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Proposal for optimum thermal insulation thickness of building exterior walls in Tehran

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Abstract: *In Iran, the buildings sector is responsible for large consumption of energy and corresponding GHG (Greenhouse Gases) emissions. The insulation of buildings is a relevant technology to reduce such energy consumption and GHG emissions. According to Paris agreement 2016 all countries in the world are obliged to reduce their GHG emission and Iran as a developing country should contribute to international agreement. This paper seeks Iran's building sector role in mitigating national GHG emission. The main objective of this study is to minimize the building environmental impacts by proper insulation. For this purpose, five details for applying thermal insulation thickness, recommended by Iran national building code were selected. The most conventional thermal insulation materials produced in Iran are selected as thermal insulation material. First, thermal insulation thickness was optimized for all surfaces comprising a single cubic thermal zone in climate of Tehran. The results are evaluated in reducing, net environmental saving and energy demand for a typical residential building located in Tehran. The results of this study represents optimized insulation thickness for all building envelope surfaces, in accordance to mandatory thermal performance, in order to optimize energy consumption of the building and minimizing its environmental footprint. The results shows that by accommodating proper insulation total environmental impact of building can reduce to more than 70% percent.*

Keywords: *Life Cycle Assessment, Thermal insulation, Global Warming Potential, Optimization, Insulation Thickness*

INTRODUCTION

Iran is the tenth largest producer of GHG in world and emits 164 million metric tons CO_2 annually (EIA, 2016). What makes these numbers look worse is lack of correlation between this high amount of GHG emission and economic development. In other words emission is the result of energy consumption in unproductive sectors. Specially in building sector GHG emission is twice average per capita, which necessitates taking control measures in to consideration. High amount of GHG emission is the result of high amount of energy consumption. Beside, low quality of construction has a magnificent role in high energy demand in residential sector. High energy consumption in unproductive sectors not only takes higher portion of national budget, but also causes many problems to the environment and leads in to numerous environmental crisis. Obviously energy consumption needs to be controlled economic and environmental wise.

One way to reduce energy consumption in buildings is applying proper thermal insulation. By the means of insulation, heat transfer will be controlled and heating and cooling load will be reduced therefor it can help reducing energy consumption in buildings but it should be considered that the process of producing, transferring and applying insulation in the building consumes energy itself and consequently produce GHG.

In other words optimum building insulation is applied in a way that minimize energy consumption in operational phase while it has the least embodied energy in production (primary) phase. Determining aforementioned insulation thickness is the main purpose of this study.

Numerous attempts have been made so far to determine the optimum thermal insulation thickness for different materials and in different climates. Researchers have approached this issue from different perspectives, though some of them have the same methods that can help future works. Hassan Afif presented the correlation between thermal conductivity and total cost of installing thermal insulation of a building in Palestine (Hassan, 1999). Similarly Riazi and Jamshidi calculated optimum thermal insulation thickness for all existing climates in Iran by minimizing total operational cost of building. They observed the effect of climate by simplifying degree days. They also calculated payback period using economic model (Riazi & Eslami, 1990). Comakli and Yuksel investigated the optimum insulation thickness of EPS for the coldest climate of Turkey with evaluations based on simplified DDs calculations. They showed that a significant energy saving can be achieved when the optimum insulation thickness is applied (Comakli et al., 2003). Ucar and Balo determined the optimum insulation thickness of external walls for four cities with different DD values (Ucar, et al., 2009). Yu et al. have optimized the insulation thicknesses of expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride, considering HDD and CDD, for the wall of a typical residential building in China (Yu et al., 2009).

