

# Reducing Buildings Operating Economics by Selecting the Optimal Nano Insulation Thickness in External Walls: Two Case Studies in Germany and USA

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**Abstract** As is well known, the cost of insulation rises linearly with thickness, obtaining the optimal thickness would result in a reduction in energy costs, lowering the building life cycle costs. Therefore, this study offers an excellent road map on the determination of the most economical nano-insulation material and its thickness. This study was applied in two existing buildings case studies located in Germany and the USA by using different nano insulation materials. Firstly, validate the degree-day approach by comparing actual and estimated energy consumption, then select the optimum thickness of used nano insulation, after that select the optimal nano insulation type and its thickness. Finally, calculate the payback periods. Results show that the nano insulation optimum point for the Seitzstraße building is 0.006 m of used nano insulation (VIP). The optimal nano insulation is expanded polystyrene with graphite with a thickness of 0.12 m. The Pentagon building is 0.007 m of used nano insulation (Aerogel Blankets), and the optimal nano insulation is expanded polystyrene with graphite with the thickness of 0.065 m. Furthermore, the optimal insulation and its thickness were estimated in the condition of considering the effects of space savings by comparing nano insulation materials to traditional insulation materials (PUR) and accounting for the expenses of renting the saved spaces.

**Keywords** Nano Insulation Materials, Optimal

Insulation Thickness, Heating& Cooling Degree-Days, Life Cycle Cost, Payback Period

## 1. Introduction

Economics of Buildings passes on five stages: (concept development -design-production -operational -end of economic life stage). To estimate costs of these stages through the life cycle costing method by calculating the sum of all stages' costs [1]. This paper investigates the life cycle costs of the operational stage, because it has the longest lifespan and has more than 80 % of total life cycle costs figure 1 by reducing energy consumption in buildings, at a time while electricity demand is increasing as a result of rising population, and expansion of growth projects. Buildings operational processes consume approximately half of the world's energy, and the annual energy consumed in buildings grows at an average rate of 1.8% every year [1-2]. Improving buildings' thermal envelope is regarded as a critical step ahead to achieve an acceptable level of thermal comfort for users especially the walls, as it gains the most heat that leads to increased energy consumption, thus finding the best methods and materials for thermal insulation of walls is a top priority to minimize heating and cooling loads to achieve an acceptable level of thermal

comfort for users. This can be accomplished by either thickening traditional thermal insulation, which causes a reduction in the available used spaces in the buildings or reorienting high-tech super-insulation materials based on nanotechnology which are considered a promising solution for providing high-performance thermal insulation in buildings due to their ultra-low thermal conductivity with extremely thin thickness compared to conventional insulation materials as a result, available space was saved (when compared to traditional insulating materials, it is thickness less than a third) [3].

Although using nano insulations in buildings reduces space heating and cooling operating expenses, it raises the initial investment in a building [3]. Thus the main aim of this research is to determine the optimal nano thermal insulation and the optimal thickness to achieve the greatest economic feasibility and reduce operating costs.

Previous researches contain many contributions regarding selecting the optimal building insulation thickness. For instance, Kaynakli [4] studied the optimum thickness of thermal insulation for building walls based on the heating and cooling degree days approach. The optimal thicknesses of five insulating materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite, and foamed polyvinyl chloride) were estimated using two different energy sources. Çomaklı and Yüksel [5] investigated the optimum insulation thicknesses for the cities of Erzurum, Kars, and Erzincan located in the coldest areas of Turkey. It has been detected that the optimum insulation thickness is 0.104, 0.107, and 0.085 m for selected cities, respectively, over a lifetime of 10 years. The optimization is based on LCC analysis using stropor insulation material. When the optimum insulation thickness is applied, energy savings up to 12%  $\$/m^2$  of wall area were obtained. Bolattürk [6] obtained the best insulation thicknesses, amount of energy saved, and payback period for 16 cities from four different climatic zones located in Turkey. Polystyrene is used as an insulation material. Life cycle cost (LCC) analysis was used to determine the optimum insulating thickness for various fuel sources. The researcher discovered that the optimum insulating thickness is between 0.02 and 0.17 m, with energy savings ranging from 22% to 79 % and a payback period of 1.3 to 4.5 years depending on the city and the type of fuel. Alsayed et al. [7] used a life cycle cost (LCC) method using several degree-days values for eight Palestinian governorates to compute the optimal insulation thickness in building exterior walls for three insulating materials options (polystyrene, rigid polyurethane foam, rock wool). The findings show that polyurethane is the optimal insulation and the optimal thickness for all cases was found to be between 0.004 and 0.09 m. Dombaycı et al. [8] calculated the optimal insulation thickness for Denizli located in Turkey, using

two different insulating materials (expanded polystyrene, rock wool) and five different fuel types (coal, natural gas, LPG, fuel oil, and electricity). A life-cycle cost analysis drives the optimization. According to the findings, using coal as an energy source and expanded polystyrene as an insulating material yielded the best results. The life cycle savings and payback duration are 14.09  $\$/m^2$  and 1.43 years, respectively when the optimal insulating thickness is applied. Nematoua et al. [9] calculated the appropriate insulation thickness, energy-saving values, and payback period. The expanded polystyrene (EPS) insulation material used for concrete and soil blocks in Yaounde' and Garoua cities is located in two different climatic regions in Cameroon. In Liu et al. [10] the optimal insulation thickness of extruded polystyrene and expanded polystyrene (EPS) insulation materials were estimated for three provinces in China (Changsha, Chengdu, and Shaoguan). The optimal thickness of extruded polystyrene has been determined to be 0.053–0.069 m, whereas the optimum thickness of EPS is 0.081–0.105 m. Kurekci [11] determined the optimal insulating thicknesses in Turkey's 81 provincial centers for four different fuels (natural gas, coal, fuel oil, and liquefied petroleum gas), and five different insulating materials were used (extruded polystyrene, expanded polystyrene, glass wool, rock wool, and polyurethane). The calculations were established for three different three cases (buildings that were heated but not cooled, cooled but not heated, and both heated and cooled). The results show that the optimum insulation thickness was required for both heated and cooled cases, and in this case, the net saving amount is the highest with the shortest payback period when compared to the other cases. Daouas et al. [12] analyzed the optimal insulation thicknesses of expanded polystyrene and rock wool for various wall types. Expanded polystyrene was shown to be the most economical insulating material for Tunisia in this investigation. Furthermore, the optimal insulation thickness was determined to be 0.057 m, which results in 58 % of energy savings and a payback period of 3.11 years for expanded polystyrene insulation material and stone/brick sandwich wall. Idchabani, et al. [13] focus on optimizing the thermal insulation thickness of a typical building's wall in Morocco's cold zones based on life cycle cost. The maximum recorded optimal thickness for expanded polystyrene, polyurethane, and Cork is 16.8 cm and the minimum is 3.4 cm, depending on insulating material and energy source type. Yu, et al. [14] investigated the optimal insulation thickness for four typical zones in China using five different insulating materials (expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite, and foamed polyvinyl chloride). Because of the biggest life cycle savings and shortest payback period, expanded polystyrene is the most cost-effective of the five insulating materials.

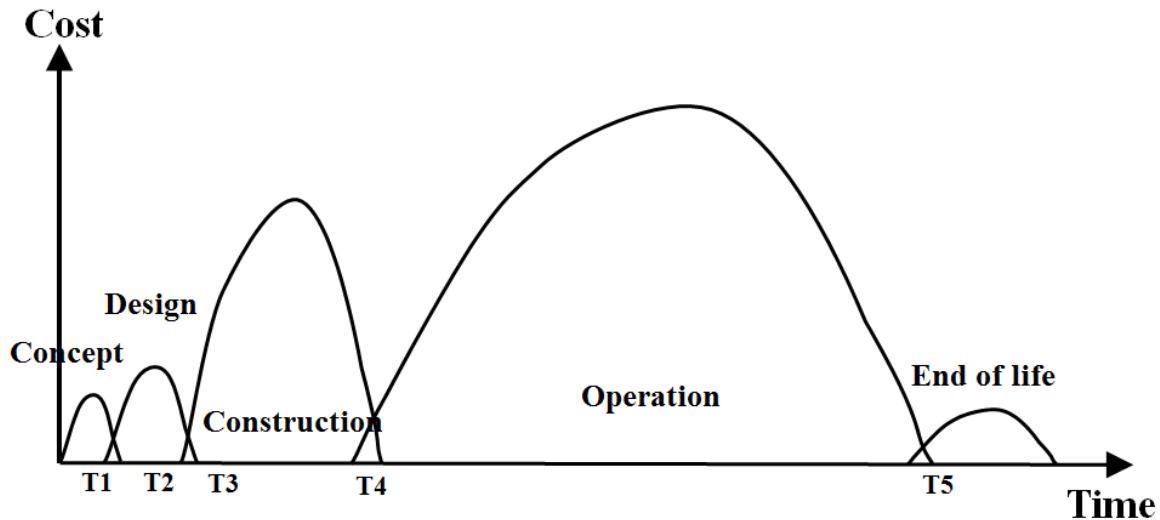


Figure 1. Stages of building economics [1].

When current literature is reviewed, it is clear that all researches calculated the optimal insulation thickness for traditional insulations such as (rock wool, cork, glass wool, expanded polystyrene, extruded polystyrene, polyurethane, perlite, and foamed polyvinyl chloride). Unfortunately, no research has been done on choosing the best nano insulation materials and their optimal thickness. Although these materials may reduce the overall cost of using space loss caused by deep traditional insulation because of their low thermal conductivities and thin thickness. Therefore, more research in the economic feasibility of using nano-insulating materials in the building industry sector is needed. The envelope thickness must be optimized to maintain an appropriate balance between insulation investment costs and the building's energy efficiency. A lifecycle cost analysis (LCC), which is a helpful economic method for enhancing buildings' long-term performance at reduced running costs may be used to determine the ideal insulation thickness. Therefore, in the present study, a thickness optimization and cost analysis based on the heating and cooling degree days approach was conducted using LCC analysis by calculating the lowest overall cost throughout the building's whole useful life, including the cost of insulation and energy usage and for nano insulation material and PUR traditional material. These calculations were applied in two case studies. First, the accuracy of degree day calculations in estimating the energy consumption was validated using the measured data. Secondly, the best insulation and its optimal thickness are determined during a lifespan of 50 years. Finally, the optimal insulation and its economical thickness are determined when considering the space savings by comparing the usage of nano insulating material to the traditional material PUR.

## 2. Problem Statement

Many studies use traditional insulation materials to

solve the problem of increasing energy consumption in buildings, but because of their large thickness, the used spaces in the building are reduced, which results in a reduction in the economic feasibility of buildings due to reducing the costs of rental spaces. Therefore, the research discusses the use of nano insulation materials instead of traditional insulating materials due to their thinner thickness. But these materials are expensive. As a result, this research discusses the economic viability of using nano-insulation materials. Even though nano thermal insulation materials can provide excellent thermal performance, the envelope thickness must be managed to maintain a proper balance between insulation investment costs and building energy efficiency by selecting the optimal nano insulation thickness.

## 3. Materials and Methods

### 3.1. Nano Insulation Materials

Nanotechnology has contributed to improving some conventional insulation materials such as expanded polystyrene and helped in the emergence of new advanced thermal insulation materials such as (aerogel and vacuum insulation panels) as the heat conduction occurs slowly inner the nanostructure because of the small interfaces between particles [15].

#### 3.1.1. Expanded Polystyrene with Graphite

Nanotechnology helps to improve the properties of expanded polystyrene (EPS) with the addition of graphite nanotubes during the manufacturing process which helps to decrease the thermal conductivity value by 20% of traditional eps, causing the radiant heat to be reflected hundreds of times as it moves through the insulation to slow the transfer of heat, while allowing its thickness to be reduced, and the other physical parameters are the same as

traditional EPS [15-16]. The best-known brand of this type of insulation is BASF Neopor **Figure 2** was invented in 1995. Neopor is EPS that has been coated with a fine layer of graphite. When the Neopor thickness is compared to traditional EPS, it may be lowered by 20%, allowing for the use of up to 50% less raw materials [17].

### 3.1.2. Aerogel

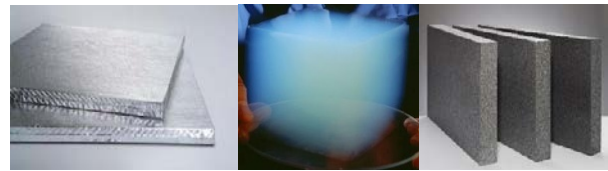
Silica aerogel is a highly porous material with up to 99.7% porosity made up of porous nano-silica and considered the lightest solid material, because of its cloudy appearance it has many nicknames such as "blue smoke", "solid air" or "frozen smoke" **Figure 2**. This material was invented in 1930 by an American chemist, Dr. Samuel Stephens Kistler by conceiving the concept of replacing the liquid phase with a gas, resulting in just a minor shrinkage of the gel [18-19]. Aerogel is a super insulation material due to its excellent characteristics, such as low thermal conductivity (0.01-0.02W/m.K) these values are lower than the thermal conductivity of air (0.025W/m.K), High mechanical strength as it is considered stronger than steel, its high fire-resistant, excellent acoustic properties, flexible, can be cut on-site [19-20]. Aerogel insulation is available on the market in several products:

- **Aerogel blanket:** aspen aerogels developed an ultra-thin aerogel blanket called (Spaceloft®). It is a highly flexible panel with a textile-like blanket available on the market in different dimensions and thicknesses range between 2-10 mm. It has a low thermal conductivity value (0.014W/m.K) and can fit well anywhere without a deficiency of rigidity and flexibility but it has low mechanical strength [21].
- **Aerogel boards:** available in the size of 2400mm x 1000mm rigid board, they are more rigid and have a greater thickness than blankets and are made by either gluing multiple layers of aerogel blankets together or binding aerogel granulate into sheets, which is normally done with a lamination. Interior insulation and external thermal insulation composite systems are two uses for boards. The latter can be attached without the use of dowels, but it is only suitable for interior use and limited exterior areas [22].
- **Aerogel plasters:** aerogel-enhanced plasters are a recent invention in the field of insulating plasters with a density of 156 kg/m<sup>3</sup> and thermal conductivity of 0.027 W/ m.K. The most used aerogel-enhanced plaster, FIXIT 222, was developed at the Swiss Federal Institute EMPA and is now commercialized. This material has a declared thermal conductivity of 0.028 W/ m. K. and contains more than 50% vol. silica aerogel. Since 2013, this material has been used to cover thousands of square meters, and its price has fallen greatly. To make FIXIT 222 plaster with a thickness of 10 mm it is required 2kg/m<sup>2</sup> of FIXIT 222 plaster [23].

