances in related category

$P_{Ayd,l}$ : power of lighting appliances in related category (W)

$t_{yıl}$ : annual operating hours (h)

<u>Energy consumption for electrical appliances (Q$_{Cih}$):</u>

$$Q_{Cih} = \sum_{ecsi=1}^{ECSi} \sum_{ecsj=1}^{ECSj} t_{yıl,ecsi} n_{ecsi}^{ECS} P_{ecsi,ecsj}^{ECS} x_{ecsi,ecsj}^{ECS}$$

$Q_{Cih}$ : annual energy consumption for electrical appliances (kWh)

$n_{ecsi,ecsj}^{ECS}$ : number of electrical appliances in the related category

$P_{ecsi,ecsj}^{ECS}$ : power of electrical appliances in related category (W)

$t_{yıl,ecsi}$ : annual operating hours of electrical appliances in related category (h)

### A2.2. Initial investment cost

The initial investment cost of the building is the sum of the costs for materials, systems, and appliances used in the building.

Y$_T$ = Mal$_{Kapı}$ + Mal$_{Pen}$ + Mal$_{Yal}$ +Mal$_{Duvar}$ + Mal$_{YDuvar}$ + Mal$_{Tavan}$ + Mal$_{Taban}$ + Mal$_{Isı}$ + Mal$_{Soğ}$ + Mal$_{SıcSu}$ + Mal$_{IsıSoğ}$ + Mal$_{IsıSu}$ + Mal$_{GK}$ + Mal$_{Ayd}$ + Mal$_{ECS}$

Mal$_{Kapı}$, Mal$_{Pen}$, Mal$_{Yal}$, Mal$_{Duv}$, Mal$_{YDuv}$, Mal$_{Tav}$, Mal$_{Tab}$, Mal$_{Isı}$, Mal$_{Soğ}$, Mal$_{SıcSu}$, Mal$_{IsıSoğ}$, Mal$_{IsıSu}$, Mal$_{GK}$, Mal$_{Ayd}$, Mal$_{ECS}$: investment costs for respective categories: doors, windows, insulation, walls, structural walls, ceilings, floors, heating systems, cooling systems, domestic hot water systems, heating–cooling systems, heating–domestic hot water systems, solar collectors, lighting, and electrical appliances.

<u>Initial investment cost for the doors:</u>

$$Mal_{Kapı} = A_{Kapı} \sum_{k=1}^{K} \left( x_k^{Kapı} m_k^{Kapı} \right)$$

$m_k^{Kapı}$ : initial investment cost for a door of type k (\$/m$^2$)

<u>Initial investment cost for the windows:</u>

$$Mal_{Pen} = A_{Pen} \sum_{p=1}^{P} \sum_{z=1}^{Z} \left( x_{pz}^{Pen} m_{pz}^{Pen} \right)$$

$m_{pz}^{Pen}$ : initial investment cost for a window of subtype z of type p (\$/m$^2$)

<u>Initial investment cost for the walls:</u>

$$Mal_{Duvar} = A_{Duvar} \sum_{d=1}^{D} \left( x_d^{Duvar} \left( \sum_{bk_{duvar}=1}^{BK_{duvar}} m_{d,bk}^{Duvar} + \sum_{y=1}^{Y} x_y^{Yal} \left( m_{d,y}^{Yal} \right) \right) \right)$$

$m_{d,bk}^{Duvar}$ : initial investment costs for the materials used in the known layers bk of wall type d (\$/m$^2$)

$m_{d,y}^{Yal}$ : initial investment costs for the insulation layers of wall type d (\$/m$^2$)

<u>Initial investment cost for the structural walls:</u>

$$Mal_{YDuvar} = A_{YDuvar} \sum_{yd=1}^{YD} \left( x_{yd}^{YDuvar} \left( \sum_{bk_{Yduvar}=1}^{BK_{Yduvar}} m_{yd,bk}^{YDuvar} + \sum_{y=1}^{Y} x_y^{Yal} \left( m_{yd,y}^{Yal} \right) \right) \right)$$

$m_{yd,bk}^{YDuvar}$ : initial investment costs for the materials used in the known layers bk of structural wall type yd (\$/m$^2$)