Apart from the above-mentioned works, some authors examined the environmental impacts of optimum insulation thickness. Comakli and Yuksel presented an analysis for the coldest regions of Turkey. They found that CO_2 emissions could be decreased about 27% by applying optimum insulation thickness in buildings (Comakli et al., 2004). Yildiz et al. underlined that the optimum insulation thickness is of vital importance, especially in colder climates. They carried out a study for Ankara, Turkey and found that CO_2 emissions could be reduced by about 35% via 6 cm insulation which corresponds to the optimum value for glass wool (Yildiz, et al., 2008). Dombayci determined the optimal insulation thickness for cities in Turkey. He concluded that energy consumption and the GHG (CO_2 and SO_2) emissions decrease 46.6 and 41.5%, respectively through optimum insulation thickness (Dombayci, 2007).

As previously reported by Comakli and Yuksel neither excessive nor deficient thermal insulation is desired due to economic reasons. Excessive insulation yields to lower life cycle energy cost but requires higher initial investment cost. On the other hand, deficient insulation has lower initial investment cost but higher life cycle energy cost. From this point of view, it is understood that the optimum insulation thickness is required to be considered for the most cost-effective application (Comakli et al., 2003)

Ozel et al. determined, environmental and economic optimum insulation thicknesses for Rockwool and glass wool. In their study, the fuel consumption and CO2 emissions and also, the environmental impact of the system and the total cost are investigated. The reported optimum insulation thickness for glass wool and rock wool are 0.15 and 0.064 m, respectively (Ozel et al., 2015).

Normally building codes define the energy consumption threshold in different climates of country. The gap in previous studies is inattention to building codes in optimizing thermal performance of building and its environmental impact. This study aims to fill this gap.

Another neglected point in previous studies is economical functional unit. In this paper, in order to gain general and practical results, an independent economical functional unit was selected for optimizing thermal and environmental behavior of building. Net energy consumption is convertible to secondary economical parameters like total cost any time and can be used for analyzing data economical wise. In this study we aim to optimize environmental impact and energy consumption in residential building with respect to Iran's national building code. Applying this results leads into environmental and financial savings.

Calculation

Nomenclature	
GHG	Greenhouse Gas
EPS	Expanded Poly Styrene
GWP	Global Warming Potential (Kg_{co2-eq})
GWP_P	Primary Global Warming Potential (Kg_{co2-eq})
GWP_{OP}	Operational Global Warming Potential(Kg_{co2-eq})
GWP_T	Total Global Warming Potential (Kg_{co2-eq})
GWP_{fuel}	Global Warming Potential of fuel (Kg_{co2-eq})
H_u	Low heat value of the fuel, (J/kg, J/m3)
η	Efficiency of the combustion system (%)
E	Annual energy need for heating (J/ year)
N	Building life span, (year)
σ	Density (Kg/m^3)
A	Area (m^2)
d	Thickness (m)
d_i	Optimum thickness insulation (m)
$\hat{H}$	Maximum required coefficient of building heat loss (W/K)
H	Coefficient of building heat loss (W/K)

In this paper, in order to evaluate environmental impact of applying thermal insulation in buildings, five recommended construction details were selected and modeled. As shown in Fig 1 to Fig 5, studied details includes inverted roof, roof with internal thermal insulation, Etics for walls, floor with internal insulation and floor with false ceiling. For thermal insulation material, mineral wool and Expanded Polystyrene (EPS) were selected which are the most common thermal insulation used in recent construction projects in Iran. Aforementioned details comprise 4 insulating scenarios that were assigned to studied model. Table 1 describes investigated scenarios. In order to calculate optimum thermal insulation thickness in general condition, insulating scenarios were assigned to a simple thermal zone. The studied zone is a cubic zone with 16 m^2 square plan, 3 m height and Window-to-Floor Ratios (WFR) of 15% in four directions. Climatic conditions of this model was simulated based on data of Mehrabad weather station.

