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A LIFE CYCLE COSTING APPROACH TO DETERMINE THE OPTIMUM INSULATION THICKNESS OF EXISTING BUILDINGS

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Abstract: The ongoing global increase of energy prices and energy use has directed many researchers to study energy conservation strategies as an instrument of sustainable development. A common yet effective strategy is to insulate the exterior envelope of existing buildings in an attempt to improve energy efficiency. While an insulation application requires an initial investment, it helps the building to spend less energy during its operation. In order to sustain feasibility, it is crucial to find an insulation thickness that is cost-effective and especially applicable in developing countries. The objective of this study is to determine the optimum insulation thickness for existing buildings by using a representative building approach. For this purpose, insulation alternatives including 15 cm stone wool on ceilings and expanded polystyrene (EPS) on exterior walls at varying thicknesses were applied on a representative existing building. A variety of EPS thicknesses (from 1 cm to 20 cm) were analyzed as alternatives for the insulation application. Annual energy requirement of the building was calculated by the heat balance method by conducting a dynamic analysis. Life cycle costing (LCC) analysis was performed to find out which alternative results in the best economical outcome. The optimum insulation thicknesses were obtained for various climate regions by considering a number of scenarios with different discount and inflation rates. The results demonstrated the inadequacy of the national regulation's current insulation limits, as it was observed that the optimum insulation thicknesses were significantly greater than the limiting values in the national standard. To overcome this inadequacy, it is suggested to effectively improve energy efficiency by lowering the limiting heat transfer coefficients in the standard.
Keywords: Optimum insulation thickness, thermal insulation requirements, energy efficiency of existing buildings, life cycle costing.

YAŞAM DÖNEMİ MALİYETLEMESİ YAKLAŞIMI İLE MEVCUT BİNALARDA OPTİMUM YALITIM KALINLIĞININ BELİRLENMESİ

Özet: Enerji kullanımının ve enerji fiyatlarının devamlı bir şekilde artması birçok araştırmacıyı bir sürdürülebilir kalkınma aracı olan enerji tasarrufu stratejilerine yönlendirmiştir. Mevcut binaların dış cephelerinin yalıtımı enerji verimliliğinin arttırılması için yaygın ve etkin bir yöntemdir. Yalıtım uygulamaları bir ilk yatırım maliyeti gerektirmesine karşın binanın gelecek senelerde daha az enerji harcamasını sağlar. Bu açıdan, özellikle gelişmekte olan ülkelerde, mali açıdan uygun bir yalıtım kalınlığının bulunması önem arz etmektedir. Bu çalışmanın amacı bir temsili bina yaklaşımı kullanarak mevcut binalar için optimum yalıtım kalınlığının belirlenmesidir. Bu amaçla, temsili bir mevcut bina için tavana 15 cm taş yünü ve dış duvarlara değişen kalınlıklarda genleşmiş polistiren (EPS) yalıtımı uygulanmıştır. Çeşitli EPS kalınlıkları (1 cm'den 20 cm'e) yalıtım alternatifleri olarak analiz edilmiştir. Binanın yıllık enerji gereksinimi dinamik analiz yapan ısı dengesi yöntemi ile belirlenmiştir. Yaşam dönemi maliyetlemesi analizi gerçekleştirilerek hangi alternatifin en iyi ekonomik sonucu verdiği belirlenmiştir. Optimum yalıtım kalınlıkları çeşitli iklim bölgeleri için farklı iskonto ve enflasyon oranlarını içeren birtakım senaryolar göz önünde bulundurularak elde edilmiştir. Sonuçlar ulusal standardın mevcut yalıtım limitlerinin yetersiz olduğunu göstermektedir. Optimum yalıtım kalınlıklarının ulusal standartta belirtilen sınırlayıcı değerlerden bariz bir şekilde daha büyük oldukları anlaşılmıştır. Bu verimsizliğin giderilmesi amacıyla standarttaki sınırlayıcı ısı transfer katsayılarının azaltılarak enerji verimliliğinin arttırılması önerilmektedir.
Anahtar Kelimler: Optimum yalıtım kalınlığı, ısı yalıtımı gereksinimleri, mevcut binaların enerji verimliliği, yaşam dönemi maliyetlemesi.

NOMENCLATURE

d	Discount rate [%]
e	Inflation rate [%]
IRR	Internal rate of return [%]
h_{ci}	Inside convection coefficient [W/m^2.°C]
h_{co}	Outside convection coefficient [W/m^2.°C]
NS	Net savings [$]
PBP	Payback period [years]
q_{CE}	Convective part of the internal loads [W]
q_{conv}	Convection heat transfer from walls to zone air [W]
q''_{conv}	Convection flux exchange with outdoor air [W/m^2]
q_{IV}	Sensible load due to ventilation and infiltration [W]
q''_{ki}	Conduction heat flux on inside face [W/m^2]
q''_{ko}	Conduction heat flux on outside face [W/m^2]
q''_{LWR}	Net long-wave-length radiation flux exchange with the air and surroundings [W/m^2]
q''_{LWS}	Long-wave radiation flux from equipment in the zone [W/m^2]
q''_{LWX}	Long-wave radiant exchange flux between zone surfaces [W/m^2]
q''_{sol}	Transmitted solar radiation from windows to inside surface [W/m^2]
q''_{SW}	Net short-wave radiation flux from lights to surface [W/m^2]
q_{SYS}	Heat transfer from heating system [W]
$q''_{\alpha sol}$	Absorbed direct and diffuse solar radiation heat flux (shortwave) [W/m^2]
SIR	Saving-to-investment ratio
T_a	Zone air temperature [°C]
T_i	Inside surface temperature [°C]
T_o	Outside surface temperature [°C]
U	Heat transfer coefficient [W/m^{2}K]
X_j	Outside conduction transfer function
Y_j	Cross conduction transfer function
Z_j	Inside conduction transfer function
Φ_j	Flux conduction transfer function

INTRODUCTION

Sustainability of the planet depends mainly on three components including energy efficiency, using renewable energy, and energy savings (Morales et al. 2016). Conservation of energy has become an essential part of the national energy strategies since the energy crises in 1973. This is of extreme importance for developing countries, as they import energy mostly from abroad in order to meet their energy needs. The increase in population and urbanization of cities result in a rapid escalation of energy consumption. Building and construction industry is majorly responsible for the total primary energy consumption globally and it has had a continuous growth since 1960s (Maleviti et al. 2013). The industry is accountable for more than 20% of global energy consumption of delivered energy and about 10% of global greenhouse gas emissions, both in developing and developed countries. The potential for reducing greenhouse gas emissions is the largest in the construction sector (IEO 2013).

There is an increasing trend in energy users, from individual home owners to corporations and even nations, to pursue energy efficiency (Nikoofard et al. 2015). Although the issue has been widely acknowledged since the 1970s, it is getting more important with the concern on climate change (Miguel et al. 2015). Energy efficiency has been mentioned as the best approach to keep energy demand under control and to facilitate a smooth transition towards a low-carbon future. This suggestion emphasizes the key role of residential sector due to having the highest cost-efficient potential to reduce CO_2 emissions (Ramos et al. 2015). In addition to reducing the energy consumption in buildings, there are alternative ways to save energy. An approach to reduce heat loss includes the application of optimum insulation thicknesses to external walls. Wall and roof insulation are known for providing an increased amount of energy savings in buildings compared to traditional methods.

