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Application of Spatial Analysis to Determine the Effect of Insulation Thickness on Energy Efficiency and Cost Savings for Cold Storage

Erdem Küçüktopcu [1,*], Bilal Cemek [1] and Halis Simsek [2]

[1] Department of Agricultural Structures and Irrigation, Ondokuz Mayıs University, Samsun 55139, Türkiye
[2] Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA
* Correspondence: erdem.kucuktopcu@omu.edu.tr

Abstract: Cold storage facilities consume a considerable amount of energy, especially in hot climates, which can be decreased using thermal insulators to maintain a stable temperature. The primary aim of this research study was to determine the effect of insulation thickness on the energy efficiency and cost savings of exterior walls for cold storage facilities in all climatic zones of Türkiye. To this end, data from the meteorological databases of 81 provinces were analyzed, and four insulation materials (expanded polystyrene, extruded polystyrene, rock wool, and polyurethane) were selected for different cold storage reference temperatures. The spatial distributions of optimal insulation thickness, energy savings, and payback periods were derived using a geographic information system (Ordinary Kriging). The optimum insulation thickness and energy savings were found to be 0.020–0.137 m and 0.030–6.883 USD/m^2, respectively. Depending on the insulation material and base temperature, the shortest payback periods (1.498–3.457 years) were obtained in the Aegean and Mediterranean regions. In addition, rock wool provided the highest energy savings and the shortest payback period among all the insulation materials studied. The results from this study can help investors to improve their design considerations for cold storage wall insulation.

Keywords: energy; degree days; geostatistics; kriging

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1. Introduction

Energy conservation is critical for the global economies in all countries, and it is especially important for countries, including Türkiye, that depend on imports to meet their energy demand. The energy demand in Türkiye has increased significantly alongside a rapidly growing economy and population, making the country increasingly dependent on imports [1]. Despite a rapid increase in domestic energy production, imported natural gas accounts for nearly all the natural gas consumed in Türkiye, whereas domestic oil production meets only about 7% of the total demand. Despite a significant increase in domestic coal production, Türkiye imports nearly 58% of its coal. In 2018, Türkiye's total final energy consumption (TFC) was 103 Mtoe, representing 71% of the total primary energy supply. The industrial sector, which consumed 36% of the TFC, was the largest energy consumer in 2018, followed by transportation (27%), residential (20%), and services (17%). The total amount of electricity consumption reached 257,273 GWh in 2018, of which the industrial and residential sectors consumed 45.6 and 21.1%, respectively [2]. The amount of energy consumed by these sectors is primarily influenced by the climate, architectural design, energy systems, and the living standards of the occupants [3]. A significant part of the energy consumption in these sectors is also caused by errors in the design phase and in the selection and application of building materials [4]. Thermal insulation problems probably contributed to this increase in consumption [5,6]. Therefore, improving thermal insulation is a popular approach for decreasing energy consumption in buildings. Installing thermal insulation increases the energy efficiency of a building and enhances the quality of the indoor environment in various ways [7,8].

Population growth is another major factor in the Turkish economy and probably contributes to the current food shortage. Preserving agricultural and livestock products is as important as increasing agricultural and livestock production. In developing countries, approximately 33% of the food consumed is perishable [9]; therefore, cold storage is critical for minimizing postharvest losses. Since a cold storage facility's primary objective is to prolong the life of products by preventing food spoilage, these structures should be designed to provide an optimum level of environmental comfort [10,11].

The electricity consumption of cold storage facilities is among the highest in the commercial building sector [12,13]. Therefore, the selection of the most appropriate insulation thickness, taking into account the investment and operating costs, is crucial in the planning and design stage. This thickness, referred to as the "optimum insulation thickness," depends on the cooling and heating loads, the structure of the building walls, the life of the building, the interest and inflation rates, and the insulation costs [14,15]. Increased insulation thickness helps to minimize heat losses and promotes energy conservation; however, it also increases the initial investment cost. Therefore, the insulation thickness is decided based on the most favorable cost level for the manufacturer.

