Quest Journals
Journal of Research in Mechanical Engineering
Volume 6 ~ Issue 1 (2020) pp: 34-43
ISSN(Online) : 2321-8185
www.questjournals.org

Research Paper

Sensitivity and Parametric Investigation of Optimum Thermal Insulation Thickness for External Walls.

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ABSTRACT:

Thermal insulation technologies in External buildings walls are one of the main methods for using energy economically. Considerable studies have estimated the optimum thickness of thermal insulation materials used in building walls for different climate conditions. The economic parameters (Interest rate i, lifetime n, and electricity cost C_{ele}), the heating, and cooling Degree Days(HDD/CDD), the wall structure such as thermal resistance R_{wt}, the properties of the insulation material such as thermal conductivity k_{ins}, and insulation material cost C_{ins} all affect the optimum insulation thickness.

This study focuses on investigating these parameters that affect the optimum thermal insulation thickness for external building walls based on life-cycle cost analysis (an economic model). As a result, the optimum thermal insulation thickness increases from 0.6 to 13.2cm with increasing the heating and cooling energy requirements, the lifetime, the electricity cost, and thermal conductivity of insulation. However, the thickness decreases from 19.5to6.5cm with increasing the interest rate, insulation material cost, thermal resistance, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER.The payback period increased from 0.62to1.93years with increasing insulation material cost, the thermal resistance, thermal conductivity of insulation, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER. However, the payback period dropped from 3.86to0.87years with increasing the interest rate, heating and cooling energy requirements, lifetime, and electricity cost. The energy savings rate increases from 31.13to91.6%when increasing the heating and cooling energy requirements, the lifetime, and electricity cost. However, the thickness decreased from 93.4to75.1% when increasing the interest rate, insulation material cost, thermal conductivity of insulation, thermal resistance, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER.

The emissions of $CO_2$are calculated for the four different thermal resistance and it's noticed that the emissions of CO_2decreasewhen increasing insulation thickness. The highest value of Emissions of CO_2 reached for the Rwt_1 is equal to 14.4kg/m^2; whereas its lowest value obtained for the Rwt_4 is equal to 6.6 kg/m^2.In addition, the effects of these parameters on the total life-cycle cost, payback periods, and energy savings were also investigated.

***R**eceived 29 October, 2020; **A**ccepted 10 November, 2020 © The author(s) 2020.*
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I. INTRODUCTION:

The demand for energy is increasing globally because of the continuous growing population and continuous technological development rate.In many countries, building energy consumption accounts for approximately 40% of global energy demands, and the energy requirement for space heating and cooling of a building is approximately 60% of the total energy consumed in buildings; which represents largest percentage of energy usage [1–4]. The concept of economic thermal insulation thickness considers the initial costs of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation. The optimum economic thickness is the value that provides the minimum total life-cycle cost. The thickness is a function of the following: the building type, function, shape, orientation, construction materials, climatic conditions, insulation material and cost, energy type, cost, and the type and efficiency of air-conditioning system [5–8]. Hasan [9] used life-cycle method in determination of the optimum insulation thickness. The results showed energy saving as 21\$/m^2 for polystyrene and rock wool. At the end of the study, the payback period is determined as 1-1.7 year for rock wool and 1.3- 2.3 years for polystyrene. Daouas [10] researched the effects of different wall sides on costs for both heating and cooling in Tunis with his study. The study concluded that the most economic result was for the south wall. In this case, optimum insulation thickness, energy saving, and payback period are respectively 10.1cm, 71.33 %, and 3.29 years. Uçar and Balo [11] researched the economic side for determining the optimum insulation thickness for four different climate regions of Turkey in their study. At the end of the study, they determined that the optimum insulation thickness varies between 1.06 and 7.64 cm, energy saving varies between 19$/m^2 and 47$/m^2, and the payback period varies between 1.8 and 3.7 years.

Dombaycı et al. [12] used different fuels and insulation materials in his studies. He concluded that when the coal is used as fuel, and expanded polystyrene is used as an insulation material; they determined that life cycle saving for optimal insulation thickness is 14.09$/m^2, and payback period is 1.43 year. Yu et al. [13] with their studies compared the different insulation materials in order to determine the optimum insulation thickness in cities during the winter and summer regions in China. The results have shown that the payback periods changed between 1.9–4.7 years according to the different climate regions and life cycle savings 39 $/m^2-54.8 $/m^2. Gwesha et al [14] determined the thermal optimum insulation thickness of external walls for three Libyan cities, using two different insulation materials only for space heating. The results showed that the optimum thickness of insulation ranges between 7.2 cm and 14.7 cm with an amount of energy savings between 6.6 – 16.2 LD/m^2. The payback periods were calculated to be 1.5 to 2.3 years. The highest value in energy saving is found in the city of Yefren where polystyrene was used. Alghoul et al [15] estimated the thermal optimum insulation thickness of external walls for the city of Tripoli. The simulation included the effect of electricity price on optimum insulation thickness, HVAC energy consumption, energy savings over a lifetime of 10 years, and payback periods. They concluded that increasing electricity price leads to an increase in optimum insulation thickness and from their case study a saving of 67.7 US dollars could be achieved for the adoption of optimum insulation in a city of 10,000 residential house.

Comakli and Yuksel [16] determined the optimum insulation thicknesses for the cities of Erzurum, Kars, and Erzincan located in the cold regions of Turkey that the optimum insulation thicknesses were 0.104, 0.107, and 0.085 m, respectively; that is for each city when coal was used as heating. Çomaklı and Yüksel [17] evaluated environmental effects of the heating insulation for the coldest region of Turkey and determined that when optimum insulation thickness is used in the external wall of the buildings; CO_2 emissions are decreased 50%. Dombaycı et al.. Another study focused on the emission reduction when conducted by Mahlia and Iqbal [18]. In addition to the calculation of optimum insulation thicknesses of some materials, they also studied the effect of having air gaps in external walls. The results of their study showed that a reduction of 65 to 77% in energy consumption and emission can be achieved by using optimum insulation thickness or by introducing air gaps of 2, 4, and 6 cm in external walls. Ali EtemGürel et al. [19] conducted a research concerning four different climatic regions of Turkey. They found that emission of CO_2 and SO_2 revealed from the high use of coal fuels during the combustion could be decreased to 67%-75% with the use of thermal insulation. Çomakl and Yüksel [20] found that CO2 emissions can be decreased by 50 % when optimum insulation thickness is used in the external wall of the buildings. Jihui Yuan et al. [21] conducted a study of optimum insulation thickness over 32 regions of China and concluded that annual CO_2 emission can be reduced by increasing the thermal insulation thickness.

