J Ther Eng, Vol. 8, No. 2, pp. 249–267, March 2022

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.1086236

Research Article

Effect of HVAC system size on the optimum insulation thickness of the buildings in different climate zones

Maryam KARAMI[1,*], Ehsan ANBARZADEH[1], Shahram DELFANI[2]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Kharazmi University, Tehran, IRAN*
[2]*Department of Mechanical and Electrical Installations, Road, Housing and Urban Development Research Center (BHRC), Tehran, IRAN*

ARTICLE INFO

Article history
Received: 7 August 2020
Accepted: 13 October 2020

Keywords:
Climate zone, Energy saving, Genetic algorithm, Heating and cooling system, Optimum insulation thickness

ABSTRACT

Thermal insulation is one of the most effective methods of reducing energy consumption in buildings. Therefore, the parameters influencing the optimum insulation thickness are widely investigated. In this study, the optimum insulation thickness is obtained using the life cycle analysis method and the genetic algorithm by considering the size of the heating and cooling systems as an optimization variable, which has not been addressed in the earlier researches. Furthermore, the effect of the climate conditions on the optimum insulation thickness is comprehensively studied using five different climate zones, including Hot-Dry, Cold-Dry, Moderate-Humid, Hot-semi Humid, and Hot-Humid. It is found that the optimum thickness of expanded polystyrene insulation increases between 5%-19% considering the size variation of the heating systems including the central heating system and wall-hung gas boilers. By size variation of the cooling systems including the evaporative cooler and split air conditioner, this increase is between 8-19%. This is because the cost reduction due to the reduction of the required size of the heating and cooling systems can be expended for insulating the building with larger thickness which results in lower energy consumption. Based on the obtained results, the energy cost saving increases between 3.5%-14.5% and also, the payback period decreases about 1 to 3 months, depending on the considered heating and cooling systems and climate zone. The results confirm that the optimum insulation thickness can be determined with significant inaccuracy, ignoring the size variation of the heating and cooling systems as a result of thermal insulation.

Cite this article as: Maryam K, Ehsan A, Shahram D. Effect of HVAC system size on the optimum insulation thickness of the buildings in different climate zones. J Ther Eng 2022;8(2):249–267.

INTRODUCTION

Energy consumption is rapidly increasing due to increasing population, urbanization, migration to large cities and improvement in standard of living [1]. Using the energy saving methods, improving the existing technologies [2-4]

***Corresponding author.**
*E-mail address: karami@khu.ac.ir

This paper was recommended for publication in revised form by Regional Editor Siamak Hoseinzadeh

Published by Yıldız Technical University Press, İstanbul, Turkey

or returning to renewables [5,6] are an excellent approaches to reduce the energy consumption, which is distributed among four main sectors: industrial, building (residential/commercial), transportation and agriculture [7]. Having 40% of all Europe's energy consumption, the building sector is the largest energy consumer following the industrial sector and 63% of this share is assigned to residential buildings [8]. In many countries, the energy required for space heating and cooling in buildings has the highest share of all and particularly in Iran, 42% of the country's energy is consumed in buildings [9].

Because of the limited energy-sources and environmental pollution coming from using the fuels, the energy saving has become unavoidable [10]. The thermal insulation of building is one of the most effective methods to preserve energy and reduce energy consumption of the buildings [11]. For that reason, there are many studies about determining the optimum thickness of the insulation and the parameters affecting it.

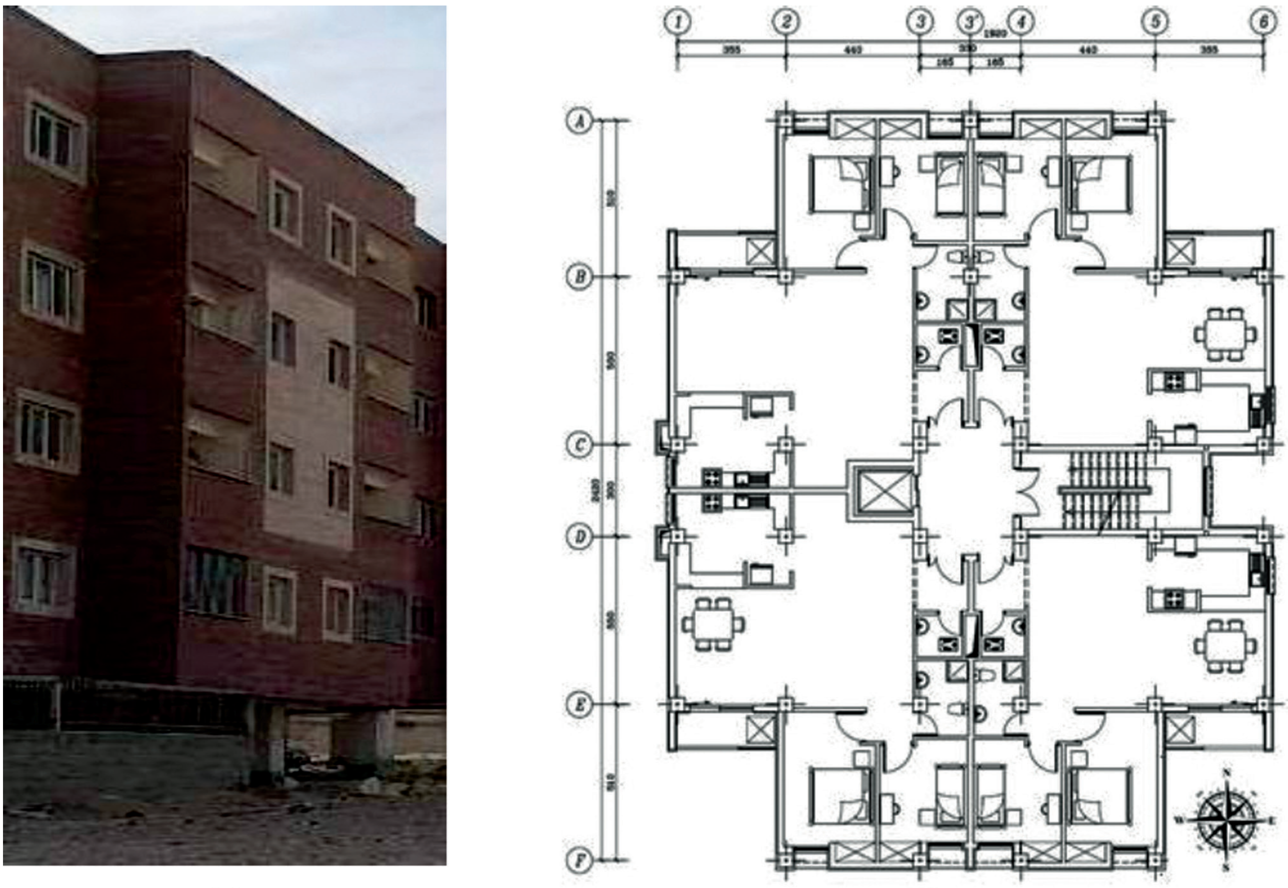
An important factor influences the optimum insulation thickness for the buildings is the weather conditions. Liu et al. [12] investigated the optimum insulation thickness for an exterior wall in hot-humid climate areas of China. The results show that the optimum thickness for extruded polystyrene (XPS) is between 5.3 to 6.9 cm and for EPS is between 8.1 and 10.5 cm. Using thermoeconomic analysis method, Dombayci et al. [13] found that the optimal thickness of EPS for Turkish cities of Ankara, Izmir, Trabzon, and Kars is 4.6 cm, 7.7 cm, 6 cm and 10.7 cm, respectively. Also, the highest and lowest energy savings were obtained in Kars with 56.6% and in Izmir with 27%. Nematchoua et al. [14] compared the optimum insulation thickness of wall in equatorial and tropical climates. They reported that the optimum insulation thickness for south orientation in equatorial region was 0.03 lower than that for north orientation in tropical region. Solgi et al. [15] considered the impact of using phase change insulating materials (PCMs) on the building energy consumption in Australian weather conditions. The results show that increasing the insulation thickness has a positive effect on energy consumption and is highly dependent on the orientation of the building.

The effect of insulation material on the building energy consumption is another parameter which has been studied by several researchers. Baniassadi et al. [16] compared the effect of using three different materials including PCM, expanded wool and polystyrene. Their findings indicate that the optimal thickness of PCM insulation in the southern region of Iran was approximately equal to zero. Regarding the current economic situation in Iran, the use of other insulation materials would be much more cost-effective than PCM insulation. Using the life cycle cost (LCC) analysis method, Idchabani et al. [17] optimized the thickness of polyurethane, polystyrene, and cork for the building in Morocco. The results showed that the maximum and minimum optimum thickness of 16.8 cm and 3.4 cm were obtained using EPS and polyurethane, respectively. Lakrafli et al. [18] reported that the energy savings using the thermal insulation capacity of leather wastes (wet-blue chrome shavings and buffing dust) and carpentry wastes (wood shavings and sawdust) is comparable with that of commercial insulation such as polystyrene and cork; so that, more than 56.9% saving in annual energy consumption is obtained using a thickness of 7.5 cm of the leather wastes as the insulation material. Rad et al. [19] found that the optimum thickness of insulations including EPS, XPS, stone wool and glass wool for an office building in Sabzevar, Iran are 8 cm, 20 cm, 7 cm and 11 cm, respectively. Kumar et al. [20] analyzed the building energy consumption for four types of polymeric insulations and 15 types of building materials using degree-day method. They concluded that the use of insulation materials in lightweight walls is not economically viable due to the low cost savings (under \$2.5/m2 per year). However, walls constructed with heavy concrete and clay materials by high cost savings (\$14-26.39/m2 per year) should be insulated. In an interesting work, Gounni et al. [21] optimized the thickness of a new insulation made from textile waste. It is observed that using the new insulation material, the lower annual thermal loads are required compared to conventional thermal insulations. The new insulation material can be a promising solution to reduce energy consumption, if its initial cost does not exceed 590 dirhams/m3. Over an analysis period of 20 years, Dlimi et al. [22] found that integrating hemp wool insulation and air cavity layers by the optimum thickness in Moroccan building walls causes the energy savings of 2.23 \$/m2. Guven [23] used the exergetic life cycle cost assessment method and reported that the optimum thickness of glass wool insulation is about 56% larger than that of rock wool insulation for Isparta province in Turkey. Huang et al. [24] investigated the energy conservation of a typical office building, located in Chinese zone of humid subtropical climate, using a new aerogel super-insulation material. In addition to the lower carbon emissions, the lower minimum optimum insulation thickness of 3.7 mm is obtained compared to the EPS (70mm), XPS (44 mm), polyurethane (38 mm) and glass fibers (45mm). Using cooling degree-day values, Alpay Kurekci [25] showed that the optimum insulation thicknesses at 0°C cold storage temperature in Istanbul is 0.109, 0.095, 0.064, 0.056, 0.023 m for EPS, glass wool, rock wool, XPS and polyurethane respectively.