As documented in numerous studies, the use of insulation materials affects energy efficiency and savings under different climatic conditions worldwide. Hasan [16] discovered that the ideal insulation thickness for Palestinian residential buildings could save approximately 21 USD/m^2 over a ten-year life cycle. Mohsen and Akash [17] studied the impact of insulation on energy savings in Jordanian residential buildings. Their results showed that polystyrene insulation could lead to energy savings of up to 76.8%. Çomaklı and Yüksel [18] calculated the optimal insulation thickness and energy savings for the coldest provinces in Türkiye and came up with 12.113 USD/m^2 in savings. Al-Khawaja [19] studied the optimum thickness of insulation materials to decrease heat transfer in buildings in hot climates. Bolattürk [20] found that the optimum insulation thicknesses, energy savings, and payback periods varied depending on the climate zone and fuel type and that they varied between 0.020 and 0.170 m, 22 and 79%, and 1.30 and 4.50 years, respectively, in Türkiye. Bolattürk [21] studied the impacts of different base temperatures on the optimum insulation thickness for the warmest region in Türkiye. For the cooling load, the optimum insulation thicknesses, energy savings, and payback periods ranged from 0.032 to 0.038 m, 8.47 to 12.19 USD/m2, and 3.39 to 3.81 years, respectively, while for the heating load, these values varied from 0.016 to 0.027 m, 2.20 to 6.60 USD/m2, and 4.15 to 5.47 years, respectively. Liu et al. [22] computed the optimum insulation thickness using the P1-P2 economic model for building walls in China. The results showed that optimum insulation thicknesses varied from 0.053 to 0.069 m and from 0.081 to 0.105 m, depending on the insulation material. Ucar and Balo [23] examined the effect of fuel type and insulation materials on the optimum thickness in Türkiye. Yu et al. [24] determined the insulation thicknesses for several cities in China using the P1-P2 model and the degree hour approach. In another study conducted in China, Zhu et al. [25] examined the optimum thickness of exterior wall insulation and its energy saving potential. A study by Lianying et al. [26] assessed the impact of insulation thickness of commercial buildings in different cities in China on heating and cooling loads. Nyers et al. [27] developed an investment-saving method for optimizing the energy efficiency of insulation thickness. Nematchoua et al. [28] investigated the most cost-effective and optimal insulation thickness for buildings in the various climate of Cameroon. To establish the optimum insulation thickness for buildings in Türkiye, Aydin and Biyikoglu [29] used economic analyses and found that using the optimal insulation thickness could lead to energy savings between 12.9 and 21.5%, depending on the region.

In reviewing the above literature, some limitations were noted in the previous studies. (1) No comprehensive research has been conducted in Türkiye on the effects of insulation thickness on energy efficiency and cost savings of exterior walls of cold storage facilities.

(2) No attempt has been made to create spatial maps of the optimum insulation thickness, savings, and payback periods of exterior walls for cold storage.

Spatial models are important tools for the statistical study of the geographic relationships among different variables. The use of a spatial modeling tool allows modelers to visualize the data and thus interpret them more efficiently [30]. Spatial modeling is widely used in various disciplines, such as health care [31], agriculture [32], tourism climatology, and meteorology [33]. However, this paper provides the first attempt to perform the local geographic modeling of optimum insulation thickness, savings, and payback periods. It can, therefore, serve as a valuable and straightforward guide for improving thermal insulation design and analysis.

To overcome the above limitations, this paper combined an economic analysis and geostatistics to investigate the spatial distribution of optimum insulation thicknesses, energy savings, and payback periods for cold storage exterior walls in all climatic zones of Türkiye on a regional basis. The application of geostatistics greatly assisted in determining insulation thickness, energy, and cost savings for the construction of cold storage spatially. The results of this study can benefit engineers and investigators in designing and implementing cold storage wall insulation.

The rest of this paper is organized as follows: Section 2 provides an overview of the methodology used to determine the energy consumption and spatial distribution of cold storage facilities in Türkiye. Section 3 discusses the analysis results and includes maps illustrating insulation thickness, energy savings, and payback periods. Finally, Section 4 summarizes the conclusions and recommendations for future research.