In terms of building insulation, various studies have also been performed to establish the optimum insulation thickness. The optimum insulation thicknesses were determined for different wall structures in Palestine (Hasan 1999), for four cities in China (Yu et al. 2009), for Tunisian buildings (Daouas 2011), for different types of building walls in India (Mishra et al. 2012), for hot regions of India (Sundaram and Bhaskaran 2014), for external walls on different orientations in Greece (Axaopouloset al. 2014), and in Cameroon as a wet and hot tropical climate (Nematchoua et al. 2015). In all of the prementioned studies, the optimum insulation thicknesses were determined according to a theoretically derived net saving/cost formula, which did not consider the building as a whole. The insulation thickness, which made the derivative of the net saving formula equal to zero, was considered as the optimum thickness.

In this study, a representative building approach is proposed to determine the optimum insulation thickness for existing buildings in four different climate regions. There has not been any study specifically done for existing buildings, where the optimum insulation thickness calculations and the limitations in national standards can be representative for energy efficiency in developing countries. Additionally, the proposed approach enables not only determining the optimum insulation option, but also generating the cash flow diagram for each insulation alternative. Therefore, financial parameters such as net savings (NS), internal rate of return (IRR), savings-to-investment ratio (SIR), and payback period (PBP) can be effectively calculated for each insulation alternative. Previously applied methods have only provided NS and PBP, whereas other parameters were missing. This study fills this gap by questioning the optimality of the limitations in the national standard, which can be adapted to other developing countries based on their own standards.

The representative building is selected as a traditional five-story building. The cost of insulation is determined by taking the average of the offers obtained from three different general contracting companies to make sure fair and feasible cost data is used. The annual energy savings are calculated by considering the annual energy requirements of the uninsulated and insulated building. The annual energy requirement is calculated according to a heat balance based software developed by Yigit and Ozorhon (2018) for four climate regions defined in the national standard. The cost of insulation application and future savings resulting from decreased energy requirements are reflected in the life cycle costing (LCC) analysis. Optimization is performed to determine the optimum insulation thickness on the exterior walls that would be the most feasible alternative economically.

RESEARCH BACKGROUND

A number of studies have been performed to investigate energy consumption and thermal insulation in buildings from various perpectives. Dylewski and Adamczyk (2011) studied both the environmental and economic benefits of thermal insulation on the exterior walls. The benefits were obtained for several versions of thermal insulation. It was concluded that thermal insulation made of polystyrene foam or ecofibre provided the best results. Briga-Sa et al. (2013) suggested using wowen fabric waste (WFW) and wowen fabric subwaste (WFS) for thermal insulation in buildings. The results of the study showed that implementation of WFW and WFS in exterior double walls could improve the thermal behavior 56% and 30%, respectively. Yildiz et al. (2014) investigated the impacts of energy efficiency measures on energy consumption in Eskisehir, Turkey. Highest energy savings (37%) were obtained by applying insulation on exterior walls, roof floor, and basement and replacing the windows. Asdrubali et al. (2015) reported a state of art of sustainable building insulation materials that are made of natural or recycled content. A recycled cotton insulator was shown to exhibit thermal insulation features comparable to EPS, extruded polystyrene (XPS), and sheep wool. Kaya et al. (2016) analyzed energy savings of thermal insulation for buildings in Erzincan, Turkey. Annual energy savings were observed to go up to 43.8% with the application of 4 cm XPS. Cristina et al. (2017) compared two different refurbishment scenarios, high investment and low investment, for an Italian vernacular building. The high investment scenario with greater insulation materials and glazing systems was realized to result in a higher income, despite its higher initial investment cost. Lucchi et al. (2017) assessed the economic benefits of energy retrofitting in historic buildings with a particular focus on the insulation materials. They identified EPS, XPS, mineral and flexible wood fibers, glass mineral wool, and rock wool as the cost-effective materials. It was also reported that PBP of an insulation system of 0.20 m changes between 5 and 18 years. Serrano et al. (2017) conducted a study to assess the residential energy consumption (heating and cooling) trends and drivers for Europe. Even though a consistent trend was detected for the drivers during the studied time period, heating and cooling energy consumption was observed to follow different trends when considered globally or at a country level.

Several studies have focused specifically on determining the optimum insulation thickness. For instance, Yu et al. (2009) studied the optimum insulation thickness for four cities in China. Both the heating and cooling energies were considered in the study. The optimum insulation thicknesses varied between 5.3 and 23.6 cm. Daouas (2011) calculated the optimum insulation thickness of walls in Tunisian buildings. Electricity and natural gas were considered as energy sources for cooling and heating, respectively. The optimum insulation thicknesses varied between 10.1 and 11.7 cm. In another study, Mishra et al. (2012) determined the optimum insulation thickness in India for different types of building walls. The optimum insulation thicknesses varied between 5.2 and 7.4 cm. Kaynakli (2013) determined the optimum insulation thickness and payback periods for the building walls in Turkey. The results showed that the optimum insulation thickness can go up to 16.6 cm depending on the city. Cuce et al. (2014) focused on the optimum insulation thickness and the environmental impacts of aerogel-based thermal superinsulation for the climate conditions of Nottingham. Sundaram and Bhaskaran (2014) studied the optimum insulation thickness of walls in hot regions of India. Only cooling energy was considered as the heating energy is zero in these regions. Electricity was used as the only energy source. Nematchoua et al. (2015) detected the optimal thermal insulation thickness in Cameroon as a wet and hot tropical climate. The optimum insulation thickness values were found to be higher than 9 cm and approximately 80% energy saving was obtained for the south-oriented wall. A higher optimum insulation thickness was observed in the concrete block wall than in compressed stabilized earth block wall. Kon and Yuksel (2016) calculated the optimum insulation thickness for an exemplary building in Balikesir. The optimum insulation thicknesses were calculated for exterior walls, basement, and roof floor. Ashouri et al. (2016) used exergetic life cycle assessment method to specify the optimum insulation thickness in a building wall. Optimal thicknesses for rockwool and glasswool were respectively specified as 9.8 cm and 21.9 cm based on environmental impact analysis; and 1.2 cm and 1.8 cm based on exergetic life cycle cost analysis. Nematchoua et al. (2017) studied the optimum insulation thickness of walls for buildings in Yaounde (equatorial region) and Garoua (tropical region) cities in Cameroon. The optimum insulation thickness and corresponding energy savings were