Table 1 - Description of scenarios

scenario	Roof	Wall	Floor
1	Inverted roof	Etics	Floor with internal insulation
2	Inverted roof	Etics	Floor with False ceiling
3	Roof with internal insulation	Etics	Floor with False ceiling
4	Roof with internal insulation	Etics	Floor with internal insulation

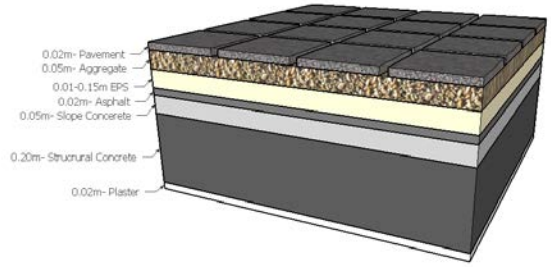

Fig 1- Inverted Roof

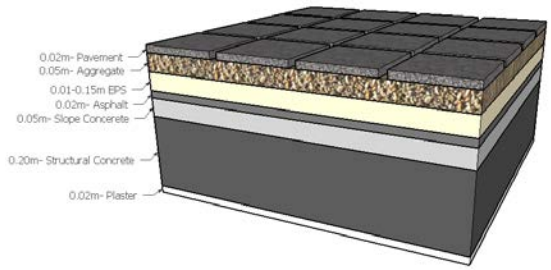

Fig 2- Roof with internal insulation

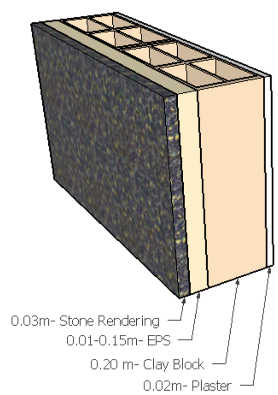

Fig 3- Insulated by Etics system.

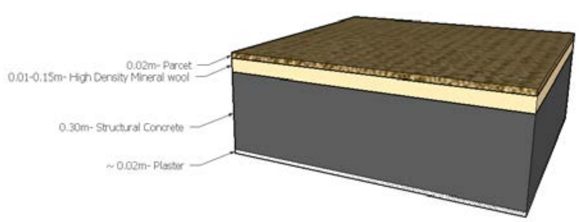

Fig 4- Floor with internal insulation

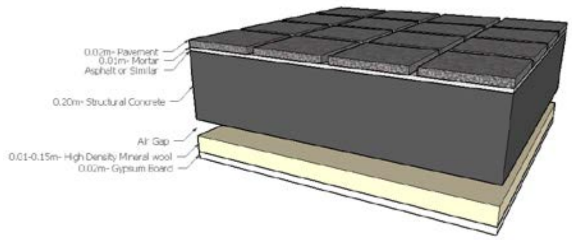

Fig 5- Floor with False Ceiling

The goal of this study is to minimize total environmental footprint of the building. The impact categories of LCA methodologies vary from system to system and environmental footprint can be measured by different impact factors. In this study building environmental footprint is measured by GWP, which characterize the change in the greenhouse effect, due to emissions and absorptions attributable to human activities.

Total GWP of the building, which is amount of emitted carbon during building life span, is calculated by this equation:

Equation 1

$$\mathrm{GWP}_{T} = \mathrm{GWP}_{P} + \mathrm{GWP}_{OP}$$

In this equation, GWP_P is the amount of carbon emitted during extracting raw material and manufacturing building materials. GWP_P for building envelope- including roof, all the walls and floor- is given by Equation 2. Values for GWP_P of the building materials (GWP_x) is determined, based on Bribian's previous work (Bribian, et al., 2011).

Equation 2

$$GWP_{P} = \sum_{x=i}^{n} (\mathrm{A}_{x} \mathrm{d}_{x}\, \sigma_{x} \mathrm{GWP}_{x}) + (GWP_{i}\, \sigma_{i} A_{i} d_{i})$$

In this equation the subscript i represent the physical properties of insulation layer and subscript X shows attributes of other layers of building. The goal of this study is to calculate optimum amount of d_i in order to reduce total GWP. The second component comprising GWP_T is operational Global warming potential (GWP_{OP}) which is determined as follows

Equation 3

$$\mathrm{GWP}_{OP} = \frac{E}{\eta}\ \mathrm{N}\ \mathrm{H}_{u}\ \mathrm{GWP}_{fuel}$$

In order to calculate GWP_{OP}, annual energy use for heating was calculated by EnergyPlus simulation software. The heating system of the zone is assumed to operates at 80% efficiency with natural gas as fuel. Actual amount of fuel is determined by Low Heating Value (LHV) of natural gas which is 47.141 MJ/Kg. Average life span of the buildings in Iran is assumed to be 30 years.