### 3.1.3. Vacuum Insulation Panels

The vacuum insulation panels (VIP) were first used to

insulate refrigerators and cold shipping boxes wherein limited insulation spaces, but nowadays they are used in building insulation to provide better insulation performance five to ten times better than traditional materials with the same thickness [24]. VIP consists of a fumed silica core, a multilayer envelope (Protective Layer-Barrier Layer-Sealing Layer), and getters & desiccants **Figure 2** [25]. Panels' thickness ranges between 10-50 mm and the panel size from 100 x 100 mm to 1250 x 3000 mm [16]. The lifespan of VIP is approximately 30-50 years for building applications. The thermal conductivity of this material is 0.002 to 0.0045 W/m.K depending on containing fumed silica, but after 25 years, thermal conductivity increases to 0.007 and 0.008 W/m.K. These panels lose their ability to insulate if the inner core loses vacuum if they are cut or there is any hole in them, so the required panel dimensions must be determined in the early stage to prepare them by the manufactory [26]. To improve the quality of VIP the "VA-Q-check" system is used to measure the gas pressure inside the panels, the measurement must vary from 0.02 to 100 bar [27].



**Figure 2.** Nano insulation materials -from left to right: Eps Graphite -Silica aerogel -Vacuum insulation panels [28-10].

## 3.2. Methodology

### 3.2.1. Degree-days Method

To select the optimal insulation and its optimal thickness this study used the mathematical model of the degree-days method. The degree/day method for cooling and heating is a climate indicator that can be used to predict the energy consumption of buildings heating and cooling. It is a summary of the differences between the outside temperature and base temperatures over a specific period (month, year, etc.) [30]. The base temperature can be defined as the equilibrium point temperature at which we do not need heating or cooling systems to achieve thermal comfort [31]. The total cooling degree-day (CDD) and heating degree-day (HDD) are calculated from (1), (2) [4]:

$$CDD = \sum_1^{365} |T_{Av} - T_b| \quad (1)$$

$$HDD = \sum_1^{365} |T_b - T_{Av}| \quad (2)$$

Where  $T_b$  is the base temperature and  $T_{Av}$  is the average outside air temperature.

The base temperature varies according to the site, design, and ambitions of the designer, but usually the base

temperature for heating ranges between 16°C to 20°C while ranges between 24°C to 28°C for cooling.

### 3.2.2. Location and Climate Data

The first step to calculate heating/cooling degree-days is to select the geographic location of the building to determine the climate conditions. There are many websites through which this data can be obtained, the most famous of them is the Bizee Degree Days site (<https://www.degree-days.net>), which is characterized by its accuracy and ease to use and it contains a giant database containing accurate climate information for many sites and cities around the world [32].

### 3.2.3. Annual Energy Requirements for Heating/Cooling

Heat loss in buildings usually occurs through exterior walls, windows, ceilings, floors, and air leaks. This study focuses only on the exterior walls' heating loss. The amount of heat loss per unit area of the external walls is calculated through (3),(4) [6]:

$$Q_{H/C} = 86400 * DD * U \quad (3)$$

Where  $Q_{H/C}$  is the Annual heating loss of heating/cooling, DD is the total cooling/heating degree-day, and U is the overall heat transfer coefficient.

The overall heat transfer coefficient (U) is influenced by the structure of building external walls (the thickness and thermal conductivity of each wall layer), it can be calculated by (4) [33]:

$$U = \frac{1}{\frac{1}{h_0} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_{ins}}{k_{ins}} \dots + \frac{x_n}{k_n} + \frac{1}{h_i}} \quad (4)$$

Where  $h_0$  &  $h_i$  are combined convection and radiation heat transfer for inside and outside surface, respectively  $k_1, k_2, k_n \dots$  etc. are the thermal conductivity of wall layers,  $x_1, x_2, x_n \dots$  etc. are their thickness and  $x_{ins}, k_{ins}$  are their insulation thickness and its thermal conductivity.

The function of the thickness and thermal conductivity is known as the Thermal resistance; therefore, the overall heat transfer coefficient (U) can be written also as (5). (7) [11]:

$$U = \frac{1}{(R_i + R_w + R_{ins} + R_o)} \quad (5)$$

Where  $R_i$  &  $R_o$  are consecutively the inside & outside air film thermal resistance,  $R_w$  is the total thermal resistance of the wall layers except for the insulation layer, and  $R_{ins}$  is the thermal resistance insulation layer.

The total resistance of insulated wall ( $R_{w,T}$ ) is calculated by (6) [11]:

$$R_{w,T} = R_i + R_w + R_o \quad (6)$$

Thus, the overall heat transfer coefficient (U) can be written also as (7) [34]:

$$U = \frac{1}{R_{w,T} + R_{ins}} = \frac{1}{R_{w,T} + \frac{x_{ins}}{k_{ins}}} \quad (7)$$

The annual energy required can be calculated in the case of heating by dividing the annual heat loss by the efficiency of the heating system  $Q_H$  as (8), and in the case of cooling by dividing the annual heat loss by the cooling system coefficient of performance as (9) [11-33-34]:

$$E_{A,H} = \frac{Q_H}{\eta_s} \quad (8)$$

$$E_{A,C} = \frac{Q_C}{COP} \quad (9)$$

Where  $\eta_s$  is the energy efficiency of the heating system, and COP is the coefficient of cooling performance.

### 3.2.4. Economic Analysis and the Optimal Insulation Thickness Selection

The thermal insulation does not eliminate heat transfer but reduces it. It is known that the greater thickness of insulation, the more it leads to a reduction in the thermal conductivity of the wall, but the cost of insulation materials increases linearly with the increase in the thickness of the insulation, while the cost of heat loss decreases exponentially; Consequently, it is necessary to analyze the life cycle costs to reach the optimum economic thickness of the thermal insulation material by weighing the economic costs of the material and the extent to which it fulfills its requirements [35-36].

The life cycle cost analysis method (LCC) is used to calculate the insulation optimum thickness through the summation of insulation cost and fuel consumed **Figure 3**. The energy costs were calculated by using the present value factor (PVF) over the insulation lifetime. The present value factor depends on the inflation rate and the interest rate. The interest rate and the inflation rate are based on the adjusted interest rate ( $r$ ) as the following (10),(11) [11-33-36]:

$$r = \begin{cases} \frac{1-g}{1+g}; & i > g \\ \frac{g-i}{1+i}; & i < g \end{cases} \quad (10)$$

The PVF calculation was defined as follows (11):

$$PVF = \begin{cases} \frac{(1+r)^N - 1}{r(1+r)^N}; & i \neq g \\ \frac{N}{(1+i)}; & i = g \end{cases} \quad (11)$$

Where  $i$  is the interest rate,  $g$  is the inflation rate and  $N$  is the insulation lifetime.

Energy costs of heating/cooling per unit area, are

calculated with the following (12),(13) [6-11-33-36]:

$$C_H = \frac{E_{A,H}}{Hu} \times C_{Fuel} \times PWF \quad (12)$$

$$C_C = E_{A,C} \times C_{Fuel} \times PWF \quad (13)$$

Where  $C_{Fuel}$  is the fuel Cost.

The cost of insulation per  $m^2$  is calculated as (14) [6-11-33-34]:

$$C_{ins} = C_y \times x \quad (14)$$

Where  $C_y$  is the cost of  $m^3$  of the insulation and  $x$  is the insulation thickness.

Eventually, the total heating or cooling costs of an insulated wall according to the LCC analysis are determined by submitting the energy cost and the insulation cost as (15) [6-11-33-36]:

$$C_{t,H/C} = C_{H/C} + C_{ins} \quad (15)$$

The optimal insulation thickness is determined by minimizing the equation of the total heating or cooling costs as shown in **Figure 3**.

$$X_{opt,H} = \left\{ \frac{120\sqrt{6 \times HDD \times C_{Fuel} \times K_{ins} \times PWF}}{\sqrt{c_y \times Hu \times \eta_s}} \right\} - k \times R_{w,T} \quad (16)$$

$$X_{opt,C} = \left\{ \frac{120\sqrt{6 \times CDD \times C_{Fuel} \times K_{ins} \times PWF}}{\sqrt{c_y \times COP}} \right\} - k \times R_{w,T} \quad (17)$$

$$X_{opt,H,C} = 293.49 \times \left( \frac{\frac{HDD \times C_{Fuel} \times K_{ins} \times PWF}{c_y \times Hu \times \eta_s} + \frac{CDD \times C_{Fuel} \times K_{ins} \times PWF}{c_y \times COP}}{\eta_s} \right) - k \times R_{w,T} \quad (18)$$

The annual energy saving ( $E_s$ ) using insulation material is the difference between the amount of energy consumption without insulation and the amount of energy consumption with insulation layer, the annual energy saving can be calculated by using the following (19) [36]:

$$E_s = E_{nins} - E_{ins} \quad (19)$$

Where  $E_{nins}$  (J/m) is the energy consumption without insulation and  $E_{ins}$  (J/m) is the energy consumption with insulation.

The life cycle saving (LCS) is calculated from the difference between the saved energy cost over the lifetime and the insulation cost. The lifecycle total saving can be written as follows (20) [33]:

$$LCS = PWF \cdot C_{Fuel} \left( \frac{0.024 \left( \frac{1}{R_{w,T}} - \frac{1}{R_{w,T} + \frac{X_{ins}}{K_{ins}}} \right) HDD}{\eta_s} + \frac{0.024 \left( \frac{1}{R_{w,T}} - \frac{1}{R_{w,T} + \frac{X_{ins}}{K_{ins}}} \right) CDD}{COP} \right) - C_{ins} \quad (20)$$

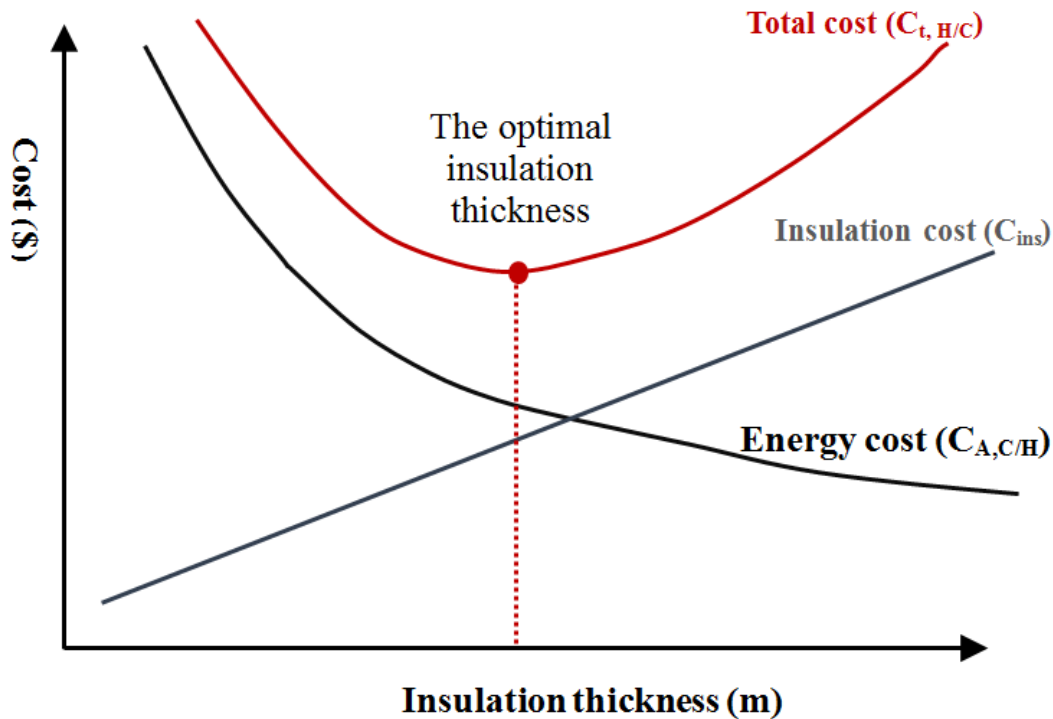


Figure 3. Selecting the optimal thickness of insulation graphically

Eventually, the payback period is calculated because it is considered a direct indicator for estimating the time required to recover the initial investment of insulation by fuel saving results from using insulation. The material thickness with the lowest payback period is the most economical material, the payback period can be calculated by (21) [33]:

$$PP = \begin{cases} \frac{\ln \left[ 1 - \frac{C_{ins} \cdot (kR_{w,T}^2 + R_{w,T} \cdot X)(g - i)}{0.024 \cdot C_{fuel} \cdot \left( \frac{HDD}{\eta_s} + \frac{CDD}{COP} \right)} \right]}{\ln \left( \frac{1+i}{1+g} \right)}; i \neq g \\ \frac{C_{ins} \cdot (kR_{w,T}^2 + R_{w,T} \cdot X)(1+i)}{0.024 \cdot C_{fuel} \cdot \left( \frac{HDD}{\eta_s} + \frac{CDD}{COP} \right)}; i = g \end{cases} \quad (21)$$