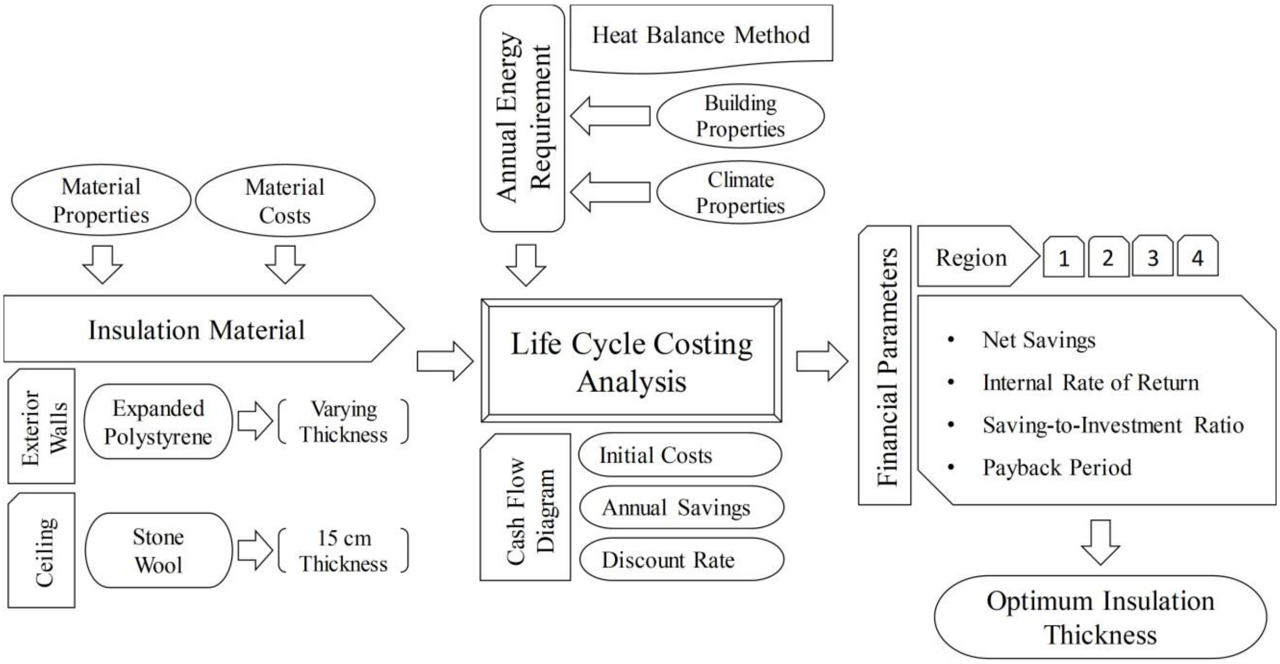

Figure 1. Flowchart of methodology

determined as 8 cm and 51.69 $/m^2 in Yaounde; and 11 cm and 97.82 $/m^2 in Garoua. Considering the approaches of the previous studies, this study adopts LCC to evaluate the insulation options on a typical existing building. This paper aims to define the optimum insulation thickness of buildings in the four different climate regions stated in the national standard. The optimum EPS thicknesses are determined for each climate region by using LCC, as described in the following sections.

RESEARCH METHODOLOGY

The flowchart of the representative building approach methodology is shown in Figure 1. Through this method, insulation alternatives are applied to a representative existing building. The methodology starts with the selection of insulation material based on material properties and costs. EPS is used for exterior walls, while stone wool is used for the ceiling. Meanwhile, annual energy requirements are derived from a heat balance based software developed by Yigit and Ozorhon (2018) based on building properties and various climate zones. Both information is used to perform LCC, which initiates cash flow diagrams and finally the financial parameters such as NS, IRR, SIR, and PBP. The aim is to determine the optimum EPS thickness that results in the best economic outcomes. The financial parameters and LCC results are used to determine the optimum insulation thicknesses for each climate region.

Annual energy requirements are calculated for uninsulated and insulated versions of a typical existing building and annual energy savings are obtained by taking the difference. Annual energy saving values are calculated for each insulation alternative (1 cm to 20 cm EPS application), separately. Considering the initial insulation cost and the following annual energy savings, cash flow diagrams are generated and net savings are calculated for each insulation thickness. The insulation thickness resulting in the highest net saving value is regarded as the optimum insulation thickness.

Building Properties

LCC is applied on insulation applications for a typical five-story existing building. The uninsulated building has a length of 25 m, a width of 20 m and each floor has a height of 3 m. Net height of each floor is 2.6 m and gross volume (V_{gross}) of the building is 7,500 m^3. The areas of the windows are 50 m^2, 20 m^2, 40 m^2 and 20 m^2 for south, north, east and west directions, respectively. It is assumed that natural ventilation is used for air-conditioning.

The building envelope cross sections are shown for the uninsulated and insulated cases in Figure 2 and Figure 3, respectively. While no change is considered for the basement (as practically this is the case for insulation application in existing buildings), the ceiling is insulated with stone wool at a thickness of 15 cm. The exterior walls, both infilled and reinforced, are insulated with EPS at varying thicknesses.

Calculation of Annual Energy Requirements

The annual energy requirement of the building was calculated by using a heat balance based software developed by Yigit and Ozorhon (2018). The heat balance method is based on hourly dynamic thermodynamic calculations. In this method, the solar