II. PARAMETERS USED IN THE ANALYSIS:

All the parameters affecting the optimum thermal insulation thickness for building walls were investigated in this study. Ones included in analysis are, respectively, the heating and cooling degree days, lifetime, interest rate, insulation material cost, cost of electricity, external wall resistance, thermal conductivity of insulation material, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER of the heating system. The influences of these parameters on the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings were investigated.

In many steady, assumptions of lifetimevaried from 10 years to 30 years (10 years in [14,15,22-25], 20 years in [26–28], 25 years in [14] and 30 years in [15,29-30]).The energy prices for heating and cooling are among the most important factors to determine the optimum insulation thickness and payback period. Compared with coal, fuel-oil, LPG, diesel, kerosene, and natural gas were the most widely used energy source for heating in the literature. Electricity was most widely used for cooling [31-32,26,29]. The table 1 shows the parameters used in the analysis and the ranges of variation.

Table 1. The parameters used in the analysis and the ranges of variation.

Case	HDD(℃)	CDD(℃)	n(year)	*i*%	Cins($m3)	Cele($/kWh)	Rwt(m2K/W)	Kins(W/mK)	COP	EER
1	**100-2000**	555.25	10	10	148	0.341	0.412	0.033	2.3	1.9
2	558.12	**100-2000**	10	10	148	0.341	0.412	0.033	2.3	1.9
3	558.12	555.25	**5-30**	10	148	0.341	0.412	0.033	2.3	1.9
4	558.12	555.25	10	**2-12**	148	0.341	0.412	0.033	2.3	1.9
5	558.12	555.25	10	10	**30-150**	0.341	0.412	0.033	2.3	1.9

6	558.12	555.25	10	10	148	**0.015-0.345**	0.412	0.033	2.3	1.9
7	558.12	555.25	10	10	148	0.341	**0.2-0.7**	0.033	2.3	1.9
8	558.12	555.25	10	10	148	0.341	0.412	**0.02-0.05**	2,3	1.9
9	558.12	555.25	10	10	148	0.341	0.412	0.033	**1.5-4**	1.9
10	558.12	555.25	10	10	148	0.341	0.412	0.033	2.3	**1.5-4**

The studies related to the optimization of thermal insulation thickness and their results are summarized in Table 2.

Table 2 The summary results of the studies related to environmental impacts of thermal insulation.

Paper	**Economic Method**	**Place**	**Opt. insulation thickness**	**Insulation material**	**Fuel**
Bolatturk[33]	LCC	Four cities for each DD region in Turkey (totally 16 cities)	They vary in a wide range (from 0.019 to 0.172 m) depending on cities and used fuel types for heating	Polystyrene	Natural gas, Coal, Fuel-oil, Electricity, LPG
Yu et al. [35]	P1–P2	China (Shanghai,Changsha, Shaoguan,Chengdu)	0.053–0.236 m	Exp. polys., extr. polys., foamed polyurethane, perlite, foamed polyvinyl chloride	Electricity
Ucar and Balo[23]	P1–P2	Turkey (Mersin, Sanliurfa, Elazig,Bitlis)	They vary in a wide range depending on HDDs, CDDs, insulation materials and fuel types	Extruded polystyrene, expanded polystyrene, nil siding, rock wool	Natural gas, Coal, Fuel-oil, Electricity, LPG
Bolatturk[31]	P1–P2	Turkey (Adana,Antalya, Aydin, Hatay, Iskenderun, Izmir, Mersin)	They vary between 0.032 and 0.038 m for CDHs and between 0.016 and 0.027 m for HDHs	Extruded polystyrene board	Natural gas for heating, Electricity for cooling
Mahlia and Iqbal [27]	LCC	Maldives	0.015–0.06 m (depending on insulation material and air gap thickness)	Fiberglass–urethane, fiberglass (rigid), urethane (rigid), perlite, extruded polystyrene, urethane (roof deck)	Diesel
Daouas et al. [30]	LCC	Tunisia	0.057 m	Expanded polystyrene, rock wool	Electricity
Dombayci et al. [22]	LCC	Denizli/Turkey	0.032-0.138 m depending on fuel types (for rock wool) 0.076-0.259 m depending on fuel types (for EPS)	Expanded polystyrene, rock wool	Natural gas, Coal, Fuel-oil, Electricity, LPG
Gwesha, et al. [14]	LCC	Libya(Tripoli, Sabha and Yefren).	ranges from 0.072 m to 0.147 m	Rockwool and Polystyrene	Electricity
Ucar and Balo [11]	P1–P2	Turkey (Kocaeli, Aydin, Elazig, Agri)	They vary between 0.0106 and 0.0764 m depending on cities, and fuel types	Foamboard 3500, foamboard 1500, extr. polystyrene, fiberglass	Natural gas, Coal, Fuel-oil, Electricity, LPG
Mahlia et al. [37]	P1–P2	Malaysia	They vary between about 0.04 and 0.10 m depending on insulation materials	Fiberglass–urethane, fiberglass (rigid), urethane (rigid), perlite, extruded polystyrene, urethane (roof deck)	Electricity
Samah et al. [15]	LCC	Tripoli /Libya	ranges from 0.005 m to 0.079 m	polystyrene	Electricity
Sisman et al. [38]	LCC	Turkey (Izmir, Bursa, Eskisehir,	0.033 m, 0.047 m, 0.061 m, 0.080 m	polyethylene foam Rock wool	Coal

		Erzurum)Tehran/Iran	(for walls)		
Awadet al. [39]	LCC	Libya(totally 20 cities)	ranges from 0.04 m to 0.0538 m	Fiberglass,Polyurethane and polystyrene	Electricity
Al-Khawaja [40]	-	Qatar	0.03 m (for wallmate)	Wallmate, fiberglass	Electricity
Comakli and Yuksel [41]	LCC	Turkey (Erzurum,Kars, Erzincan)	0.105 m, 0.107 m, 0.085 m	Styrofoam	Coal

III. THE MATHEMATICAL MODELING

This section presents the mathematical treatment of the work; starting with the calculation of the degree days, and then the energy-economic analysis for the derivation of the optimum thickness, and finally the annual savings in energy requirements and its cost; with estimation of the associated reduction in CO_2 emission.

3-1 Calculation of Cooling and Heating Degree-Days

One of the methods to estimate the amount of energy required for heating and cooling has been used by many authors to calculate the number of degree-days [11-30]. Cooling and heating degree-days are vital for the estimation of thermal loads. The mean daily outdoor temperature is used for the calculations of degree-days. The HDD and CDD are calculated using the following formulas:

$$\mathrm{CDD}_{24} = \sum_{1}^{365} |\mathrm{T}_{\mathrm{av}} - \mathrm{T}_{\mathrm{b}}|^{+} \qquad (\;)$$

$$\mathrm{HDD}_{18} = \sum_{1}^{365} |\mathrm{T}_{\mathrm{b}} - \mathrm{T}_{\mathrm{av}}|^{+} \qquad (\;)$$

Where $CDD_{24}$is the cooling degree-days calculated at base temperature of 24 °C, HDD_{18} is the heating degree-days calculated at base temperature of 18 °C; T_b is the base temperature; T_{av} is the average daily temperature.