2. Methodology

The simulation model was built to determine the effect of insulation thickness on energy and cost savings for cold storage by applying a spatial analysis (Figure 1). In the beginning, long-term temperature data from meteorological stations were included in this model. Then, based on the reference temperatures, the cooling degree day (CDD) values were calculated for each province in the location, which is Türkiye in this study. The annual energy requirement was calculated based on the selected insulation materials and the type of exterior wall construction. With the help of an economic analysis, the optimum insulation thicknesses, energy savings, and payback periods were defined for each province in Türkiye. Finally, spatial distribution maps were created by combining these data with the Ordinary Kriging method (OK).

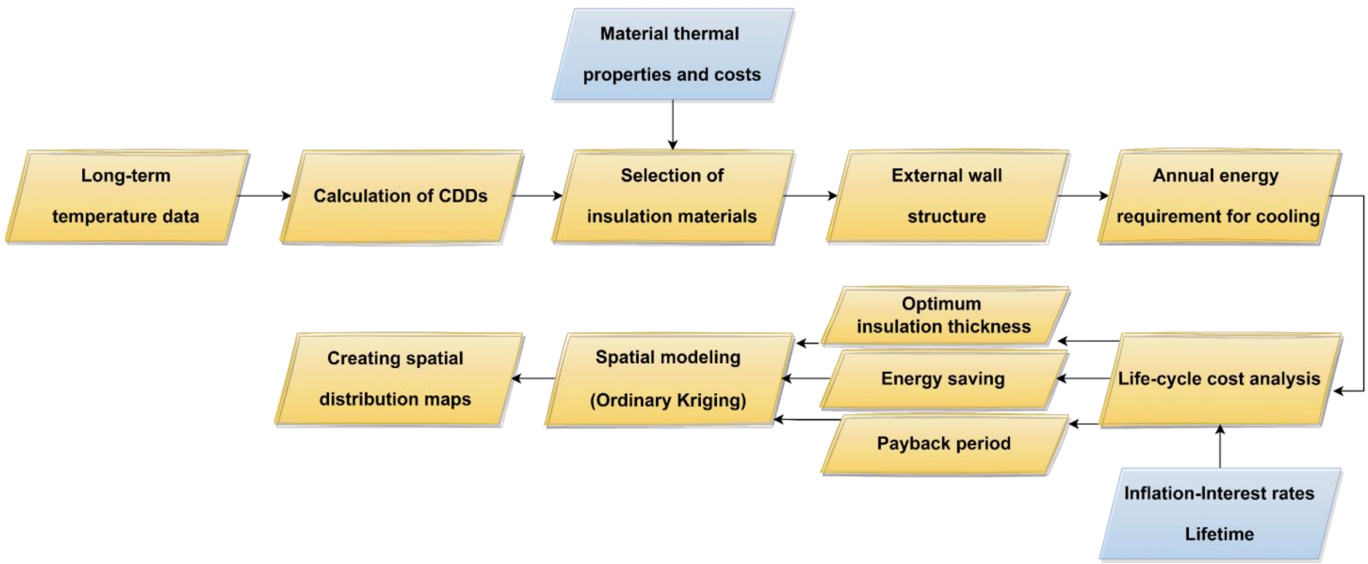

Figure 1. Flowchart of the simulation model.

2.1. Study Area

Türkiye is situated between 36 and 42° north latitude and 26 and 45° east longitude and covers an area of 780,000 km^2. The country is geographically divided into seven regions: Aegean, Marmara, Central Anatolia, Mediterranean, Black Sea, Southeastern Anatolia, and Eastern Anatolia. Regional temperatures in Türkiye vary considerably, with average annual temperatures ranging from 10.2 to 16.4 °C. January is the coldest month, with average temperatures ranging from 0.7 to 6.4 °C, while July is the hottest month, with average temperatures ranging from 22.0 to 29.8 °C [30].

Building energy analyses require accurate and reliable weather data. Therefore, long-term daily average temperatures were used to calculate the CDDs. The data were obtained from General Directorate of State Meteorological Affairs for 81 provinces in Türkiye [34] (Figure 2).