Some researches focused on the effect of different orientations of building walls on the optimum insulation thickness. Using the International Building Physics Toolbox (IBPT) software, Nematchoua et al. [26] pointed out that the most economical wall orientations for EPS are the southern walls. The optimum insulation thickness of 8 cm and 11 cm and the energy cost savings of \$51.69 and \$97.82 per square meter are obtained for southern walls of a building in two cities of Cameroon (Yavindijk and Garwa), respectively. Ramin et al. [27] developed a one-dimensional transient heat transfer model for determination of the optimum insulation thickness for conventional walls in Tehran. Results show that the highest and lowest optimum insulation thickness belongs to the horizontal and south-facing walls, respectively. The results of the study done by Arsalan and Karagoz [28] indicated that the optimum thickness of XPS insulation is 0.052 m, 0.045 m, 0.061 m and 0.054 m for wall orientation of south, north, east and west, respectively. In the interesting work, Rosti et al. [29] claimed that the lowest or highest value of optimum thickness depends on the specific orientation for each climate zone. Their results show that the southern wall has the minimum insulation thickness in moderate and rainy climate (Rasht), while in very hot and dry climate (Ahvaz), the east/west-oriented walls has the maximum optimum insulation thickness.

Another effective parameter in determining the optimum insulation thickness can also be considered the glazing area percentage of the buildings. Derradji et al. [30] compared the energy performance and the thermal behavior of the prototype and classic building in Algeria and evaluated the effect of glazing area percentage on the optimum insulation thickness. Depending on the glazing type and percentage, the optimum insulation thickness varies between 1 cm and 2.5 cm and the energy cost saving is between 0.5 and 1.5 $ per square meter. The energy performance of a school building is studied by Alwetaishi and Taki [31]. The results revealed that a combination of applying thermal insulation along with minimizing glazing area percentage is essential in existing buildings within hot and dry regions. The maximum glazing area percentage of 35%, 25% and 20% was recommended for northwest, southeast and southwest building facades, respectively.

In this study, the optimum insulation thickness is analyzed and compared considering the heating, ventilating and air conditioning (HVAC) system size as an optimization variable, which are neglected in the previous studies, in different climate zones including Cold-Dry, Moderate-Humid, Hot-Dry, Hot–semi Humid, and Hot-Humid. A wide variety of HVAC systems are used in residential buildings, which makes it difficult to choose the HVAC system for investigation. To make the results of this research more applicable, more widely used systems have been selected,



(a) (b)

Figure 1. (a) Photo and (b) floor plan of the prototype building.

including four different centralized and decentralized heating and cooling systems, which are the central heating system, wall-hung gas boiler, evaporative cooler and split air conditioner. After estimation of building heating and cooling load using Design Builder software, the optimum insulation thickness is determined using the genetic algorithm. The effect of size variation of the HVAC system on the energy cost savings and the payback period are also considered.

PROTOTYPE BUILDING

The prototype building is chosen from the Mehr Mass-Housing Construction project which is a typical residential building in Iran with 4-story and 16 apartment units. Every apartment's area is 95m^2 and the overall foundation is 1397m^2. The ground floor contains the parking, storerooms and the janitor room and every apartment contains two bedrooms, a bathroom, a washroom and a kitchen. The photo and the floor plan of the prototype building is shown in Figure 1. In this study, the building external walls (Figure 2) are considered as a composite structure, which is generally formed with bricks in the middle, plaster layers on both sides, insulation material on the inside of the brick layer and granite on the most outside layer. The window-to-wall ratio is 32.5% for both northern and southern walls, while for eastern and western walls the ratio is 4.5%. The characteristics of the materials used in the elements of the building are listed in Table 1.

HVAC SYSTEM

HVAC systems, depending on the location of the primary equipment, can be classified into two major types of central system or decentralized or local system. Conditioning entire building as a whole unit is performed

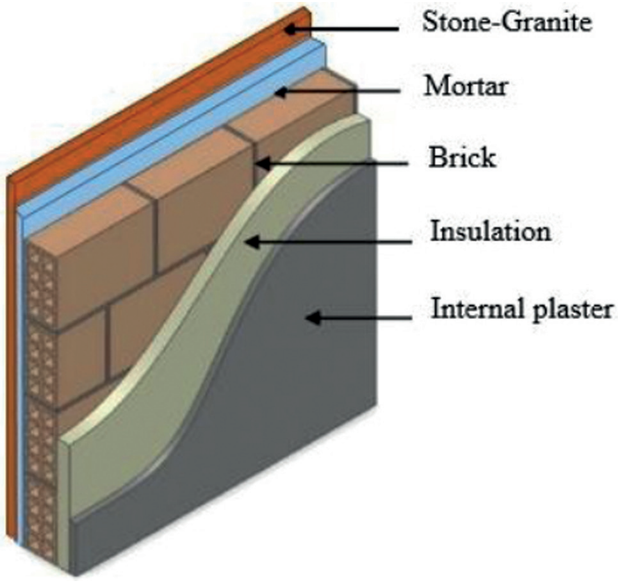


Figure 2. Structure of the external wall.

Table 1. Characteristics of the materials used in the components of the prototype building [32]

Component	Composition		Thickness (cm)	ρ (kg/m^3)	c_p $(kj/kg.K)$	k $(W/m.K)$
External Wall	Plaster		2	1000	0.91	0.45
	Insulation (EPS)		To be optimized	15	1.41	0.04
	Hollow brick		15	950	0.84	0.31
	Mortar		2	2800	0.89	0.85
	Stone-Granite		1.5	2880	0.84	3.49
Floor/Ceiling	Ceramic Tile		0.5	1700	0.85	0.81
	Mortar		1.5	2800	0.89	0.83
	Cement Block		30	1200	0.93	0.45
	Plaster		2	1000	0.91	0.45
Roof	Asphalt		3	2330	0.84	1.15
	Mortar		1.5	2800	0.89	0.83
	Cement Block		30	1200	0.93	0.45
	Plaster		3	1000	0.91	0.45
Window	Double wall	Glass	0.6	–	–	0.82
	(SHGC = 0.71 and VLT = 0.75)	Air Space	0.6	–	–	0.05

Table 2. Features of HVAC systems used in this study

System Type	Heating systems		Cooling systems	
	Decentralized system Wall-hung gas boilers	Central system Central heating systems	Decentralized system Split air conditioners	Decentralized system Evaporative coolers
Fuel used	Natural gas	Natural gas	Electricity	Electricity
Efficiency (%)	79 – 89	75 – 86	–	51 – 53
COP	–	–	2 – 2.8	-

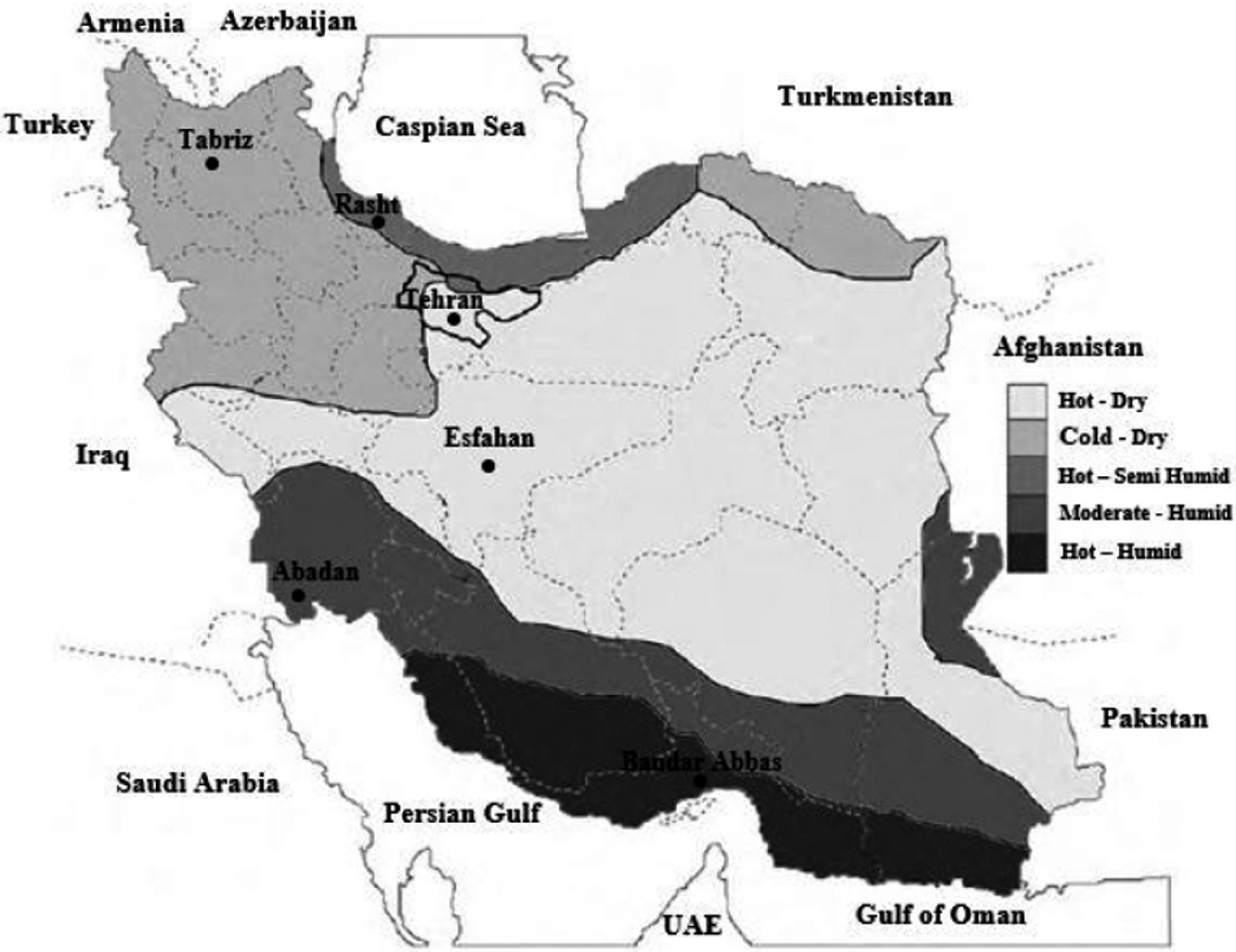


Figure 3. Different climate zones of Iran [33].

by a central system, whereas a decentralized system conditions separately a specific zone as part of a building.