3-2 Overall Heat Transfer Coefficient:

The overall heat transfer coefficient of the wall can be expressed in $W/m^2.^0C$ as:

$$\mathrm{U} = \frac{1}{\mathrm{R_O} + \mathrm{R_W} + \mathrm{R_{ins}} + \mathrm{R_i}} \qquad (\;)$$

where, R_w is thermal resistance of the composite wall materials without the insulation ($m^2.C^0/W$), R_i and R_0 are the inside and outside air film thermal resistances ($m^2.C^0/W$), respectively. R_{ins} is the thermal resistance of the insulation. The overall heat transfer coefficient can then be written as:

$$\mathrm{U} = [\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]^{-1} \qquad (\;)$$

3-3 Annual Heating and Cooling Thermal Loads

The amount of heat transfer through a unit area (Q, W/m^2) can be calculated using overall heat transfer coefficient by the following equation:

$$\mathrm{Q} = \mathrm{U}\,\Delta\mathrm{T} \qquad (\;)$$

Where, U is the overall heat transfer coefficient, and ΔT is the difference between the base temperature and the mean daily temperature. In this work a heat pump is considered to operate for 24 hours a day to maintain the design inside temperature constant**.** Therefore, the amount of annual energy consumption that depends on the value of Heating Degree-Days (HDD) in heating season can be expressed by:

$$\mathrm{E_H} = \frac{\mathrm{Q_H}}{\mathrm{COP}} = \frac{0.024 * \mathrm{HDD} * \mathrm{U}}{\mathrm{COP}} = \frac{0.024 * \mathrm{HDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{COP}} \qquad (\;)$$

While the annual cooling energy requirement by the heat pump can be expressed as:

$$\mathrm{E_C} = \frac{\mathrm{Q_C}}{\mathrm{EER}} = \frac{0.024 * \mathrm{CDD} * \mathrm{U}}{\mathrm{EER}} = \frac{0.024 * \mathrm{CDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{EER}} \qquad (\;)$$

Where: Q_C = cooling load(kWh/m^2).
Q_H = heating load(kWh/m^2).
E_C = Energy consumption by the heat pump due to cooling load(kWh/m^2).
E_H = Energy consumption by the heat pump due to heating load(kWh/m^2).
COP = Coefficient of performance.
EER = Energy efficiency rating.

3-4 Life-Cycle Analysis and Optimization of Insulation Thickness:

The life-cycle cost analysis (LCC) is used to compute and analyze the total heating and cooling energy costs of the building over its entire lifetime. The total energy cost over a lifetime of n years is converted to the present worth value by multiplying it by the present worth factor (PWF) which is defined as follows [33-35]:

$$\mathrm{PWF} = \begin{cases} \dfrac{(1+r)^n - 1}{r(1+r)^n} \begin{cases} r = \dfrac{i-g}{1+g} i > g \\ r = \dfrac{g-i}{1+i} i < g \end{cases} \\ \dfrac{n}{(1+i)} i = g \end{cases} \qquad (\ )$$

Where i is the interest rate and g represents the inflation rate.

The life-cycle cost of energy consumption (CEC, \$/m^2) can be calculated as;

$$\mathrm{CEC} = \mathrm{PWF} \times \mathrm{C_{el}} \times [\mathrm{E_H} + \mathrm{E_C}] \qquad (\ )$$

Where $\mathrm{C_{el}}$ is the electricity cost. Substituting equation 6 and 7 in equation 9, one can get:

$$\mathrm{CEC} = \mathrm{PWF} \times \mathrm{C_{el}} \times \left[\frac{0.024 * \mathrm{HDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{COP}} + \frac{0.024 * \mathrm{CDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{EER}} \right] \qquad (\ )$$

Therefore, the life cycle total cost ($\mathrm{C_T}$, \$/m^2) of the insulation material and the energy consumption can be calculated by:

$$\mathrm{C_T} = \mathrm{PWF} \times \mathrm{C_{el}} \times \left[\frac{0.024 * \mathrm{HDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{COP}} + \frac{0.024 * \mathrm{CDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{EER}} \right] + \mathrm{C_{ins}} \times \mathrm{X_{ins}} \qquad (\ )$$

Where $\mathrm{C_{ins}}$ is the insulation cost per unit volume and $\mathrm{X_{ins}}$ is the insulation thickness.

Differentiating equation 11 with respect to $\mathrm{X_{ins}}$ to find the optimum insulation thickness yields:

$$\mathrm{X_{opt}} = \sqrt{\frac{0.024 * \mathrm{PWF} * \mathrm{K_{ins}} * \mathrm{C_{el}} * \mathrm{DD}}{\mathrm{C_{ins}}}} - \mathrm{R_{Wt}k_{ins}} \qquad (\ )$$

where, DD is a combined heating and cooling degree days [28], which is defined as:

$$\mathrm{DD} = \frac{\mathrm{HDD}}{\mathrm{COP}} + \frac{\mathrm{CDD}}{\mathrm{EER}} \qquad (\ )$$

The life cycle saving (LCS, \$/m^2) is defined as the difference between the value of the saved energy over the lifetime and the total insulation cost, which can be calculated by the following equation:

$$\mathrm{LCS} = \mathrm{C_{el}}\left[\left(\mathrm{E_{H,no\ ins}} - \mathrm{E_{H,with\ ins}} \right) + \left(\mathrm{E_{C,no\ ins}} - \mathrm{E_{C,with\ ins}} \right) \right] \mathrm{PWF} - \mathrm{C_{ins}X_{ins}} \qquad (\ )$$

The total cost of annual energy saving (EAS, \$/m^2), using the optimum insulation thickness ($\mathrm{X_{opt}}$), can then be calculated as follows:

$$\mathrm{EAS} = \mathrm{C_{el}} \left[\left(\mathrm{E_{H,no\ ins}} - \mathrm{E_{H,X_{opt}}} \right) + \left(\mathrm{E_{C,no\ ins}} - \mathrm{E_{C,X_{opt}}} \right) \right] \qquad (\ )$$

Finally, the payback period (PP, year) can be obtained by the following formula, [29,30]:

$$\mathrm{PP} = \begin{cases} \dfrac{(\mathrm{k_{ins}R_w^2} + \mathrm{xR_{wt}})(i+1)\mathrm{C_{ins}}}{0.024\mathrm{C_{el}DD}} i = g \\ (1+i) * \dfrac{\mathrm{c_{ins}}}{\mathrm{EAS}}\ i \neq g \end{cases} \qquad (\ )$$

3-5 CO$_2$ Emission Calculation:

The annual CO$_2$ emissions per unit area of building exterior walls can be expressed as [36]:

$$\mathrm{E_{C_{o2}}} = [\mathrm{E_H} + \mathrm{E_C}] \times a = \left[\frac{0.024 * \mathrm{HDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{COP}} + \frac{0.024 * \mathrm{CDD}}{[\mathrm{R_{Wt}} + \frac{\mathrm{x_{ins}}}{\mathrm{k_{ins}}}]\mathrm{EER}} \right] \times a \qquad (\ )$$

Where a is the coefficient of CO$_2$ emissions which could be approximated to 0.45 $\mathrm{kg_{CO2}}$/kWh [21, 34].

