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Two-Phase Decision Support Tool to Select Construction Strategies and Heating-Cooling Systems: A Case Study in a Desert Region

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Abstract

More than 40% of energy sources in the world are consumed in buildings; hence, greening all the activities in this sector, from design to operations and also retrofit, is challenging and necessary. This research aims to identify, evaluate and select various eco-friendly construction strategies and heating-cooling systems in the early stages of designing greenhouses. A decision support tool based on a two-phase framework is developed to make the corresponding decisions. As the first phase, an efficient bi-objective optimization model is formulated to optimize the envelope establishing a reasonable trade-off between construction costs and energy consumption. Accordingly, the heating and cooling loads are calculated considering all forms of heat exchange. In the second phase, the alternative heating-cooling systems are evaluated using an energy-cost criterion over a 10-year life cycle. The developed tool is implemented for a typical house in a desert region. As the results of the first phase, the total heat exchange of selected construction strategies for the house's envelope is significantly less than the values of well-known standards, so the resulting energy consumption is only 0.22 times Iran's standard. In the second phase, the required annual electricity of the house's selected heating-cooling systems is approximately 21% lower than the reported values for the same place in that region.

Keywords: Construction strategy, Cost, Decision support tool, Energy efficiency, Greenhouse, Heating-cooling system, Optimization.

1 | Introduction

Energy efficiency and emission reduction are two issues in today's world. The rapid growth of global energy consumption has created serious severe problems regarding the energy supply and environment. Among the different sectors in society, construction needs special attention due to its role in total energy consumption and emissions. More than 40% of total energy consumption and 24% of total greenhouse gas emissions worldwide is related to residential and commercial buildings, Laustsen (2008). In Iran, a developing country, the average energy consumption per m2 of buildings is 2.6 times of the developed countries. The energy consumption in the desert regions of Iran, e.g., Yazd, is up to 4 times the world average. Moreover, with a 38% contribution to greenhouse gas emissions, Iran is ranked in first in the Middle East, Saki Pour et al. (2011). Accordingly, it is necessary to consider the energy efficiency and emission reduction measures in the new and rebuilding

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constructions. Such measures could be implemented in the different stages of construction, from design to operations and also the retrofit stage, but the best performance is yielded when we implement them for the design stage. Green architecture, as an approach to sustainability in the design stage of an eco-friendly building, aims at efficiently using the energy in the buildings, preventing prejudicial climate changes, and finally, protecting the environment.

Today, innovative technologies and energy efficiency measures are widely employed in the different stages of the construction industry; however, the main problem is selecting the most efficient and reliable strategies (i.e., the combination of the existing technologies and measures) considering the characteristics of a particular region. A decision maker (DM) needs to identify and make a decision among many choices, which is usually not easy. Moreover, to resolve such a problem, they have to address and establish a compromise among the corresponding environmental, financial, social, and energy factors subject to the prevailing constraints in order to achieve the best performance.

In this paper, the identified strategies, proposed based on the principles of green architecture Roaf et al. (2011), are categorized into the following two groups:

- Those related to the house's envelope,
- Those associated with the heating-cooling systems.

The primary motivation of this research is to develop an efficient interactive decision support tool for decision-making in the early stage of designing the greenhouses, implement it for the desert regions as the most problematic case, and compare the results to those of traditional houses. To do so, a two-phase framework is proposed in which the different construction strategies for the house's envelope and heating-cooling systems are identified and evaluated, and the best combination of them is selected based on the financial and energy criteria. Notably, the other two factors, i.e., environmental and social, are implicitly considered in the identification process. Moreover, we will compare the performance of the resulting construction combination to the traditional construction methods based on the principles of green architecture.

The rest of the paper is organized as follows. Section 2 provides the problem description, the proposed framework, and the developed decision support tool. In Section 3, we implement it for a real case and discuss the computational experiments and analytical results. Finally, the concluding remarks and future direction are provided. The appendix is devoted to some detailed data.

2. Literature review

To design a greenhouse, the DM needs to compromise between several conflicting objectives. For example, insulating the house's envelope reduces energy loss; however, it is more expensive. Therefore, using some kinds of modeling and computation methods is necessary for decision-making in designing a greenhouse. Two alternatives are I) simulation techniques, and II) analytical methods and optimization models.

The literature review reveals that some simulation studies were developed. In the following, we present the two relevant ones. Delgarm et al. (2016) designed an efficient simulation study based on combining multi-objective PSO and "EnergyPlus", the building energy simulation program, for evaluating the orientation, shading specifications, window size, and glazing and wall materials. The developed method was applied to the different climatic regions of Iran. Hamdy et al. (2013) proposed a three-stage simulation-based optimization to find cost-optimal solutions toward nearly-zero-energy buildings under the European energy performance of Buildings Directive (EPBD-recast 2010). Different options of envelope parameters, heat-recovery units, and heating/cooling systems, as well as various sizes of thermal and photovoltaic solar systems, were explored as design options. The method was implemented for a single-family house in Finland. The simulation methods are time-consuming and need much computation effort. At the same time, the accuracy of results is fewer since they inherently cannot search the total solution space of design strategies. Gugul et al. (2018) provided a techno-economic feasibility study of applying a wide range of energy efficiency measures and renewable energy technologies to existing single-family homes using monitored energy consumption data and a building energy simulation program. The findings are extrapolated to the existing single-family housing stock in three major cities of Turkey to estimate the potential for energy and emission reductions. The results indicated that applying window glazing, roof, and a combination of window, wall, and roof improvements reduces heating energy demand with favorable payback periods.

To tackle the above shortcomings, the authors applied analytical methods and optimization models. Shen et al. (2015) developed building energy efficiency policies and implemented them in some countries. The policies were classified into three groups: the mandatory administration instrument, the economic incentive instrument, and the voluntary scheme instruments. The countries, by adopting the different types of policy instrument, achieved better energy efficiency results for the buildings. A good insight into energy consumption in the buildings is important for understanding the energy and climate change policies in the future. Allouhi et al. (2015) discussed and analyzed the past data, current status, and future trends in energy consumption in residential and commercial buildings in selected countries. In an experimental program, Dan et al. (2016) built an energy-efficient house following the passive house design principles reflecting the Romanian local climate conditions, materials, and construction techniques. They monitor and compare it to a reference house in the design phase to emphasize the differences in terms of energy demand and life-cycle cost.

Notably, to be more effective, most of the energy efficiency decisions have to be made in the early stages of a building design. In the recent decade, researchers developed different construction strategies for energy efficiency in buildings. Chen et al. (2017) proposed a renovated passive design assessment system for green building labeling. The system was applied to cooling and lighting-related criteria because these criteria were affected by selected passive design strategies. Tan et al. (2016) used a mathematical programming approach to choose the proper energy efficiency measures based on the financial and environmental objectives considering budget and other constraints in single and multi-period settings. Their proposed approach was applied on a university campus. The effects of all the relevant energy efficiency measures were determined using engineering measurements and modeling. Hong et al. (2017) integrated a multi-regional input-output method with field-based operational data to quantify the total embodied energy consumption and energy transfers. The method was applied to evaluate the life cycle energy use of residential and office buildings in the Province of Guangdong. They have concluded that it is crucial to improve the accuracy of input-output analysis by providing sufficient economic information.

Wu et al. (2016) developed a multi-objective optimization model for sustainable building conceptual design by considering the design objectives of cost and energy consumption minimization and occupant comfort level maximization. They showed in a case study that the model can derive a set of suitable design solutions in terms of life cycle cost, energy consumption, and indoor environmental quality to help the client and design team gain a better understanding of the design space and trade-off patterns between different design objectives. Echenagucia et al. (2015) proposed an integrated multi-objective genetic approach in the early stages of a building design to minimize the required energy for heating, cooling, and lighting. The decisions were the number, location, type, and size of the windows and walls, but the effects of ceiling, roof, and openings were not considered. Ren et al. (2010) proposed a multi-objective optimization model for the minimization of energy cost and CO2 emission in order to analyze the optimal operating strategy of a distributed energy system. The trade-off curve was obtained using the compromise programming method. The model was applied to an eco-campus in Japan. To reduce energy consumption on a school campus, Ho et al. (2014) formulated a two-stage fuzzy multi-objective linear programming model for the different types of roofs. The objectives were the maximization of the investment rate of return and the energy generated by solar cells and solar heating plants. Wang et al. (2005) considering the building orientation,

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window types, window-to-wall ratio, wall types, and roof types as the decision variables, developed a multi-objective optimization model to design a greenhouse. They conducted a life cycle analysis to evaluate the design alternatives with economic and environmental criteria. Pal et al. (2017) discussed the optimization results of using operational energy (OE) + embodied energy (EE) together and operational energy only on the building envelope. They considered different options for insulation thickness of the external wall, roof, floor, and window types as the decision variables and minimizing life cycle energy (LCE) and life cycle costs (LCC) as the optimization objectives. The novelty of this study was the inclusion of EE along with OE in a single optimization scheme.