The architectural model was created in Rhinoceros software and optimization calculation was performed by Galapagos in Grasshopper, using genetic algorithm. The simulation of heat transfer through building envelope was conducted using EnergyPlus software, joint to rhinoceros by Honeybee plugin. Heat gain and loss through opaque and transparent part of building envelope was considered in respect to the orientation, solar and wind exposure and adjacencies. The calculation was conducted with 6 time steps per hour. It was assumed that the building is located in city terrain and is not exposed to high wind. In simulation model, all internal gain was taken in to account considering residential occupancy. Equipment load per area is estimated to be 3.875 kWh/m^2. The zone is fully conditioned with ideal heat load and set points are set to 25 and 18 °C to provide thermal comfort condition. Infiltration rate per area is 0.000107 m^2/s.

In determining amount of GWP_T, operational GWP is much more influential than GWP_P and can affect the amount of GWP_T remarkably. Reducing GWP_{op} should be priortized for minimizing GWPT. It's good to remind that although d_i is not seen in GWP_{OP} equation, it affects amount of energy consumption (E) and therefore sufficient insulation can reduce both GWP_P and GWP_{OP} factors. In order to minimize the GWP_{OP}, minimizing energy need (E) should be considered. The optimization procedure continued until both following conditions were fulfilled:

1. GWP_T is minimum.
2. $H \leq \hat{H}$ (Accordance with Iranian building energy code)

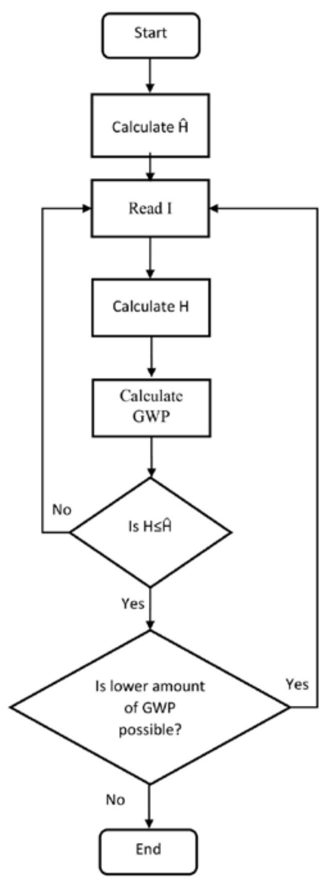

Fig 6. Optimization Process

H and Ĥ are determined based on instruction in Iran national building energy code no.19. Optimization process was conducted according to fellow chart below.

Results and discussions

While increasing thermal insulation thickness, GWP_P increases and GWP_{OP} decreases. In optimum thickness this hybrid change has been balanced and we gain the least GWP_T .Top ten results for each scenario with lowest total GWP and energy consumption are presented in Fig 7 to Fig 0. Table 2 shows the optimum insulation thickness of all scenarios and compares their respective thermal properties. These results are in very good agreement with the previous works of Comakli et al and Hassan (Comakli et al., 2003) (Hassan, 1999).