Figure 2. The location of weather stations within the study area (81 provinces of Türkiye).

2.2. External Wall Structure

The insulated exterior walls consisted of a 20 cm thick porous concrete block covered with 2 cm thick lime-based interior plaster and 3 cm thick cement-based exterior plaster. The physical properties of the wall elements are listed in Table 1.

This study examined the optimum insulation thickness of a cold storage exterior wall by applying four different insulation materials: expanded polystyrene (EPS), extruded polystyrene (XPS), rock wool (RW), and polyurethane (PU). The main reasons for selecting these insulation materials were that they are widely used in insulation applications and that their thermal properties and prices are quite different when compared [35,36]. The thermal conductivities and prices of the insulation materials employed in wall construction are listed in Table 2.

Table 1. Physical properties of the external wall in the study area [15,37].

Wall Structure	Thickness (m)	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)	Resistance (m^{2}K/W)
Internal plaster (lime based)	0.02	0.870	840	1600	0.023
Porous concrete block	0.20	0.220	840	580	0.909
External plaster (cement based)	0.03	1.400	840	1450	0.021
R_{ip}	-	-			0.040
R_{op}	-	-			0.130
R_{tw}	-	-			1.123

Note: R_{ip} and R_{op} are the inner and outer plasters' thermal resistance, respectively. R_{tw} is the total thermal resistance of an uninsulated wall.

Table 2. Thermal properties and costs of insulation materials [15,37].

Insulation Material	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)	Price (USD/m^3)
XPS	0.031	1400	35	180
EPS	0.039	1400	15	120
RW	0.040	1030	24	75
PU	0.024	1590	35	260

2.3. Cooling Degree Day Calculation

A degree day is widely considered to be one of the most straightforward methods of calculating the energy required to heat and cool a building [38]. The term "degree day" refers to the temperature difference between the average daily ambient temperature and the base temperature over a period. Numerous techniques have been used to compute the degree days [38–44]. In this study, CDD values were computed based on seven cold storage reference temperatures (0 °C, −5 °C, −10 °C, −15 °C, −20 °C, −25 °C, and −30 °C) [45]. CDDs can be calculated by limiting the cooling season to the whole year based on the available degree days (Equation (1)).

$$For\ T_o \geq T_r,\ CDD = \sum_{i=1}^{N_c} (T_o - T_r)_i = N_c(\Delta TD_c). \tag{1}$$

2.4. Heat Transfer and Energy Requirement

A typical wall's overall heat transfer coefficient is calculated using Equation (2).

$$U = \frac{1}{\frac{1}{h_i} + \frac{\delta_{ip}}{k_{ip}} + \frac{\delta_{wm}}{k_{wm}} + \frac{\delta_{ins}}{k_{ins}} + \frac{\delta_{op}}{k_{op}} + \frac{1}{h_o}} \ . \tag{2}$$

Equation (2) can be rewritten in the following form (Equation (3)):

$$U = \frac{1}{R_i + R_{ip} + R_{wm} + R_{ins} + R_{op} + R_o} \ . \tag{3}$$

If R_{tw} is the thermal resistance of an uninsulated wall ($R_{tw} = R_i + R_{ip} + R_{wm} + R_{op} + R_o$), Equation (3) can be rearranged (Equation (4)).

$$U = \frac{1}{R_{tw} + \frac{\delta_{ins}}{k_{ins}}}. \tag{4}$$

The annual cooling energy consumption is calculated as shown in Equation (5) [46,47].

$$E_C = \frac{0.024 \times U \times CDD}{COP}. \tag{5}$$

COP is the cooling performance coefficient, which is assumed to be 3 in this study. The annual cooling energy cost is calculated as shown in Equation (6).

$$C_{A,C} = \frac{0.024 \times U \times CDD \times C_e}{COP}. \tag{6}$$

2.5. Optimum Insulation Thickness

The term "life cycle cost (LCC) analysis" refers to a technique for performing a systematic assessment of the costs of a system or process over its entire life. The LCC method was used in this article to determine the total cost of cold storage over its lifetime. The present-worth factor (PWF) value is determined using Equation (7) [16].