## 4. Case Studies

Nanomaterial insulation solutions have been used in the integral retrofitting of two existing buildings; the office and apartment building called Seitzstraße building located in 23 central Munich (Germany) in a humid continental climate area, and the headquarters building of the United States Department of Defense (Pentagon) located in Arlington county, Virginia (USA), in a humid subtropical climatic area Figure 4 both buildings are located in space heating-dominated climates. The target of retrofitting the outer envelope of the two-case studies by using nano insulation materials was to improve the thermal performance of the building's envelope and reduce the operating economics by reducing the energy consumption. This paper focuses on the effect of used nano insulation material in two retrofitting projects on the total life cycle cost and rationalizing energy consumption and compare it with the effect of using other nano insulation materials on building operation economics and reducing life-cycle costs to choose the optimal nano insulation material and the optimal thickness then calculating payback period to recover the cost of insulation material through saving in fuel costs because of rationalizing energy consumption by using mentioned degree-days method. Then consider the savings in space by comparing the use of nano insulation material with the traditional material PUR. Table 1 compares insulation materials. (*The prices of 1€1.1= 6\$ in 15.03.21*)

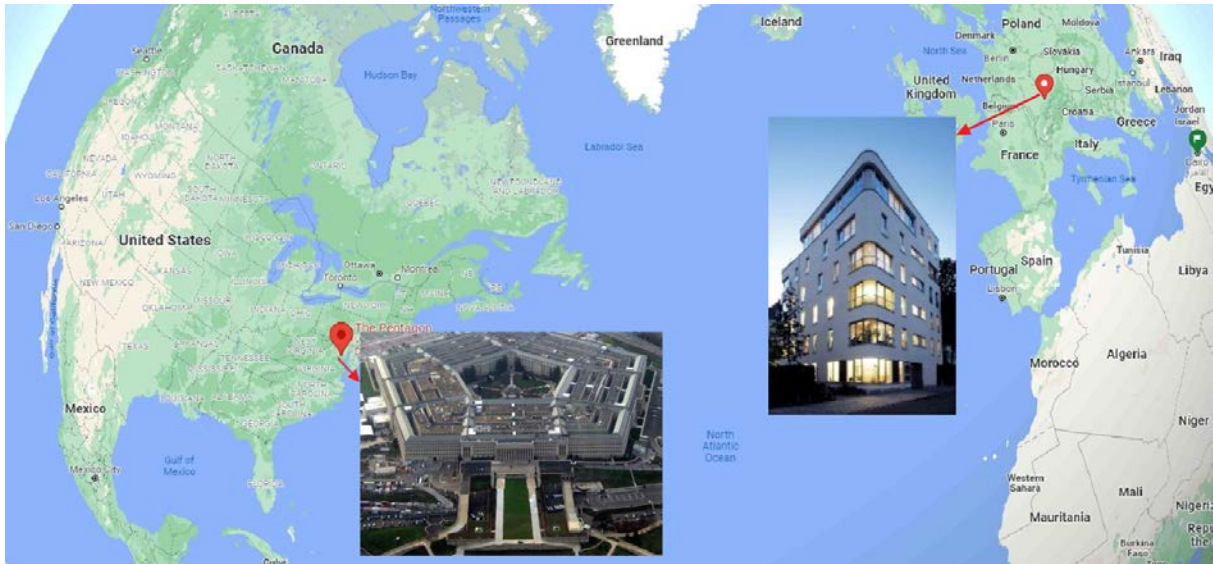
**Table 1.** Insulation materials data (Thermal conductivity & costs)

Insulation material	Thermal conductivity $k_{ins}(W/mK)$	Cost (\$/m <sup>3</sup> )
EPS with graphite	0.031 [15]	168 [38]
Aerogel blanket	0.014 [21-37]	1500 [39]
Aerogel boards	0.016 [22]	1950 [40]
Aerogel plasters	0.028 [22]	462 [41-42]
VIP	0.007 [26]	2314 [42-43]
PUR	0.028[13]	346.1[13]

### 4.1. Seitzstraße Building

Seitzstraße building was designed by architect Martin Pool, built between 2000 and 2005. The building is mixed-use as it consists of seven floors, the first three floors are of administrative use containing six offices and the rest of the floors are residential containing six apartments, and there are two floors with basement garages. The floor plan of the building is rectangular, the units are divided into rooms on the outer wall and grouped around a core that collects service and the building contains large windows in its corners **figure 5**. The structure of the building is compact and divided into warm and cold zones. Inside and outside spaces are separated and well-insulated spaces. Building located on a site that is heavily overshadowed by tall buildings to the south, east, and west, thus that was a necessity to achieve a low-energy building proved the primary challenge. The building's ventilation is automatic, with a heat exchanger. Groundwater cools the offices directly and tempers the air in the summer and winter. A small heat-led combined heat and power unit provides heat, and the surplus electricity is fed into the grid, accounting for approximately a third of the building's energy needs [26-44].

Due to the high property prices in this part of Munich, as well as the customer's desire to build according to the super-building standard, the Seitzstraße building is the first building with more than two floors and the first privately funded building to be fully isolated using vacuum insulation panels (VIP) to save space and energy. In 2005, the structure was awarded the German Building Physics Prize and the Bavarian Energy Prize in 2006. The building is considered the first building in Munich to achieve an ultra-low energy consumption, as the building's heating load per year reaches (20 kWh/m<sup>2</sup>), while similar buildings in the city have a heating load of (200-300 kWh/m<sup>2</sup>) per year, and buildings that consume (30-70 kWh/m<sup>2</sup>) are classified as "low energy" houses [44-47].



**Figure 4.** Geographic locations of case studies: the left location of the Pentagon building (in the USA) and the other of Seitzstraße building (in Germany) [26-45-46]

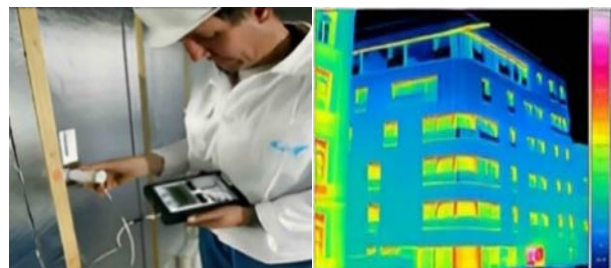
The envelope of the building that consists of a vapor barrier was placed on the concrete with a thickness of 2 cm, 850 m<sup>2</sup> of VIP panels were installed in the eastern, southern, and western façades and the ceiling of the last floor in standard sizes 45 x 200 cm with thickness 2cm. The VIP panels were attached between recycled compressed polyurethane battens, the panels were checked against any voids through a sensor (VA-Q-VIP) as in Error! Reference source not found. And after that, the sheets with a thickness of 8 cm of polyurethane (PUR) were installed to protect VIP panels from heat stress, humidity, and mechanical damage to lengthen their life, then PUR sheets were covered with plaster. VIPs were also incorporated into the window panels at various locations. VIPs are sandwiched between two enameled glass panes and kept in an altered wooden window frame [44-47]. The installation of VIP panels required a set of demands during the planning and running stages:

- The façade drawn on a 1 x 1 m grid for proportional purposes was a fortunate coincidence, since it significantly minimized the number of different panel formats available.
- Low tolerances on dimensions and wall straightness were necessary on the building core, which needed extra precision.
- With a sketch and catalog of each column, the façade company took an accurate survey of the building core when it was designed.
- The panels were shipped in good condition and placed in ship containers awaiting construction.



**Figure 5.** (on the left) The floor plan, offices, level 1, (on the right) The floor plan, apartments, level 3 [48]

A thermal image of the building was taken, and it was found that there are no heat retention places in the building except in limited areas, as in **Figure 6**, which is often at the edges of the windows, and it has been found that no damage has occurred in the panels. The use of VIPs also helped in increasing the useable spaces in the building by 10% due to the lack of thickness of VIP panels with a total thickness of 12cm, while to achieve the same thermal insulation efficiency with traditional insulation materials, the insulation thickness reaches 25 cm, and this has resulted in increasing of 125m<sup>2</sup> of useable floor spaces, or about one-half of a floor [44-47].



**Figure 6.** (on the left) testing VIP by VA-Q-VIP sensor,(on the right) the thermal image of Seitzstraße building [26-47]

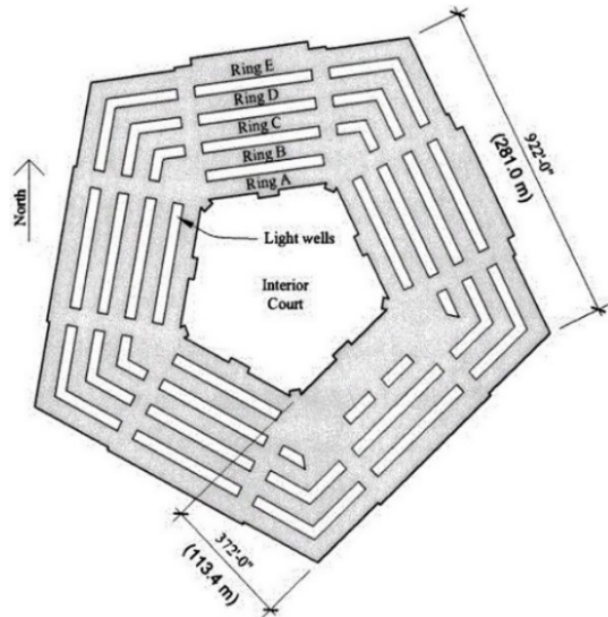
**Table 2** shows the parameters used in the calculations of the optimal insulation thickness including the outer wall properties coefficient of thermal conductivity & heat transfer coefficients, the values for heating & cooling degree-days for building location, the basic heating and cooling temperatures were set at 20°C and 26°C, respectively, the fuels used for heating & efficiency of heating system, the price of fuel and the financial parameters.

**4.2. The Pentagon Building**

The Pentagon, the United States Department of Defense's headquarters, is one of the world's biggest office buildings with a total floor area of 6.6 million square feet (613,000 m<sup>2</sup>). The building was constructed in 16 months by the US Army Corps of Engineers between September 1941 and January 1943 with wartime urgency. It has five sides and consists of five floors and two floors underground. It is further divided into five circumferential rings which are numbered A to E from the inner courtyard to the outside Figure 7. The rings are divided by light wells in the upper three floors. The interior well's second well stretches to the ground for most of its length, serving as an interior driveway known as AE drive [49].

The pentagon shape was chosen to create shorter walking distances within the building, as it is less than 30:50% of the rectangle, so it does not take more than 6 minutes to walk between any two points. The Pentagon's renovation started in the late 1980s when the structure approached its 50th year of operation, but during renovations on September 11, 2001, at 9:38 a.m., a plane

crashed into the Pentagon's first floor. The effect, deflagration, and fire resulted in the deaths of 189 people and the destruction of a portion of the building. The American Society of Civil Engineers formed a building performance study (BPS) team the same day to assess the damaged structure and make recommendations, the building was then renovated and repaired by replacing the damaged portions of the structure, with the renovation process being expanded to address the shortcomings revealed by the attack [51-52-53].

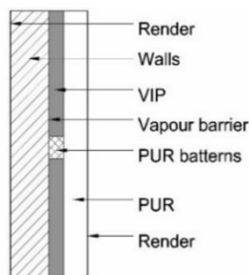


**Figure 7.** Overall plan of the Pentagon at the upper stories [50]

**Table 2.** The parameters used in the Seitzstraße building calculations

Parameter	Value
<b>Location &amp; Climate data [32-45]</b>	
Building site coordinates	48°08'32.5"N 11°35'05.5"E
Station code (Name)	10863(WeihenstephandÄrnast,DE)
Station coordinates	48°40'N, 11°11.69'E
HDD <sub>20</sub>	3950
CDD <sub>26</sub>	17

**Wall structure data [6-54-55]**



**Figure 8.** wall section in the Seitzstraße building

Table 2. Continued

0.02m Internal plaster	k=0.87 W/mK
0.08m expanded polyurethane (PUR)	k= 0.028 W/mK
Nano insulation layer (vacuum insulated panels)	
0.24m Concrete wall	k=1.75 W/mK
0.02m External plaster	k=0.87 W/mK
Inside Air Resistance	0.130 m <sup>2</sup> K/W
Outside Air Resistance	0.040 m <sup>2</sup> K/W
	R <sub>w,T</sub> =3.21 m <sup>2</sup> K/W
	U=0.31 W/m <sup>2</sup> K
Nano insulation layer data (VIP) [22-43-44]	
Thermal conductivity (k)	k=0.007 W/mK
thickness	0.02m
Material cost (C <sub>inscluding</sub> )	2314\$/m <sup>3</sup>
Fuel data (Fuel - Oil ) [6-56]	
Lower heating value (Hu)	40.594*106 j/kg
Price (C <sub>Fuel</sub> )	0.928 \$/kg
The efficiency of the heating system (η <sub>s</sub> )	0.8
Coefficient of performance of cooling system (COP)	2.5
Financial parameters [57-58-59]	
Interest rate (i)%	0
Inflation rate (g)%	0.028
Lifetime (N)	50 years
Present worth factor (PWF)	26.74
Rent cost	19.9\$/m <sup>2</sup>