Although the solely cost-optimal strategies are beneficial in improving building energy efficiency, the literature review reveals that these proposed strategies cannot be applied in real situations. Araújo et al. (2016) provided a computational method so that the construction costs and DM's expectations might be considered in the selection process. Yang et al. (2017) discussed the implementation of a multi-objective model to minimize the construction costs and heat loss from the building envelope as well as to maximize the window-to-wall ratio. Notably, they studied the energy efficiency of different types of windows, walls, and roofs; however, the other floor designs and doors were ignored. Pal et al. (2017) studied the optimization results of using operational energy (OE) + embodied energy (EE) together and operational energy on building envelope based on the life cycle method. They considered different options for insulation thickness of the external wall, roof, floor, and window types as the decision variables and minimizing life cycle energy (LCE) and life cycle costs (LCC) as the optimization objectives. Diakaki et al. (2010) evaluated various alternative strategies for the building envelope based on the annual energy consumption, Co2 emission, and construction costs. As an extension of Ho et al. (2014), Karmellos et al. (2015) presented two models for new buildings and retrofitting cases considering lighting systems, electrical devices, and renewable energy resources.

To the best of our knowledge, from the construction costs and energy consumption point of view, the following research gaps exist in the literature on designing the greenhouses:

- Lack of attention to formulating the different forms of heat exchange like conduction and radiation in the existing optimization models. This results in the inaccurate estimation of heating-cooling loads,
- The existing models and tools need much detailed data, such as the exact dimensions and areas of different spaces in the house, which will be on hand only in the final stages of design,
- Lack of efficient but simple energy-cost optimal methods to select heating-cooling systems,
- Interactive optimization tools to support decision-making in the early stages of house design.

Concerning the above gaps, we propose a decision support tool based on a two-phase framework to identify, evaluate and select the best construction strategies for the house's envelope and the best heating-cooling system. Accordingly, the main novelties of our work are to:

- Divide all house spaces into two parts in the optimization model based on the temperature difference. In this way, the efficiency of the proposed model is improved (fewer input parameters and decision variables with fewer details), and it may be applied in the early stages of house design,
- Consider all forms of heat exchange (i.e., conductive, convective, and radiation) to have a more accurate estimation of heating and cooling loads,
- Propose an efficient but straightforward energy-cost method to select the best heating-cooling syste,
- Develop an interactive decision support tool in which the proposed framework is embedded.

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3. The two-phase decision support tool

A building envelope is a primary protection against harmful weather factors; it determines the amount of heat exchange with the environment. Evaluating the alternative construction strategies (i.e., various methods for constructing different parts of the building, such as walls, roofs, floors, windows, and doors) to optimize the envelope of a residential building is a challenging problem because it needs to treat the multiple conflicting criteria like energy consumption, costs and environmental effects subject to some prevailing constraints. As shown in Figure 1, this research is intended to provide a decision support tool for deciding on the construction strategies and the heating-cooling system of an eco-friendly greenhouse by the following two phases:

Phase 1: identify (considering implicitly the environmental and social factors), evaluate, and select the best construction strategies for the house's envelope based on the construction costs and energy consumption criteria.

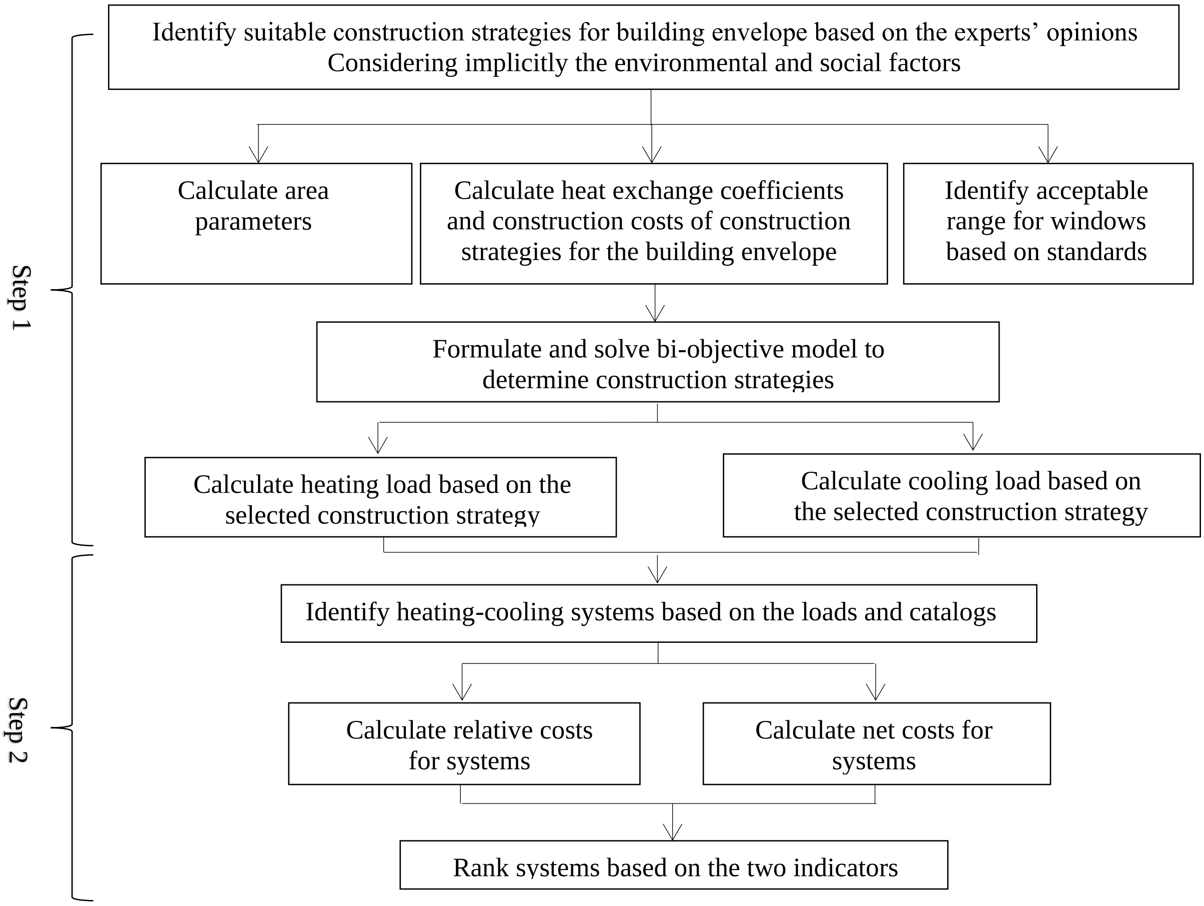

Figure 1. Two-phase framework for eco-friendly green house.

Phase 2: identify (considering implicitly the environmental and social factors), evaluate, and select the best heating-cooling system based on the required loads.

Because the quality of spaces in the house affects the internal temperature and, accordingly, the amount of heat exchange, a multi-objective optimization model is developed in phase 1 to consider the effects of different house spaces. For this aim, all the internal areas are divided into two distinct groups: "in the vicinity of uncontrolled space" and "in the vicinity of outer space". The uncontrolled area like a garage, aisles, etc. needs not be either cooled down by any cooling device or warmed up by any heating device during the year. The temperature of such spaces is the average temperature of the inside and outside of the house. The outer areas in the house are those that are directly connected to the external environment through one or more walls; spaces like the bedrooms are in the vicinity of outer areas. By such a division, there is no need to enter the plan and detailed data of house spaces; therefore, the optimization model may

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be used in the early stages of house design. Moreover, the optimization model would become easier to solve since the input data would be substantially reduced. Another characteristic of the proposed model is that it will be able to evaluate the different values of the window-to-wall ratio. In phase 2, at first, all forms of the heat exchange from the house's envelope would be calculated in order to estimate the accurate heating-cooling loads. Thereafter, for selecting among the different heating-cooling systems, instead of a complex mathematical model, we employ an innovative method based on the relative costs concept.

3.1. Mathematical model

In this section, a bi-objective mixed-integer non-linear model is provided for evaluating and optimizing the house's envelope strategies based on construction costs and energy loss objectives. The notations of the model are given in below.