$$\begin{aligned} &if\ \ (i < g) \quad r = \tfrac{g-i}{1+i}\ , \\ &if\ \ (g < i) \quad r = \tfrac{i-g}{1+g}\ , \\ &Then \\ &PWF = \tfrac{(1+r)^N - 1}{r(1+r)^N}. \end{aligned} \tag{7}$$

where the interest (i) and the inflation (g) rates were taken as 19.00% and 17.14%, respectively [48]. Lifetime (N) was taken as ten years. The optimum insulation thickness is calculated using Equation (8) [49].

$$OIT = \left(\frac{0.024 \ \times \ C_e \ \times \ PWF \ \times \ k \ \times \ CDD}{C_{ins} \ \times \ COP} \right)^{0.5} - k \ \times \ R_{tw}. \tag{8}$$

2.6. Energy Savings and Payback Period1

Energy savings and payback periods can be determined using Equations (9) and (10) [46,47].

$$ES = C_e(E_{C,noins} - \ E_{C,withins}), \tag{9}$$

$$PP = \frac{IT \ \times \ C_{ins}}{LCT_{noins} - \ LCT_{withins}}. \tag{10}$$

2.7. Spatial Modeling

The distribution maps were produced using Geostatistical Analyst Model of ArcGIS software (v. 10.3; ESRI, Redlands, CA, USA) using the OK method, which is the most accurate and frequently used method [50]. This method facilitates the prediction of variability in the regions where autocorrelative spatial data were obtained. In practice, exact interpolation may not be attractive because of the nugget effect. Nevertheless, the effect of nugget variance can be avoided by either shifting the kriging grid so that no data points are estimated or by omitting a data point if it matches a target point [51].

OK is based on a linear combination of weights at known locations, where the values for a given location are determined and used to approximate an unknown location. It has the advantage of incorporating estimated surface error or uncertainty. Based on OK, the estimated variable at an unsampled location is determined using Equation (11).

$$Z(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i). \tag{11}$$

Theoretically, OK provides the most accurate and unbiased linear prediction for unobserved locations. In other words, the expected value of the estimator is equal to the actual value, and the variance of the prediction error is minimized. To obtain an unbiased estimate, all observed points must have a weighting coefficient of 1 for the unobserved point. In this way, a matrix-form linear equation system is created (Equation (12)).

$$\begin{bmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1n} & 1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \gamma_{n1} & \gamma_{n2} & \cdots & \gamma_{nn} & 1 \\ 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_n \\ \mu \end{bmatrix} = \begin{bmatrix} \gamma_{01} \\ \vdots \\ \gamma_{01} \\ 1 \end{bmatrix} \tag{12}$$

Parallel algorithms compute the weight vector by matrix–vector multiplication after calculating the inverse of the coefficient matrix to solve Equation (12). The classical algorithm for OK interpolation consists of five steps [52]:

(1) Fitting theoretical variogram models with empirical variogram values at different lags.

(2) Creating a variogram coefficient matrix and its decomposition.
(3) Obtaining the variogram vector between one unobserved point and all observed points.
(4) Calculating the estimate of an unobserved point by solving the decomposed linear system of equations.
(5) Repeating steps 3 and 4 until all unobserved points have been calculated.

3. Results and Discussion

3.1. Annual Cooling Degree Days

Temperature management is the most important tool in the postharvest treatment of crop products to control both physiological and pathological damage. Temperature affects shelf life differently depending on the physicochemical properties of fruits and vegetables. For example, the optimum temperature range for apples is −1 to 4.4 °C for a shelf life of 1–12 months, while this range for watermelons is 10–15.6 °C for a shelf life of 2–3 weeks [53]. As a rule, the temperature is further lowered to a storage level of −18 °C. Microbial growth is halted below −18 °C, and enzymatic and non-enzymatic changes occur much more slowly during frozen storage [54]. Therefore, in this study, we calculated the annual CDD values using long-term temperature data from all provinces of Türkiye for the reference temperatures of 0, −5, −10, −15, −20, −25, and −30 °C (Supplementary Material, Table S1). Türkiye categorizes four climatic regions for installation purposes, as defined in Turkish Thermal Insulation Standard (TS, 825) (Figure 3).