The walls of the building before the renovation were non-insulated solid walls with very poor thermal performance. Therefore, the major renovation included an increase in the thermal resistance of the walls by insulating them within a metal frame on the inner part of the building and applying one layer of Space loft® (10 mm, 0.4”) with an area of 8361.3 m<sup>2</sup> behind the metal stud frame wall and new cavity insulation to the existing solid masonry wall. Spray adhesive and insulation pins were used to add aerogel Space loft® insulation. An infrared image of the interior walls was taken before and after using aerogel Space loft®, and it was found that there are thermal bridges in through metal frames before using Space loft®, but after using it thermal bridges completely disappeared as shown in Figure 9. The use of Space loft® improved the thermal resistance of the walls by 23% resulting from an annual energy saving of 122,797 kWh (419 MMBtu), a 48.6 thousand pounds reduction in annual emitted CO<sub>2</sub>. In addition to space-saving, aerogel insulation would have yielded much more advantages if it had been used earlier in the design process:

- Save up to 40,000 sq ft (3716m<sup>2</sup>) of space.
- Better energy efficiency.
- Lower cost of installation.
- Higher CO<sub>2</sub> reduction [60-61]

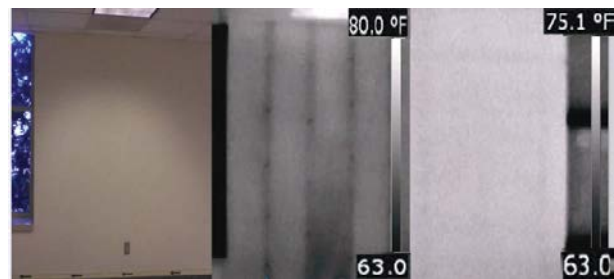


Figure 9. From left to right: visible image of pentagon wall-an infrared image of the wall before the use of the aerogel insulation- an infrared image of the wall after the use of the aerogel insulation shows the disappearance of thermal bridges after using the insulation [60]

The parameters of calculation used to determine OIT in the building are presented in Table 3 including the HDD & CDD values for base temperature 16°C and 25°C, respectively, wall structure properties, fuel cost, insulation material properties & cost and PWF value.

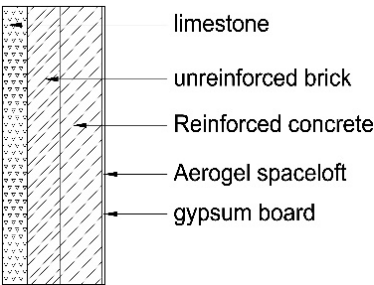
## 5. Results and Discussion

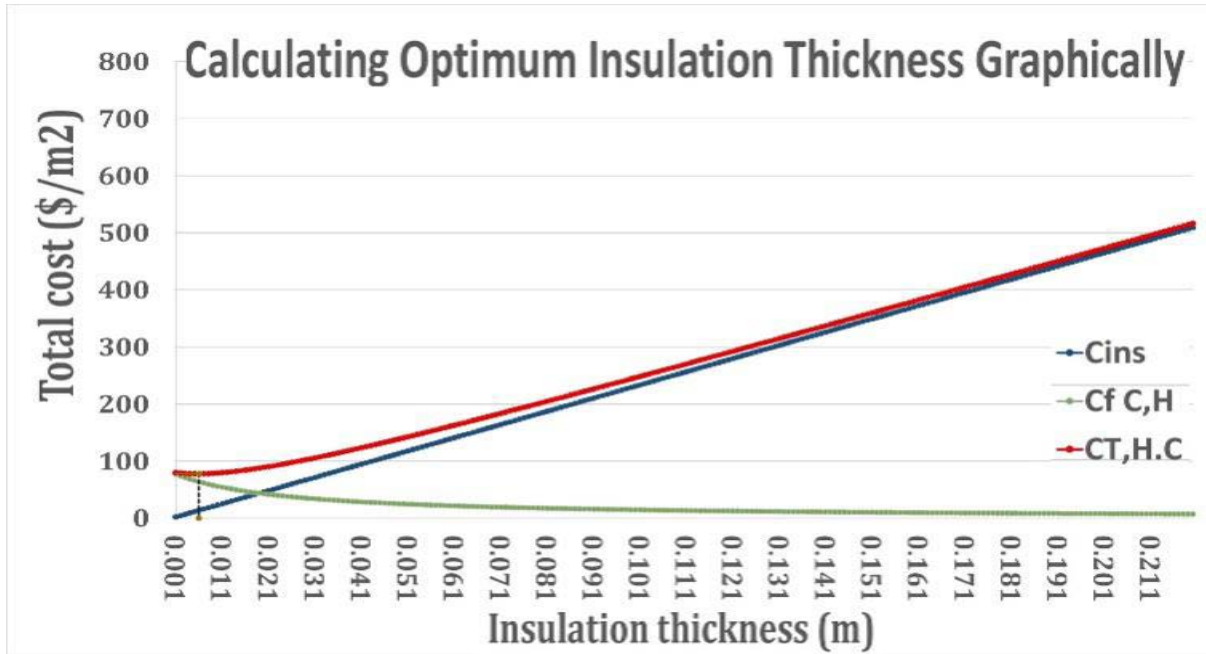
By comparing the actual measured energy loads in Seitzstraße building with the mathematical technique

(degree day method) which is used in calculating the energy loads to validate the accuracy of the degree days method used in this study. The actual measured energy consumption (for heating) in the Seitzstraße building was 20 kWh/m<sup>2</sup> after using vacuum insulated panels, and the

mathematical approach of energy consumption by using Eq. No. (8) resulted in building heating 19.53 kWh/m<sup>2</sup>. The mathematical value of energy consumption is extremely close to the real energy consumption (error rate 2.35%), which is an acceptable value.

**Table 3.** The parameters used in the pentagon building calculations

Parameter	Value
Location & Climate data [32-45]	
Building site coordinates	38°52'30.2"N 77°03'20.1"W
Station code (Name)	KDCA (Washington national airport, VA, Us )
Station coordinates	38°85'N, 77°03'W
HDD <sub>16</sub>	1608
CDD <sub>28</sub>	93
Wall structure data [62-63-64]	
	
<b>Figure 10.</b> wall section in the Pentagon building	
0.15m Limestone	k=0.8 W/mK
0.20m Unreinforced brick	k= 0.4 W/mK
Nano insulation layer (Aerogel Blankets-Space loft®)	
0.25m Reinforced Concrete	k=1.75 W/mK
0.0064m gypsum board	k=0.17 W/mK
Inside Air Resistance	0.130 m <sup>2</sup> K/W
Outside Air Resistance	0.040 m <sup>2</sup> K/W
	R <sub>w,T</sub> =1.038 m <sup>2</sup> K/W
	U=0.96 W/m <sup>2</sup> K
Nano insulation layer data (Aerogel Space loft®) [21-39-60]	
Thermal conductivity (k)	k=0.014W/mK
thickness	0.01m
Material cost ( C <sub>ins</sub> )	1500 \$/m <sup>3</sup>
Fuel data (Natural gas ) [6-65]	
Lower heating value (Hu)	34.526*106 j/kg
Price ( C <sub>Fuel</sub> )	0.37 \$/m <sup>3</sup>
The efficiency of the heating system (η <sub>s</sub> )	0.93
Coefficient of performance of cooling system (COP)	3
Financial parameters [66-67-68]	
Interest rate (i)%	0.0025
Inflation rate (g)%	0.0226
Lifetime (N)	50 years
Present worth factor (PWF)	31.39
Rent cost	475 \$/m <sup>2</sup>



**Figure 11.** Determination of optimal insulation thickness of vacuum insulated panels using economical analyses for exterior walls in the Seitzstraße building

**Table 4.** Optimum insulation thicknesses, life cycle cost, energy savings, and payback periods for nano and traditional thermal insulation in the Seitzstraße building

Insulation material	Optimal thickness (m)	Energy saving (kwh/m <sup>2</sup> . Year)	LCC (\$/m <sup>2</sup> )	LCS (\$/m <sup>2</sup> )	Payback period (years)
Used VIP thickness	0.02	17.38	89.25	8.03	3.03
VIP	0.006	8.76	77.99	3.23	1.97
<b>EPS with graphite</b>	<b>0.12</b>	<b>20.18</b>	<b>56.98</b>	<b>24.24</b>	<b>1.11</b>
Aerogel blanket	0.004	3.01	80.58	0.64	2.25
Aerogel boards	-0.005	0	0	0	∞
Aerogel plasters	0.036	10.38	74.62	6.60	1.75
PUR	0.055	14.01	69.42	11.79	1.52

The economical optimal insulation thickness of vacuum insulated panels is 6 mm Figure 11. As it has the minimum total cost of 77.9 \$/m<sup>2</sup> achieves a saving in life cycle costs of 3.2 \$/m<sup>2</sup> while the used thickness in the building has the total cost of 89.2 \$/m<sup>2</sup> achieves a life cycle cost savings by 8.03 \$/m<sup>2</sup>.

Table 4 summarizes the values of the optimum insulation thickness, energy saving, the life cycle cost, the life cycle saving, and payback period for five different nano insulations. According to the results, it is found that the optimum insulation thickness varies relatively in a

wide range of 4 to 120 mm. Aerogel boards did not achieve economic feasibility.

EPS with graphite is the optimal insulation with a thickness of 120 mm in the Seitzstraße building as shown in. Figure 12, Figure 13. Because it has the minimum life cycle cost, the maximum energy saving and life cycle saving, and the shortest payback period but it is observed that the optimal thickness of this material is the largest as Figure 12 which will reduce the used areas and rental costs.

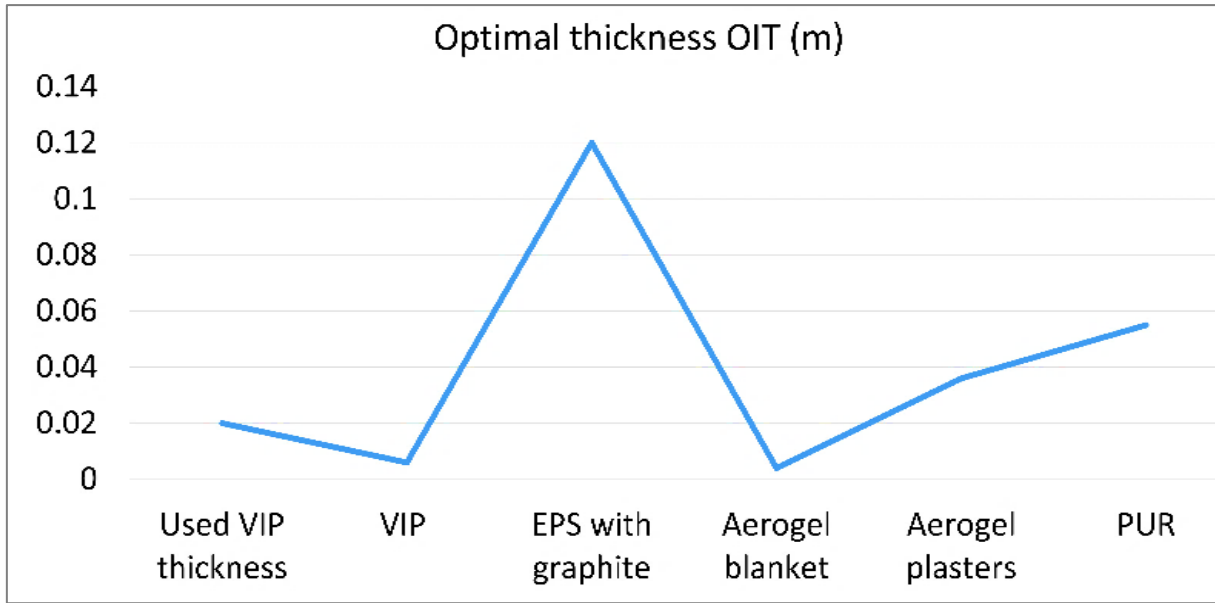


Figure 12. Variation of the optimal thickness of insulations depending on life-cycle cost analysis of the Seitzstraße building

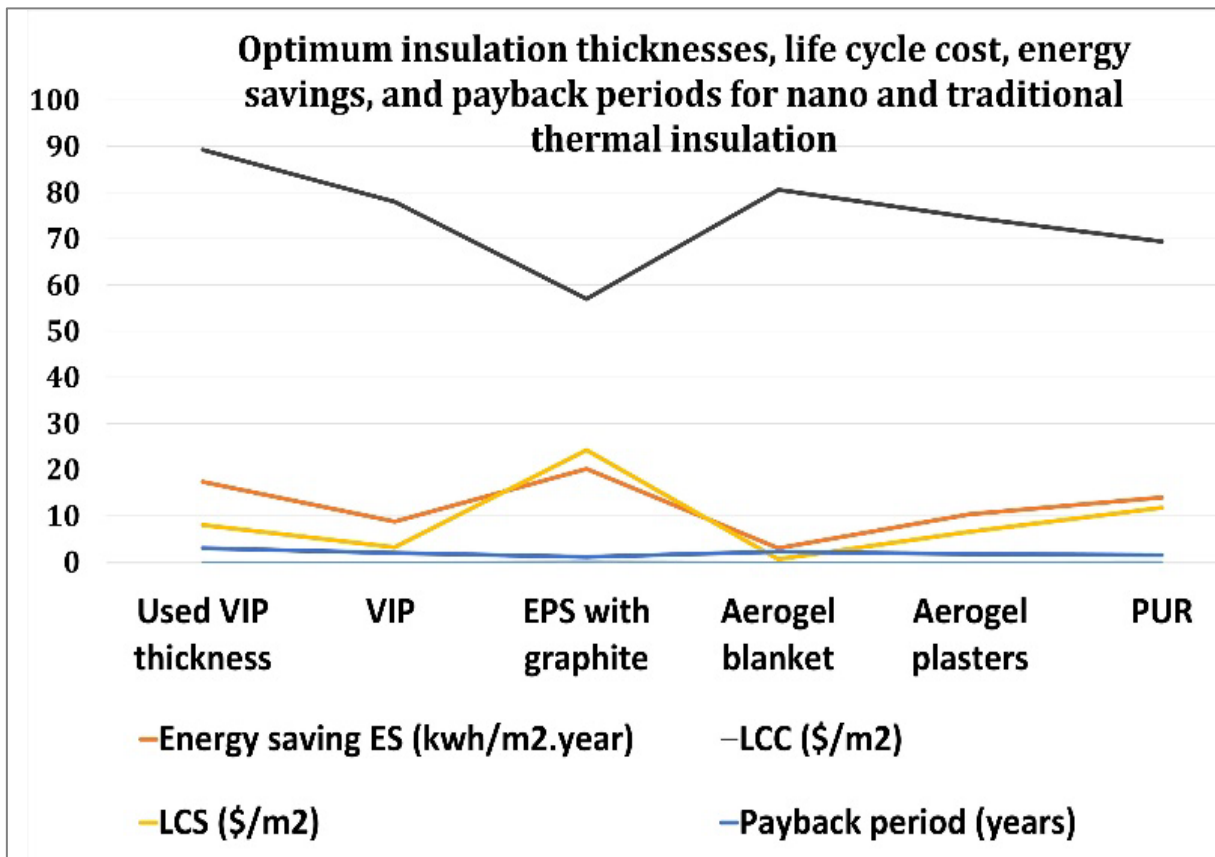


Figure 13. Total costs, energy-saving, and payback period versus insulation optimal thickness showing the optimal insulation EPS with graphite in the Seitzstraße building

In the case of considering the savings in spaces for calculating the optimal nano insulation and the optimal thickness by comparing the use of nano insulation material with the traditional material expanded polyurethane (PUR) as shown in Table 5.