IV. RESULTS AND DISCUSSIONS:

The influence of variables affecting the optimization results were investigated under different cases. Predictions were generated by simulating the Ten cases described in Table 1. In order to investigate the effects of each parameter; only one parameter was varied, the rest were kept constant as shown in this table.

Cooling and heating degree days vary in a quite wide range depending on climatic conditions.The effects of heating and cooling degree days on the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings are shown in Figures 1 and 2. In this analysis, the cooling and heating degree days varied from 100 to 2000, respectively; while the other parameters remained constant as presented in Table 1. As shown in Figures 1 and 2, when the heating and cooling energy requirements of a building increases, the thickness of the thermal insulation required also increases from 6.1to12.5 cm and from 5.6to13.3 cm respectively. The total cost over the lifetime of 10 years increases with increasing cooling and heating degree days, because it includes the energy cost. On the other hand, the energy savings rate reached up to 88% when using insulation and the payback period of insulation cost decreased when increasing energy requirements. The payback period dropped from 1.61 years to 0.91 years while increasing heating degree days, and 1.7 years to 0.87 years when increasing Cooling degree days.

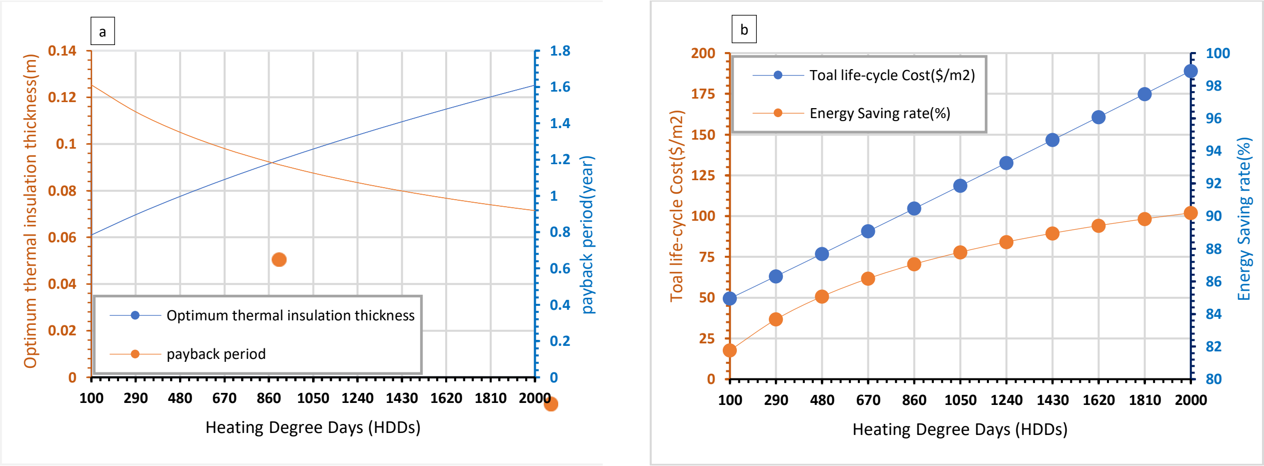

Figure 1. The effects of *HDD* :a- on optimum thermal insulation thickness and paybackperiod; b- on total life-cycle cost and energy savings.

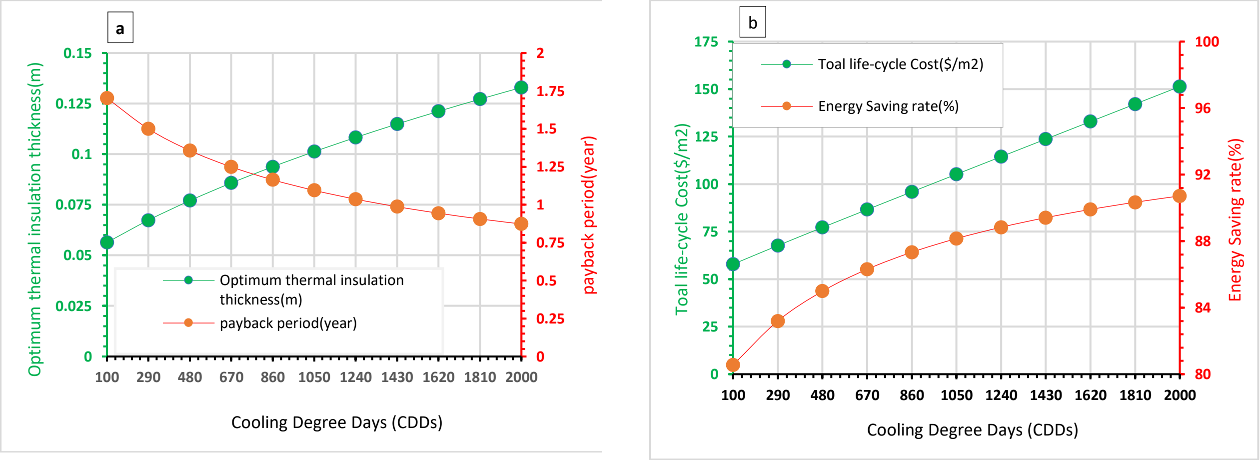

Figure 2. The effects of *CDD* :a- on optimum thermal insulation thickness and paybackperiod; b- on total life-cycle cost and energy savings.

The influences of lifetimeon the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings are shown in Figure 3. The payback period increases from 0.87 years to 2.3 years when the increasing lifetime; and the energy savings rate reached up to 90% when increasing lifetime.Figures 4 shows the effects of particular economic parameters such as interest rate on the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings.As shown in Figures 4, the interest rate greatly affected the optimum insulation thickness and payback periods. Although the interest rate decreases when increasing optimum insulation thickness from 7.3to 8.4cm; it increases with increasing payback periods from 2.05to1.36 years.