In this paper, various HVAC systems are selected and compared in terms of the effect on the optimum insulation thickness. As heating systems, a central heating system and a wall-hung gas boiler, and as cooling systems, two decentralized cooling systems including evaporative cooler and split air conditioner are used to satisfy the thermal comfort of occupants in the prototype building. It should be noted that the cooling load of the prototype building is not high enough to use the central cooling system. Based on the required capacity and the system manufacturer, the efficiency of the central heating systems and the wall-hung gas boilers, used as the HVAC systems in this study, lies in the

Table 3. Characteristics of the selected cities [6]

City	Climate	Sea level (m)	Longitude (°E)	Latitude (°N)	Relative humidity (%)		Outdoor design temperature (°C)	
					Winter	Summer	Winter	Summer
Tehran	Hot-Dry	1191	35.41	51.19	74	30.4	-4	40
Isfahan	Hot-Dry	1549	51.67	32.65	81	11.5	-8	43
Tabriz	Cold-Dry	1361	46.27	38.10	80	23.8	-11	35
Rasht	Moderate-Humid	-8	49.59	37.27	92	62.3	-3	32
Abadan	Hot- Semi Humid	4	48.29	30.35	37	15.5	3	47
Bandar Abbas	Hot-Humid	11	56.27	27.18	80	57.5	9	51

range of 75 -86%, 79-89%, respectively. The coefficient of performance (COP) of the split air conditioners varies from 2 to 2.8 and the efficiency of the evaporative coolers is 51 -53%. More information about HVAC systems used in this study can be found in Table 2.

CLIMATE ZONES

In this study, the effect of the outdoor design conditions, required for the thermal load estimation of the prototype building, on the optimum insulation thickness is also considered. Figure 3 displays five different climate zones of Iran including Hot-Dry, Hot-Humid, Hot-semi Humid, Cold-Dry, and Moderate-Humid which were classified based on the outdoor design conditions [28]. In this study, one city of each climate zone is selected: Isfahan from Hot-Dry zone, which is the largest climatic zone of Iran, Abadan from Hot-Semi Humid zone, Bandar Abbas from Hot-Humid zone, Tabriz from Cold-Dry zone and Rasht from Moderate & Humid zone. Tehran is also selected because of its importance as the capital of Iran with approximately 8.3 million populations and 3.3 million houses which have a large share in the energy consumption of Iran. Characteristics of the selected cities are presented in Table 3.

METHODOLOGY

Thermal Load Estimation

In this paper, the cooling and heating loads of the prototype building are calculated using Design Builder 5.5. Design Builder software is high-quality, easy-to-use simulation software that helps you to quickly assess the environmental performance of new and existing buildings, graphically. The energy simulation engine of this software is Energy Plus 8.6 which is built by U.S Department of energy and is one of the most accurate software on the energy basis and has a very high calculation accuracy. The model of the prototype building and plan view including kitchens, bedrooms, bathrooms, halls, guestrooms and stairways in Design Builder software are depicted in Figure 4. All thermal loss or gain caused by heat transfer from/to the walls and glazing, infiltration or ventilation, internal loads, solar heat gain are considered for estimating loads. Internal loads including cooking, computer, TV, refrigerators, wash machine, etc. with time schedule have been considered. Lights are assumed LED with power of 7.5 W/m2. For all residential areas of the building such as bedrooms, halls and reception rooms, kitchens, bathrooms, and sanitary facilities, the temperatures required for the thermal comfort (22°C in winter and 26°C in summer) is specified. For all spaces of the apartment, the details of time schedule including the number of occupants, their kind of activities and clothing and the number hours of their residence in the considered space are also determined. In addition to the precise definition of exterior and interior walls, ceiling and floor of units and the ceiling referred to the highest floor, the material and dimensions of all doors and windows were determined. The windows by different dimensions for the living room, the bedroom and the kitchen were selected from a double-walled type. The wooden doors for each unit measured 2m×1m. Four people are considered in every apartment: three with adult metabolism and one with child metabolism.

To validate the modeling, a four-story building in Tehran that manually calculated by Gholizadeh et al. [34] is simulated again in Design Builder and the calculated thermal loads are compared in Figure 5. As can be seen, the results from Design Builder are very close to manual results by an approximate error of 3.7% which proves the accuracy of the modeling method.

P1–P2 Method

Optimization methods have important role in different research fields of the thermal engineering [35-37]. One of the most common economic analysis methods is life cycle cost (LCC) analysis in which the time value of money considered and the detailed consideration of the complete range of costs is implemented [38,39]. In this study, the

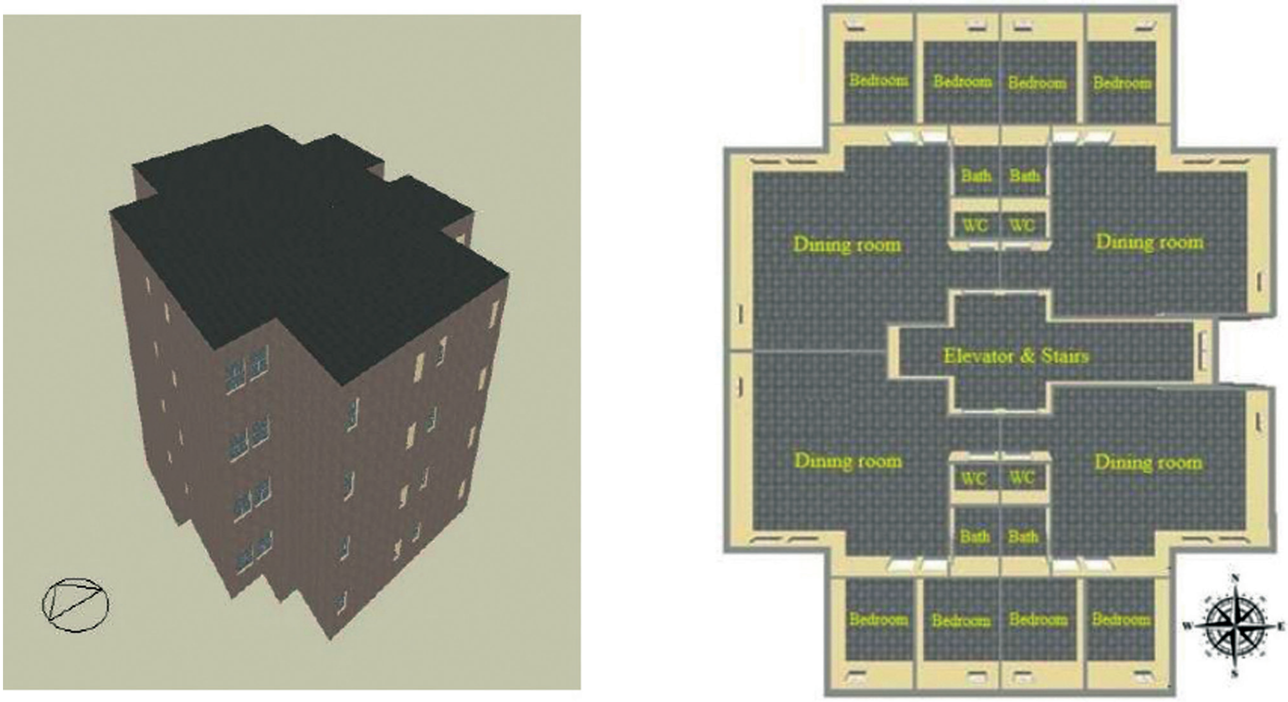


Figure 4. Modeling the prototype building in Design Builder software.

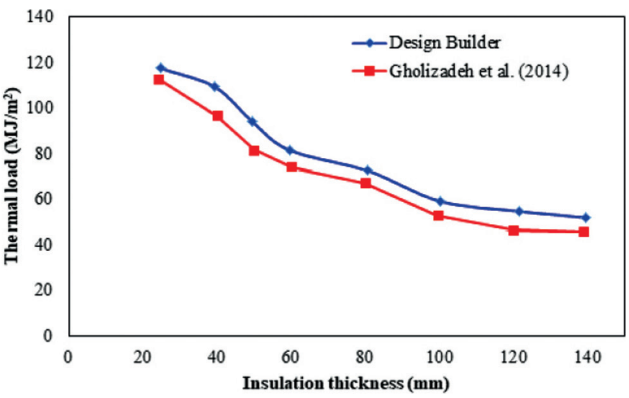


Figure 5. Comparison of the results of Design builder modeling and the study by Gholizadeh et al. [34].