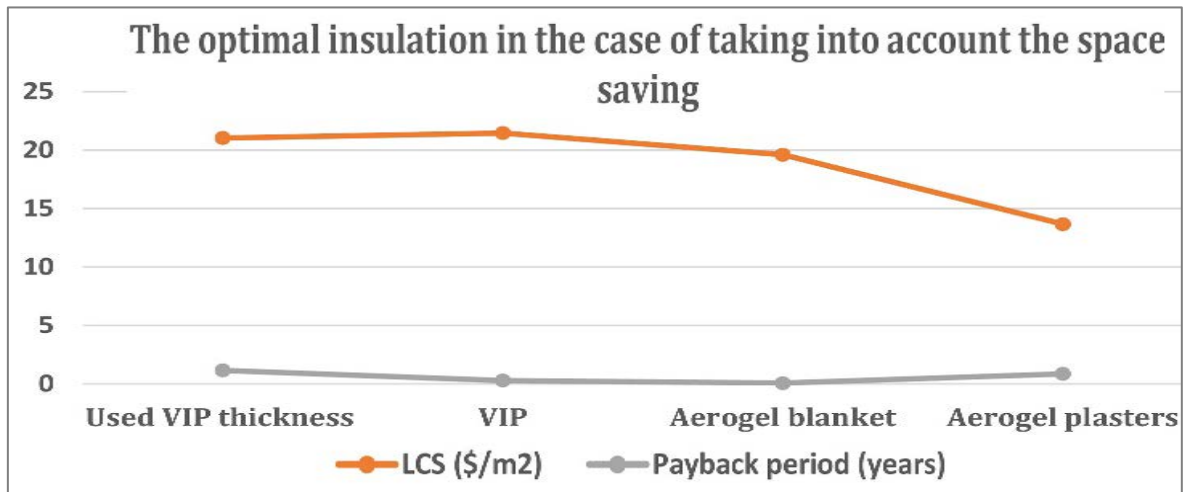
**Table 5.** A comparative analysis of life cycle savings between nano insulation materials when space savings is taken into account in the Seitzstraße building

Nano insulation material	Area saving (m <sup>2</sup> )	LCS (\$/m <sup>2</sup> )	Payback period (years)
Used VIP thickness	33.56	21.04	1.16
VIP	46.99	21.44	0.29
EPS with graphite	-62.33	0.085	315.84
Aerogel blanket	48.91	19.59	0.07
Aerogel plasters	18.22	13.66	0.85

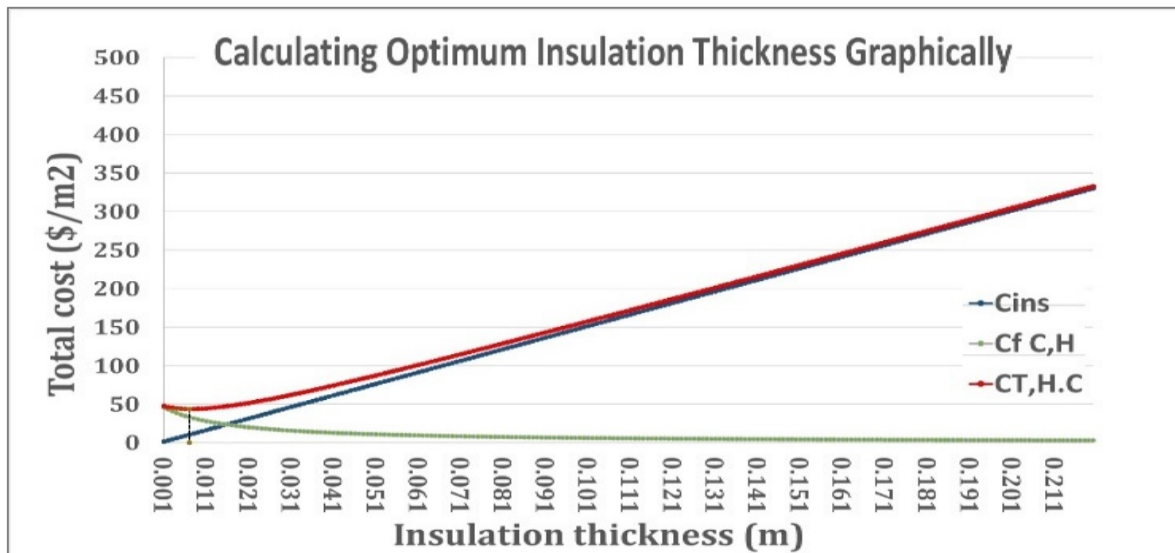
EPS with graphite could not attain economic feasibility when taking into consideration the space savings due to

its large thickness. The calculations for aerogel board insulation were not completed since their application in this building was not economically viable. Aerogel blanket nano insulation is the optimal economical insulation in the Seitzstraße building as it has the shortest payback period when space savings are considered, as well VIP insulation can be considered the economical insulation as it has the maximum life cycle saving as presented in Figure 14.

In the pentagon building the recorded energy consumption (for heating/cooling) after applying aerogel blankets (Space loft®) is 15 kWh/ m<sup>2</sup>, and the mathematical approach of energy consumption by using Eq. No. (8) Gives a value of 16.5 kWh/m<sup>2</sup> for heating and cooling in the building. The real energy consumption is fairly close to the mathematical value of energy consumption (Error rate 10%) and it is an acceptable value.



**Figure 14.** Variation of life cycle saving and the payback period when space savings is considered in the Seitzstraße building



**Figure 15.** Determination of optimal insulation thickness of vacuum insulated panels using economical analyses for exterior walls of the Pentagon building

The economical optimal insulation thickness of applied insulation (aerogel Space loft®) is 7mm as presented in Figure 15 which has the minimum total cost of 43.7 \$/m<sup>2</sup> and saves 5.2 \$/m<sup>2</sup> along with the lifespan of the material, while the used thickness (10 mm) has the total cost of 43.6 \$/m<sup>2</sup> achieves a decreasing in life cycle cost savings by 5.08 \$/m<sup>2</sup>.

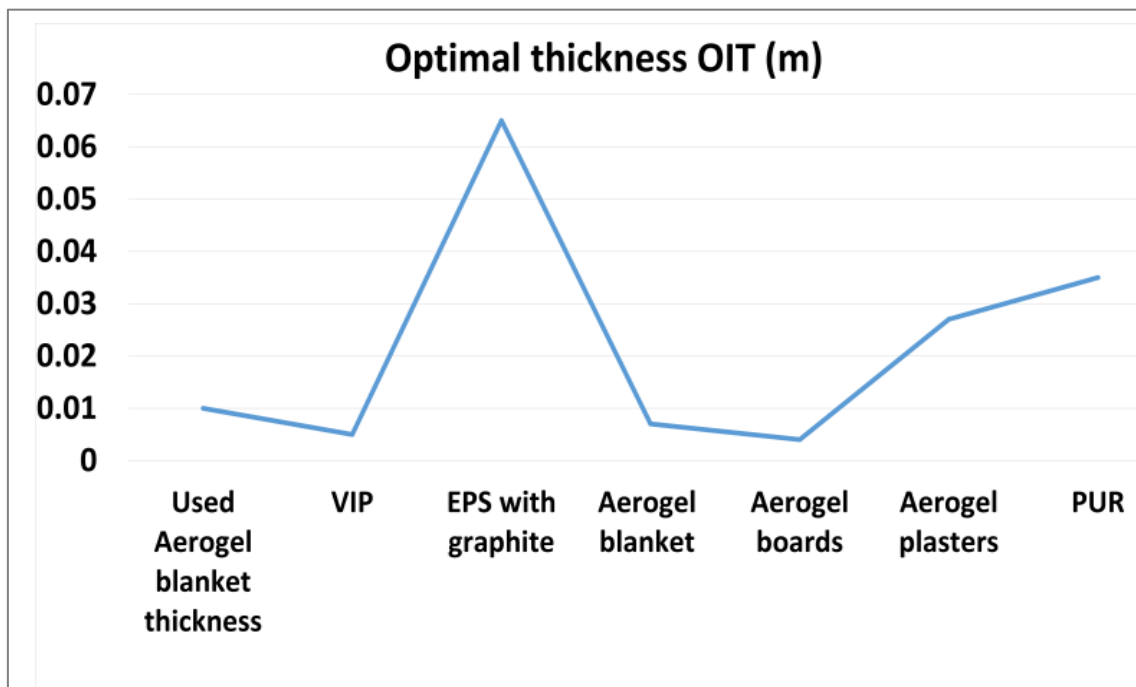
**Table 6** presents the variation of insulation optimal thickness due to material type depending on the life cycle cost, the life cycle saving, and payback period values. The

economic insulation thickness varies between 4 and 65mm for exterior insulated walls.

EPS with graphite is the optimal insulation with a thickness of 65 mm in the pentagon building as shown in Figure 16, Figure 17. Because it has the minimum life cycle cost, the maximum energy saving, life cycle saving, and the shortest payback period but it is observed that the optimal thickness of this material is the largest as shown in Figure 17 which will reduce the used areas and rental costs.

**Table 6.** Optimum insulation thicknesses, life cycle cost, energy savings, and payback periods for nano and traditional thermal insulation of the Pentagon building

Insulation material	Optimal thickness (m)	Energy saving (kwh/m <sup>2</sup> .year)	LCC (\$/m <sup>2</sup> )	LCS (\$/m <sup>2</sup> )	Payback period (years)
Used Aerogel blanket thickness	0.01	16.7	43.67	5.08	2.53
VIP	0.005	16.59	40.76	11.22	1.97
<b>EPS with graphite</b>	<b>0.065</b>	<b>26.79</b>	<b>27.25</b>	<b>21.46</b>	<b>1.11</b>
Aerogel blanket	0.007	13.23	43.76	5.24	2.25
Aerogel boards	0.004	7.89	32.79	1.76	2.76
Aerogel plasters	0.027	19.59	38.02	11.26	1.76
PUR	0.035	22.23	34.47	14.81	1.52



**Figure 16.** Variation of the optimal thickness of insulations depending on life-cycle cost analysis of the Pentagon building

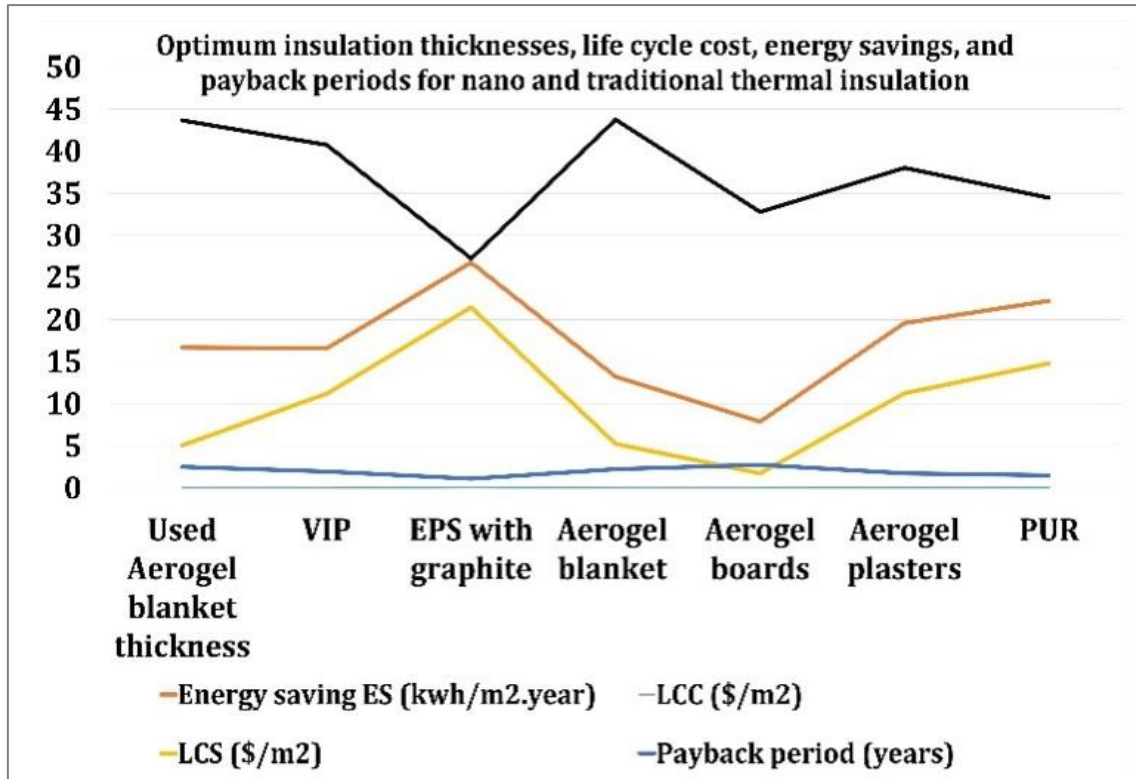


Figure 17. Total costs, energy-saving, and payback period versus insulation optimal thickness showing the optimal insulation EPS with graphite in the Pentagon building