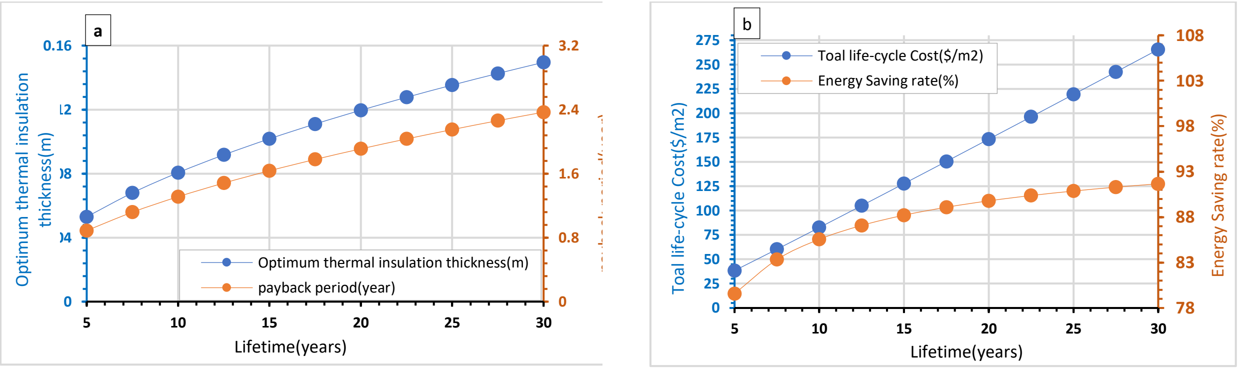

Figure 3. The effects of lifetime: a-on optimum thermal insulation thickness and paybackperiod; b-on total life-cycle costand energy savings.

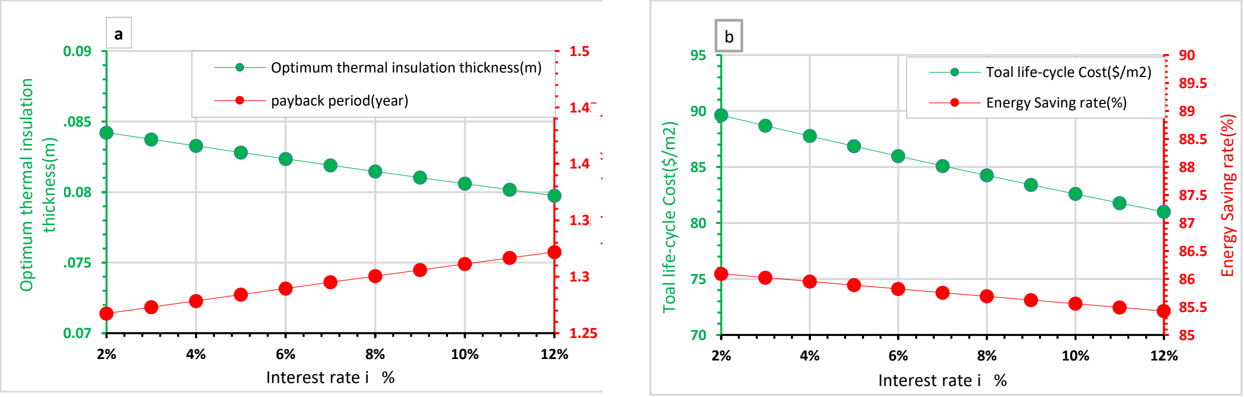

Figure 4. The effects of Interest rate: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

One of the most important parameters affecting the optimum insulation thickness is the cost of thermal insulation material. Figures 5 show the effects of insulation material cost on the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings. When the insulation material cost is increasing, the optimum value of the insulation thickness decreases from 19.5 to 7.9cm. Naturally, if the costs of insulation material increases, the payback period will increase from 0.62 to 1.31, as shown in Figure5a. The energy savings rate due to thermal insulation increased from 93.40to85.46% with insulation material cost. However, the optimum insulation thickness was not a function of the cost of installation, as seen in Equation (12). The effects of electricity costs on the optimum insulation thickness, payback periods, and energy savings are shown in Figures 6. In contrast to the insulation cost, the optimum insulation thickness increased from 0.6to8.11cm;while payback period decreased from 3.86to1.3years with increasing the electricity costs. In addition, the energy savings rate due to thermal insulation increased from 31.13to85.64% with electricity cost.

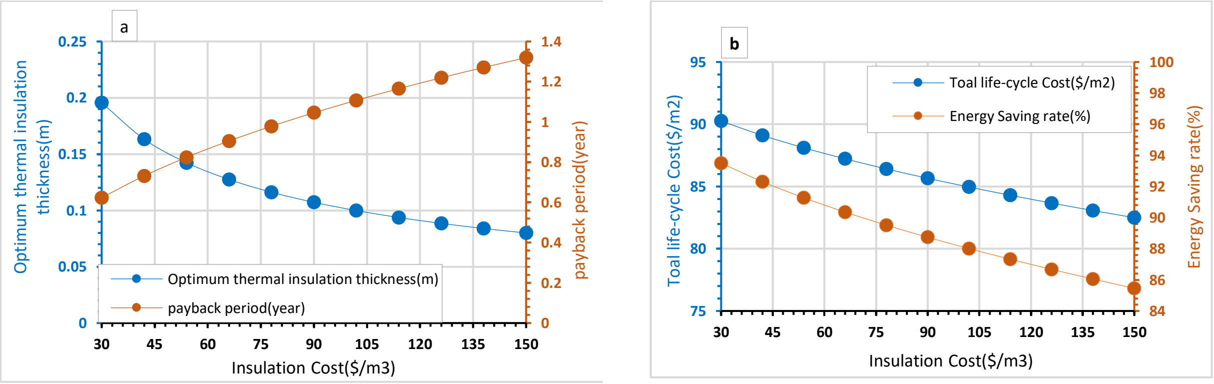

Figure 5. The effects of thermal insulation cost: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