Sets:

i Space type (1. in the vicinity of uncontrolled space, 2. in the vicinity of outer space)

j Wall type

r Roof type

f Floor type

g Window type

d Door type

Parameters:

Areas:

A_i^{wall} Area of the walls in the vicinity of space type i (m^2)

A^{roof} Roof area (m^2)

A_i^{floor} Area of the floors in the vicinity of space *i* (m^2)

A^{door} Doors area (m^2)

A^{total} Total area of land (m^2)

A^{SW} Total area of the eastern and western walls containing windows (m^2)

Temperatures:

T_{out} Exterior temperature ($°\boldsymbol{K}$)

T_{int} Interior temperature ($°\boldsymbol{K}$)

ΔT_i^{floor} Temperature difference of both sides of floor connecting space type *i* to ground

ΔT_i^{wall} Temperature difference of both sides of walls connecting two spaces of type *i*

Heat exchange coefficients:

U_{ij}^{wall} Heat exchange coefficient of wall *i* in the vicinity of space *i* ($\boldsymbol{W}/_{(\boldsymbol{m}^2.\boldsymbol{K})}$)

U_r^{roof} Heat exchange coefficient of roof *r* ($\boldsymbol{W}/_{(\boldsymbol{m}^2.\boldsymbol{K})}$)

U_{if}^{floor} Heat exchange coefficient of floor *f* in the vicinity of space *i* ($\boldsymbol{W}/_{(\boldsymbol{m}^2.\boldsymbol{K})}$)

U_g^{glass} Heat exchange coefficient of window *g* ($\boldsymbol{W}/_{(\boldsymbol{m}^2.\boldsymbol{K})}$)

U_d^{door} Heat exchange coefficient of door *d* ($\boldsymbol{W}/_{(\boldsymbol{m}^2.\boldsymbol{K})}$)

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Construction costs:

C_{ij}^{wall}	Construction cost of wall *i* in the vicinity of space *i* $({}^{\boldsymbol{W}}/_{(\boldsymbol{m^2}.\boldsymbol{K})})$
C_{r}^{roof}	Construction cost of roof *r* $({}^{\boldsymbol{W}}/_{(\boldsymbol{m^2}.\boldsymbol{K})})$
C_{if}^{floor}	Construction cost of floor *f* in the vicinity of space *i* $({}^{\boldsymbol{W}}/_{(\boldsymbol{m^2}.\boldsymbol{K})})$
C_{g}^{glass}	Construction cost of window *g* $({}^{\boldsymbol{W}}/_{(\boldsymbol{m^2}.\boldsymbol{K})})$
C_{d}^{door}	Construction cost of door *d* $({}^{\boldsymbol{W}}/_{(\boldsymbol{m^2}.\boldsymbol{K})})$
$Budjet$	Maximum available budget for the house's envelope construction (Rials)

Variables:

Five binary variables are defined for the house's envelope; they are used to select the different types of doors, windows, walls, roofs, and floors.

$X_{ij}^{wall} = 1,$ Selecting wall *j* in the vicinity of space *i*,

$X_{r}^{roof} = 1,$ Selecting roof *r*,

$X_{if}^{floor} = 1,$ Selecting floor *f* in the vicinity of space *i*,

$X_{g}^{window} = 1,$ Selecting window *g*,

$X_{d}^{door} = 1,$ Selecting door *d*.

The following continuous variables determine the proper areas for the windows:

per: the ratio of windows area to the floor area

A_2^{wall}: Area of the walls in the vicinity of uncontrolled space (m^2)

A^{glass}: Windows area (m^2)

Based on the Yazd climatic conditions and latitude, the highest efficiency of natural sunlight occurs when the windows are designed on the east and west sides of the house. "per" factor is a variable that determines the ratio of window area to floor area.

The amount of heat exchange for all the house's external surfaces is calculated in Equation (1).

$$Q = U.A\,.(T_{out} - T_{int}) \tag{1}$$

$$U = \frac{1}{{}^{1}/_{f_{out}} + \sum_{l=1}^{n} R_l + {}^{1}/_{f_{int}}} \tag{2}$$

$$R_l = \frac{X_l}{K_l} \tag{3}$$

Q: Heat exchange for a surface with an area of *A* (W)

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U: Heat exchange coefficient calculated by Equation (2), (ASHRAE, 2017 and Lienhard IV and Lienhard V, 2000) $\left({W}/{m^2.K}\right)$

R_l : Thermal resistance of layer *l* of the considered wall calculated in Equation (3) $\left({m^2.K}/{W}\right)$

K_l: Thermal conductivity of materials of layer *l* of the considered wall $\left({W}/{m.K}\right)$

X_l: Thickness of layer *l* of the considered wall (m)

f_{out}: External airflow resistance $\left({m^2.K}/{W}\right)$

f_{int}: Internal airflow resistance $\left({m^2.K}/{W}\right)$

$$Min\, G_1 = \Big\{\textstyle\sum_{i,j}\left(U_{ij}^{wall}.A_1^{wall}.\Delta T_i^{wall}.X_{ij}^{wall}\right) + \sum_{i,j}\left(U_{ij}^{wall}.A_2^{wall}.\Delta T_i^{wall}.X_{ij}^{wall}\right) + \sum_{i,f}\left(U_{if}^{floor}.A_i^{floor}.\Delta T_i^{floor}.X_{if}^{floor}\right) + \sum_{r}\left(U_r^{roof}.A^{roof}.\left|T_{out}-T_{int}\right|.X_r^{roof}\right) + \sum_{g}\left(U_g^{glass}.A^{glass}.\left|T_{out}-T_{int}\right|.X_g^{glass}\right) + \sum_{d}\left(U_d^{door}.A^{door}.\left|T_{out}-T_{int}\right|.X_d^{door}\right)\Big\} \quad (4)$$

$$\text{Min}\, G_2 = \Big\{\textstyle\sum_{i,j}\left(C_{ij}^{wall}.A_1^{wall}.X_{ij}^{wall}\right) + \sum_{i,j}\left(C_{ij}^{wall}.A_2^{wall}.X_{ij}^{wall}\right) + \sum_{i,f}\left(C_{if}^{floor}.A^{floor}.X_{if}^{floor}\right) + \sum_{r}\left(C_r^{roof}.A^{roof}.X_r^{roof}\right) + \sum_{g}\left(C_g^{glass}.A^{glass}.X_g^{glass}\right) + \sum_{d}\left(C_d^{door}.A^{door}.X_d^{door}\right)\Big\} \quad (5)$$

$$\textstyle\sum_{j} X_{ij}^{wall} = 1 \;\; \forall i \quad (6)$$

$$\textstyle\sum_{f} X_{if}^{floor} = 1 \; \forall i \quad (7)$$

$$\textstyle\sum_{r} X_r^{roof} = 1 \quad (8)$$

$$\textstyle\sum_{g} X_g^{glass} = 1 \quad (9)$$

$$\textstyle\sum_{d} X_d^{door} = 1 \quad (10)$$

$$\tfrac{1}{8} \le per \le \tfrac{1}{5} \quad (11)$$

$$A^{glass} = per.A^{total} \quad (12)$$

$$A_2^{wall} = A^{SW} - A^{glass} \quad (13)$$

$$\textstyle\sum_{i,j}\left(C_{ij}^{wall}.A_1^{wall}.X_{ij}^{wall}\right) + \left(C_{ij}^{wall}.A_2^{wall}.X_{ij}^{wall}\right) + \sum_{i,f}\left(C_{if}^{floor}.A_i^{floor}.X_{if}^{floor}\right) + \sum_{r}\left(C_r^{roof}.A^{roof}.X_r^{roof}\right) + \sum_{g}\left(C_g^{glass}.A^{glass}.X_g^{glass}\right) + \sum_{d}\left(C_d^{door}.A^{door}.X_d^{door}\right) \le budget \quad (14)$$

Notably, by minimizing the heat exchange of the house's envelope, the energy consumption would be reduced; hence, the energy consumption objective (G1) in Equation (4) is to minimize the total heat exchange. Accordingly, all the alternative construction strategies may be evaluated based on their Q values. Equation (5) shows the construction cost objective (G2). The model can select only one construction strategy for each part of the house's envelope. Equations (6) to (10) draw these constraints. As mentioned beforehand, one of the main features of the proposed model is its ability to evaluate the different values of the window-to-floor ratio. The windows are important in the total heat exchange through the house's envelope. Furthermore, the window affects the normal lighting during the day.

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Based on the 4th Iranian engineering organization regulations[1], the window area of a residential building should be 1/8 to 1/5 times the floor area; hence, Equations (11) to (13) determine the most appropriate areas for the windows. Knowing the area of the glasses, the size of the walls in the vicinity of outer space (eastern and western walls) would be obtained. The budget limitation for construction is shown in Equation (14).

The proposed model consists of 82 decision variables and 12 constraints which is significantly fewer than those in similar studies like Karmellos et al. (2015). It could be solved by the exact methods in the logical computation time. It should be noted that because of non-linearity and non-convexity, its solution would not necessarily be the global optimal solution.