It's observed that GWP_P may fluctuate wildly, but it's balanced with regular trend of GWP_{op}. Graphs also show that the trend of GWP_T is very similar to GWP_{OP} which again highlights the importance of GWP_{op} versus GWP_P

Fig 7. Environmental impact of first scenario

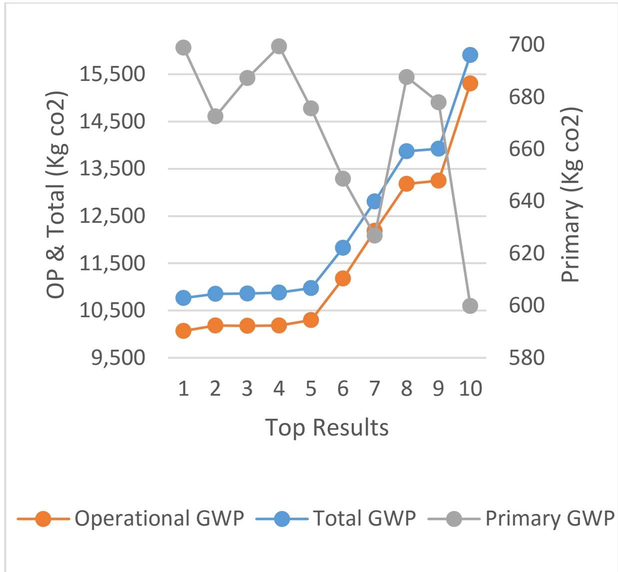

Fig 8. Environmental impact of second scenario

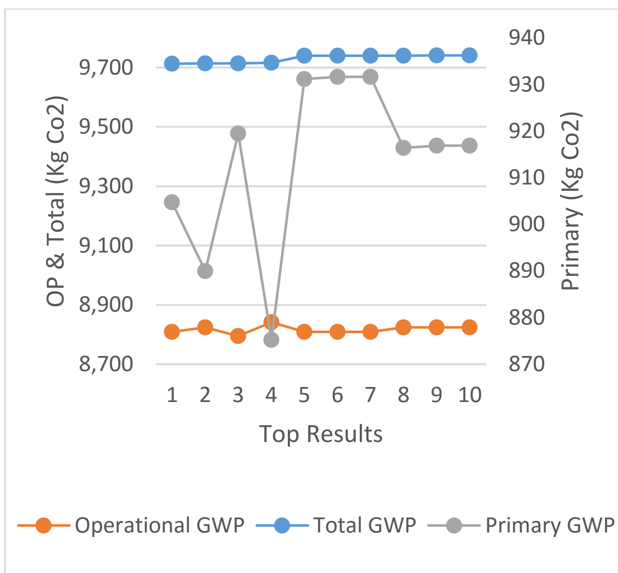

Fig 9. Environmental impact of third scenario

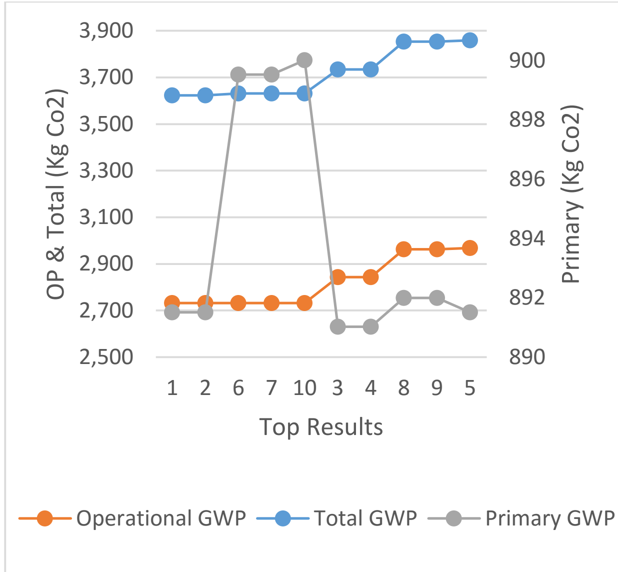

Fig 10. Environmental impact of fourth scenario

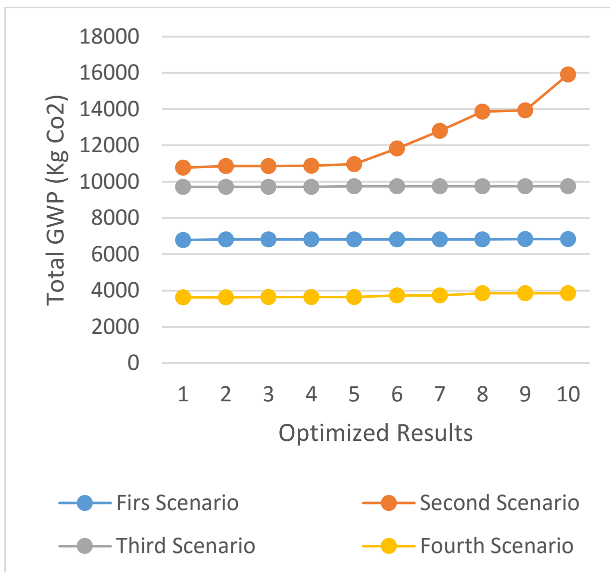

Fig 11. Total GWP of optimum insulation in studied scenarios

The top results of optimization of thermal insulation thickness are combined together in Fig 11. It is understood from the graph that applying optimum thermal insulation thickness in fourth scenario results in to the least total GWP value for the zone among all possible cases of studied scenarios and corresponding model shows the best environmental behavior. In the next step First scenario is suggested. Second and third scenarios have the highest GHG emissions and are not suggested.

Results also highlight the necessity of putting maximum thickness of thermal insulation in North oriented walls and floors where the most heat loss through building envelope is observed. Minimum thickness is related to South walls. In this orientation the solar gain is roughly in balance to heat loss and lower amount of insulation is required.

Beside theoretical works presented, a practical performance analysis of optimum thermal insulation thickness is performed in order to verify the reliability of outputs. In this respect a typical residential building in Tehran was modeled. This three- bedroom flat is 135 square meter and has 4 stories. As shown in Fig 2 this residential unit is exposed to outdoor in three faces. All simulation details are based on the optimization model afore described in methodology. Energy consumption and environmental impact of the insulated building, based on the studied scenarios was measured. Table 3 reports the results of simulation and compares the result to noninsulated model.