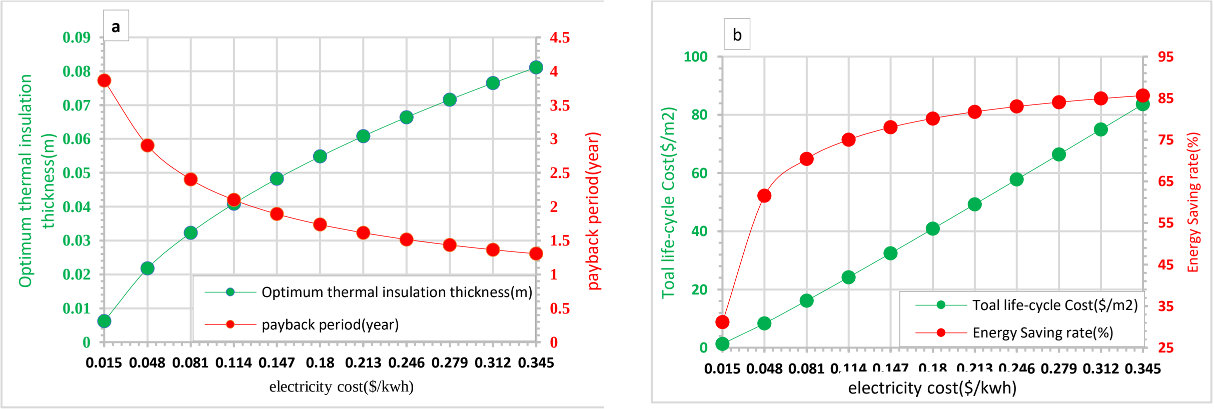

Figure 6. The effects of electricity cost: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

The effects of external wall resistance excluding the insulation layer and the thermal conductivity of the insulation material are given in Figures 7 and 8, respectively. An increase in the thermal conductivity of the insulation decreases the total resistance, which increases the total cost over the lifetime of 10 years and the required insulation thickness. Due to same circumstances, an increase in the wall resistance decreases the optimum insulation thickness from 8.7 to 7.1cm, payback period increases from 0.75to1.93 years, the energy savings rate decreases from 92.9 to75.4%, an increase in the thermal conductivity of the insulation the optimum insulation thickness increases from 6.5 to 9.5cm, payback period increased from 1.04to1.57years, and finally the energy savings rate decreased from 88.7 to 82.22%.

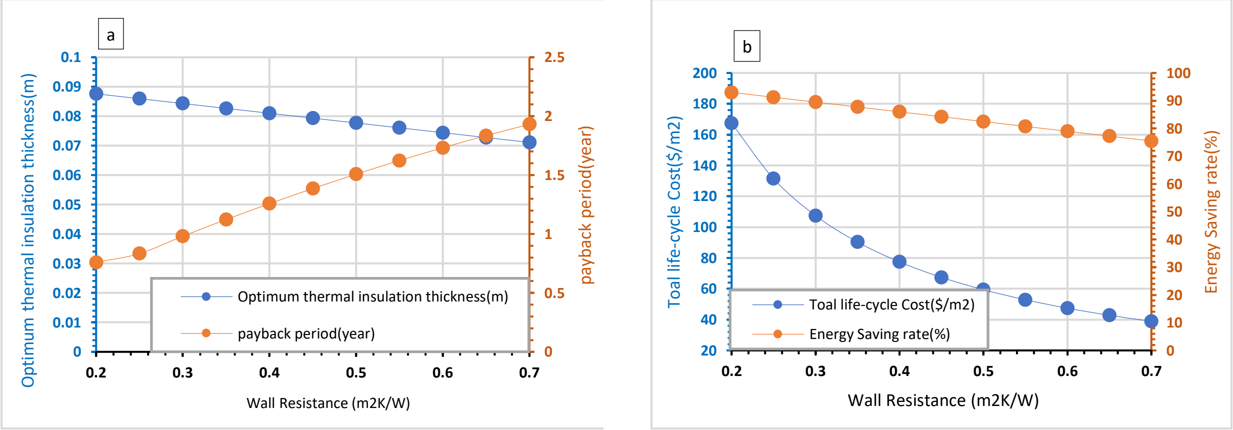

Figure 7. The effects of wall resistance excluding the insulation layer: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

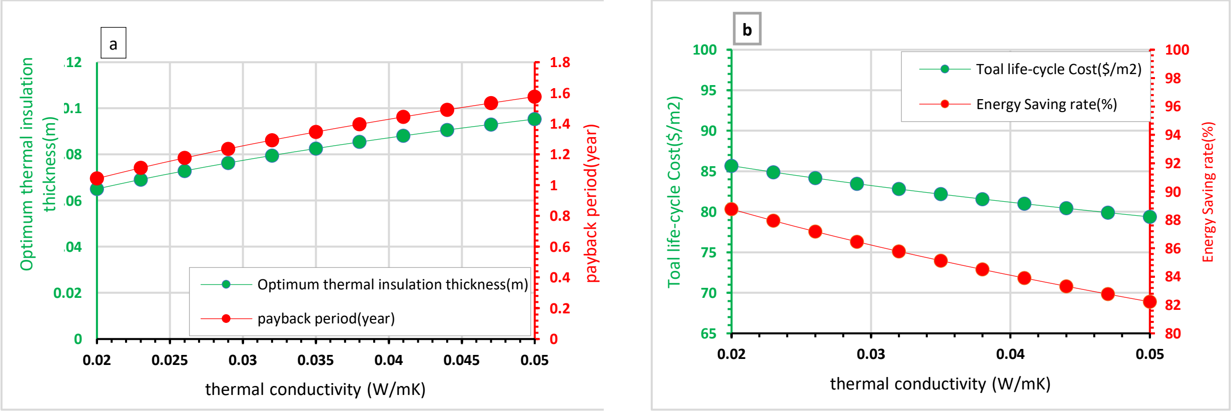

Figure 8. The effects of thermal conductivity of insulation: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

The Coefficient of performance COP and Energy Efficiency rating EER of the cooling and heating system respectively depend on the operating conditions of the system.The Coefficient of performance COP and Energy Efficiency rating EER on the optimum insulation thickness, payback periods, total life-cycle cost, and energy savings are given in Figures 9 and 10, respectively. An increase in COP causes the optimum insulation thickness to decrease from 9.1 to 7.1 cm, payback period increases from 1.4 to 1.8 years, energy savings rate decreases from 87.04 to83.9%, an increase in EER, optimum insulation thickness decreases from 8.7to6.5cm, payback period increases from 1.23 to 1.52years, and finally energy savings rate decreasing from 86.5 to82.8%. The system efficiency improved when increasing in COP and EER values, the cooling and heating cost, and decreasing the total cost. However, the value of COP and EER did not affect the optimum insulation thickness as significantly as the other parameters because it only affected the cooling cost.