3.2. Calculating the heating and cooling loads

To reach the desired internal temperature and to estimate the required heating-cooling capacity, at first, the amount of heating and cooling loads should be determined by Equations (15) to (18). Equations (15) to (18) are related to the heating loads, and the remaining are for cooling loads Carrier Air Conditioning Company (1966). In bellow, the considered symbols for heating and cooling calculations are

The total thermal losses from the house's envelope are calculated as follows:

1. Thermal loss through the walls (Q_1^H) calculated by Equation (15). Q_1^H is the first term of Equation (4), determined by solving the optimization model.

$$Q_1^H = \sum_{i,j}\left(U_{ij}^{wall}.A_1^{wall}.\Delta T_i^{wall}.X_{ij}^{wall}\right) + \sum_{i,j}\left(U_{ij}^{wall}.A_2^{wall}.\Delta T_i^{wall}.X_{ij}^{wall}\right) + \sum_{i,f}\left(U_{if}^{floor}.A_i^{floor}.\Delta T_i^{floor}.X_{if}^{floor}\right) + \sum_r\left(U_r^{roof}.A^{roof}.\left|T_{out} - T_{int}\right|.X_r^{roof}\right) + \sum_g\left(U_g^{glass}.A^{glass}.\left|T_{out} - T_{int}\right|.X_g^{glass}\right) + \sum_d\left(U_d^{door}.A^{door}.\left|T_{out} - T_{int}\right|.X_d^{door}\right) \quad (15)$$

2. Thermal loss through penetration or air conditioning (Q_2^H): To calculate this parameter, we need the amount of air intruding to the inside of the house which can be obtained by the volumetric method and the crack method. In the first method, it is calculated based on the room volume, and in the second one, the amount of air penetration is calculated based on the length of the windows and doors. We use the volumetric method Carrier Air Conditioning Company (1966) in which Q_2^H is denoted as Equation (16).

$$Q_2^H = 0.0749 \times 0.241 \times V^1.\left|T_{int} - T_{out}\right| \quad (16)$$

0.0749: Special air mass in the standard conditions ($^{ft^3}/_{lb}$)

0.241: Air-specific temperature in constant pressure ($^{Btu}/_{lb.F}$)

V^1: The amount of intruding air to the inside of the house (Cubic feet per hour)

$Q_1^H + Q_2^H$ is the base for selecting the heat exchanger equipment (radiator, fan coil, etc.)

3. Hot water thermal load (Q_3^H): Firstly, the actual hot water required for the house should be estimated. Then, Q_3^H is determined by Equation (17).

$$Q_3^H = 8.33 \times V^2 \times \left|T_2 - T_1\right| \quad (17)$$

[1] *Iran national building regulations*, 4th section, Basic requirements of building, 2010.

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8.33: Specific gravity of water (Pound per gallon)

V^2: The required hot water (Gallons per hour)

T_1: The temperature of input hot water to the water heater (F)

T_2: The temperature of output hot water from the water heater (F)

Finally, the total heating load of the house is denoted as Equation (18).

$$Q_{TR}^H = 1.1.(Q_1^H + Q_2^H) + Q_3^H \tag{18}$$

1.1: The confidence coefficient as a measure of the accuracy of estimating the thermal loads.

The total cooling load of the house is determined as follows:

1. Radiation from external windows and glasses (Q_1^C) calculated by Equation (19).

$$Q_1^C = \text{Acquired heat from the sun} \times \text{Correction factor} \times \text{Saving factor} \times \text{Window area} \tag{19}$$

Tables 3-4 in Carrier Air Conditioning Company (1966) for each hour of the other months gives the acquired heat of windows with various glass from the sun according to the latitude. Tables 3-5 in Carrier Air Conditioning Company (1966) presents the correction factor for each type of the glasses based on the available situations.

2. Conduction from external windows and glasses (Q_2^C) determined by Equation (20).

$$Q_2^C = A^1.U.\left|T_{int} - T_{out}\right| \tag{20}$$

A^1: Area of the windows (ft²)

3. Radiation and conduction through external walls (Q_3^C) calculated by Equation (21).

$$Q_3^C = A^2.U.\Delta t_e \tag{21}$$

A^2: Area of the external walls (ft²)

Δt_e: The equivalent temperature difference (F) provided by Tables 3-11 and 3-12 in Carrier Air Conditioning Company (1966).

4. Conduction through internal walls, windows, and doors (Q_4^C) calculated by Equation (22). It is equal to zero in our study because we have assumed that convenience temperature is the same in different internal parts of the house.

$$Q_4^C = A^3.U.\Delta t \tag{22}$$

A^3: Area of the internal walls, window, and doors (ft²)

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Δt: Temperature difference between two sides of the internal windows, doors, and walls (F)

5. Sensible cooling load caused by the house ventilation (Q_5^C) determined by Equation (23).

$$Q_5^C = 1.08 \times V^3 . \left| T_{int} - T_{out} \right| . BF \tag{23}$$

1.08: 0.0749 ($^{lb}/_{ft^3}$, air specific mass in standard conditions) × 0.24 ($^{Btu}/_{lb.F}$, air-specific temperature) × 60 ($\frac{minutes}{hour}$)

V^3: Air volume required for ventilation obtained by different methods. In our study, we calculate it based on the number of habitats. The amount of air for each habitant is determined through Table 3-14 in Carrier Air Conditioning Company (1966).

V^3: Air volume required for ventilation (CFM)

BF: Bypass factor extracted from Tables 3-1 and 3-2 in Carrier Air Conditioning Company (1966).

6. Sensible cooling load caused by habitants and inner room heaters (Q_6^C) denoted as Equation (24).

$$Q_6^C = (Q_{\text{sp}} = \text{number of habitants} \times q_{s_p}) + (\text{Input electrical power to the lamp} \times 1.25 \times 3.4) + (\text{Cooling load of the heating devices inside the house}) \tag{24}$$

q_{s_p}: Sensible cooling load of each habitant ($^{Btu}/_{hr}$) determined from Tables 3-15 in Incropera and DeWitt (2002)

Q_{sp}: Total sensible cooling load caused by the habitants ($^{Btu}/_{hr}$)

Motors in the rooms like those of fan-coil increase the moderate heat by wasting the input energy. Its amount can be derived from Tables 3-17 in Carrier Air Conditioning Company (1966), based on the motor efficiency and power.

7. Effective hidden cooling load (Q_7^C) calculated by Equation (25).

$$Q_7^C = Q_{lv} + Q_{l_p} + \text{Latent cooling load caused by heating devices inside the room} \tag{25}$$

$$Q_{lv} = V^3 . \Delta W . (1 - BF) . \frac{60 h_{fg}}{7000 v^1}$$

Q_{lv}: The hidden cooling load of the input external air to the house through the ventilation devices ($^{Btu}/_{hr}$)

$$Q_{l_p} = \text{The number of habitants} \, . \, q_{l_p}$$

Q_{l_p}: The hidden cooling load of the habitants ($^{Btu}/_{hr}$)

q_{l_p}: The hidden cooling load of each habitant ($^{Btu}/_{hr}$) extracted from Table 3-15 in Carrier Air Conditioning Company (1966).

ΔW: Difference in the humidity of the external and internal air ($^{Grain}/_{lb}$)

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h_{fg}: The steam hidden heat ($^{Btu}/_{lb}$)

v^1: Special volume of the external air ($^{ft^3}/_{lb}$) from the air profile chart

7000: Pound to Grain (Mass measurement unit=64.79891 milligrams) conversion coefficient

8. Sensible cooling load of the rest of the outside air (Q_8^C) determined by Equation (26).

$$Q_8^C = V^3.(T_{out} - T_{int}).(1 - BF) \times 1.08 \quad (26)$$

9. Hidden cooling load of the rest of outside air (Q_9^C) calculated by Equation (27).

$$Q_9^C = V^3.\Delta W.(1 - BF).\frac{600.h_{fg}}{7000.v^1} \quad (27)$$

Finally, the total cooling load is obtained by Equation (28).

$$Q_{TR}^C = (Q_1^C + Q_2^C + \cdots + Q_9^C) \quad (28)$$

3.3. Equipment selection

The estimated heating and cooling loads are the bases for the required equipment capacity. The selection of the heating-cooling system is performed in three steps as follows:

Step 1: Identify the candidate heating-cooling systems from the catalogs. The devices which can produce a capacity at least equal to the estimated heating-cooling loads are identified for the evaluation process.

Step 2: Calculate the total costs and the relative cost index of each heating-cooling system. The total costs would be calculated as the sum of purchasing and installing costs, maintenance costs, and energy (i.e., gas and electricity) consumption costs. Notably, to calculate the energy consumption costs for each year, the energy consumption of each equipment is multiplied by the energy tariff regulated by the government. The government in Iran sets stair-wise tariffs for electricity and gas consumption in residential buildings. According to the growth rate of the tariffs in the past 10 years, we use the reasonable growth rates for electricity and gas consumption costs in the following years. Maintenance costs are determined by the aid of the equipment specialists for the first year and would be increased considering the reasonable annual interest rate. Then, the present value is calculated by transmitting the corresponding costs of different years to the first year, considering the annual interest rate. The result is added to purchasing and installation costs.

The relative cost index is denoted as Equation (29). It evaluates the heating-cooling system based on the actual required heating and cooling capacity.

$$\text{Relative cost index} = \frac{12 \times \text{Total cost}}{(\#\text{ of cold months} \times \text{total heating loads}) + (\#\text{ of warm months} \times \text{total cooling loads})} \quad (29)$$

Step 3: Rank the heating-cooling systems based on their total costs and relative cost index and determine the best one.