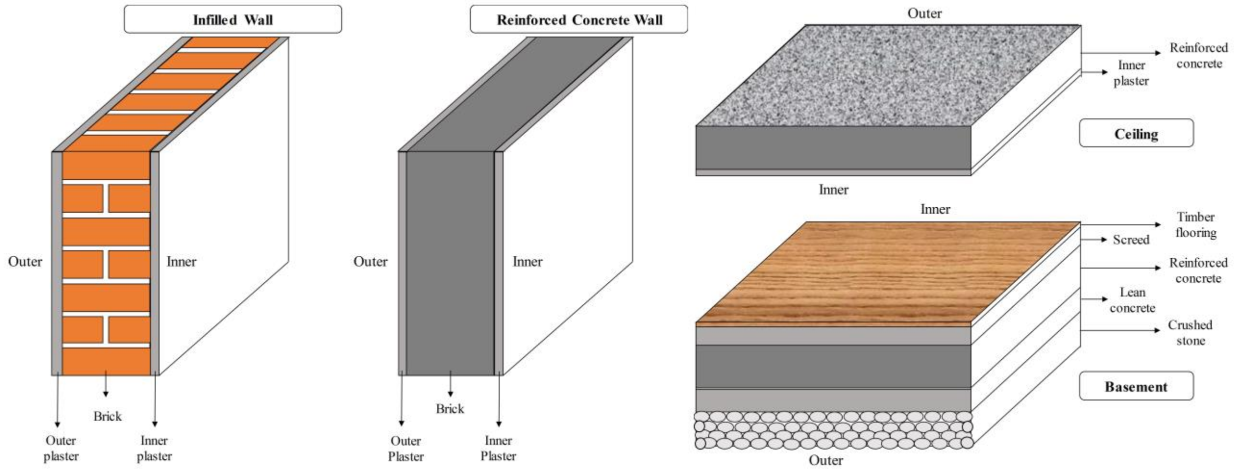

Figure 2. Building envelope cross section for the uninsulated case

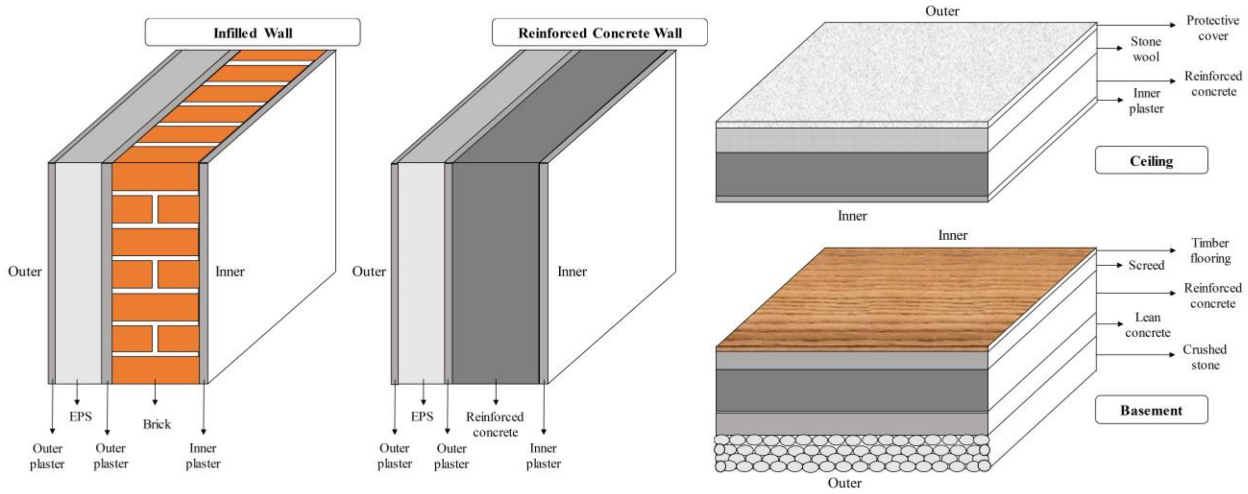

Figure 3. Building envelope cross section for the insulated case

heat gains and internal loads that are caused by occupants, appliances, and lightings are calculated in detail. The internal surface temperatures of the buildings are calculated separately. The heat balance method reduces the number of assumptions and its models are closest to real physical buildings. The method takes its name from the first law of thermodynamics. "Energy is conserved" in the inner and outer surfaces and the zone air of the buildings (ASHRAE 2013). The formulation of the heat balance method for cooling load calculations was published in 1997 and accepted to be the most scientifically rigorous method (Pedersen et al. 1997). Designers use the heat balance method to calculate instantaneous heating and cooling loads (ASHRAE 1997).

The procedure of heat balance method calculations consists following processes (Spitler 2013);

- Outside face heat balance
- Wall conduction process
- Inside face heat balance
- Air heat balance

Outside Face Heat Balance

There are four heat exchange processes between outside zone air and outside surface of the walls and the heat balance of the exterior surface can be formulated as:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \qquad (1)$$

Wall Conduction Process

Wall conduction process can be conducted in various ways (Spitler 2013):

- Numerical finite difference
- Numerical finite element
- Transform Methods
- Time Series Methods

To make simultaneous calculations for both surfaces of the walls, conductions transfer function coefficients are utilized. Conduction transfer function procedures provide a faster calculation than numerical methods with a little loss of generality.

The general form for inside heat flux:

$$q''_{ki}(t) = -Z_0 T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_0 T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,i,t-j\delta} \quad (2)$$

The general form for outside heat flux is:

$$q''_{ko}(t) = -Y_0 T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + X_0 T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,i,t-j\delta} \quad (3)$$

Inside Face Heat Balance

Inside face heat balance is generally modeled by four coupled heat transfer components (ASHRAE 1997):

- Conduction through the building walls
- Convection from walls to zone air
- Short-wave radiant absorption and reflection
- Long-wave radiant interchange

Long-wave radiation includes the emittance from people and equipment while shortwave radiation consist the radiation enters the zone through windows and emitted from internal sources such as lights.

The general form of inside face heat balance can be formulated as:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \quad (4)$$

Air Heat Balance

The components contributing to the heat balance equation are: convection from inside surface of the walls, infiltration and ventilation, convective part of internal loads and heating, ventilation, and air conditioning (HVAC) system.

$$q_{conv} + q_{CE} + q_{IV} + q_{sys} = 0 \quad (5)$$

Heat Balance Procedure

The general zone for a heat balance procedure has 12 inside surfaces and 12 outside surfaces; four wall surfaces, five window surfaces (for walls and the roof), slab surface and roof surface. The heat balance method consists for each element’s inside and outside face and HVAC system as variables for 24 hours. This makes a total of about 600 variables. Therefore, a routine needed to iterate all these variables for 24 hours in a day. In the following part of the study, the mathematical procedure of heat balance calculation for generalized zone will be described.

The variables of the procedure are 12 inside face and 12 outside face for each 24 hours of the day. Subscript “i” is assigned as the surface index subscript and “j” is assigned as the hour index.

The heat balance equation for outside surfaces:

$$T_{so_{i,j}} = \frac{\sum_{k=1}^{nz} T_{si_{i,j-k}} Y_{i,k}}{Z_{i,0} + h_{co_{i,j}}} - \frac{\sum_{k=1}^{nz} T_{so_{i,j-k}} Z_{i,k} + \sum_{k=1}^{nq} \Phi_{i,k} q''_{ko_{i,j-k}}}{Z_{i,0} + h_{co_{i,j}}} + \frac{q''_{\alpha sol_{i,j}} + q''_{LWR_{i,j}} + T_{si_{i,j}} Y_{i,0} + T_{o_j} h_{co_{i,j}}}{Z_{i,0} + h_{co_{i,j}}} \quad (6)$$

The heat balance equation for inside surfaces:

$$T_{si_{i,j}} = \frac{T_{so_{i,j}} Y_{i,0} + \sum_{k=1}^{nz} T_{so_{i,j-k}} Y_{i,k}}{Z_{i,0} + h_{ci_{i,j}}} - \frac{\sum_{k=1}^{nz} T_{si_{i,j-k}} Z_{i,k} - \sum_{k=1}^{nq} \Phi_{i,k} q''_{ki_{i,j-k}}}{Z_{i,0} + h_{ci_{i,j}}} + \frac{T_{a_j} h_{ci_j} + q''_{LWS} + q''_{LWX_{i,j}} + q''_{SW} + q''_{sol}}{Z_{i,0} + h_{ci_{i,j}}} \quad (7)$$

The remaining equation for the heat balance method is derived from air heat balance equation:

$$q_{sys_j} = \sum_{i=1}^{12} A_i h_{c,i} (T_{si_{i,j}} - T_{a_j}) + q_{CE} + q_{IV} \quad (8)$$

Heat Balance Iterative Solution Procedure

The steps of heat balance calculations are listed below:
1. Identify the area properties, face temperatures for surfaces and other properties, for all 24 hours.
2. Incident and transmitted solar fluxes for the building surfaces calculated.
3. The calculated transmitted solar energy is distributed to all surfaces inside (incident transmitted solar radiation is intercepted by floor).
4. Internal load quantities, for all 24 hours (people, lighting, machines etc.).
5. Long-wave, short-wave, and convective energy from internal loads to all surfaces for all 24 hours is calculated.
6. Infiltration and ventilation loads are calculated for all 24 hours.

7. Iteration is utilized for heat balance equations according to following pseudo-code scheme (Pedersen et al. 1997):

For Day = 1 to Maxdays
For j = 1 to 24 (Hours in a day)
For SurfaceIteration = 1 to MaxIter
For i=1 to 12 (Number of Zone Surfaces)
Evaluate Equation of T_{si} *and* T_{so}
Next Surface "i"
Next SurfaceIteration
Evaluation Equation of q_{sys}
Next "j"
If not converged, Next Day
Display Results

8. Present the results.

Limitations of the National Standard

In the national standard, it is stated that "*when substantial repair, amendment and additions are made to the whole or independent sections of the existing buildings, the limiting heat transfer coefficient values should be observed in terms of providing the values equal or smaller than these for the section in which applications are made*" (TSI 2008). The limiting values are shown in Table 1, where U_{ew}, U_{ce}, U_{bs}, and U_{gl} represent the heat transfer coefficients of exterior walls, ceiling, basement, and glazing, respectively.