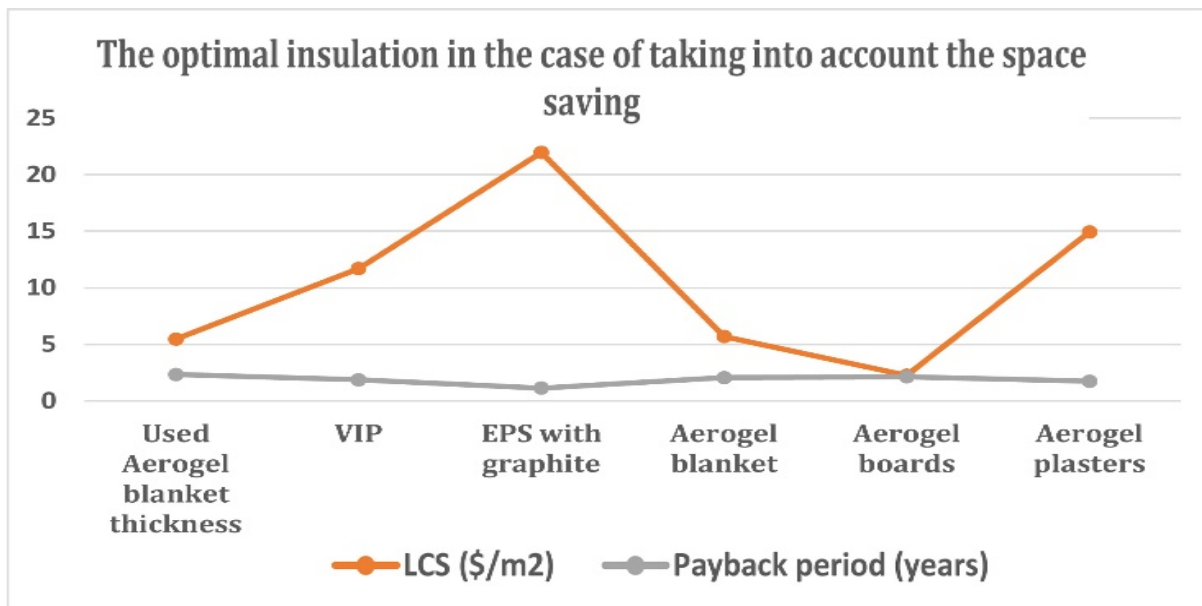


Figure 18. Variation of life cycle saving and the payback period when space savings is considered showing the optimal insulation EPS with graphite In the Pentagon building

**Table 7.** A comparative analysis of life cycle savings between nano insulation materials when space savings is taken into account of the Pentagon building

Nano insulation material	Area saving (m <sup>2</sup> )	LCS (\$/m <sup>2</sup> )	Payback period (years)
Used Aerogel blanket thickness	523.75	5.48	2.35
VIP	628.5	11.71	1.88
EPS with graphite	-628.5	21.95	1.14
Aerogel blanket	586.6	5.69	2.07
Aerogel boards	649.45	2.26	2.15
Aerogel plasters	167.6	14.94	1.74

When determining the appropriate nano insulation and thickness, the space savings are taken into account by comparing the use of nano insulation materials with the traditional material expanded polyurethane (PUR) as presented in **Table 7**.

When it comes to determine the optimal nano insulation and its optimal thickness, EPS with graphite is also the most cost-effective option inside the Pentagon despite its large thickness; it provides the quickest payback time and the greatest life cycle cost savings as presented in **Figure 18**.

## 6. Conclusions

Excessive insulation and low insulation are not acceptable from an economic perspective. Extreme insulation requires a large upfront expenditure, whereas poor insulation results in high heating and cooling energy expenses. To reduce the overall cost, a balanced insulation scale must be found. This study focuses on choosing the appropriate insulation and the optimal thickness to ensure energy savings and reduce building operating economics. The yearly heating and cooling transmission loads of the building under static conditions were estimated using the degree-day method concept which is the most common method for calculating loads to determine the optimal thickness of nano insulation materials. The degree-day concept considers climate conditions, wall composition, insulation type & cost, energy cost, and other economic parameters.

The calculations for the chosen two existing case studies geographical regions of (Germany) Seitzstraße building and (USA) the Pentagon building are based on life-cycle cost analysis of nano insulations through calculating their efficiency in energy savings & payback periods over their lifespan to optimize the insulation thickness to reduce building operating costs. The accuracy of the model is validated by the measured data.

In the Seitzstraße building (Germany), the results show that optimum insulation thicknesses of nano insulations vary between 0.004 and 0.12 m, energy savings vary between 8 % and 55%, and payback periods vary between 1.11 and 3.03 years. The optimal insulation thickness is

0.006 m for vacuum insulation panels, 0.12 m for expanded polystyrene with graphite, 0.004 m for aerogel blanket, 0.036 m for aerogel plasters and aerogel boards did not achieve economic feasibility. The EPS with graphite is considered optimal insulation, with a thickness of 0.12m because it has the lowest life cycle cost, the greatest energy & life cycle savings, and the quickest payback time. When considering the space-saving, EPS with graphite was unable to achieve economic feasibility because of its substantial thickness and the most cost-effective insulation is aerogel blanket nano insulation as it saves 48.91 m<sup>2</sup> in available spaces which leads to a lifecycle saving of 19.59 \$/m<sup>2</sup> and it has the shortest payback period, as well as VIP insulation can be considered the economical insulation since it has the greatest life cycle savings when space savings are considered.

In the Pentagon building, the results show that optimal nano insulation thicknesses range from 0.005 to 0.065 m, energy savings range from 19 % to 66%, and payback durations range from 1.11 to 2.76 years. The optimal insulation thickness for vacuum insulation panels is 0.005m, 0.065 m for expanded polystyrene with graphite, 0.007 m for Aerogel blanket, 0.004 m for Aerogel boards, and 0.027m for Aerogel plasters. EPS with graphite is considered optimal insulation, with a thickness of 0.065, because it has the lowest life cycle cost, the greatest energy and life cycle savings, and the quickest payback time. When considering space-saving, in the Pentagon, EPS with graphite is likewise the most cost-effective solution. Despite its enormous thickness, it has the fastest payback period and the most cost reductions across the life cycle, as it saves in the life cycle cost by 21.95 \$/m<sup>2</sup> and it has the shortest payback period of 1.14 years.

These findings highlight the value of nano thermal insulation in terms of energy savings. In comparison to traditional insulation materials, the results show that nano thermal insulation allows significantly thinner structures and greater available areas in buildings. The investigations were performed with the aid of a model created with Microsoft EXCEL sheets. It was constructed based on real-world economic and technical aspects.

It's recommended that:

- Insulating building envelopes from the outside is

recommended to cut thermal bridges and save energy consumption.

- The optimal insulation studies and selecting the economical thickness should be done at the design stage to help in achieving the greatest economic savings.
- The optimal insulation calculations should be done individually for each building because the findings of various buildings for the same location vary based on several aspects like wall structure and the used fuel type.
- It is important to encourage the use of nanotechnology applications in the field of thermal insulation to help in reducing building economies and solve energy problems.
- Efforts should be done to make nano insulation materials cheaper.

## 7. Research Limitations

The implementation of selecting the optimal insulation and its thickness calculation approach is well known for estimating the economic benefits of external wall insulation. However, it should be kept in mind that since it depends on the degree-days method it considered assumptions that might cause deviation from reality in some cases because it is assumed that the air conditioner is turned on 24 hours a day, seven days a week, all year. This may not be the case in a sizable percentage of

buildings, and it may not reflect the situation in all case studies under consideration. Consequently, in the study cases used in the research, the amount of divergence from the actual results was verified, and by comparing the results, the amount of variation was extremely little.

The findings of this research are unique to the given case studies and the different locations, degree-days insulation types and prices, fuel prices, cooling system COP, heating system efficiency, and other economic parameters would result in different optimal thicknesses.

## 8. Future Works

The future research direction will focus on designing a software application to make it easier to compute the optimal economic thermal insulation thickness by resolving the difficulty of calculating equations repeatedly. More in-depth economic studies are needed to explore the feasibility of using nanomaterials in the thermal insulation of buildings in the present and future. Moreover, future works researchers should investigate developing the degree day method computation by creating a daily plan in the future. Despite the fact that this may be a time-consuming data gathering task, it is worth investigating to see how much deviation will occur. Finally, the building's orientation should be taken into account when calculating the optimum nano insulation thickness to obtain highly accurate results. Besides, consider the environmental effects of installing the optimal nano insulation materials.

Nomenclature			
C	Cost, \$	X	material thickness, m
CDD	cooling degree-day, °C- day	Subscripts	
COP	Cooling performance coefficient	A, C	Annual, cooling
DD	degree-day, °C- day	A, H	Annual, Heating
E	annual energy consumption per unit area of external wall J/m <sup>2</sup> -year	Av	Average
g	inflation rate, %	b	base
h	surface heat transfer coefficient, W/m <sup>2</sup> K	C	Cooling
HDD	Heating degree-day, °C- day	Fuel	Fuel
Hu	Lower heating value, J/ kg, J/ m <sup>3</sup> , J/kW h	H	Heating
i	Interest rate, %	H, C	Heating and Cooling
k	coefficient of thermal conductivity, W/m-°k	H/C	Heating or cooling
LCC	life cycle cost	i	inside
LCS	life cycle saving	ins	m <sup>2</sup> of Insulation
N	The lifetime of material, year	nins	non-insulation
OIT	optimal insulation thickness	o	outside
PP	payback period, year	opt	Optimal thickness
PUR	Expanded polyurethane	r	Actual interest rate
PWF	present worth factor	S	Saving
Q	heat transfer per unit area of external wall, W/ m <sup>2</sup>	t	total
R	thermal resistance, m <sup>2</sup> -k/W	w	Wall
T	Temperature	w,t	total wall excluding insulation material
U	heat transfer coefficient, W/m <sup>2</sup> -°k	y	m <sup>3</sup> of insulation
VIP	Vacuum insulation panel		Greek symbols
		η <sub>s</sub>	heating system efficiency, %

Appendix

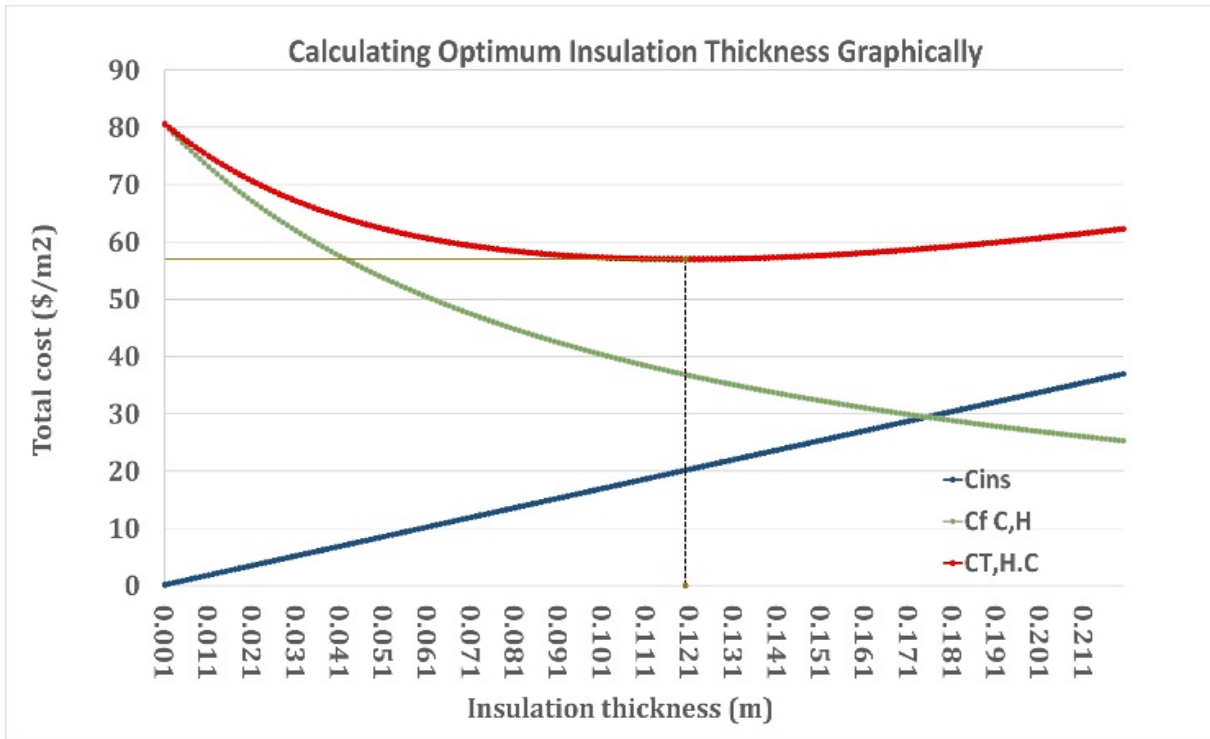


Figure 19. Determination of optimal insulation thickness of EPS with graphite using economical analyses for exterior walls in Seitzstraße building