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3.4. Decision support tool

In order to efficiently implement the proposed two-phase framework, we develop a software-based decision support tool as a combination of Excel and GAMS (optimization package). The inputs and outputs are performed in Excel, while running the models is done in GAMS. An automatic relationship between Excel and GAMS generates the desired outputs. Figure 2 shows the corresponding details of the decision support tool. Final users of this software will be the house owners, architects, engineers, and utility companies. All required input data is divided into two groups: system database (pre-calculated data in the system) and user-defined factors. The output of the first phase is used as the input of the second phase. The outputs include the best construction strategies and related costs, total required loads, the best heating/cooling system, and its related budget. Notably, the DM can use this software to evaluate and select the best greening strategies in the early stages of designing the house.

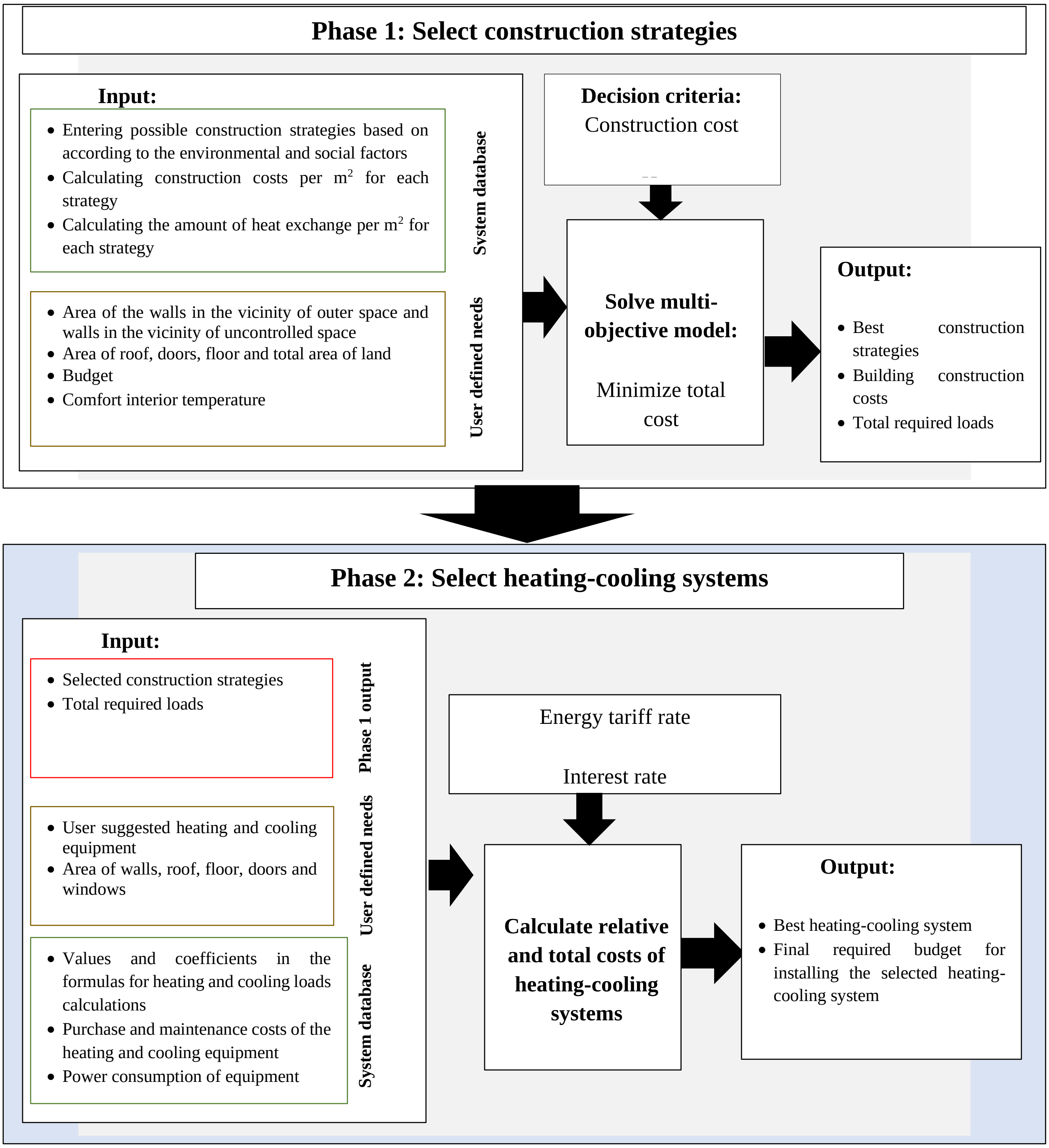

Figure 2. The decision support tool.

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4. Computational experiments

To confirm the performance of our framework and the decision support tool, it is implemented for a case study in Yazd City, Iran. Figure 3 shows the first and second floor plans with 162.5 m^2 and 125 m^2 areas, respectively, for a house in Yazd. Although this plan is common and widely used in Yazd, a major novelty of our proposed approach is that it is independent of the details of the house plan. One of the main characteristics of the proposed framework is that it has a low dependency on the detailed plan, so, it may be applied to other residential structures.

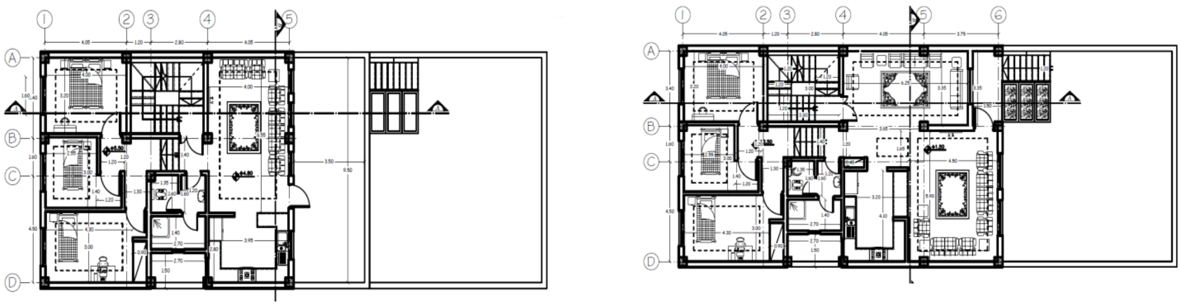

Figure 3. The house plan.

According to the environmental and social factors, the potential construction strategies for the different parts of the house's envelope were extracted from the 137th publication of Iran's program and budget organization[2] including 23 types of walls, nine types of roofs, ten types of floors, two types of windows, and types of doors. The corresponding construction costs (CC) and heat exchange coefficients (HEC) of each layer for all the construction strategies were extracted from the newest building price list of Iran's program and budget organization[3] and 19th subject of the Iranian Engineering organization[4]. At first, the HECs of construction strategies are calculated based on the reference values and related formulas. Then, the CCs are calculated computed using the newest building price list. CC is the product of building prices and the area of each layer for the construction strategies. All the prices are presented per square meter. The results are given in Tables A1 to A6 of the Appendix. The other parameter values of the model are shown in Table 1.

Table 1. Parameter values of the optimization model.

Parameter	Value	
A^{roof} (m^2)	158.5	
A_i^{floor} (m^2)	i=1	108.4
	i=2	54.1
A^{door} (m^2)	12.5	
A^{total} (m^2)	210	
A^{SW} (m^2)	359.1	
A_1^{wall}	39.2	
ΔT_i^{floor} (K)	i=1	20
	i=2	27
ΔT_i^{wall}(K)	i=1	28
	i=2	54
Budget (Million Rials)	1,800	
$T_{int}(K)$	20	
$T_{out}(K)$	74	

[2] *Regulations and operational and design criteria for building types details*, 2006. Volume III, Iran Management and Planning Organization Publication.
[3] Price list for the base unit buildings, 2016. Buildings and industrial buildings, *Iran management and planning organization*.
[4] *Iran national building regulations*, 2010. 19th section, Energy saving.

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4.1. Phase 1: optimization model results

The thermal losses of construction strategies are calculated in an Excel spreadsheet. The model was run in the well-known optimization package, General Algebraic Modeling System (GAMS), using COUENNE solver. GAMS is a high-level modeling system for modeling and solving linear, nonlinear, and mixed-integer optimization problems on various computer platforms. The system is tailored for complex, large-scale modeling applications and allows the user to build large maintainable models that can be adapted to new situations. COUENNE is a global optimization solver for non-convex mixed-integer non-linear programs, similar to the commercial solvers' BARON and LINDO Global. The solver is still in an experimental phase and is hidden in the GAMS system. The ε-constraint method was used for generating the different non-dominate solutions. There are many non-dominate solutions in this case that meet the constraints by changing ε values. Non-dominate solutions are presented in Table 2, and the Pareto chart is drawn in Figure 4. Notably, the model is non-linear because of the product of two binary and continuous variables; hence, the final result may be a local-optimal solution. But, in this case study, the solution quality is outstanding since the relative optimality gap[5] reported by GAMS was 0.5. In Figure 4, all the non-dominate solutions are divided into groups: group 1 and 2. The solutions in Group 1 have high construction costs. For more clarity, Group 2 is distinctly presented in Figure 5, in which the Pareto points are also divided into two groups 1-2 and 2-2. As shown in Figure 5, reducing energy consumption in the house requires more construction budget. This means the DM needs to specify their weight importance to establish a reasonable trade-off between energy consumption and construction costs.