Table 1. The limiting values for existing buildings (TSI 2008)

Region	U_{ew} (W/m^2K)	U_{ce} (W/m^2K)	U_{bs} (W/m^2K)	U_{gl} (W/m^2K)
Region 1	0.70	0.45	0.70	2.4
Region 2	0.60	0.40	0.60	2.4
Region 3	0.50	0.30	0.45	2.4
Region 4	0.40	0.25	0.40	2.4

Life Cycle Costing Analysis

An insulation application possesses an initial cost and annual savings in the following years. The initial or the capital cost is the cost of insulation application. It includes the material cost, the auxiliary items cost and the application cost. It is obtained by taking offers from companies and taking the average of them. Annual savings are the savings achieved by the reductions in the operational cost of buildings. The operational cost represents the annual energy requirement of buildings. After an insulation application, the annual energy requirement decreases. As a consequence, annual savings are achieved due to the decrease in operational costs.

LCC method predicts savings based on the initial cost of insulations and the annual savings due to decreased operational costs. Annual savings occur over a certain period of time, which is assumed to be 20 years. Previous studies have assumed lifetimes between 10 to 30 years (Yu et al. 2009; Daouas 2011; Mishra et al. 2012; Sundaram and Bhaskaran 2014; Cuce et al. 2014). After determining the initial cost and savings over 20 years, the cash flow diagram is generated. The savings are discounted back to present with an appropriate discount rate in order to find net savings (NS), internal rate of return (IRR), savings-to-investment ratio (SIR) and payback period (PBP).

RESULTS AND DISCUSSION

In this study, different types of insulation are applied on the building envelope, specificly on the ceilings and exterior walls. The ceiling is insulated with stone wool that has a thickness of 15 cm. The resultant conductance is 0.219. This value satisfies the requirements for all the regions as shown in the column U_{ce} of the Table 1. The exterior walls are insulated with EPS with varying thicknesses. The resultant heat transfer coefficient values must be lower than the values stated in the column U_{ew}. The shaded values in Table 2 indicate that these insulation thicknesses satisfy the minimum conditions as defined by the standard. The limiting values in the national standard are identified as 4 cm, 5 cm, 6 cm, and 8 cm in Region 1, Region 2, Region 3, and Region 4, respectively.

Table 2. Heat transfer coefficient values of insulation applications

	U_{ew} values (W/m^2K)	Region 1 U_{ew}'=0.7	Region 2 U_{ew}'=0.6	Region 3 U_{ew}'=0.5	Region 4 U_{ew}'=0.4
Insulation Thickness (cm)	None	3.24	3.24	3.24	3.24
	1	1.62	1.62	1.62	1.62
	2	1.11	1.11	1.11	1.11
	3	0.84	0.84	0.84	0.84
	4	0.68	0.68	0.68	0.68
	5	0.57	0.57	0.57	0.57
	6	0.49	0.49	0.49	0.49
	7	0.43	0.43	0.43	0.43
	8	0.38	0.38	0.38	0.38
	9	0.34	0.34	0.34	0.34
	10	0.31	0.31	0.31	0.31
	11	0.29	0.29	0.29	0.29
	12	0.27	0.27	0.27	0.27
	13	0.25	0.25	0.25	0.25
	14	0.23	0.23	0.23	0.23
	15	0.22	0.22	0.22	0.22
	16	0.20	0.20	0.20	0.20
	17	0.19	0.19	0.19	0.19
	18	0.18	0.18	0.18	0.18
	19	0.17	0.17	0.17	0.17
	20	0.17	0.17	0.17	0.17

Annual Energy Requirements & Savings

Table 3 and Figure 4 show the annual energy requirements calculated for 4 climate regions. It is observed that a considerable difference exists in the energy consumption values of the building in different climate regions. Heating energy consumption of the uninsulated building in Region 4 is roughly 9-10 times greater than its energy consumption in Region 1. On the other hand, cooling energy consumption in Region 1 is about 7 times higher than Region 4. Consequently, different optimum thickness values are expected to be

Table 3. Annual energy requirements (kWh/year)

Annual Energy Requirements		Heating Energy Requirement				Cooling Energy Requirement			
		Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Insulation Thickness (cm)	None	37,193	134,880	211,900	356,650	178,830	76,368	45,913	25,531
	1	26,461	105,073	167,520	285,590	153,290	66,461	40,496	25,459
	2	12,924	64,060	108,910	190,630	140,930	66,175	40,430	25,382
	3	11,991	58,860	101,210	178,030	139,150	66,101	40,362	25,294
	4	11,265	55,240	96,051	169,580	137,700	66,024	40,283	25,200
	5	10,669	52,690	92,403	163,550	136,530	65,933	40,198	25,094
	6	10,235	50,780	89,730	159,080	135,560	65,838	40,103	24,973
	7	9,847	49,220	87,711	155,630	134,760	65,735	39,993	24,838
	8	9,488	48,040	86,139	152,930	134,130	65,662	39,671	24,483
	9	9,140	46,920	84,905	150,690	133,590	65,618	39,130	24,106
	10	8,808	45,810	83,699	148,700	133,340	65,587	38,272	23,453
	11	8,492	44,780	82,553	146,720	133,170	65,557	37,459	22,768
	12	8,188	43,850	81,477	144,760	133,070	65,491	36,875	22,271
	13	7,966	43,310	80,421	142,820	133,050	65,461	36,340	21,951
	14	7,831	42,810	79,415	140,940	133,030	65,382	36,197	21,849
	15	7,711	42,310	78,559	139,230	133,020	65,342	36,028	21,713
	16	7,601	41,790	77,925	137,870	133,020	65,262	35,950	21,548
	17	7,508	41,360	77,352	136,870	133,020	65,198	35,832	21,339
	18	7,424	40,967	76,804	136,070	133,020	65,139	35,637	21,027
	19	7,349	40,611	76,300	135,350	133,010	65,088	35,347	20,508
	20	7,289	40,284	75,834	134,680	133,010	65,075	34,880	20,508