P_1-P_2 method which is one of the LCC analysis methods is used for optimizing the insulation thickness. In this method, all of the economic parameters are concentrated into the two economic indicators named P_1 and P_2. The first indicator (P_1) is the ratio of the life-cycle fuel cost to the first year fuel cost. A low value of P_1 indicates that fuel costs are high and that consequently, potential fuel savings are important. The second indicator (P_2) is the ratio of life cycle expenditures incurred as a result of the additional investment to the initial investment [20]. A high value of P_2 indicates that the investment has a low first cost but higher costs over the life of the equipment. The equations for P_1 and P_2 are defined as (Nematchoua et al. 2015):

$$P_1(N,i,d)=\sum_{j=1}^{N}\frac{(1+i)^{j-1}}{(1+d)^{j}} = \begin{cases} \frac{1}{d}\left[1-\left(\frac{1+1}{1+d}\right)^{N}\right] & if\ \ i\neq d \\ \frac{N}{1+i}\ \ if\ \ i=d \end{cases} \quad (1)$$

$$P_2 = 1+P_1M_s - R_v(1+d)^{-N} \quad (2)$$

where M_s is the ratio of the annual maintenance and operation cost to the original first cost, R_v is the ratio of the resale value to the first cost. P_2 can be taken as 1 if the maintenance and operation cost is zero [20]. If the inflation rate d is equal to the interest rate i, then P_1 becomes [40]:

$$P_1 = \frac{N}{1+i} \quad (3)$$

The cost of insulation is given by:

$$C_{ins} = C_i x \quad (4)$$

where C_{ins} is the cost of insulation in \$/m^2 and C_i is the cost of insulation in \$/m^3. The life cycle cost (LCS) over the life time can be formulated with P_1-P_2 method as:

$$LCS = C_{en}P_1 - P_2C_{ins} \quad (5)$$

where C_{en} is the energy cost, which is calculated using the heating and cooling loads obtained from Design Builder model, the efficiency of the heating and cooling systems and the fuel (electricity or natural gas) cost. In Table 4, the financial parameters used in this study are listed. The data are taken from the market and the official websites of Central bank, Ministry of Energy and National Iranian Gas Company (NIGC) in 2017 (Central bank of the Islamic republic of Iran, Ministry of Energy, National Iranian Gas Company).

In this study, the HVAC system size is considered as an optimization variable; therefore, the capital investment made by reducing the system size (C_{pt}) should be deducted from the total insulation cost [41]:

$$C_t = C_{en} + C_{ins} - C_{pt} \quad (6)$$

Table 4. Financial parameters used in this study

Parameter	Value	Unit
Inflation rate	9.6%	-
Interest rate	15%	-
Life time	10	Year
Electricity cost	0.065	\$/kWh
Natural gas cost	0.07	\$/m3
Insulation cost (C_{ins})	50	\$/m3

where C_t is the total cost of insulation. It is clear that when the thickness of the insulation increases, the quantity (C_{ins}– C_{pt}) also increases and (C_{en}) decreases. As a result, C_t first decreases, drops to a minimum, and then increases. To calculate LCS in this case, Eq. (6) should be substituted in Eq. (5) and the following equation is used instead:

$$LCS = C_{en}P_1 - P_2\left(C_{ins} - C_{pt}\right) \quad (7)$$

The optimum value of LCS can be determined by maximizing Eq. (7). It should be noted that C_{pt} is calculated using the cost of the HVAC systems in the market. To study the effect of system size, all simulations are performed once with a fixed HVAC system size, similar to the previous studies. Afterwards, the HVAC system size varies in each simulation, so that a new HVAC system is selected by increasing the insulation thickness, because the building thermal load reduces, and as a result, the required size of HVAC system decreases. The energy consumption of the new HVAC system is then calculated, which affects the obtained optimum insulation thickness. Payback periods for different insulation thicknesses are derived from the LCS graphs over the life time of 10 years by comparing each case with the uninsulated case [42].

Genetic Algorithm Optimization

By using MATLAB's optimization toolbox and the genetic algorithm method, both optimum values of insulation thickness and LCS are obtained. Genetic algorithms search parallel from a population of points. Therefore, it has the ability to avoid being trapped in local optimal solution like traditional methods, which search from a single point. On the other hand, Genetic algorithms use probabilistic selection rules, not deterministic ones. Since the genetic algorithm was used to solve the optimization problem, a

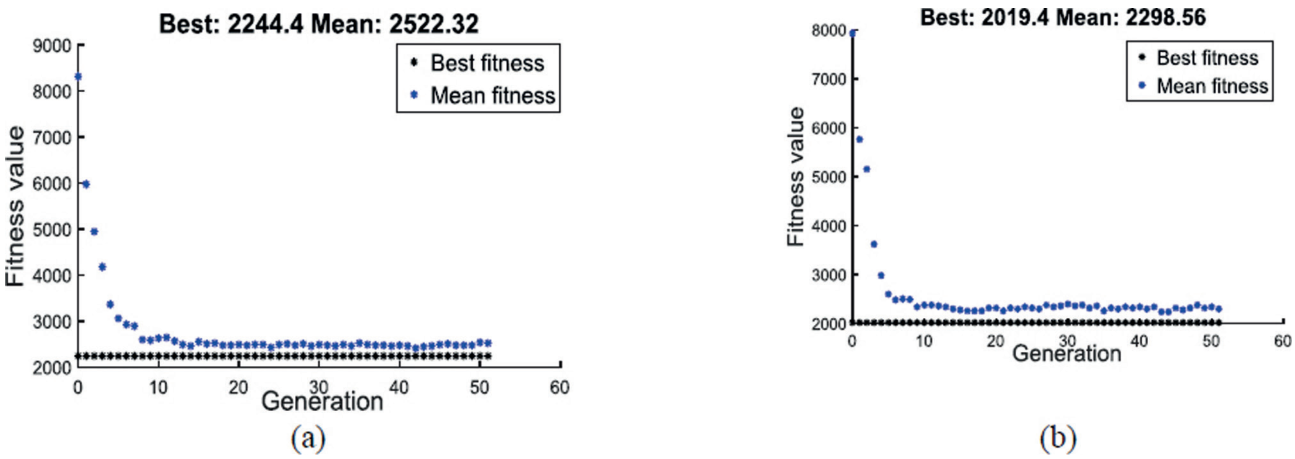


Figure 6. Variation of best and mean fitness for a life time of 10 years for wall-hung boilers in Tehran (a) with and (b) without considering HVAC system size.

fitness function must be selected. The fitness function is the sum of capital and operating costs of the system. The optimization variable is the insulation layer thickness. To find the total cost function, annual simulations need to be done for each insulation layer thickness. For this reason, both genetic algorithm and Energy Plus software must work simultaneously. Initially, each layer thickness is simulated using Design Builder software. Then, the required outputs are imported to the genetic algorithm in MATLAB. The initial population of genetic algorithm is 9. For all cases, the algorithm converged on a solution before the 51st generation. Parameters used inside the toolbox are as follows: the maximum number of generations is taken to be 100, crossover function as two-point because it is the most accurate among all crossover functions and mutation function as constraint dependent.

Figure 6 indicates the variation of best fitness and mean fitness for a life time of 10 years for wall-hung boilers in Tehran. The value of LCS can be calculated by subtracting the best fitness value in which is the minimum total cost from the total cost of the uninsulated case. It can be seen that the total cost value is considerably higher for the case in which the system size is fixed (Figurer 6 (a)) than when the system size variation is considered (Figurer 6 (b)). The flowchart of the calculation process in this study, from calculating thermal loads to getting final results, is illustrated in Figurer 7.

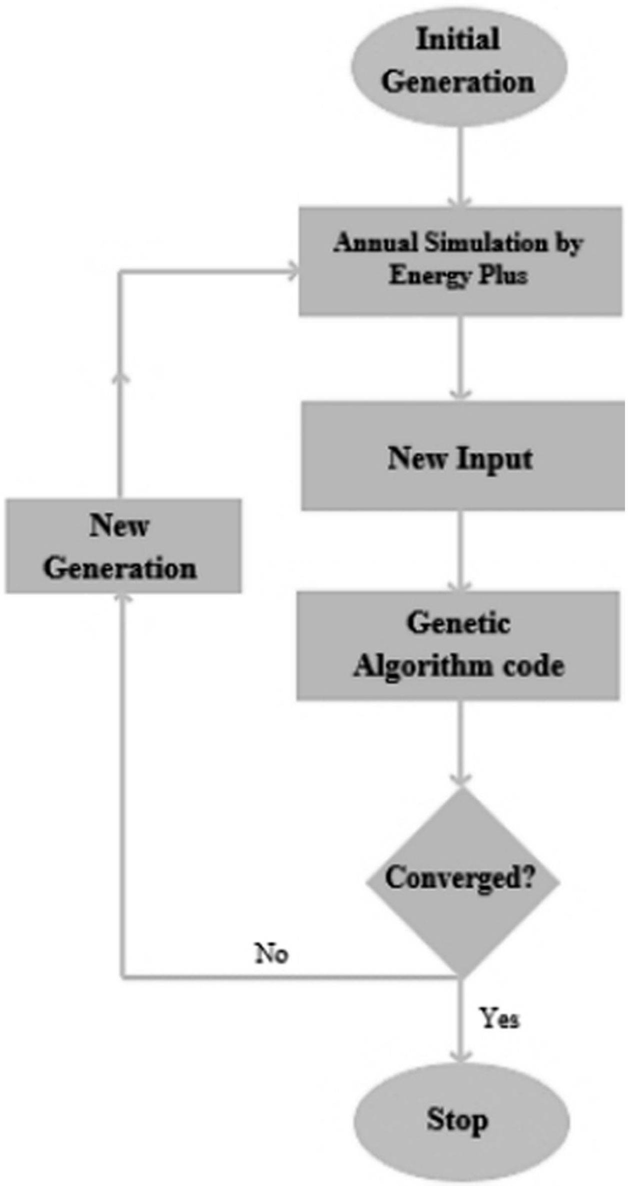
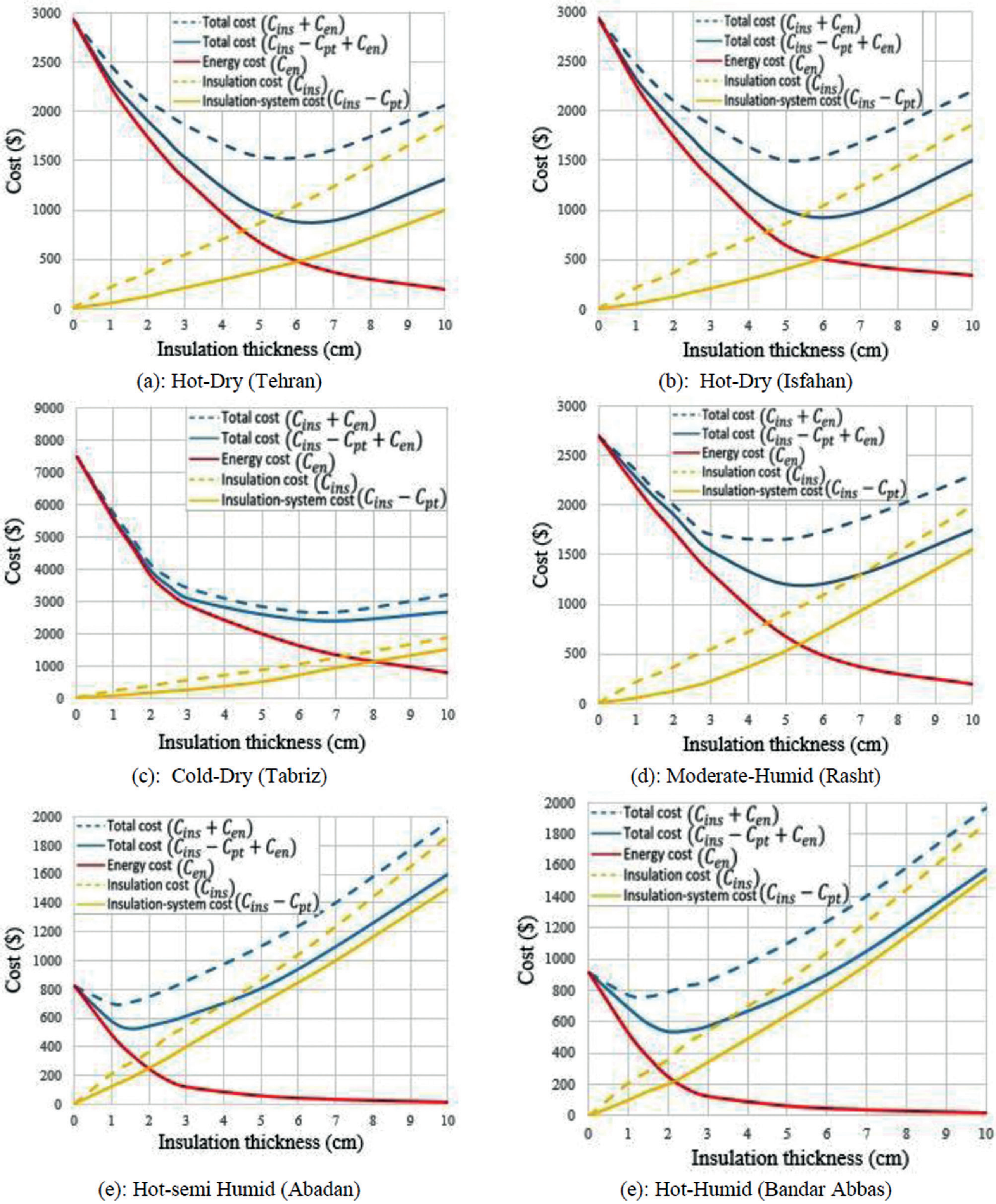