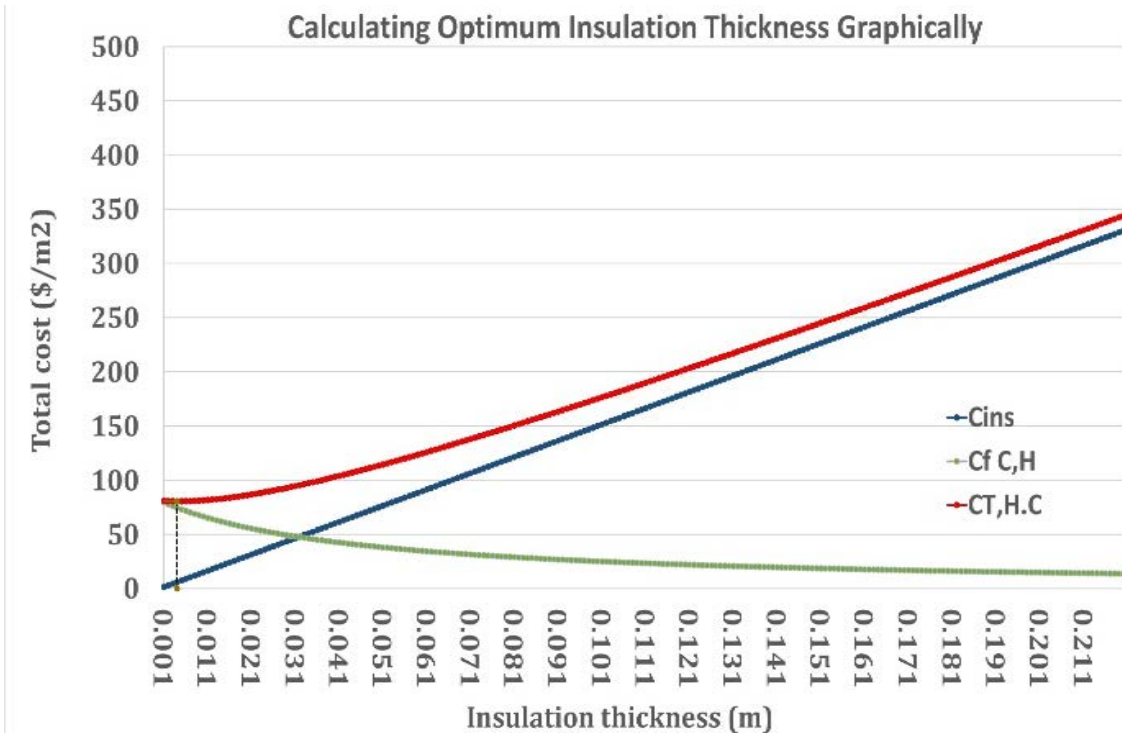


Figure 20. Determination of optimal insulation thickness of Aerogel blanket using economical analyses for exterior walls in Seitzstraße building

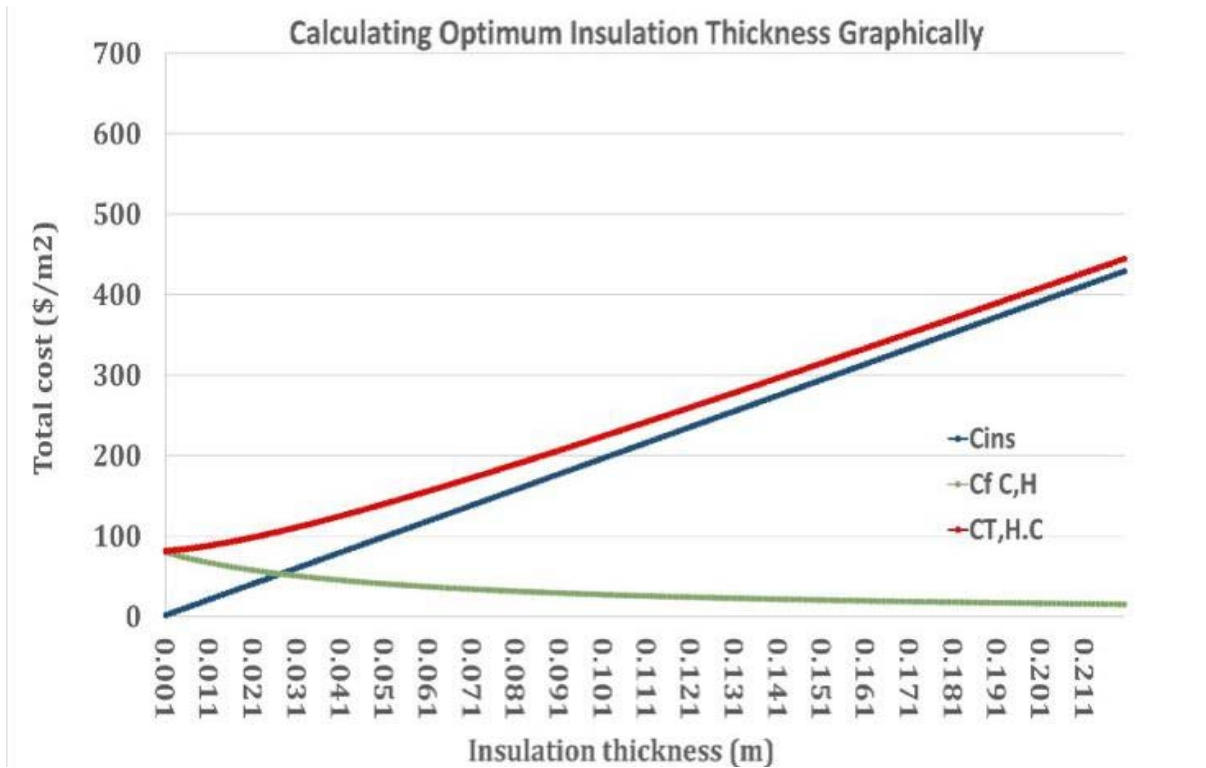


Figure 21. Determination of optimal insulation thickness of Aerogel boards using economical analyses for exterior walls in Seitzstraße building

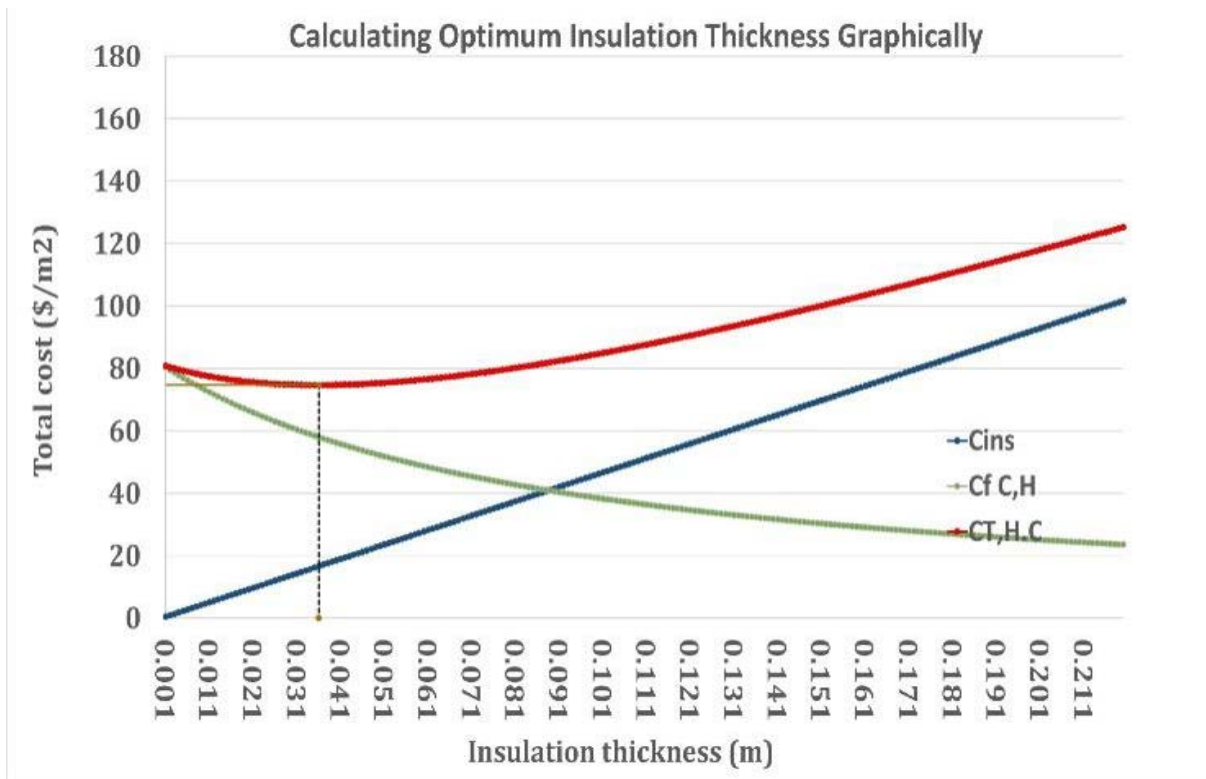


Figure 22. Determination of optimal insulation thickness of Aerogel plaster using economical analyses for exterior walls in Seitzstraße building

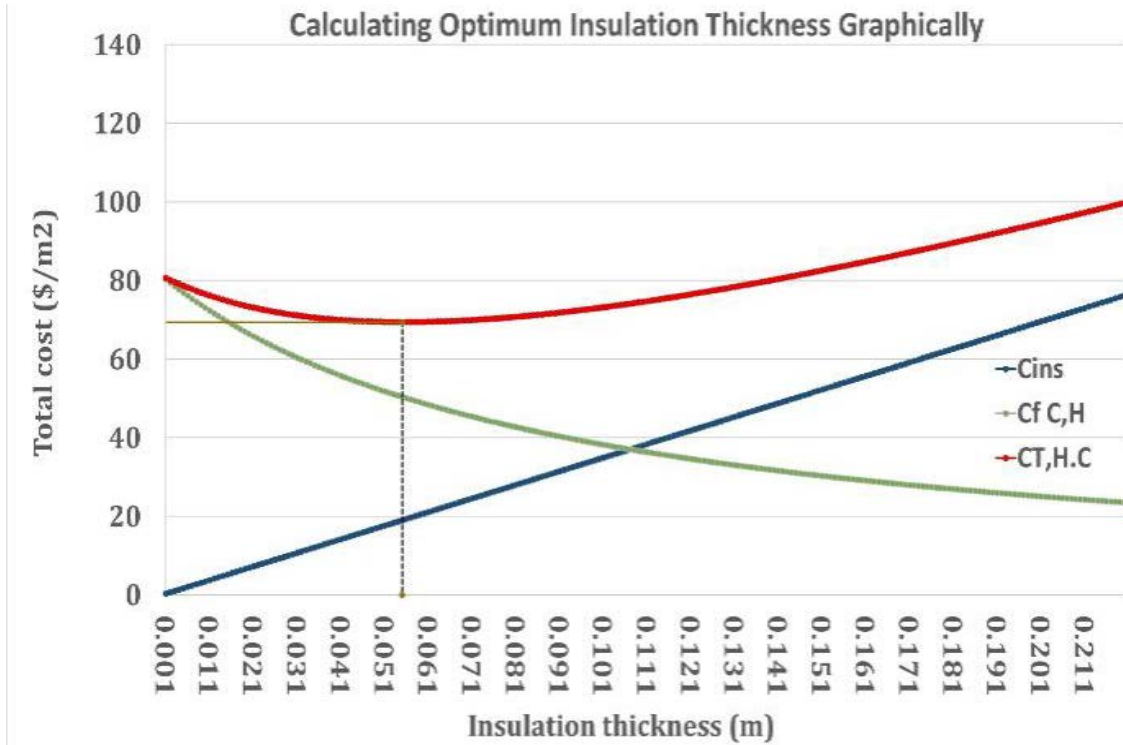


Figure 23. Determination of the optimal insulation thickness of PUR traditional insulation for exterior walls in Seitzstraße building