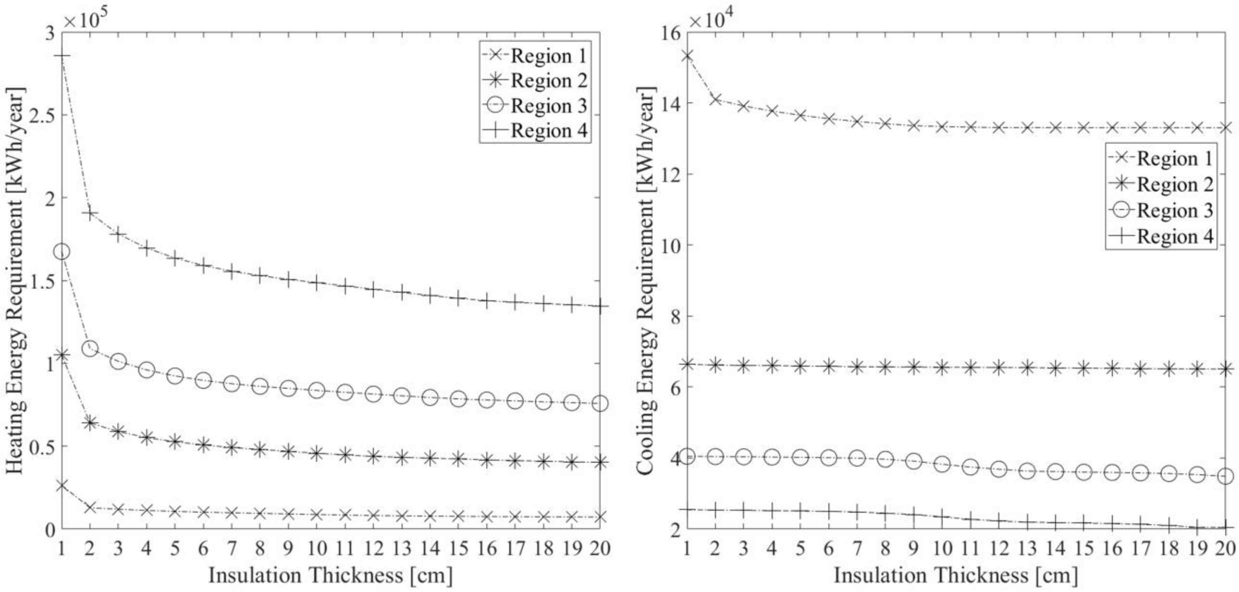

Figure 4. Annual energy requirements

determined for each region. It can also be inferred that insulation implementation in existing buildings can theoretically decrease the heating and cooling energy consumptions up to 60-80% and 15-25%, respectively. However, it does not imply that the insulation thickness, which provides the maximum energy conservation, is the optimum one. Considering the fact that increasing insulation thicknesses would bring additional costs, the optimum insulation thickness can be described as the one that provides maximum net benefit, which is obtained by subtracting the cost from the benefits obtained.

Table 4 and Figure 5 present the annual energy savings. It is noticed that the minimum insulation thicknesses that satisfy the conditions in the standard can provide heating energy savings between 26 kWh/year and 204 kWh/year in different climate regions. However, it is possible to obtain an additional heating energy saving up to 15%, which indicates that there is still room for achieving better economic outcomes by implementing thicker insulations.

Table 4. Annual energy savings (kWh/year)

Annual Energy Savings		Heating Energy Savings				Cooling Energy Savings			
		Region 1	Region 2	Region 3	Region 4	Region 1	Region 2	Region 3	Region 4
Insulation Thickness (cm)	None	0	0	0	0	0	0	0	0
	1	10,732	29,807	44,380	71,060	25,540	9,907	5,417	72
	2	24,269	70,820	102,990	166,020	37,900	10,193	5,483	149
	3	25,202	76,020	110,690	178,620	39,680	10,267	5,551	237
	4	25,928	79,640	115,849	187,070	41,130	10,344	5,630	331
	5	26,524	82,190	119,497	193,100	42,300	10,435	5,715	437
	6	26,958	84,100	122,170	197,570	43,270	10,530	5,810	558
	7	27,346	85,660	124,189	201,020	44,070	10,633	5,920	693
	8	27,705	86,840	125,761	203,720	44,700	10,706	6,242	1,048
	9	28,053	87,960	126,995	205,960	45,240	10,750	6,783	1,425
	10	28,385	89,070	128,201	207,950	45,490	10,781	7,641	2,078
	11	28,701	90,100	129,347	209,930	45,660	10,811	8,454	2,763
	12	29,005	91,030	130,423	211,890	45,760	10,877	9,038	3,260
	13	29,227	91,570	131,479	213,830	45,780	10,907	9,573	3,580
	14	29,362	92,070	132,485	215,710	45,800	10,986	9,716	3,682
	15	29,482	92,570	133,341	217,420	45,810	11,026	9,885	3,818
	16	29,592	93,090	133,975	218,780	45,810	11,106	9,963	3,983
	17	29,685	93,520	134,548	219,780	45,810	11,170	10,081	4,192
	18	29,769	93,913	135,096	220,580	45,810	11,229	10,276	4,504
	19	29,844	94,269	135,600	221,300	45,820	11,280	10,566	5,023
	20	29,904	94,596	136,066	221,970	45,820	11,293	11,033	5,023

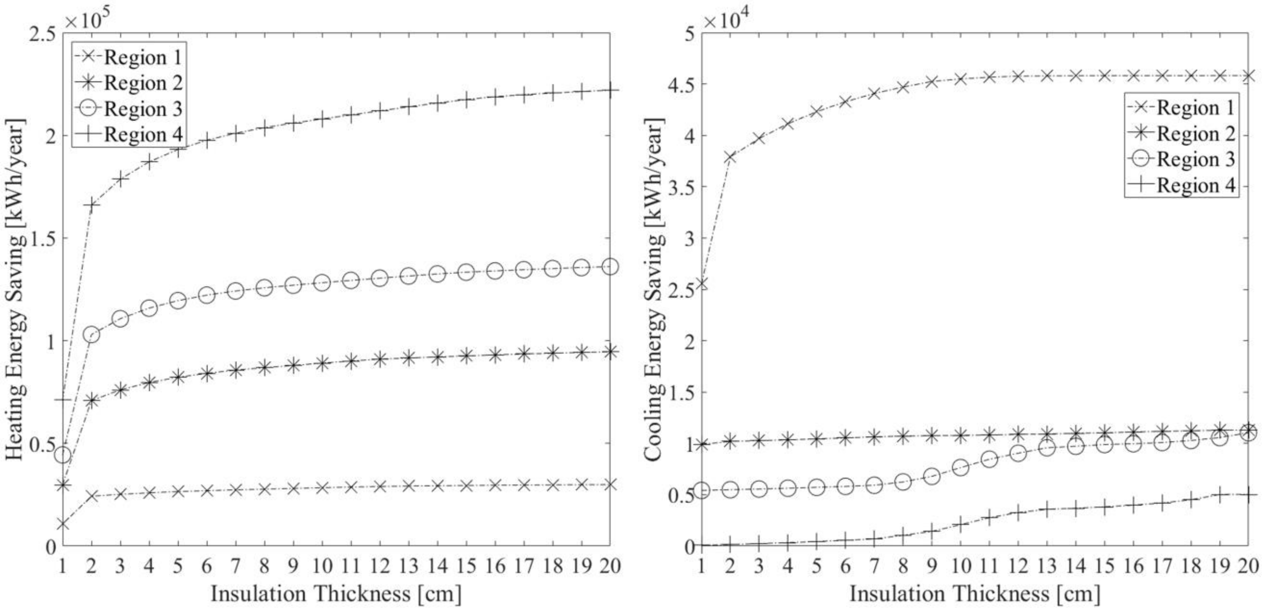

Figure 5. Annual energy savings

Cost of Insulation

The cost of insulation is determined by taking offers from three general contracting companies. The offers are received in the same format so that they can be compared and their averages can be taken in order to determine the cost of insulation. The total cost of insulation, as shown in Table 5, is determined by taking the average of the three offers. It should be noted that the costs are presented in United States (U.S.) Dollars ($). As it can be seen from the table that for EPS, the material and installation costs increase, as the insulation thickness increases. There is one average cost for stone wool insulation, as only one insulation thickness is used.