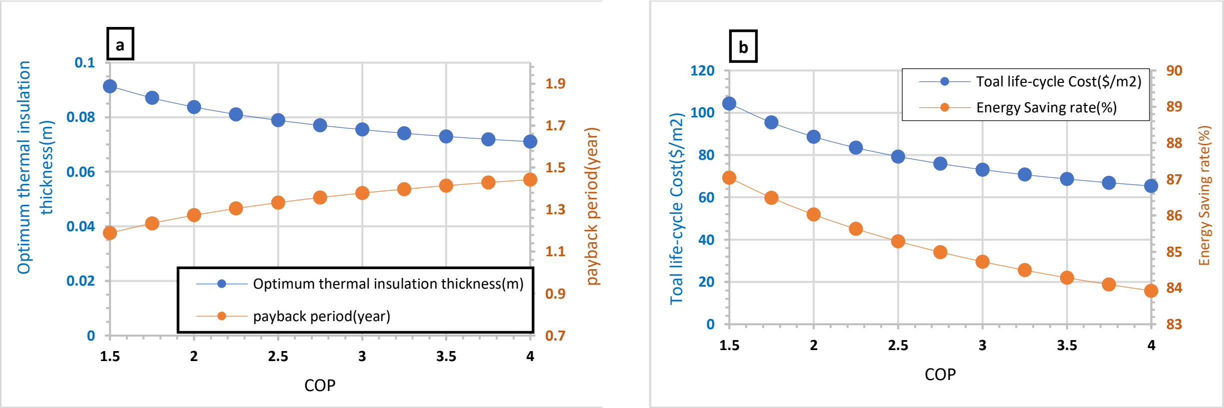

Figure 9. The effects of Coefficient of Performance: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

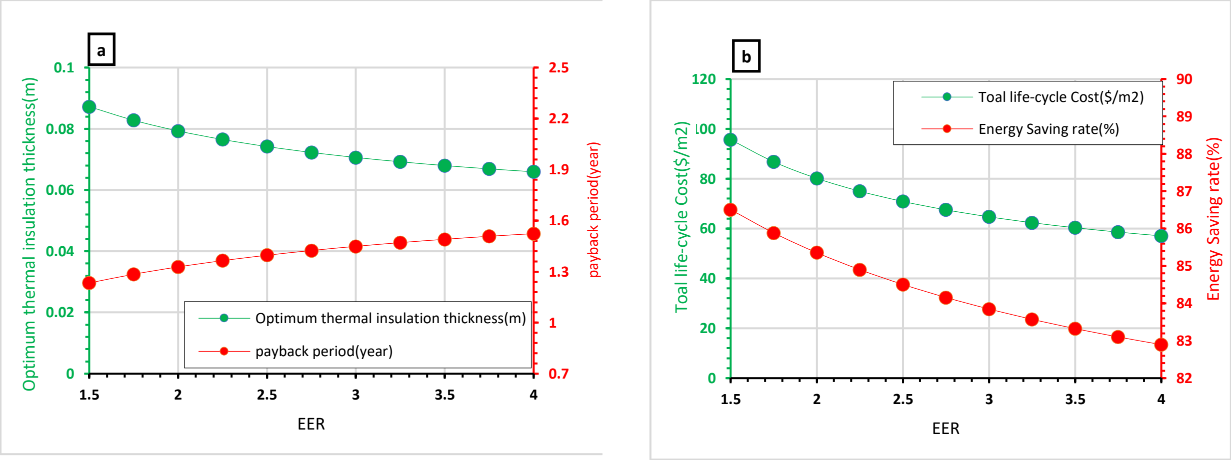

Figure 10. The effects of Energy Efficiency Rating: a- on optimum thermal insulation thickness andpayback period; b- on total life-cycle cost and energy savings.

The effect of degree days on insulation thickness for the different wall resistance excluding the insulation layer is shown in Figure 11. It is shown that insulation thickness increases with degree days. The climates having higher degree days require larger layers of insulation. At a given number of degree days, buildings have a higher thermal resistance and require less insulation. The results show that the optimum insulation thicknesses vary between 2.8 and 17.27 cm depending on the degree days and thermal resistance.The effect of degree days on the payback period of the different wall types is shown in Figure 12. It representsthat the payback periods range between 0.95 and 3.31 year depending on degree days and thermal resistance. The payback period is shortened while degree days has increased. This clearly indicates that the payback period is shorter, whereas applying insulation thickness costs in high DDs regions increases. Therefore, the application of insulation in high DDs climates is more advantageous.

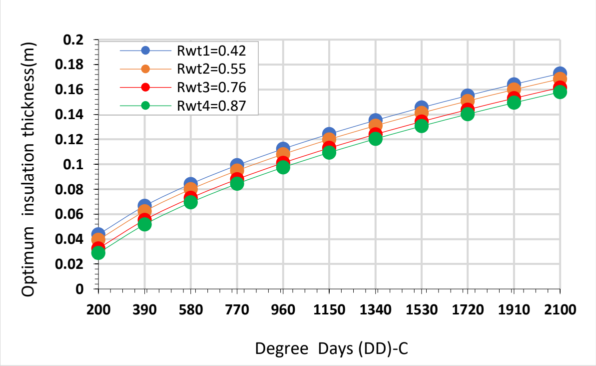

Figure **11**. Effect of degree-days on insulation thickness for different wall resistance excluding the insulation layer

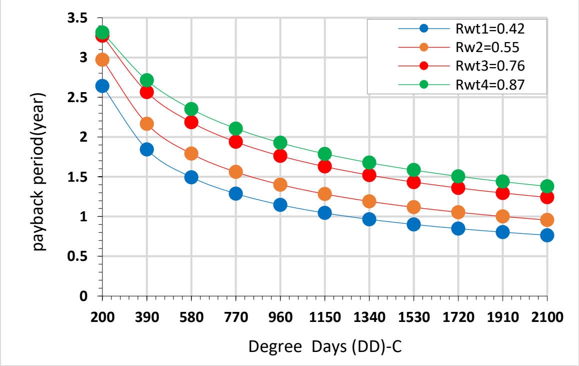

Figure **12**. Effect of degree-days on the payback period for different wall resistance excluding the insulation layer

Figure 13 shows the effect of insulation thickness on energy cost savings for the different thermal resistance It's shown that energy cost savings depend on the thermal resistance. The highest value of energy cost savings reached for the Rwt1 is equal to 68.4\$/m^2; whereas its lowest value obtained for the Rwt4 is at 22.05\$/m^2.Figure 14 shows the effect of degree days on energy cost savings for different thermal resistance. It displays that energy cost savings increases with lifetime for all the thermal resistances. Figure 15 shows optimum insulation thickness versus present worth for different thermal resistance. The optimum insulation thickness increases with the increase of PWF, based on economic data.