Fig 22- Studied residential building

The comparison of net environmental saving of investigated scenarios is shown in Fig 13. Improvement in environmental behavior of building in third and fourth scenarios are remarkable. Applying fourth scenario in the studied building can cause a dramatic drop in building GWP up to 72%. Insulating building with thermal insulation thickness of third scenario can help mitigating GHG of building up to 63% versus noninsulated scenario which is conventional at the time in Tehran. Less reduction in environmental saving is observed in scenario 1 and 2. Applying mentioned scenarios leads in to 20 percent less GHG emission which worth insulating the building.

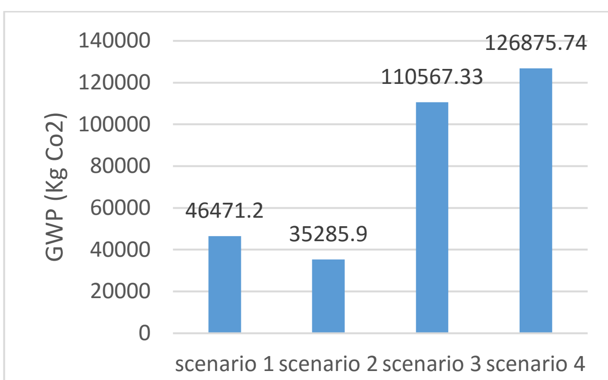

Fig 33- Net Environmental Saving

Conclusion:

Present study is conducted with the idea of reducing buildings environmental impact and mitigation in GHG emission as a result of built environment. In this study residential buildings, as the most common type of buildings, were studied. We tried to enhance the performance of current construction details simply by optimizing the physical and thermal properties of existing layer.

Domain of study is not only consisting of manufacturing and construction phase, but also it covers the whole operational period; so comprehensive observation and evaluation of the environmental impact of building is possible.

In order to reach accurate results, recomended modeling scenario with the aim of accurate energy simulating softwares was used. Optimization process was conducted with the purpose of minimizing building environmental footprint. This process was carried out in conjunction to physical properties of thermal insulation, optimized in a continuous range to form environmental friendly construction details for Tehran based on Iran's national energy code.