$m_{yd,y}^{Yal}$ : initial investment costs for the insulation layers of structural wall type yd (\$/m$^2$)

<u>Initial investment cost for the ceilings:</u>

$$Mal_{Tavan} = A_{Tavan} \sum_{tav=1}^{TAV} \left( x_{tav}^{Tavan} \left( \sum_{bk_{tav}=1}^{BK_{tav}} m_{tav,bk}^{Tavan} + \sum_{y=1}^{Y} x_y^{Yal} \left( m_{tav,y}^{Yal} \right) \right) \right)$$

$m_{tav,bk}^{Tavan}$ : initial investment costs for the materials used in the known layers bk of ceiling type tav (\$/m$^2$)

$m_{tav,y}^{Yal}$ : initial investment costs for the insulation layers of ceiling type tav (\$/m$^2$)

<u>Initial investment cost for the floors:</u>

$$Mal_{Taban} = A_{Taban} \sum_{tab=1}^{TAB} \left( x_{tab}^{Taban} \left( \sum_{bk_{tab}=1}^{BK_{tab}} m_{tab,bk}^{Taban} + \sum_{y=1}^{Y} x_y^{Yal} \left( m_{tab,y}^{Yal} \right) \right) \right)$$

$m_{tab,bk}^{Taban}$ : initial investment costs for the materials used in the known layers bk of floor type tab (\$/m$^2$)

$m_{tab,y}^{Yal}$ : initial investment costs for the insulation layers of floor type tav (\$/m$^2$)

<u>Initial investment costs for the electrical and nonelectrical heating systems:</u>

$$Mal_{Isi} = \sum_{eisi=1}^{EISi} \sum_{eisj=1}^{EISj} \left( x_{eisi,eisj}^{EIS} m_{eisi,eisj}^{EIS} \right) + \sum_{eoisi=1}^{EOISi} \sum_{eoisj=1}^{EOISj} \left( x_{eoisi,eoisj}^{EOIS} m_{eoisi,eoisj}^{EOIS} \right)$$

$m_{eisi,eisj}^{EIS}$ : initial investment cost for the electrical heating system eisj of category eisi (\$)

$m_{eo\imath si,eo\imath sj}^{EOIS}$ : initial investment cost for the nonelectrical heating system eoisj of category eoisi (\$)

<u>Initial investment cost for the electrical cooling systems:</u>

$$Mal_{So\breve{g}} = \sum_{ssi=1}^{SSi} \sum_{ssj=1}^{SSj} \left( x_{ssi,ssj}^{SS} m_{ssi,ssj}^{SS} \right)$$

$m^{SS}_{ssi,ssj}$ : initial investment cost for the electrical cooling system ssj of category ssi ($)

Initial investment cost for electrical domestic hot water systems:

$$Mal_{SıcSu} = \sum_{essi=1}^{ESSi} \sum_{essj=1}^{ESSj} \left( x^{ESS}_{essi,essj} m^{ESS}_{essi,essj} \right)$$

$m^{ESS}_{essi,essj}$ : initial investment cost for the electrical domestic hot water essj of category essi ($)

Initial investment cost for electrical heating–cooling systems:

$$Mal_{IsıSoğ} = \sum_{ıssi=1}^{ISSi} \sum_{ıssj=1}^{ISSj} \left( x^{ISS}_{ıssi,ıssj} m^{ISS}_{ıssi,ıssj} \right)$$

$m^{ISS}_{issi,issj}$ : initial investment cost for the electrical heating–cooling system issj of category issi ($)

Initial investment cost for electrical and nonelectrical heating–domestic hot water systems:

$$Mal_{IsıSu} = \sum_{eisssi=1}^{EISSSi} \sum_{eisssj=1}^{EISSSj} \left( x^{EISSS}_{eisssi,eisssj} m^{EISSS}_{eisssi,eisssj} \right) + \sum_{eoisssi=1}^{EOISSSi} \sum_{eoisssj=1}^{EOISSSj} \left( x^{EOISSS}_{eoisssi,eoisssj} m^{EOISSS}_{eoisssi,eoisssj} \right)$$