Figure 7. Flowchart of the calculation process.

RESULTS AND DISCUSSION

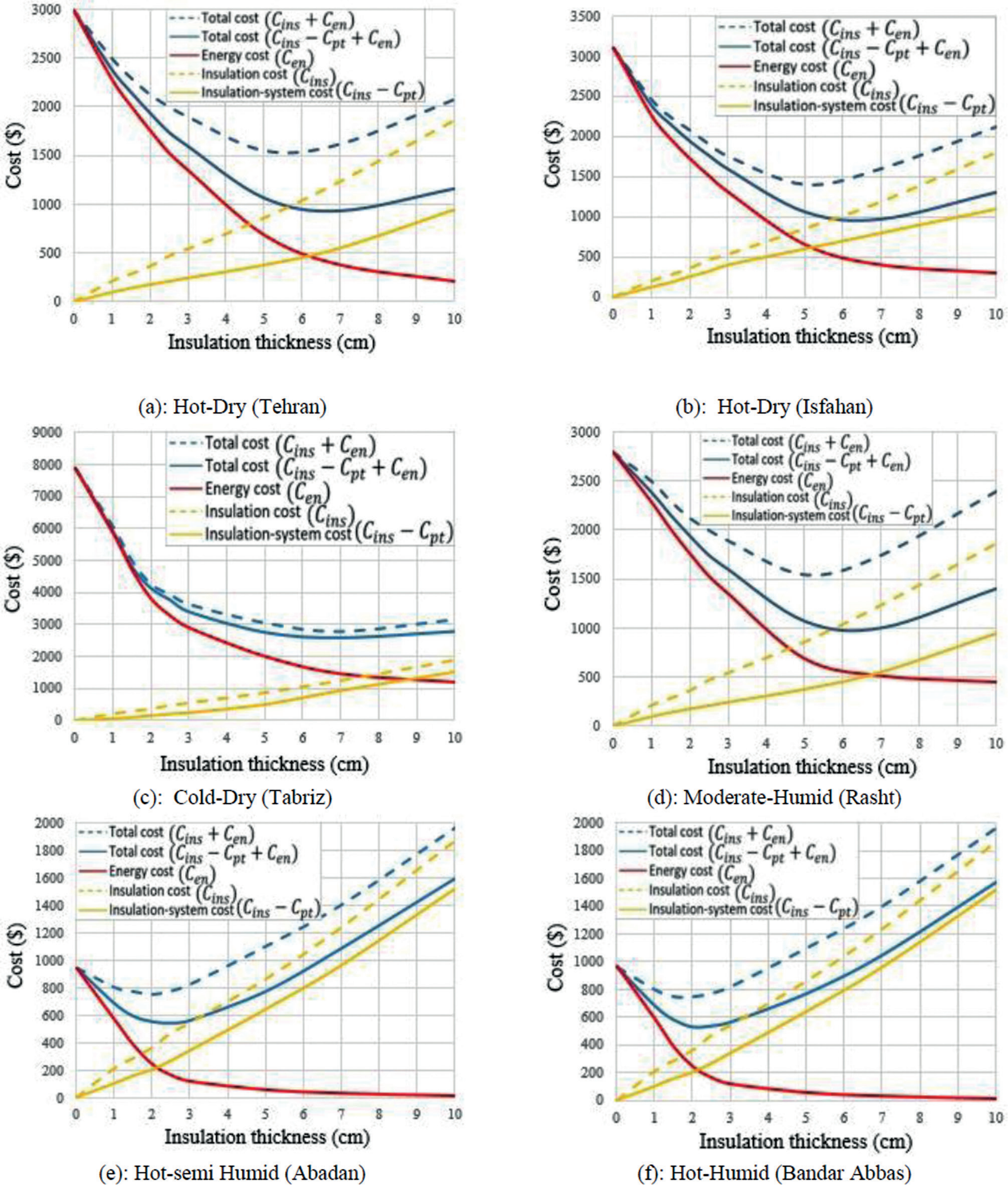
In Figures 8-11, the effect of insulation thickness on the energy cost (C_{en}), insulation cost (C_{ins}) and total cost (C_{ins}+ C_{en}) using the HVAC system with a fixed size and also, insulation cost (C_{ins}— C_{pt}) and total cost (C_{ins} — C_{pt} + C_{en}) with considering the size variation of HVAC system is shown in different climate zones. It is found that both total cost (C_{ins} + C_{en} and C_{ins} — C_{pt} + C_{en}) reduces initially with insulation thickness but after reaching the lowest value, there is an increasing trend with insulation thickness in all climate zones and by using all HVAC systems. This is because the energy cost decreases drastically even at low insulation thickness, whereas the insulation cost is practically small in the small thicknesses. As the insulation thickness and consequently, the insulation cost, increases, the energy cost decreases slightly; therefore, the total costs increases. This trend is the same in the cities of Tehran and Isfahan, both of which located in Hot-Dry zone. Looking Figure 8 (c) and 9 (c), it is observed that, in Tabriz (Cold-Dry zone), the increasing trend after reaching the lowest value is slow using both heating systems, because the heating load in this zone is high and the reduction of energy costs with insulation is so significant that the higher optimum insulation thicknesses can be used in comparison with the other cities. It should be noted that in Abadan (Hot-semi Humid) and Bandar Abbas (Hot-Humid), the increasing trend after reaching the lowest value occurs in the lower optimum insulation thickness comparing with other cities; this is because of the lower heating load in these zones, which requires in the lower optimum insulation thickness.

It is interesting to note that the higher optimum insulation thickness is obtained considering the reduction of the HVAC system size, because the cost reduction due to the system size can be expended for insulating the building with larger thickness which results in lower energy consumption. Looking Figure 8 (a), it is seen that the total cost of 1500 $ is obtained using the optimum insulation thickness of 5.6 cm; whereas, by reducing the size of the central heating, the total cost of 850 $ is obtained using



(a): Hot-Dry (Tehran)
(b): Hot-Dry (Isfahan)
(c): Cold-Dry (Tabriz)
(d): Moderate-Humid (Rasht)
(e): Hot-semi Humid (Abadan)
(e): Hot-Humid (Bandar Abbas)

Figure 8. Effect of insulation thickness on life cycle costs using central heating system.



(a): Hot-Dry (Tehran)

(b): Hot-Dry (Isfahan)

(c): Cold-Dry (Tabriz)

(d): Moderate-Humid (Rasht)

(e): Hot-semi Humid (Abadan)

(f): Hot-Humid (Bandar Abbas)

Figure 9. Effect of insulation thickness on life cycle costs using wall-hung gas boiler.