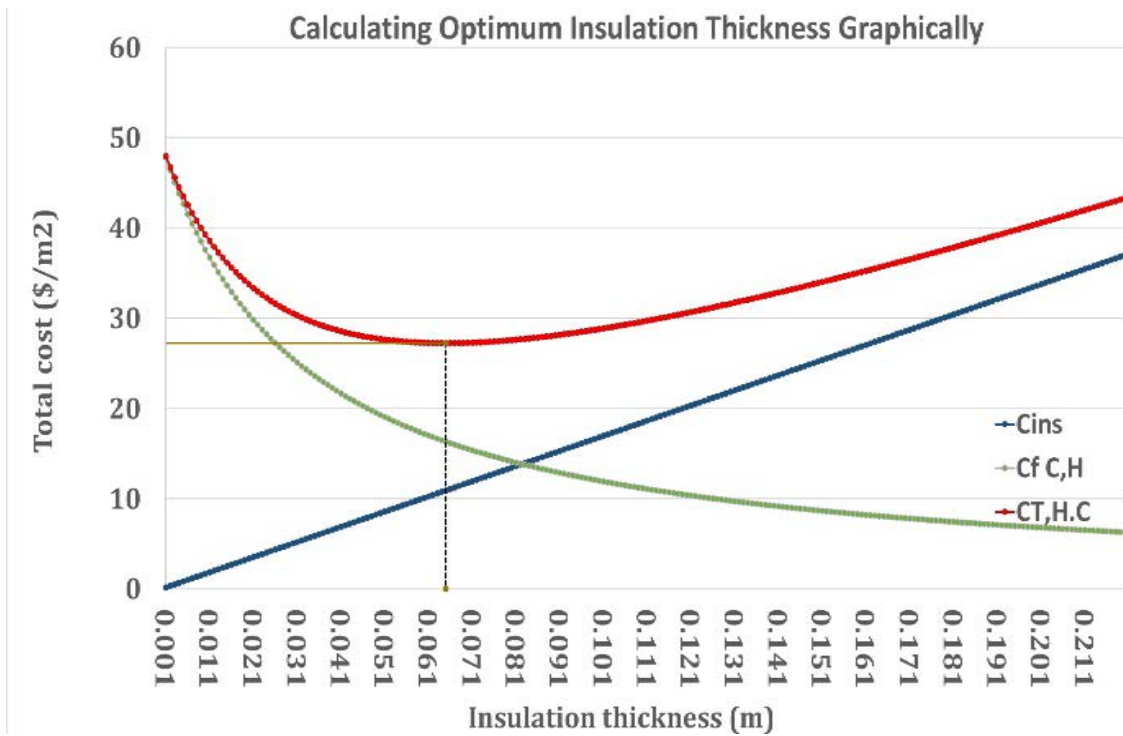


Figure 24. Determination of the optimal insulation thickness of EPS with graphite nano insulation in the Pentagon building

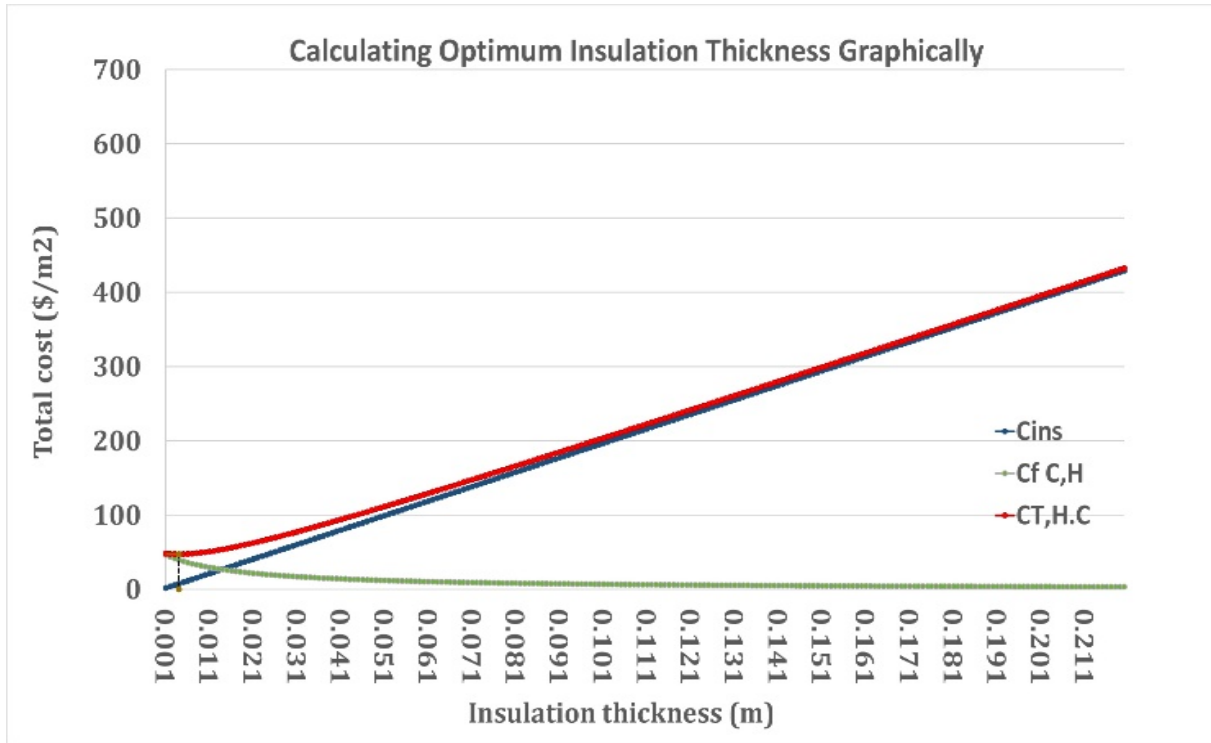


Figure 25. Determination of the optimal insulation thickness of EPS with graphite nano insulation in the Pentagon building

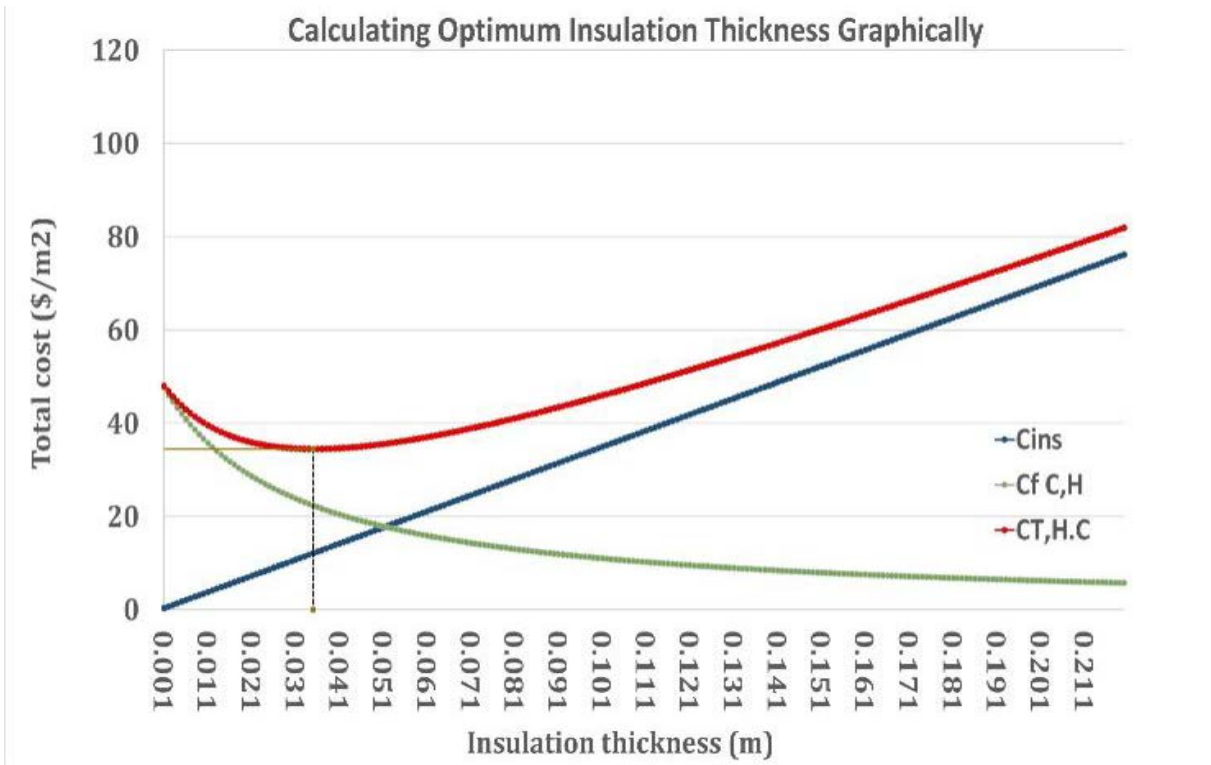


Figure 26. Determination of the optimal insulation thickness of EPS with graphite nano insulation in the Pentagon building

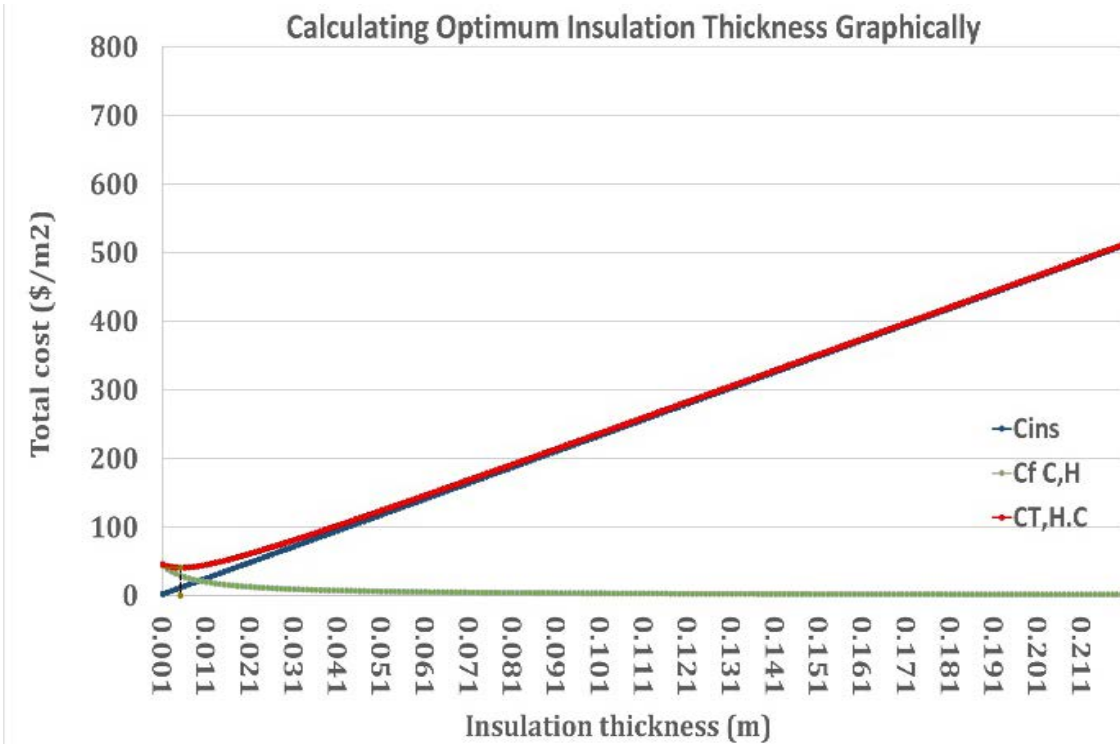


Figure 27. Determination of the optimal insulation thickness of VIP nano insulation in the Pentagon building

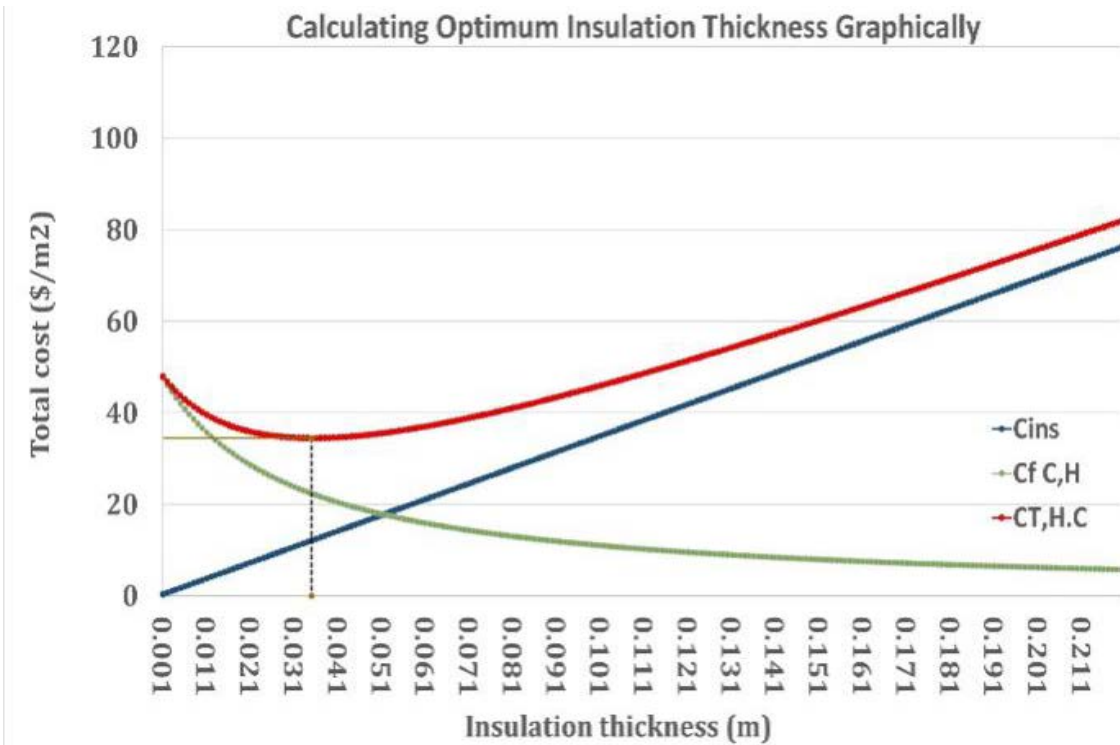


Figure 28. Determination of the optimal insulation thickness of PUR traditional insulation in the Pentagon building

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