Table 2. Non-dominate solutions of the optimization model.

Solution	*per*	Objective 2 (Rials)	Objective 1 (W)
1	0.125	632,738,600	6.45
2	0.125	345,373,400	6.46
3	0.125	345,223,400	8.02
4	0.128	342,516,200	11.45
5	0.143	342,225,700	12.45
6	0.158	341,935,100	13.45
7	0.173	341,644,500	14.45
8	0.189	341,353,900	15.45
9	0.189	341,136,200	16.20
10	0.195	341,073,900	17.45

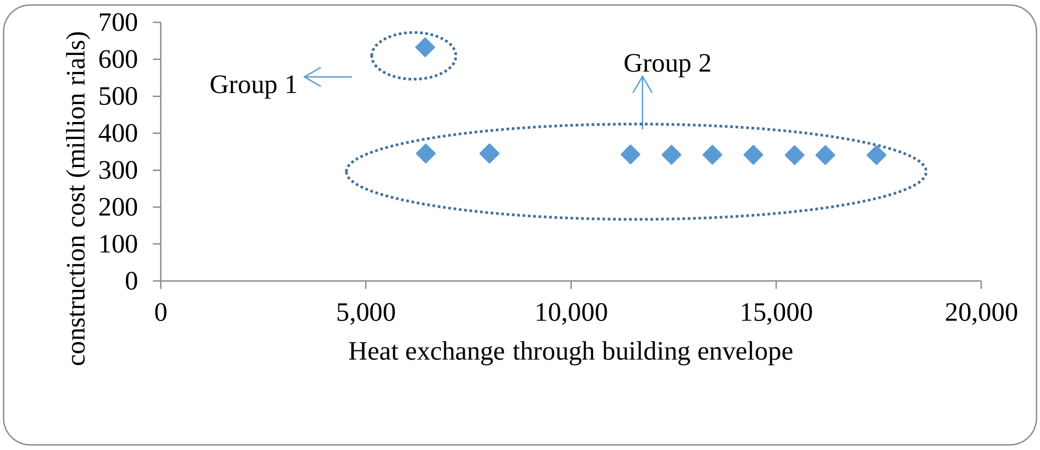

Figure 4. Pareto chart of non-dominate solutions.

[5] OPTCR = ("best estimate"-"best integer)/max (abs("best estimate"), abs("best integer")). The "best estimate" is the best possible value for the problem while the "best integer" is the solution found by the solver.

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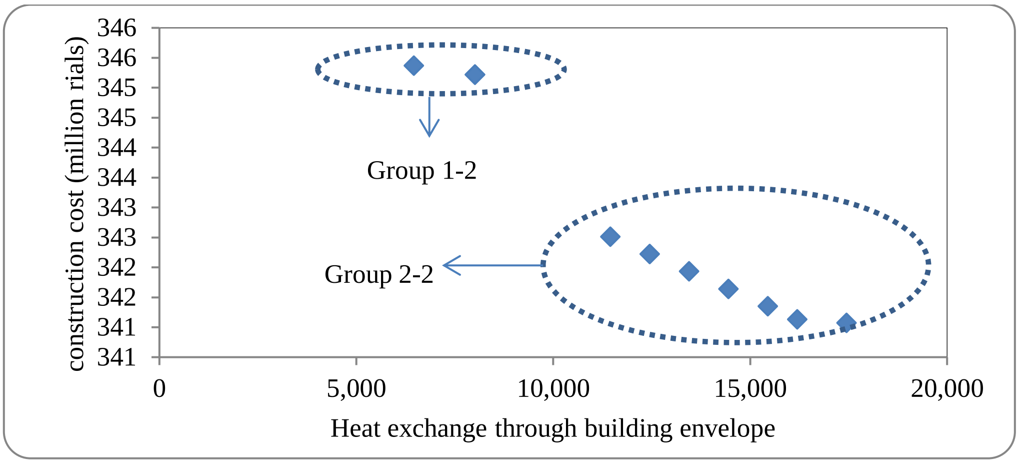

Figure 5. Pareto chart of solutions in group 2.

According to the DM, a solution in groups 1-2 (the second row in Table 2) with reasonable construction costs and heat exchange of 6464.198 W and 345,373,400 Rials, respectively, was selected. Binary variables for this solution are $X_{1,1}^{wall} = 1$, $X_{2,11}^{wall} = 1$, $X_{2}^{roof} = 1$, $X_{1,3}^{floor} = 1$, $X_{2,3}^{floor} = 1$, $X_{2}^{glass} = 1$, $X_{1}^{door} = 1$, and *per* value is 0.125. The solution is selected because it has the lowest amount of heat exchange in groups 1-2 and has a lower cost than the solution in Group 1. As a result, the suggested construction strategy for the envelope of our case is as follows:

- Walls in the vicinity of outer space: 35 mm of galvanized foil + 100 mm of thermal insulator + 100 mm of steel shaft;
- Walls in the vicinity of uncontrolled space: 2 mm of plaster + 10 mm of plaster mortar + 10 mm of artillery of soil and plaster + 105 mm of building bricks;
- Roof: 3 cm of floor covering + 3 cm of cement mortar + 1 cm of waterproof + 2 cm of final mortar;
- Floors: 5 cm of waterproof + 30 cm of concrete roof + 1 cm of cement mortar + 5 cm of false ceiling + 70 cm of air;
- Windows: 26.25 m² of double-glazed with air filler gas;
- Door: wooden doors.

One of the most critical factors affecting the heat exchange through the house's envelope is the area of the windows. In this regard, Figure 6 shows a sensitivity analysis of Q values for the different per values. As seen, the more per factor, the more value of Q. The heat exchange from the windows can be controlled, for example, with the double-glazed windows. Because there is no software package in Iran for evaluating the final energy consumption of a house, we cannot compare our results to an actual case. Hence, to assess the performance of our approach, we compare it to the standards.

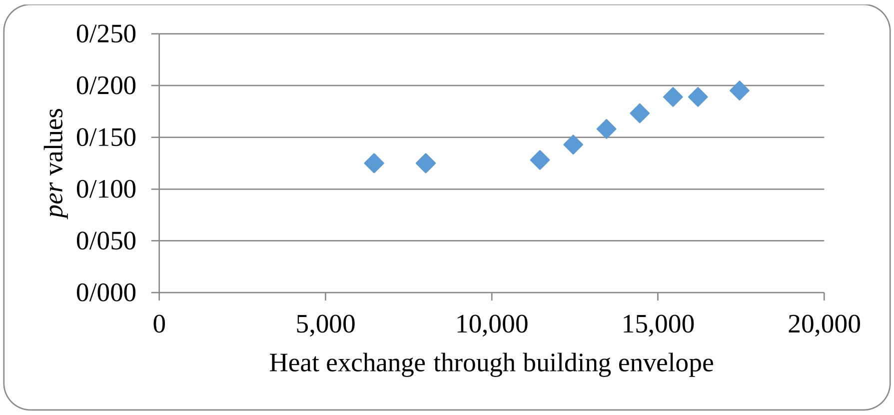

Figure 6. Sensitivity analysis on *per* factor.

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To validate the optimization model, its results for this case are compared to the three well-known standards on the heat exchange; namely, Iran building heat transfer reference standard[6], EBPD (Concerted Action, 2016), and 2012 IECC (IECC, 2012). As seen in Figure 7, our optimization model results are 0.22, 0.79, and 2.67 times of Iran standard, EBPD, and 2012 IECC, respectively, which confirms the model efficiency. Yazd is considered to have a desert climate. It is the driest major city in Iran. Notably, the average annual temperature is 18.9°C. About 50 mm of precipitation falls annually, and the humidity percentage is about 14%. Summer temperatures are frequently above 40 °C in blazing sunshine with no humidity. Even at night, the temperatures in summer are rather uncomfortable. In the winter, the days remain mild and sunny, but in the morning, the thin air and low cloudiness cause very cold temperatures that can sometimes fall well below 0 °C. Furthermore, the difference between night and day temperatures is very high[7]. The climatic conditions are significantly different than those of European countries. Indeed, comparing our results to the IECC standard confirms the efficiency of our model. Notably, the most proper standard for our case is the Iran standard because it is more consistent with our climate and people's culture. Comparing Iran's standard, the model performance in terms of the quality of results is outstanding. It should be noted that the energy consumption capitation in Iran is nearly seven times the same for the European countries. The outcome is more favorable when we see that the required inputs of our model are fewer than the previous ones. This means its performance in terms of computational effort is also very good.