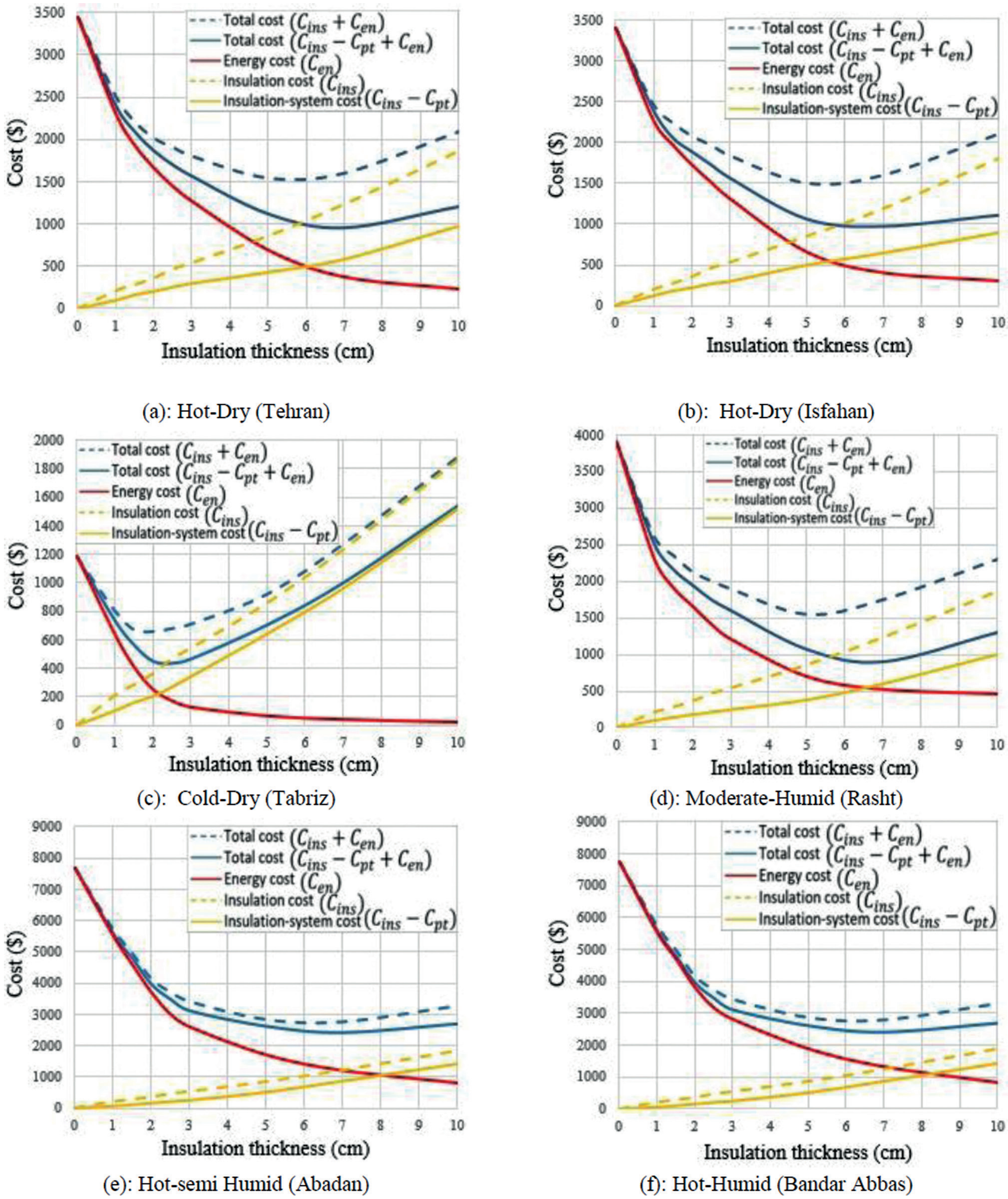


Figure 10. Effect of insulation thickness on life cycle costs using split air conditioner.

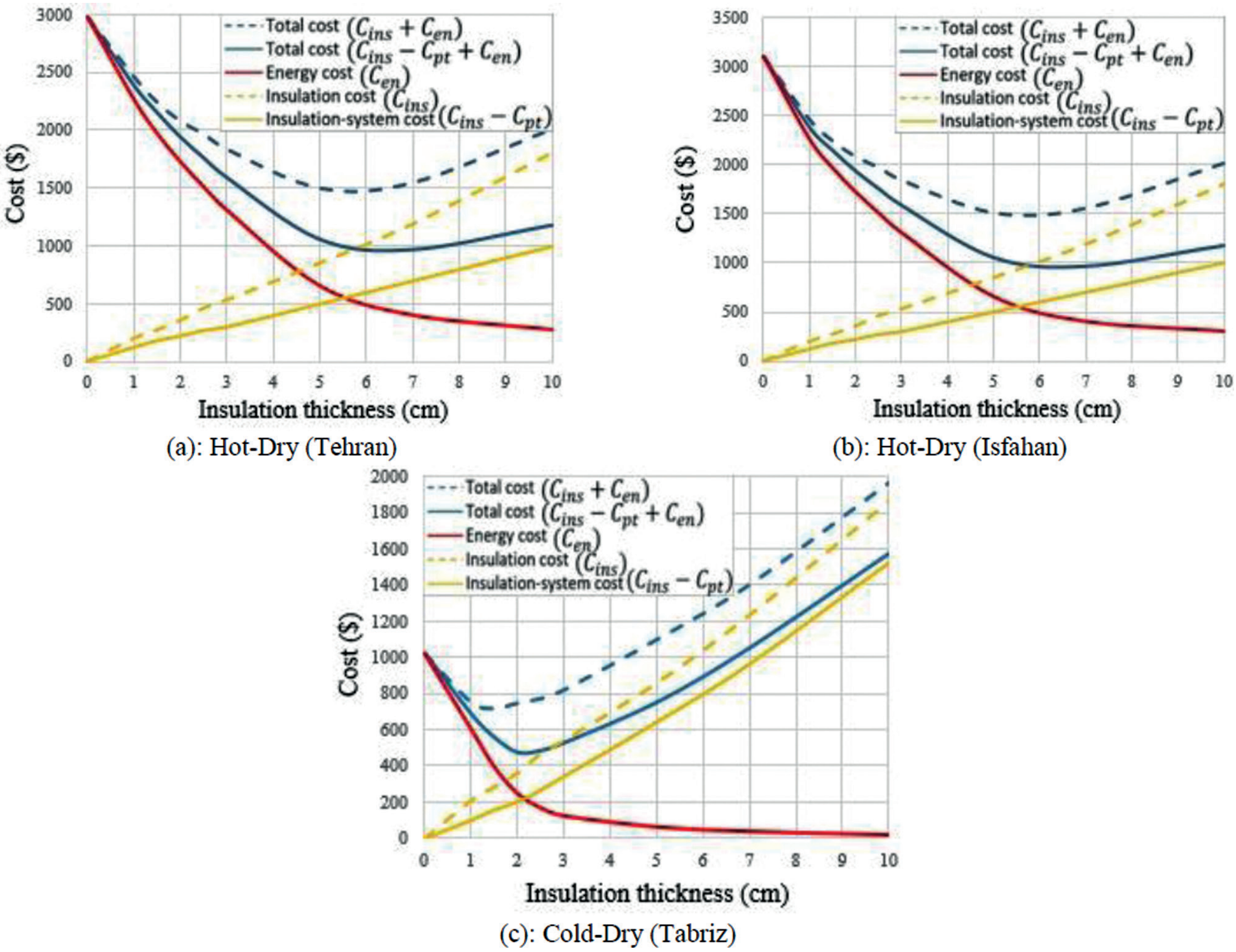


Figure 11. Effect of insulation thickness on life cycle costs using evaporative cooler.

the optimum insulation thickness of 6.4 cm. The optimum insulation thickness of 7.3 cm by total cost of 2300 $ (see Figure 8(c)) and 2.1 cm by total cost of 500 $ (see Figure 8 (f)) are obtained in Cold-Dry zone (Tabriz) and in Hot-Humid zone (Bandar Abbas), respectively. Because of the same climate conditions, the results for Tehran and Isfahan are approximately similar.

Comparison of Figure 9 with Figure 8 shows that the optimum insulation thickness using the wall-hung gas boiler is higher than that using the central heating system, because the initial cost of the central heating system is slightly higher than that of the wall-hung gas boiler and also because of the easier choice and purchase of decentralized systems, which have low heat capacities and cost. This difference between the initial cost of the central heating system and wall-hung gas boiler can be used for higher insulation thickness. For example, the optimum insulation thickness is 6.4 cm for central heating system and 6.5 cm for wall-hung gas boiler, considering the effect of reducing the cost of heating system by insulation for Tehran. However, due to the life time of 10 years, the thickness difference is negligible.

Figure 10 illustrates the effect of insulation thickness on the different costs using the split air conditioner. It is observed that the lowest optimum insulation thickness (2.3 cm) and total cost ($ 420) is obtained in Cold-Dry zone (Tabriz), while the highest optimum insulation thickness (7.1 cm) and total cost ($ 2400) belongs to the Hot-Humid zone (Bandar Abbas).

In Figure 11, the variation of costs by the insulation thickness using an evaporative cooler as a cooling system is shown. It should be noted that the evaporative cooler is not applicable in the zones of Moderate-Humid, Hot-semi Humid and Hot-Humid, due to the high outdoor air humidity. It is also clear that the two cities of Tehran and Isfahan have very close optimum insulation thickness as a result of similar heating and cooling loads.

Table 5. HVAC system size for different climate zones

Climate zone	Heating system				Cooling system			
	Central heating system (kW)		Wall-hung gas boiler (kW)		Evaporative cooler (m^3/h)		Split air conditioner (kW)	
	Optimum insulated building	Uninsulated building	Optimum insulated building	Uninsulated building	Optimum insulated building	Uninsulated building	Optimum insulated building	Uninsulated building
Hot-Dry (Tehran)	231	342	16	24	4650	6350	2.9	8.8
Hot-Dry (Isfahan)	231	342	16	24	4300	6350	3.9	8.8
Cold-Dry (Tabriz)	266	435	16	25	4750	5100	3.5	7.0
Moderate-Humid (Rasht)	231	342	16	24	–	–	2.9	10.5
Hot-semi Humid (Abadan)	216	312	14	23	–	–	3.5	10.5
Hot-Humid (Bandar Abbas)	231	295	18	22	–	–	3.9	10.5

Table 5 shows the required HVAC system size for supplying the building thermal load in two cases without insulation and with the optimum insulation thickness in all climate zones. As can be seen, the insulation of building significantly reduces the required HVAC system size. For example, the size (capacity) of the wall-hung gas boilers reduces from 24 kW to 16 kW in Tehran. This size reduction is from 10.5 kW to 3.5 kW using the split air conditioner for supplying the building cooling load in Abadan, which causes considerable energy savings regarding the electricity cost.