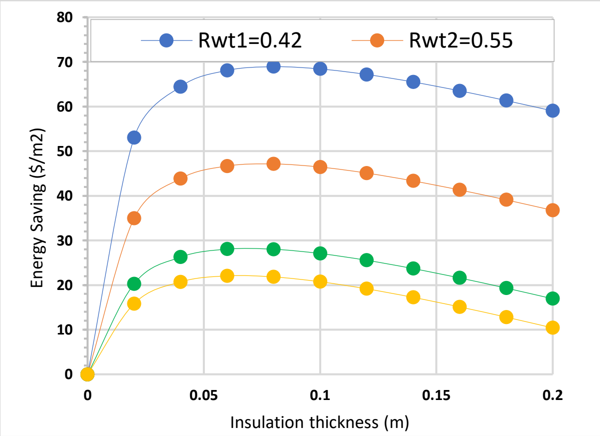

Figure **13**. Effect of insulation thickness on energy savings for different wall resistance excluding the insulation layer

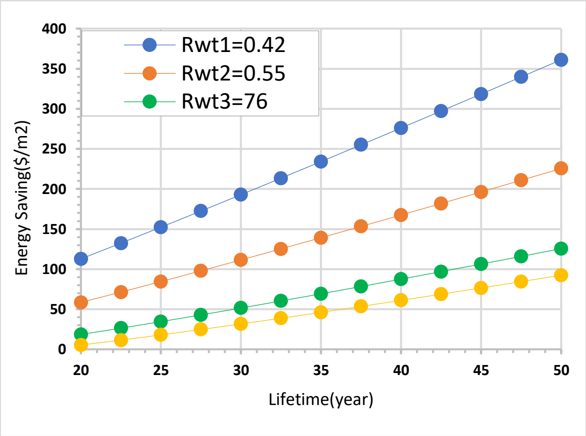

Figure **14**. Effect of lifetime on energy savings for different wall resistance excluding the insulation layer.

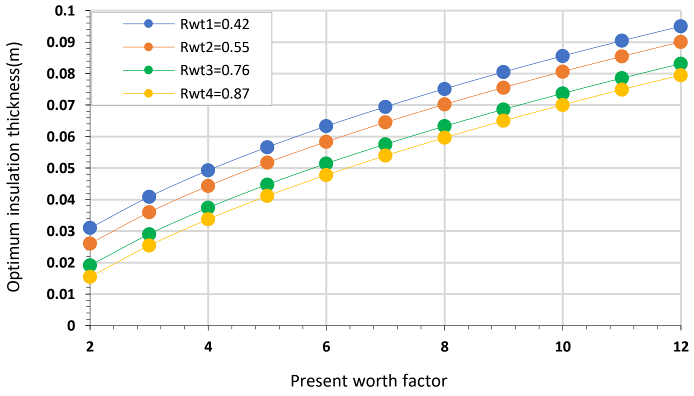

Figure **15**. Optimum insulation thickness versus present worth for different wall resistance excluding the insulation layer

Figure 16 shows the effect of degree days on energy cost savings for the different wall resistance excluding the insulation layer. It is seen that the energy cost savings are directly proportional to the climatic conditions and different wall resistance excluding the insulation layer. The energy cost savings increases with degree days for all the thermal resistance.The variations of the emissions of CO_2 and SO_2 versus insulation thickness for a 1 m^2 external wall of a building are shown in Figures 13. It is seen that the emissions of CO_2 decreases when increasing insulation thickness. The highest value of Emissions of CO2 reached for the Rwt1 is equal to 14.4kg/m^2;where its lowest value obtained for the Rwt4 which is equal to 6.6 kg/m^2.

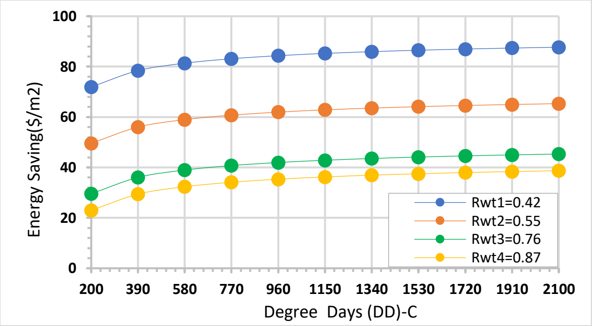

Figure **16**. Effect of degree-days on energy savings for different wall resistance excluding the insulation layer

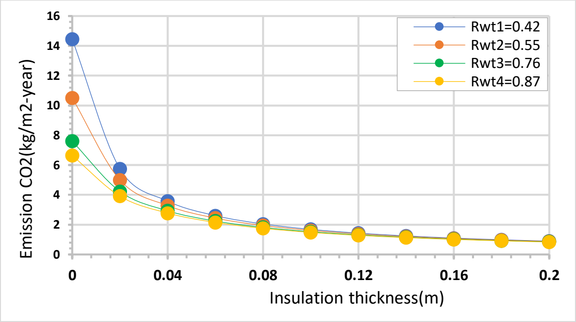

Figure **17**. Emissions of CO2 versus insulation thickness for different wall resistance excluding the insulation layer

V. CONCLUSION:

In Libya, heat losses from buildings is one of the primary sources of energy waste, and thus considerable energy savings can be obtained by using proper insulation material in buildings. This study has presented the results of a parametric analysis which is carried out to investigate the effect of various parameters on the optimum insulation thickness for external walls by considering payback period, total cost, and energy savings. The investigated parameters in this analysis are, respectively, the heating and cooling degree days, lifetime, interest rates, cost of insulation material, electricity cost, total wall resistance, thermal conductivity of the insulation, COP, and EER.

According to obtained results, the parameters that increase the optimum thermal insulation thickness increased from o.6to13.2cm when increasing the heating and cooling energy requirements, the lifetime, the electricity cost, and thermal conductivity of insulation. However, the thickness decreased from 19.5to6.5cm when increasing the interest rate, the insulation material cost, thermal resistance, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER. The payback period increased from 0.62to1.93years when increasing insulation material cost, thermal resistance, thermal conductivity of insulation, coefficient of performance COP of the cooling system, and Energy Efficiency rating EER. However, the payback period dropped from 3.86 to 0.87years when increasing the interest rate, heating and cooling energy requirements, lifetime, and electricity cost.The energy savings rate increased from 31.13to91.6% when increasing the heating, and cooling energy requirements, the lifetime, and the electricity cost. However, the thickness decreased from 93.4to75.1% with increasing the interest rate, the insulation material cost, thermal conductivity of insulation, the thermal resistance, the coefficient of performance COP of the cooling system, and Energy Efficiency rating EER. This study has also shown that the parameters having the most significant effect on optimizing the thermal insulation thickness are the energy requirements, lifetime, and the insulation cost; however, the electricity cost, thermal resistance, thermal conductivity of insulation, COP and EER have found to be relatively less effective.

The emissions of $CO_2$are calculated for the four different thermal resistance and shown that the emissions of CO_2decreasewith increasing insulation thickness. The highest value of Emissions of CO_2 reached the Rwt$_1$ which is equal to 14.4kg/m^2.

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