$m^{EISSS}_{eisssi,eisssj}$ : initial investment cost for the electrical heating–domestic hot water system eisssj of category eisssi ($)

$m^{EOISSS}_{eoisssi,eoisssj}$ : initial investment cost for the nonelectrical heating–domestic hot water system eoisssj of category eoisssi ($)

Initial investment cost for solar collector system:

$$Mal_{GK} = A_{gk} \sum_{gk=1}^{GK} \left( x^{GK}_{gk} m^{GK}_{gk} \right)$$

$m^{GK}_{gk}$ : initial investment cost for a solar collector of type gk ($/m$^2$)

Initial investment cost for lighting:

$$Mal_{Ayd} = \sum_{l=1}^{L} \left( x^{Ayd}_{l} m^{Ayd}_{l} n^{Ayd}_{l} \right)$$

$m^{Ayd}_{l}$ : initial investment cost for lighting appliances of type l ($)

$n^{Ayd}_{l}$ : number of lighting appliances of type l

Initial investment cost for electrical appliances:

$$Mal_{ECS} = \sum_{ecsi=1}^{ECSi} n^{ECS}_{ecsi} \sum_{ecsj=1}^{ECSj} \left( x^{ECS}_{ecsi,ecsj} m^{ECS}_{ecsi,ecsj} \right)$$

$m^{ECS}_{ecsi,ecsj}$ : initial investment cost for the electrical appliance ecsj of category ecsi ($)

### A2.3. $\mathbf{CO_2}$ emissions

Total annual $CO_2$ emissions are based on the total energy consumption described in the previous chapters. The $CO_2$ emissions of the appliances or systems vary according to the fuel they use. If $CO_2$ emissions for electrical systems are $S_e$ and for nonelectrical systems $S_d$, total annual $CO_2$ emissions of the building are:

$$\mathrm{CO}_2^{\mathrm{T}} = CO_2^{Isı} + CO_2^{Soğ} + CO_2^{SıcSu} + CO_2^{IsıSoğ} + CO_2^{IsıSu} + CO_2^{Ayd} + CO_2^{Cih}$$

$CO_2^{Isı} CO_2^{Soğ} CO_2^{SıcSu} CO_2^{IsıSoğ} CO_2^{IsıSu} CO_2^{Ayd} CO_2^{Cih}$ : $CO_2$ emissions for the respective categories: heating systems, cooling systems, domestic hot water systems, heating–cooling systems, heating–domestic hot water systems, lighting, and electrical appliances (kg equivalent $CO_2$).

$S_e$ : $CO_2$ emissions for electrical systems (kg equivalent $CO_2$/kWh)

$S_d$ : $CO_2$ emissions for electrical systems (kg equivalent $CO_2$/kWh)

$CO_2$ emissions for electrical and nonelectrical heating systems:

$$CO_2^{Isi} = \sum_{eisi=1}^{EISi} \sum_{eisj=1}^{EISj} \left( x_{eisi,eisj}^{EIS} Q_{Isi} S_e \right) + \sum_{eoisi=1}^{EOISi} \sum_{eoisj=1}^{EOISj} \left( x_{eisi,eisj}^{EOIS} Q_{Isi} S_d \right)$$

$CO_2$ emissions for electrical cooling systems:

$$CO_2^{Soğ} = \sum_{ssi=1}^{SSi} \sum_{ssj=1}^{SSj} \left( x_{ssi,ssj}^{SS} Q_{Soğ}\, S_e \right)$$

$CO_2$ emissions for electrical domestic hot water systems:

$$CO_2^{SıcSu} = \sum_{essi=1}^{ESSi} \sum_{essj=1}^{ESSj} \left( x_{essi,essj}^{ESS} Q_{Sıcsu} S_e \right)$$

$CO_2$ emissions for electrical heating–cooling systems:

$$CO_2^{IsıSoğ} = \sum_{issi=1}^{ISSi} \sum_{issj=1}^{ISSj} \left( x_{issi,issj}^{ISS} \left( Q_{Isi} + Q_{Soğ} \right) S_e \right)$$