Figure 12 shows the effect of the insulation thickness on the energy cost savings for all heating and cooling systems and different climate zones over a life time of 10 years. As previously mentioned, in all climatic zones, because the initial cost of the centralized heating system is more than the decentralized one, as well as by increasing the insulation thickness and reducing the heating load, the decentralized heating system are more flexible in reducing capacity and initial costs than the centralized heating system; therefore, the larger optimum insulation thickness and the higher energy cost saving can be expected using the wall-hung gas boiler. For instance, in Rasht, the optimum insulation thickness considering the cost reduction effect due to the smaller size of heating system, for the central heating system is 5.5cm with an energy cost saving of 4008$ and for the wall-hung gas boiler is 6.3 cm with energy cost saving of 4298 $. The results show that the thermal insulation of building walls concerning cooling loads results in more significant energy cost saving compared that concerning heating loads in climate zones of Iran.

A summary of the results of Figures 8-12 including the optimum insulation thicknesses, energy cost savings and also, payback periods are listed in Table 6. It is interesting to note that the energy cost saving increases by about 5% and 11% by size variation of the central heating system for Hot-Dry (Isfahan) and Cold-Dry (Tabriz) climate zones, respectively. This increase is about 14.5% and 6% by size variation of the wall-hung gas boiler for Cold-Dry (Tabriz) and Hot-Dry (Isfahan& Tehran) climate zones, respectively. The energy cost saving by size variation of cooling systems is obtained about 10.7% for Hot-Dry climate zone (Isfahan) and about 10.3% for Hot-Humid climate zone (Bandar Abbas). In all climate zones, the payback period decreases about 1-3 months considering the size variation of heating and cooling systems, respectively. Results show that considering system size as an optimization variable led to a reduction of energy consumption from 2% to 14.5% depending on the HVAC system and climate zone.

Since it is generally necessary to introduce one insulation thickness for the buildings in different climate zones, and to introduce two or more insulation thicknesses due to the difference in air temperature or humidity in cold or hot seasons of the year is not practical, one optimum

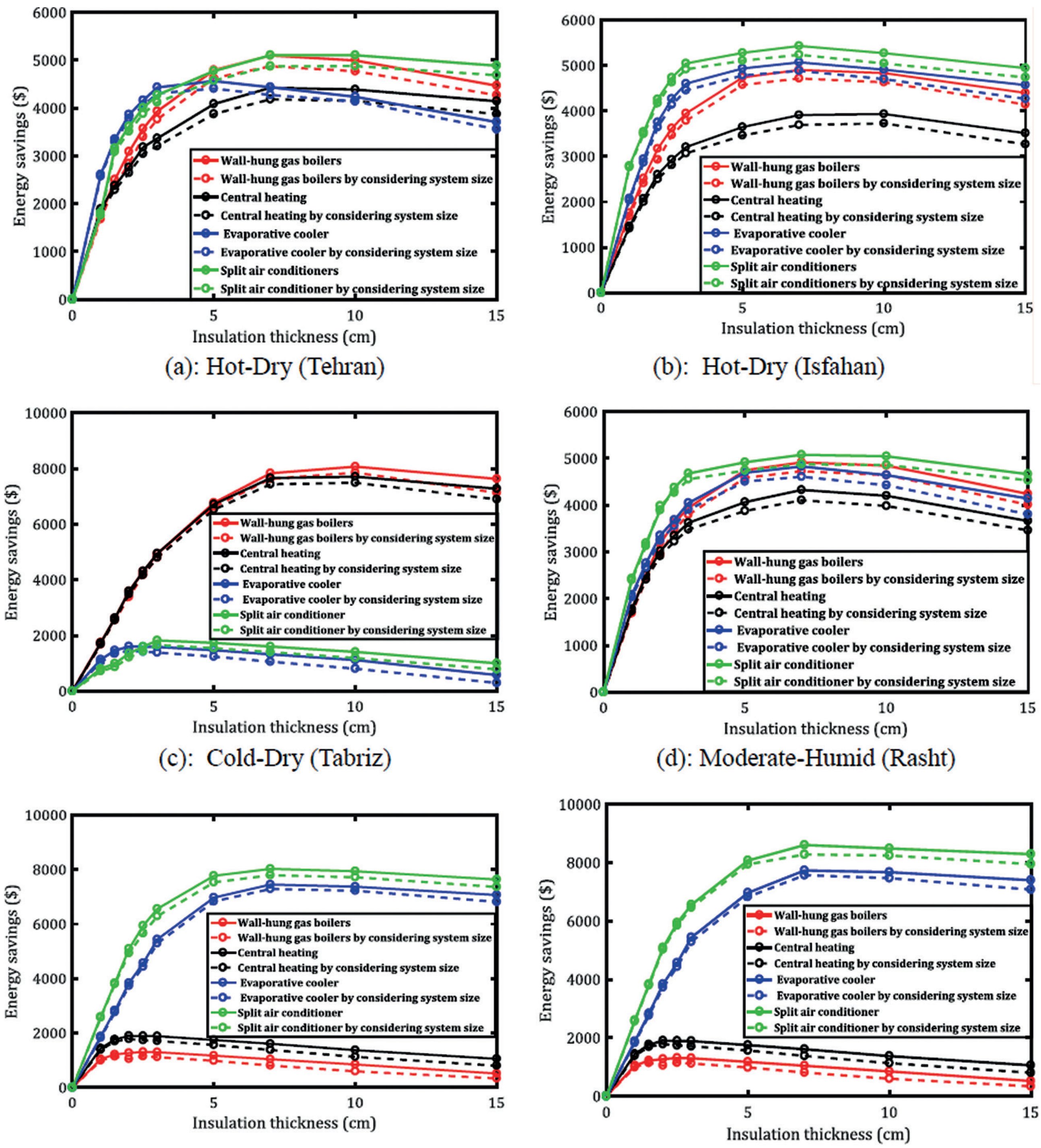


Figure 12. Comparison of energy cost saving over the life time of 10 years for EPS.

Table 6. Optimum insulation thickness, energy cost saving and payback period with and without considering HVAC system size

Climate zone	Heating system					
	Central heating system			Wall-hung gas boilers		
	Optimum insulation thickness (cm)	Energy cost saving ($)	Payback period (year)	Optimum insulation thickness (cm)	Energy cost saving ($)	Payback period (year)
Hot-Dry (Tehran)	5.8 → 6.3	3967 → 4113	3.6 → 3.4	5.8 → 6.4	4123 → 4382	3.5 → 3.3
Hot-Dry (Isfahan)	5.3 → 6	3452 → 3631	4.2 → 4	5.3 → 6.2	4007 → 4276	4.1 → 4
Cold-Dry (Tabriz)	6.4 → 7.3	7034 → 7898	2.4 → 2.3	6.4 → 7.4	7753 → 9073	2.2 → 2.1
Moderate-Humid (Rasht)	4.8 → 5.5	3735 → 4008	4.3 → 4.1	5.5 → 6.3	4013 → 4298	4.2 → 4
Hot-Semi Humid (Abadan)	1.2 → 1.4	1123 → 1268	5.9 → 5.6	2 → 2.2	689 → 753	5.7 → 5.4
Hot-Humid (Bandar Abbas)	1.8 → 2	1007 → 1126	6 → 5.7	1.9 → 2.1	614 → 703	5.8 → 5.5

Climate zone	Cooling system					
	Evaporative cooler			Split air conditioner		
	Optimum insulation thickness (cm)	Energy cost savings ($)	Payback period (year)	Optimum insulation thickness (cm)	Energy cost saving ($)	Payback period (year)
Hot-Dry (Tehran)	5.8 → 6.4	3841 → 3924	3.2 → 3	5.5 → 6.4	4662 → 4969	3 → 2.8
Hot-Dry (Isfahan)	5.9 → 6.5	4376 → 4898	3.3 → 3.1	5.6 → 6.5	4768 → 4957	3.2 → 3
Cold-Dry (Tabriz)	1.7 → 1.9	781 → 853	4.7 → 4.4	1.8 → 2.2	1146 → 1227	5.7 → 5.4
Moderate-Humid (Rasht)	–	–	–	5.3 → 6.2	4487 → 4803	3.2 → 3
Hot-Semi Humid (Abadan)	–	–	–	6 → 7.1	7084 → 7822	2.5 → 2.4
Hot-Humid (Bandar Abbas)	–	–	–	6.1→ 7.3	7768 → 8659	2.3 → 2.2

Table 7. Optimum insulation thickness for different combinations of heating and cooling systems

Climate zone	Optimum insulation thickness for EPS (cm)			
	Central heating system/ Split air conditioner	Central heating system/Evaporative cooler	Wall-hung gas boiler/Split air conditioner	Wall-hung gas boiler/ Evaporative cooler
Hot-Dry (Tehran)	6.5	6.4	6.7	6.5
Hot-Dry (Isfahan)	6.6	6.4	6.6	6.4
Cold-Dry (Tabriz)	7.1	7.1	7.3	7.3
Moderate-Humid (Rasht)	5.9	5.9	6.3	6.3
Hot-semi Humid (Abadan)	6.9	1.4	6.9	2.4
Hot-Humid (Bandar Abbas)	7.1	2.1	7.1	2.3

insulation thickness for different combinations of heating and cooling systems (considering the larger and the most effective thickness in the considered climate zone) is listed in Table 7.

CONCLUSION

In this paper, the effect of size variation of HVAC system by increasing the insulation thickness has been investigated at different climate zones. The findings can be summarized as follows:

- By reducing the HVAC system size as a result of thermal insulation, the higher optimum insulation thickness and thus, the lower energy consumption is obtained.
- Using central heating system, the optimum insulation thickness with and without considering the size variation of the HVAC system in climate zones of Cold-Dry, Moderate-Humid, Hot-Dry, Hot-semi Humid, and Hot-Humid increases 12.3%, 12.7%, 9.5%, 14.2% and 10%, respectively. Using wall-hung gas boiler, the increases are 13.5%, 12.5%, 6%, 9% and 9.5%, respectively.
- Using evaporative cooler, the optimum insulation thickness with and without considering the size variation of the HVAC system in climate zones of Cold-Dry and Hot-Dry increases 10.5% and 9.3%, respectively. Using split air conditioner, the increases are 6.6%, 6.6%, 5%, 9.4% and 10.3%, respectively.
- Considering the size reduction of HVAC system by thermal insulation, the maximum increase of the energy cost saving is obtained 14.5% using the wall-hung gas boiler as a heating system in Cold-Dry climate zone (Tabriz). The energy cost saving increases 10.3% using split air conditioner in Hot-Humid climate zone (Bandar Abbas).
- In all climate zones, the payback period decreases about 5% - 6% considering the size variation of heating and cooling systems.
- Based on the results, ignoring the size variation of the HVAC system as a result of thermal insulation leads to a significant inaccuracy in determining optimum insulation thickness.
- The proposed calculation process in this study can be used for more accurate determination of the optimum insulation thickness which affects the building energy consumption significantly.
- As the future works, the optimum insulation thickness can be obtained by the proposed calculation process using other heating and cooling systems such as absorption chiller and floor heating systems. Furthermore, the effect of other building types, the building orientation and the window-to-wall ratio on the optimum insulation thickness, along with the effect of HVAC system size, can be considered.