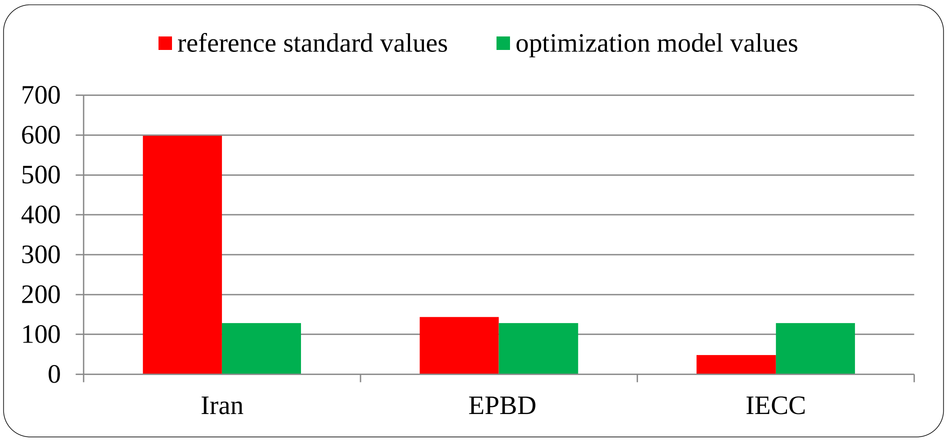

Figure 7. Model performance validation.

4.2. Phase 1: optimization model results

The estimated heating and cooling loads based on the selected strategies for the house's envelope are shown in Table 3. As mentioned before, one innovation of our research is to consider the different types of heat exchange because of their undeniable effects on the final heating-cooling loads. The total heating and cooling loads for this house are 146561$^{Btu}/_{hr}$ and 84816 $^{Btu}/_{hr}$, respectively. The required data was extracted from sections 2 and 3 in Spiegel and Meadows (2012) based on the Yazd geographic location, sunlight hours, moisture percentage, hottest and coolest hours, etc.

Table 3. Heating and cooling loads of the selected strategies for house's envelope.

Heating loads ($^{Btu}/_{hr}$)	Q_1	Q_2	Q_3						
	22062	20847	99361						
Cooling loads ($^{Btu}/_{hr}$)	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9
	18747	5590	449	0	15725	34318	2078	4296	3613

According to the available appropriate systems for heating and cooling in Yazd City, Iran, ten different systems were identified, which are presented in Table 4. The amounts of heating and cooling capacities for

[6] *Iran national building regulations*, 2010. 19th section, Energy saving.
[7] http://www.irimo.ir

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the systems were derived from the catalogs. We set the average time required to use cooling systems in warm months and the heating systems in cold months. Based on the temperature data of Yazd and the expert's opinion, heating systems are generally required for 135 days in autumn and winter and cooling systems for 139 days in spring and summer.

$$\text{Annual average heating and cooling loads} = \frac{(135 \times \text{total heating loads}) + (139 \times \text{total cooling loads})}{365} \quad (30)$$

The average required energy for the house is 86766 $Btu/_{hr}$, so, the relative costs can be calculated.

Table 4. Heating-Cooling systems characteristics.

	System details	Type
1	Radiators + Package +Water Cooler	Heating-Cooling
2	Fan coil unit + Package +Water Cooler	Heating-Cooling
3	Fan coil unit + Powerhouse +Water Cooler	Heating-Cooling
4	Radiators + Powerhouse +Water Cooler	Heating-Cooling
5	Fan coil unit+ Package+ Mini chiller	Heating-Cooling
6	Fan coil unit+ Powerhouse + Mini chiller	Heating-Cooling
7	Hot water coil+ Package+ Duct Split	Heating-Cooling
8	Hot water coil+ Powerhouse +Duct Split	Heating-Cooling
9	Mini chiller+ Fan coil unit+ Mural water heater	Dual system
10	Duct Split+ Mural water heater	Dual system

The total and relative costs of the systems are shown in Table 5. Note worthily, the costs of Photovoltaic systems are the same in all the heating-cooling systems; therefore, we do not consider it in the cost analysis of systems. Based on the energy source for each system, the total and relative costs for each year in the interval of the next ten years are calculated according to the tariffs regulated by the government. Notably, the tariffs for electricity and gas were estimated to grow 1.2 times and 1.15 times each year, respectively. For example, the details for the cost estimation of System 2 are presented in Table 6. Figures 8 and 9 show the system ranking based on the total costs and relative costs, respectively. Finally, System 1 is concerned as the best one. The performance of our model is to minimize the energy requirements as well as no current energy costs for the selected heating-cooling system.

Table 5. Relative and total costs of heating-cooling systems.

System	Relative cost ($^{hr.Rial}/_{Btu}$)	Total cost (Rials)
1	8711	755,847,342
2	9465	821,225,223
3	10078	874,464,218
4	9323	808,933,385
5	12735	1,104,955,169
6	13349	1,158,213,092
7	12589	1,092,321,624
8	13203	1,145,579,382
9	12715	1,103,264,357
10	12385	1,074,578,124

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Table 6. Details of cost estimation for system 2.

Year	Total cost per year	Maintenance cost	Electricity consumption cost	Gas consumption cost
0	821,004,748	0	0	0
1	3,929,838	3,300,000	30,600	599,238
2	4,619,844	3,894,000	36,720	689,124
3	5,431,476	4,594,920	44,064	792,492
4	6,386,248	5,422,006	52,877	911,366
5	7,509,490	6,397,967	63,452	1,048,071
6	8,831,025	7,549,600	76,143	1,205,282
7	10,385,974	8,908,529	91,371	1,386,074
8	12,215,694	10,512,064	109,645	1,593,985
9	14,368,893	12,404,235	131,574	1,833,083
10	16,902,932	14,636,998	157,889	2,108,045
Total costs (Rials)		821,225,223		

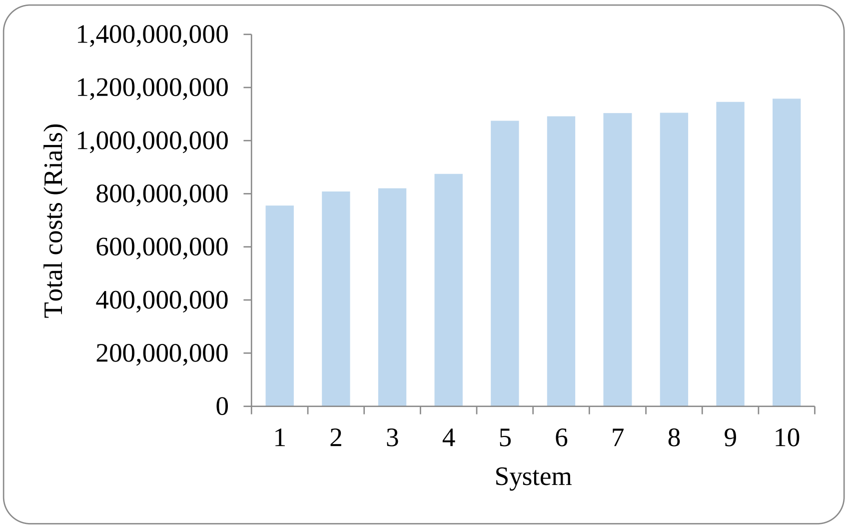

Figure 8. Ranking of heating-cooling systems based on the total costs.

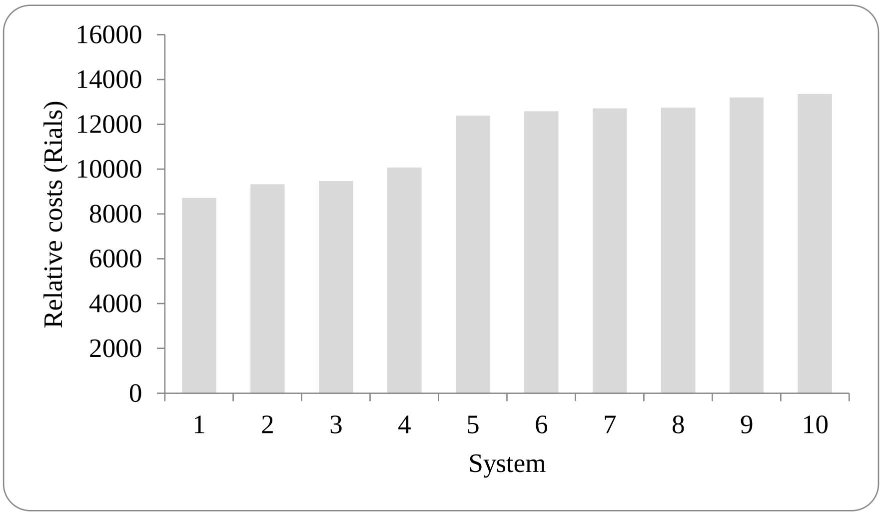

Figure 9. Ranking of heating-cooling systems based on relative cost index.