Table 5. The total cost of insulation applications

EPS Insulation Thickness	Material Cost ($/m^2)	Auxiliary Items Cost ($/m^2)	Installation Cost ($/m^2)	Total Unit Cost ($/m^2)	Total Cost ($)
1 cm	0.71	4.41	7.00	12.12	14,727.74
2 cm	1.18	4.41	7.00	12.59	15,300.71
3 cm	1.91	4.41	7.00	13.31	16,177.56
4 cm	2.63	4.41	7.00	14.04	17,054.41
5 cm	3.35	4.52	7.00	14.86	18,057.43
6 cm	4.07	4.52	7.00	15.58	18,934.28
7 cm	4.79	4.59	7.09	16.47	20,010.47
8 cm	5.51	4.59	7.18	17.28	20,997.72
9 cm	6.24	4.67	7.18	18.08	21,969.82
10 cm	6.96	4.67	7.18	18.80	22,846.67
11 cm	7.79	5.01	7.27	20.07	24,389.04
12 cm	8.53	5.09	7.27	20.88	25,373.13
13 cm	9.26	5.15	7.27	21.68	26,338.30
14 cm	9.99	5.15	7.45	22.59	27,448.55
15 cm	10.72	5.29	7.45	23.46	28,508.34
16 cm	11.58	5.29	7.45	24.32	29,549.21
17 cm	12.23	5.35	7.63	25.22	30,637.39
18 cm	12.96	5.46	7.63	26.05	31,656.17
19 cm	13.70	5.52	7.81	27.03	32,845.28
20 cm	14.43	5.52	7.81	27.77	33,737.90
EPS Insulation Thickness	Material Cost ($/m^2)	Auxiliary Items Cost ($/m^2)	Installation Cost ($/m^2)	Total Unit Cost ($/m^2)	Total Cost ($)
15 cm	16.87	5.94	9.14	31.96	15,979.66

Optimum Insulation Thicknesses

Cash flow diagram is generated using the initial cost and the operational savings over 20 years. The initial cost is the cost of insulation, which is calculated by adding the cost of 15 cm stone wool insulation on the ceiling to the cost of EPS insulation at various thicknesses on the exterior walls. The operational savings are the savings resulted from the decrease in annual energy requirements of the building. An operational saving in a specific year is determined by multiplying the annual energy saving amount (kWh) by the average energy price in this year, which is the average of the prices ($/kWh) at the beginning and at the end of the corresponding year. The energy prices in the following years are determined by the following formula:

$$Energy\,\mathrm{Pr}\,ice(n) = Energy\,\mathrm{Pr}\,ice(0) * (1+e)^{n} \tag{9}$$

where Energy Price (n) is the energy price in year n, e is the inflation rate, and n is the year. Here, Energy Price (0) is the energy price in the base year, which is 0.038 $/kWh and 0.161 $/kWh for natural gas and electricity, respectively.

The operational saving in year "n" can be formulated as follows:

$$OperationalSaving(n) = AnnualEnergySaving(kWh) * \frac{Energy\,\mathrm{Pr}\,ice(n-1) + Energy\,\mathrm{Pr}\,ice(n)}{2} \tag{10}$$

Operational savings include both the heating and cooling energy savings. Therefore, operational savings in a specific year are obtained by adding up the natural gas and electricity savings multiplied by the corresponding year's average energy prices.

The two variables in the cash flow diagram are the inflation and discount rates. Due to the fluctuations in those rates, more than one value is assigned to each of the inflation and discount rates and then, optimized thicknesses are determined for each combination. 7%, 9% and 11% are the values assigned to the discount and inflation rates. NS, IRR, SIR and PBP are calculated for each combination. The option having the highest net saving value is considered as the optimized option.

Table 6 shows the cash flow diagram in Region 1 for discount and inflation rates of 9% and 11%, respectively. As it can be observed from the table, insulation at a thickness of 9 cm results in the highest net saving amount, which is $60,278. Also, it is observed that this optimum option has an IRR, SIR, and PBP values of 20.53%, 2.59, and 8-9 years, respectively. Table 7 summarizes the optimized insulation thicknesses for the stated discount and

Table 6. Cash flow diagram for discount rate 9% and inflation rate %11 in Region 1

Thickness	Years							NS ($)	IRR (%)	SIR (-)	PBP (years)
	0	1	2	5	10	15	20				
1 cm	-30,707	2,273	2,523	3,451	5,815	9,798	16,510	19,137	14.24	1.62	13-14
2 cm	-31,280	3,791	4,208	5,755	9,698	16,342	27,537	51,854	20.94	2.66	8-9
3 cm	-32,157	3,959	4,394	6,010	10,127	17,064	28,755	54,654	21.18	2.70	8-9
4 cm	-33,034	4,094	4,544	6,215	10,472	17,646	29,734	56,735	21.29	2.72	8-9
5 cm	-34,037	4,203	4,665	6,381	10,752	18,117	30,529	58,130	21.23	2.71	8-9
6 cm	-34,914	4,291	4,763	6,514	10,976	18,495	31,165	59,176	21.16	2.69	8-9
7 cm	-35,990	4,365	4,845	6,626	11,165	18,813	31,701	59,718	20.95	2.66	8-9
8 cm	-36,977	4,425	4,912	6,718	11,320	19,075	32,143	60,063	20.74	2.62	8-9
9 cm	-37,949	4,480	4,972	6,800	11,459	19,309	32,536	60,278	20.53	2.59	8-9
10 cm	-38,826	4,513	5,010	6,851	11,545	19,454	32,780	60,139	20.30	2.55	8-9
11 cm	-40,369	4,541	5,040	6,893	11,615	19,572	32,979	59,197	19.80	2.47	9-10
12 cm	-41,353	4,563	5,064	6,926	11,671	19,667	33,139	58,696	19.52	2.42	9-10
13 cm	-42,318	4,575	5,078	6,945	11,703	19,720	33,230	58,004	19.22	2.37	9-10
14 cm	-43,428	4,583	5,087	6,958	11,724	19,755	33,289	57,072	18.87	2.31	9-10
15 cm	-44,488	4,590	5,095	6,968	11,741	19,784	33,338	56,159	18.55	2.26	9-10
16 cm	-45,529	4,595	5,101	6,976	11,755	19,808	33,378	55,239	18.24	2.21	9-10
17 cm	-46,617	4,600	5,106	6,983	11,767	19,828	33,411	54,253	17.93	2.16	10-11
18 cm	-47,636	4,604	5,111	6,990	11,778	19,846	33,442	53,327	17.64	2.12	10-11
19 cm	-48,825	4,609	5,116	6,996	11,789	19,865	33,474	52,235	17.32	2.07	10-11
20 cm	-49,718	4,612	5,119	7,001	11,797	19,878	33,496	51,408	17.09	2.03	10-11

Table 7. Optimized insulation thicknesses for discount rate 9% and inflation rate %11