NOMENCLATURE

C_{ins}	Insulation cost ($)
C_{en}	Energy cost ($)
C_{pt}	Insulation cost savings made by considering system size ($)
C_t	Total cost ($)
d	Discount rate
i	Inflation rate
LCS	Life cycle saving ($)
N	Life time (years)
P_1	Economic indicator
P_2	Economic indicator
R_v	Ratio of the resale value to the first cost
$SHGC$	Solar Heat Gain Coefficient
VLT	Visible Light Transmittance
x	Thickness of the insulation material (m)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Ahmad EH. Dynamic simulation of a trigeneration system using an absorption cooling system and building integrated photovoltaic thermal solar collectors. J Build Eng 2021;43:102482. [CrossRef]

[2] Kariman H, Hoseinzadeh S, Heyns PS. Energetic and exergetic analysis of evaporation desalination system integrated with mechanical vapor recompression circulation. Case Stud Therm Eng 2019;16:100548. [CrossRef]

[3] Kariman H, Hoseinzadeh S, Heyns S, Sohani A. Modeling and exergy analysis of domestic MED

desalination with brine tank. Desalination Water Treat 2020;197:1–13. [CrossRef]

[4] Kariman H, Hoseinzadeh S, Shirkhani A, Heyns PS, Wannenburg J. Energy and economic analysis of evaporative vacuum easy desalination system with brine tank. J Therm Anal Calorim 2020;140:1935–1944. [CrossRef]

[5] Sharifishourabi M, Alimoradiyan H, Atikol Atikol U. Modeling of hybrid renewable energy system: the case study of Istanbul, Turkey. J Therm Eng 2016;2:990–994. [CrossRef]

[6] Karami M, Javanmardi F. Performance assessment of a solar thermal combisystem in different climate zones. Asian J Civil Eng 2020;21:751–762. [CrossRef]

[7] Bazarchi S, Nabi Bidhendi G, Ghazi I, Kasaeian A. A techno-economic feasibility study for reducing the energy consumption in a building: a solar energy case Study for Bandar Abbas. J Therm Eng 2020;6:633–650. [CrossRef]

[8] Özkan DB, Onan C. Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey. Appl Energy 2011;88:1331–1342. [CrossRef]

[9] Delfani S, Pasdarshahri H, Karami M. Experimental investigation of dehumidification process in cooling coil by utilizing air-to-air heat exchanger in humid climate of Iran. Energy Build 2010;42:822–827. [CrossRef]

[10] Nyers J, Kajtar L, Tomić S, Nyers A. Investment-savings method for energy-economic optimization of external wall thermal insulation thickness. Energy Build 2015;86:268–274. [CrossRef]

[11] Anand Y, Anand S, Gupta A, Tyagi SK. Building envelop performance with different insuating materials: an exergy approach. J Therm Eng 2015;1:433–439. [CrossRef]

[12] Liu X, Chen Y, Ge H, Fazio P, Chen G, Guo X. Determination of optimum insulation thickness for building walls with moisture transfer in hot summer and cold winter zone of China. Energy Build 2015;109:361–368. [CrossRef]

[13] Dombayci ÖA, Atalay Ö, Acar ŞG, Ulu EY, Ozturk HK. Thermoeconomic method for determination of optimum insulation thickness of external walls for the houses: Case study for Turkey. Sust Energy Technol Assess 2017;22:1-8. [CrossRef]

[14] Nematchoua M, Ricciardi P, Reiter S, Yvon A. A comparative study on optimum insulation thickness of walls and energy savings in equatorial and tropical climate. Int J Sustain Built Environ 2017;6:170–182. [CrossRef]

[15] Solgi E, Hamedani Z, Fernando R, Kari BM. A parametric study of phase change material characteristics when coupled with thermal insulation for different Australian climatic zones. Build Environ 2019;163:106317. [CrossRef]

[16] Baniassadi A, Sajadi B, Amidpour M, Noori N. Economic optimization of PCM and insulation layer thickness in residential buildings. Sustain Energy Technol Assess 2016;14:92–99. [CrossRef]

[17] Idchabani R, Khyad A, Ganaoui ME. Optimizing insulation thickness of external walls in cold region of Morocco based on life cycle cost analysis. Energy Procedia 2017;139:117–121. [CrossRef]

[18] Lakrafli H, Tahiri S, Albizane A, Houssaini SE, Bouhria M. Effect of thermal insulation using leather and carpentry wastes on thermal comfort and energy consumption in a residential building. Energy Effic 2017;10:1189–1199. [CrossRef]

[19] Rad EA, Fallahi E. Optimizing the insulation thickness of external wall by a novel 3E (energy, environmental, economic) method. Construct Build Mater 2019;205:196–212. [CrossRef]

[20] Kumar D, Zou PX, Memon RA, Alam MM, Sanjayan JG, Kumar S. Life-cycle cost analysis of building wall and insulation materials. J Build Phys 2019;43:428–455. [CrossRef]

[21] Gounni A, Mabrouk MT, Wazna ME, Kheiri A, Alami ME, Bouari AE, Cherkaoui O. Thermal and economic evaluation of new insulation materials for building envelope based on textile waste. Appl Therm Eng 2019;149:475–483. [CrossRef]

[22] Dlimi M, Iken O, Agounoun R, Zoubir A, Kadiri I, Sbai K. Energy performance and thickness optimization of hemp wool insulation and air cavity layers integrated in Moroccan building walls. Sustain Prod Consum 2019;20:273–288. [CrossRef]

[23] Guven S. Calculation of optimum insulation thickness of external walls in residential buildings by using exergetic life cycle cost assessment method: Case study for Turkey. Environ Prog Sustain Energy 2019:e13232. [CrossRef]

[24] Huang H, Zhou Y, Huang R, Wu H, Sun Y, Huang G, Xu T. Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate. Sustain Cities Soc 2020;52:101840. [CrossRef]

[25] Alpay Kurekci N. Optimum insulation thickness for cold storage walls: Case study for Turkey. J Therm Eng 2020:6:873–887. [CrossRef]

[26] Nematchoua M, Raminosoa C, Mamiharijaona R. Study of the economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate: Case of Cameroon. Renew Sustain Energy Rev 2015;50:1192–1202. [CrossRef]

[27] Ramin H, Hanafizadeh, P, Akhavan-Behabadi MA. Determination of optimum insulation thickness in different wall orientations and locations in Iran. Adv Build Energy Res 2016;10:149–171. [CrossRef]

[28] Arslan E, Karagoz I. Determination of Optimum Insulation Thickness on Different Wall Orientations in a Hot Climate. Proceedings of 3rd International Sustainable Buildings Symposium (ISBS 2017), Lecture Notes in Civil Engineering 2017;7:145–157. [CrossRef]
[29] Rosti B, Omidvar A, Monghasemi N. Optimal insulation thickness of common classic and modern exterior walls in different climate zones of Iran. J Build Eng 2020;27:100954. [CrossRef]
[30] Derradji L, Imessad K, Amara M, Errebai FB. A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness. Appl Therm Eng 2017;112:975–985. [CrossRef]
[31] Alwetaishi M, Taki A. Investigation into energy performance of a school building in a hot climate: Optimum of window-to-wall ratio. Indoor Built Environ 2019;29:24–39. [CrossRef]
[32] Carrier System Design Manuals Part 1: Load estimating, Carrier Air Conditioning Company, 1960.
[33] Delfani S, Pasdarshahri H, Karami M. The effects of climate change on energy consumption of cooling systems in Tehran. Energy Build 2010;42:1952–1957. [CrossRef]
[34] Gholizadeh F, Saba HR, Shakeri E. Impact of insulation on reducation of energy consumption in building based on climate in Iran. American-Eurasian J Agric Sci 2014;14:97–103.
[35] Mostashari-Rad F, Nabavi-Pelesaraei A, Soheilifard F, Hosseini-Fashami F, Chau K. Energy optimization and greenhouse gas emissions mitigation for agricultural and horticultural systems in Northern Iran. Energy 2019;186:115845. [CrossRef]
[36] Faizollahzadeh Ardabili S, Najafi B, Shamshirband S, Minaei Bidgoli B, Deo RC, Chau K. Computational intelligence approach for modeling hydrogen production: a review. Eng Appl Comput Fluid Mech 2018;12:438–458. [CrossRef]
[37] Ahmadi A, Sadeghzadeh M, Raffiee AH, Chau K. Applying GMDH neural network to estimate the thermal resistance and thermal conductivity of pulsating heat pipes. J Eng Appl Comput Fluid Mech 2019;13:327–336. [CrossRef]
[38] Huo H, Jing C, Huo H. Effect of natural ventilation on transmission load of building external walls and optimization of insulation thickness. J Therm Sci Technol 2015;10: JTST0023. [CrossRef]
[39] Kaab A, Sharifi M, Mobli H, Nabavi-Pelesaraei A, Chau K. Use of optimization techniques for energy use efficiency and environmental life cycle assessment modification in sugarcane production. Energy 2019;181:1298–1320. [CrossRef]
[40] Kalogirou SA. Solar energy engineering: Processes and Systems, 2nd ed. New York: Academic Press, 2014. [CrossRef]
[41] Wang SK. Handbook of Air Conditioning and Refrigeration. 2nd ed. New York: McGraw Hills, 2000.
[42] Yu J, Yang C, Tian L, Liao D. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. Appl Energy 2009;86:2520–2529. [CrossRef]