$CO_2$ emissions for electrical and nonelectrical heating–domestic hot water systems:

$$CO_2^{IsıSu} = \sum_{eisssi=1}^{EISSSi} \sum_{eisssj=1}^{EISSSj} \left( x_{eisssi,eisssj}^{EISSS} \left( Q_{Isi} + Q_{SıcSu} \right) S_e \right) + \sum_{eoisssi=1}^{EOISSSi} \sum_{eoisssj=1}^{EOISSSj} \left( x_{eoisssi,eoisssj}^{EOISSS} \left( Q_{Isi} + Q_{SıcSu} \right) S_d \right)$$

$CO_2$ emissions for lighting:

$$CO_2^{Ayd} = \sum_{l=1}^{L} \left( x_l^{Ayd} Q_{Ayd} S_e \right)$$

$CO_2$ emissions for electrical appliances:

$$CO_2^{Cih} = \sum_{ecsi=1}^{ECSi} \sum_{ecsj=1}^{ECSj} \left( x_{ecsi,ecsj}^{ECS} Q_{Cih} S_e \right)$$

### A.3. Constraints

Only one type of door alternative can be selected:

$$\sum_{k=1}^{K} x_{k}^{Kapı} = 1$$

Only one type of window alternative can be selected:

$$\sum_{p=1}^{P}\sum_{z=1}^{Z} x_{pz}^{Pen} = 1$$

Only one type of insulation alternative can be selected:

$$\sum_{y=1}^{Y} x_{y}^{Yal} = 1$$

Only one type of wall structure alternative can be selected:

$$\sum_{d=1}^{D} x_{d}^{Duvar} = 1$$

Only one type of structural wall alternative can be selected:

$$\sum_{yd=1}^{YD} x_{yd}^{YDuvar} = 1$$

Only one type of ceiling structure alternative can be selected:

$$\sum_{tav=1}^{TAV} x_{tav}^{Tavan} = 1$$

Only one type of the floor structure alternative can be selected:

$$\sum_{tab=1}^{TAB} x_{tab}^{Taban} = 1$$

To select only one heating system among the alternatives:

$$\sum_{eisi=1}^{EISi}\sum_{eisj=1}^{EISj} x_{eisi,eisj}^{EIS} + \sum_{eoisi=1}^{EOISi}\sum_{eoisj=1}^{EOISj} x_{eoisi,eoisj}^{EOIS} + \sum_{issi=1}^{ISSi}\sum_{issj=1}^{ISSj} x_{issi,issj}^{ISS} +$$

$$\sum_{eisssi=1}^{EISSSi}\sum_{eisssj=1}^{EISSSj} x_{eisssi,eisssj}^{EISSS} + \sum_{eoisssi=1}^{EOISSSi}\sum_{eoisssj=1}^{EOISSSj} x_{eoisssi,eoisssj}^{EOISSS} = 1$$

To select only one cooling system among the alternatives:

$$\sum_{ssi=1}^{SSi}\sum_{ssj=1}^{SSj} x_{ssi,ssj}^{SS} + \sum_{issi=1}^{ISSi}\sum_{issj=1}^{ISSj} x_{issi,issj}^{ISS} = 1$$

To select only one domestic hot water system among the alternatives:

$$\sum_{essi=1}^{ESSi}\sum_{essj=1}^{ESSj} x_{essi,essj}^{ESS} + \sum_{eisssi=1}^{EISSSi}\sum_{eisssj=1}^{EISSSj} x_{eisssi,eisssj}^{EISSS} +$$

$$\sum_{eoisssi=1}^{EOISSSi}\sum_{eoisssj=1}^{EOISSSj} x_{eoisssi,eoisssj}^{EOISSS} = 1$$

To select only one solar collector system among the alternatives:

$$\sum_{gk=1}^{GK} x_{gk}^{GK} = 1$$

To select only one lighting system among the alternatives:

$$\sum_{l=1}^{L} x_{l}^{Ayd} = 1$$

To select only one electrical appliance from each category among the alternatives:

$$\sum_{ecsj=1}^{ECSj} x_{ecsi,ecsj}^{ECS} = 1$$