The electricity consumption of System 1 is about 2985 KWh per year. On the other hand, the total electricity consumption of electrical appliances like washing machines, kitchen electrical appliances, lamps, etc, is about 14232 KWh based on the fundamental values presented in IECC (2012). So, using System 1, the final electricity consumption of this building would be approximately 17217 KWh per a year; comparing this value with the fundamental power consumption of Iran for one year reveals a significant gap. The average power consumption for such a house is about 21816 KWh per year. It is evident that just 0.17 times the total power consumption of this house is related to the heating-cooling system; this issue shows the efficiency of our proposed approach for selecting construction strategies and heating and cooling systems. By performing the suggested construction strategies by the optimization model, exact calculating cooling and heating loads to estimate the proper capacity for heating and cooling systems and using relative and total costs as the indexes for ranking the heating-cooling systems, the approximate final power consumption of the house reduced. The required annual electricity of the house heating-cooling systems is approximately 21% lower than the reported values for the same home in that region. This is possible to provide a part of the electricity demand of the house through a solar photovoltaic system.

4.3. Discussion

In this research, we aim to develop a decision support tool based on the principles of green architecture for evaluating and selecting the best construction strategies and heating-cooling systems to increase energy efficiency in residential buildings. In the first phase, we develop an efficient mathematical model to select the best construction strategies based on two criteria: construction costs and total energy consumption. Note worthily, the environmental and social factors are implicitly taken in the identification process into account. The novelty of the optimization model is dividing the internal spaces of the house into two groups, including "in the vicinity of uncontrolled space" and "in the vicinity of outer space" to decrease the amount of required input data for the optimization model. Accordingly, there is no need to enter detailed data about the house plan, which causes the model to be used at the early stages of house design. Moreover, the optimization model would become easier to solve. Comparing the results with well-known standards reveals the model's efficiency in selecting the best construction strategies and reducing the computational effort. The next phase is to choose the heating-cooling system based on the total heating and cooling loads of the house extracted from the output of the first phase. The candidate systems are determined based on the full loads, and the best one is selected based on two criteria named total costs and relative costs.

According to the high difference between the day and night temperature in desert regions like Yazd City, Iran, the proposed construction strategies for the house's envelope extracted from the optimization model help to insulate the envelope in the vicinity of outer space. As a result, an outstanding performance regarding the amount of heat exchange through the house's envelope is obtained due to the Iran building heat transfer reference standard and Yazd climatic situations, as shown in Figure 7. Considering the high insulation costs. It's more logical to insulate the external envelope which faces a higher temperature difference. As said before, one of the important features of our optimization model is to evaluate the different values of window area. Accordingly, determining the lowest acceptable value for *per* decreases significantly the transferred heat through the house's envelope. More attention must be paid to this part of the house's envelope, and insulation has a significant effect on the total heat exchange. Note worthily, one characteristic of the proposed model is to prioritize the different parts of the house's envelope for insulation.

Considering all types of heating and cooling loads in the calculations causes an accurate estimation of heating-cooling capacities. Table 3 reveals that these loads cannot be ignored. As reported in Table 3, about 19196 $^{Btu}/_{hr}$ of the total cooling loads is related to radiation, and about 20847 $^{Btu}/_{hr}$ of the total thermal losses is related to conduction. This means that neglecting those types of heat exchange leads to incorrect decisions regarding the capacity of heating-cooling systems. For the cooling system, the water cooler was selected as the most proper alternative based on the two indices, which is notable due

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to the low percentage of humidity in Yazd. The internal moisture increases to some extent using the water cooler. The most proper heating-cooling system for the two floors consists of two wall packages with a capacity of 28 KW connecting to 9 radiators and two water coolers.

6. Conclusion and future research

This study aimed to develop a decision support tool to evaluate the different construction strategies and heating-cooling systems based on the energy consumption and costs in the early stages of design for an eco-friendly greenhouse. To do so, a two-phase framework was developed; in the first phase, an efficient bi-objective optimization model was formulated to select the best construction strategy for the house's envelope. The results for a two-floor house in Yazd City, Iran, showed that by employing the suggested system, the reference heat transfer coefficient would be reduced to 0.22 and 0.79 times of Iran standard and EPBD, respectively. Notably, the model could be applied to the different structures and building plans. In the second phase, an accurate estimation of the heating and cooling loads concerning all forms of heat exchange, especially conduction, and radiation, were calculated using optimization model results. Also, by implementing the proposed method for selecting the heating-cooling system, energy consumption and lifecycle costs were minimized simultaneously. In contrast, the chosen system, based on the available technology and facilities, and other electrical appliances, had lower power consumption than the Iran average power consumption. Study of uncertainty in the parameters like budget and internal comfort temperature, evaluation of the wind-catcher strategy for residential buildings in hot and dry climates, and extension of the proposed approach for commercial buildings may be the directions for future research.

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Appendix

Table A1. HEC and CC for the wall construction strategies.

Wall type (*j*)	In the vicinity of uncontrolled space		In the vicinity of outer space	
	HEC ($W/_{m^2.K}$)	CC (Rials)	HEC ($W/_{m^2.K}$)	CC (Rials)
1	0.037927	371,200	M	M
2	0.038535	1,004,900	M	M
3	M*	M	0.038535	1,178,400
4	0.038132	1,871,100	M	M
5	0.038353	544,700	M	M
6	M	M	0.038325	2,256,900
7	M	M	0.038287	2,306,533
8	0.038348	1,648,300	M	M
9	M	M	0.038296	2,009,500
10	M	M	0.038522	2,067,500
11	M	M	0.033880	569,700
12	0.038613	1,222,100	M	M
13	0.038229	1,354,000	M	M
14	M	M	0.038377	1,875,900
15	M	M	0.038429	1,840,300
16	M	M	0.038017	2,008,500
17	M	M	0.037982	1,795,600
18	M	M	0.037761	1,591,400
19	M	M	0.037322	1,453,600
20	M	M	0.038427	2,341,750
21	M	M	0.028511	1,724,800
22	M	M	0.029153	2,040,300
23	M	M	0.028904	1,742,800

* Big number

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Table A2. HEC and CC for the roof construction strategies.

Roof type (*r*)	HEC ($W/_{m^2.K}$)	CC (Rials)
1	0.03746885	1,927,800
2	0.01848083	648,300
3	0.03667156	1,874,800
4	0.02563466	2,234,800
5	0.03664096	2,355,800
6	0.03671735	2,295,800
7	0.03753714	880,300
8	0.02603515	1,782,900
9	0.01826570	1,428,800

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Table A3. HEC and CC for the floor construction strategies.

Floor type (*f*)	In the vicinity of uncontrolled space		In the vicinity of outer space	
	HEC ($^{W}/_{m^2.K}$)	CC (Rials)	HEC ($^{W}/_{m^2.K}$)	CC (Rials)
1	0.031377620	2,016,956	0.031377620	2,016,956
2	0.031447927	1,778,600	0.031447927	1,778,600
3	0.032047371	527,200	0.032047371	527,200
4	0.032047371	527,200	0.032047371	527,200
5	0.031533504	1,396,000	0.031533504	1,396,000
6	0.031419971	1,197,356	0.031419971	1,197,356
7	0.031482626	1,459,500	0.031482626	1,459,500
8	0.031649683	2,251,200	0.031649683	2,251,200
9	0.031710905	1,946,600	0.031710905	1,946,600
10	0.031821106	1,380,600	0.031821106	1,380,600

Table A4. HEC and CC for the window construction strategies.

Window type (*g*)	**HEC ($^{W}/_{m^2.K}$)**	**CC (Rials)**
1	5.8	280,500
2	2.4	387,500

Table A5. HEC and CC for the door construction strategies.

Door type (*d*)	**HEC ($^{W}/_{m^2.K}$)**	**CC (Rials)**
1	3.5	70,000
2	5.8	58,000

For an example, Table A6 shows the thickness and thermal conductivity of different layers for wall *j*=1. It consists of plaster, soil and building bricks. Then, its HEC can be calculated using Eqs. 1 to 3 which is equal to 0.037927 $^{W}/_{m^2.K}$ and its construction cost is 371,200 Rials.

$$R_1^T = \sum_i R_i = \sum_i \frac{\text{Thickness }(mm)}{\text{Thermal conductivity }(^{W}/_{m^2.K})} = \frac{\frac{105}{1000}}{0.184} + \frac{\frac{10}{1000}}{1.1} + \frac{\frac{10}{1000}}{0.485} + \frac{\frac{2}{1000}}{0.495} = 0.60895$$

$$U_1 = \frac{1}{^{1}/_{h_{out}} + \sum_{i=1}^{n} R_l + ^{1}/_{h_{int}}} = 0.0379269$$

Table A6. Details of wall *j*=1.

Thermal conductivity ($^{W}/_{m^2.K}$)	**Thickness (*mm*)**	**Material**
0.184	105	Building bricks
1.100	10	Plaster and soil mortar
0.485	10	plastering
0.495	2	stucco