1. The result of simulation clearly states that although insulating buildings causes GHG emission in manufacturing and construction phase, but it can prevent much larger amount of emission during operational period. This is implemented through noticeable drop in heating load and energy consumption of building in operational period and can totally compensates primary GWP in manufacturing and construction phase and eventually results in a remarkable decrease in environmental impact of building.
2. In this study thermal insulation thickness was evaluated and optimized for selected construction scenarios. Among all, fourth scenario shows the best environmental behavior and is highly suggested in residential buildings. Applying mentioned scenario can reduce total GWP of the building up to 72 percent in comparison to non-insulated building that is conventional at the time in Iran. In the next place, the third scenario is the most environmental friendly and leads to a drop of 63% of total GWP of the building. First and second Scenarios show the least net environmental saving among all, however by applying them we still manage to decrease total GWP of building to respectively 26 and 20 percent.
3. In convergence to previous studies the influential parameter in total GWP is operational GWP and that can totally cover the influence of Primary GWP. As an example the second scenario has the lowest primary and the highest operational GWP among all investigated scenarios, which overall result in highest amount of total GWP.
4. In the first and third scenario, architectural details are the same except for the roof. Nevertheless, total heat loss coefficients in optimum state are roughly equal. Considering different insulation materials and their thickness, it can be concluded that although polymeric thermal insulations, in comparison to mineral insulations, have higher GWP in manufacture phase, due to proper thermal behavior and higher thermal resistance, they help reduce total thermal transmittance, leading to much lower total GWP.

Future studies:

This study is one of the early stages of a revision research program on energy requirements of building code environmental wise in Iran. In this parametric study, we tried to investigate thermal transmittance under simulated close-to-real condition and fill the gap in previous works. Thermal insulation thickness is dependent to climatic conditions. Therefore, in future studies, conducting a comprehensive study for determining optimum insulation thickness for other climates of Iran and cities with different HDD and CDD is desired. This optimization study was performed based on assumptions according to current conventional mechanical systems and fuel used in residential buildings. In further studies conducting the same simulation and optimization for more efficient equipment or other fuels like electricity may be considered. Conducting study for annual process is desired. In this study we focused on residential buildings whereas considering buildings with non-continuous like commercial or office units can be the subject for researchers.

	Primary GWP (kg co_2-eq)	Thermal insulation thickness (m)						Heating Load (kWh)	Coefficient of Heat Loss (W/K)	Fuel Consumption (m^3)	Operational GWP (kg co_2-eq)	Total GWP (kg co_2-eq)
		Roof	Walls				Floor					
			E	S	W	N						
1	903.65	0.05	0.01	0.02	0.01	0.15	0.15	712.11	69.33	104.58	5885.528	6789.18
2	725.34	0.02	0.01	0.01	0.01	0.15	0.12	1205.39	79.98	177.02	9962.393	10687.7
3	904.75	0.15	0.01	0.01	0.01	0.15	0.14	1065.79	67.12	156.52	8808.631	9713.38
4	891.51	0.04	0.02	0.01	0.05	0.15	0.15	330.54	67.14	48.54	2731.917	3623.42

Table 2 - Optimum value for insulation thickness in studied scenarios

	Primary GWP	Heat loss Coefficient	Total Heating Load	Fuel Consumption	Operational GWP	Total GWP
	kg Co_2-eq	W/K	kWh	m^3	kg Co_2-eq	kg Co_2-eq
scenario 1	5170.46	229.43	940.73	3386.64	7775.02	129450.5
scenario 2	3591.29	340.46	16581.6	59693.77	137044.5	140635.8
scenario 3	4969.24	263.056	7306.25	26302.51	60385.12	65354.37
scenario 4	444.58	224.77	5880.48	21169.76	48601.38	49045.96
noninsulated	0	1117.61	21285.52	76627.87	175921.7	175921.7

Table 3- Thermal behaviour of building

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