Option	NS ($)	IRR (%)	SIR (-)	PBP (years)
Region 1, 9 cm	60,278	20.53	2.59	8-9
Region 2, 10 cm	75,113	22.53	2.93	7-8
Region 3, 15 cm	116,765	26.28	3.62	6-7
Region 4, 19 cm	201,841	33.86	5.13	4-5

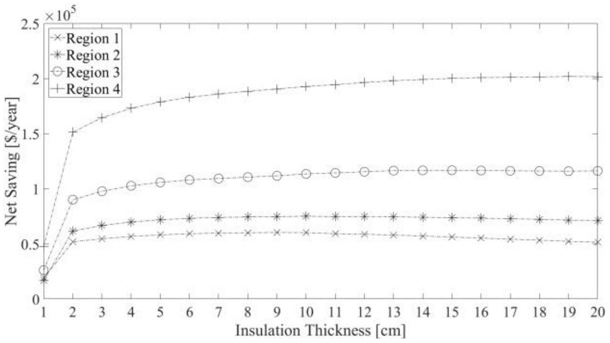

Figure 6. NS values for discount rate 9% and inflation rate 11%

inflation rates. Figure 6 shows the NS values for the same discount and inflation rates as an example. Table 8 shows the optimum insulation thickness corresponding to all 9 combinations of discount rates and inflation rates. There are notable variations in the optimum insulation thickness values of all climate regions. The optimized thicknesses change between 6-10 cm, 7-12 cm, 13-20 cm, and 15-20 cm in the first, second, third, and fourth regions, respectively. The optimized thicknesses are observed to be significantly greater than the limiting insulation thicknesses, which are 4 cm, 5 cm, 6 cm, and 8 cm in the first, second, third, and fourth regions, respectively. Therefore, it can be concluded that the national regulation's current insulation limits are by no means at the optimum level.

Table 8. Optimum insulation thicknesses for all combinations

No	Disc. Rate	Inf. Rate	Reg.1	Reg.2	Reg.3	Reg.4
1	7%	7%	9 cm	10 cm	13 cm	19 cm
2	7%	9%	9 cm	10 cm	15 cm	19 cm
3	7%	11%	10 cm	12 cm	20 cm	20 cm
4	9%	7%	7 cm	7 cm	13 cm	16 cm
5	9%	9%	9 cm	10 cm	13 cm	19 cm
6	9%	11%	9 cm	10 cm	15 cm	19 cm
7	11%	7%	6 cm	7 cm	13 cm	15 cm
8	11%	9%	7 cm	7 cm	13 cm	16 cm
9	11%	11%	9 cm	10 cm	13 cm	19 cm

Table 9 shows U_{ew} values for the optimized thicknesses in four climate regions. Considering the limiting U_{ew}' values which are 0.70 W/m^{2}K, 0.60 W/m^{2}K, 0.50 W/m^{2}K, and 0.40 W/m^{2}K for the first, second, third and fourth regions, respectively; it can be stated that the optimized U_{ew} values are far less than the limiting values.

Table 9. Corresponding U_{ew} values for the optimized thicknesses (W/m^{2}K)

Option	Optimized Thicknesses	Corresponding U_{ew} Values
Region 1	6 - 10 cm	0.31 - 0.49
Region 2	7 - 12 cm	0.27 - 0.43
Region 3	13 - 20 cm	0.17 - 0.25
Region 4	15 - 20 cm	0.17 - 0.22

In literature, there are several studies that have utilized the LCC approach to determine the optimum insulation thickness. Even though this study uses the same LCC approach to the previous ones, there are significant differences in the objective, methodology, and findings. First of all, the objective of this study is to determine the optimum insulation thickness specifically for existing buildings. Previous studies have not distinguished whether the building is an existing or a new building. For a symbolic wall cross section, they considered the insulation thickness value that made the derivative of the net saving formula equal to zero as the optimum insulation thickness. However, in existing buildings, insulation is applied on the exterior walls and ceiling in practice. It is not common to see insulation applications on the basement. Therefore, determining the optimum insulation thickness for existing buildings requires an approach that takes the whole building into account rather than a single cross section. The methodology employed in this study assumes fixed insulation on the ceiling and insulation at varying thickness on the exterior walls. The insulation thickness resulting in the best economic outcomes is regarded as the optimum insulation thickness. The methodology adopted in previous studies was not suitable for existing buildings. Furthermore, findings obtained in this study enable evaluating and questioning the limitations stated in the national standard for insulation applications in existing buildings. The study paves the way for discussion on the sufficiency of the limitations, whether they should be increased or decreased. It is expected to guide the potential modifications to be done in the standard.

CONCLUSIONS

This paper contributes to the body of knowledge by proposing an improved and effective way to calculate the optimum insulation thickness of existing buildings in developing countries. In previous studies, optimum insulation thicknesses were calculated by making derivative of the net saving formula equal to zero. As opposed to those studies, in this study, the optimized thicknesses were calculated by adopting a representative building approach. The cost of insulation implementation and operational savings resulting from the decreases in annual energy requirements were reflected on the LCC analysis. Annual energy requirements were determined according to a heat balance based software. Optimized thicknesses were determined for four climate regions defined in the national standard.

The findings suggested that optimum thicknesses and U_{ew} values were quite different than the limiting values stated in the national standard. The optimized thicknesses were found to be far greater than the requirements, which were established as 4 cm, 5 cm, 6 cm, and 8 cm for the first, second, third, and fourth regions, respectively. The same could be stated for the U_{ew} values. The optimized U_{ew} values were far less than the requirements, which were 0.70 W/m^{2}K, 0.60 W/m^{2}K, 0.50 W/m^{2}K, and 0.40 W/m^{2}K for the first, second, third and fourth regions, respectively. It can be interpreted that the minimum requirements for existing buildings were not at the optimum levels in the standard. Based on the findings, it is possible to come up with some recommendations for the government and the owners of the existing buildings.

First of all, the governments are advised to lower the limiting heat transfer coefficients in the standard. This advice is applicable to all countries where the standard limitations are insufficient. Scholars in various regions and countries should conduct similar studies to observe the sufficiency of the national standards. It is clearly shown in this study that it would economically be more feasible to apply thicker insulations than the limits stated in the standard. Considering the environmental concerns, it is obvious that the thicker the insulation is, the less the environment impact of the building would be.

Secondly, the home owners are strongly recommended to apply the optimum insulation thicknesses rather than the minimum insulation thicknesses that satisfy the limiting conditions in the standards. The increasing initial costs most of the time make the home owners reluctant to apply thicker insulations and pay more money. However, they should appreciate the future operational savings. They must be aware of the fact that as clearly demonstrated in this study, the minimum insulation thicknesses satisfying the conditions in the standards are not the most economically feasible ones and there is still room for economically better outcomes with the application of optimum insulation thickness.

This study questions the optimality of thermal insulation requirements applicable in a developing country. It presents a novel approach by calculating the optimum insulation thicknesses for a typical existing building. In this respect, it goes beyond the previous studies adopting a single formula. The methodology employed in previous studies can be used neither to determine the optimum insulation thickness specifically for existing buildings nor to question the sufficiency of the corresponding standard, while the methodology proposed in this study can fulfill both needs and fill this gap in the literature. By repeating the methodology, similar studies can be performed in other countries to compare their results to the national standards. This would allow to decide on the applicability and appropriateness of these standards in terms of LCC and economically viable construction values.

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