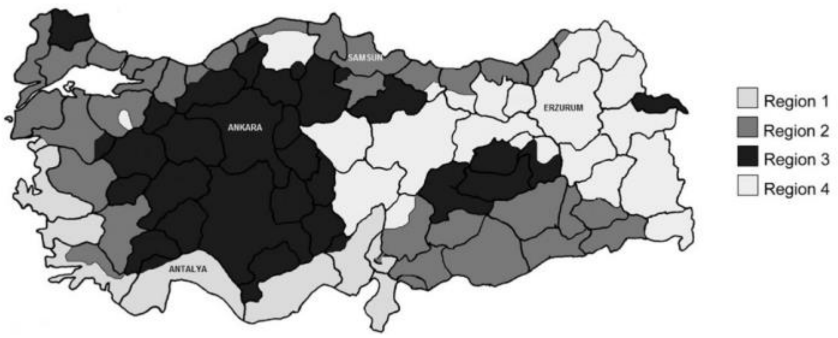

Figure 3. Climate zones of selected cities in the study (TS, 825).

Consequently, four sample provinces from different climatic regions were selected for this research study to demonstrate the impact on insulation thickness selection. The province of Erzurum, located in the fourth region, has the harshest winter conditions, while Antalya, located in the first region, is the warmest. Samsun and Ankara, located in the second and third thermal zones, are temperate cities. The main reason for selecting these provinces is that they play an important role in regional transportation. Antalya accounts for almost 20% of Türkiye's fresh fruit and vegetable exports [55]. Samsun is an important port city in the Black Sea region [56]. Ankara is located in Türkiye's Central Anatolia region and is the hub of Türkiye's highway network [57]. Erzurum is the most important railroad junction in the region of Eastern Anatolia [58].

The provinces selected, their climate classifications, annual temperatures, and CDD values are summarized in Table 3. The annual CDD values of these provinces varied significantly within regions with the same reference temperature (Table 3). For example, the CDD value for Antalya was 8736, while it was 4160 for Erzurum with a reference temperature of −5 °C. According to these values, cold storage in Antalya requires almost twice as much cooling energy as Erzurum under the same building conditions.

Table 3. Climate zones and CDD values for selected cities.

City	TS 825	Annual Temperature (°C, Mean ± SD)	0 °C	−5 °C	−10 °C	−15 °C	−20 °C	−25 °C	−30 °C
Antalya	1st zone	18.98 ± 8.47	6901	8736	10,571	12,406	14,241	16,076	17,911
Samsun	2nd zone	14.68 ± 6.89	5357	7192	9027	10,862	12,697	14,532	16,367
Ankara	3rd zone	12.12 ± 10.09	4386	6221	8056	9891	11,726	13,561	15,396
Erzurum	4th zone	5.75 ± 11.88	2863	4160	5759	7594	9429	11,264	13,099

Note: SD is the standard deviation.

Figure 4 provides spatial maps of the CDDs in all climate zones of Türkiye for selected reference temperatures. The climate of Türkiye was observed to be non-uniform, while CDD values were higher in provinces adjacent to coastal areas than in central and eastern provinces; this implied that the former category had a higher energy requirement during the cooling period than the latter. The provinces of Ardahan, Kars, Erzurum, Ağrı, and Bayburt (Eastern Anatolia), as well as Yozgat and Sivas (Central Anatolia), experienced the lowest CDD values. The provinces of Mersin, Adana, and Antalya (Mediterranean) had the highest CDD values. This variation can most likely be explained by the effects of being close to the sea, landforms, and the consequences of latitude [30,59]. Dombaycı [60] determined the average annual CDD values for various base temperatures in 79 Turkish city centers. At a base temperature of 22 °C, Şanlurfa had the highest CDD value (CDD = 970), while Ardahan had the lowest (CDD = 61). Similar results were also obtained by Büyükalaca et al. [43]. These results clearly show that the cooling energy demand for eastern and central regions is significantly lower than for Mediterranean and southeastern areas.

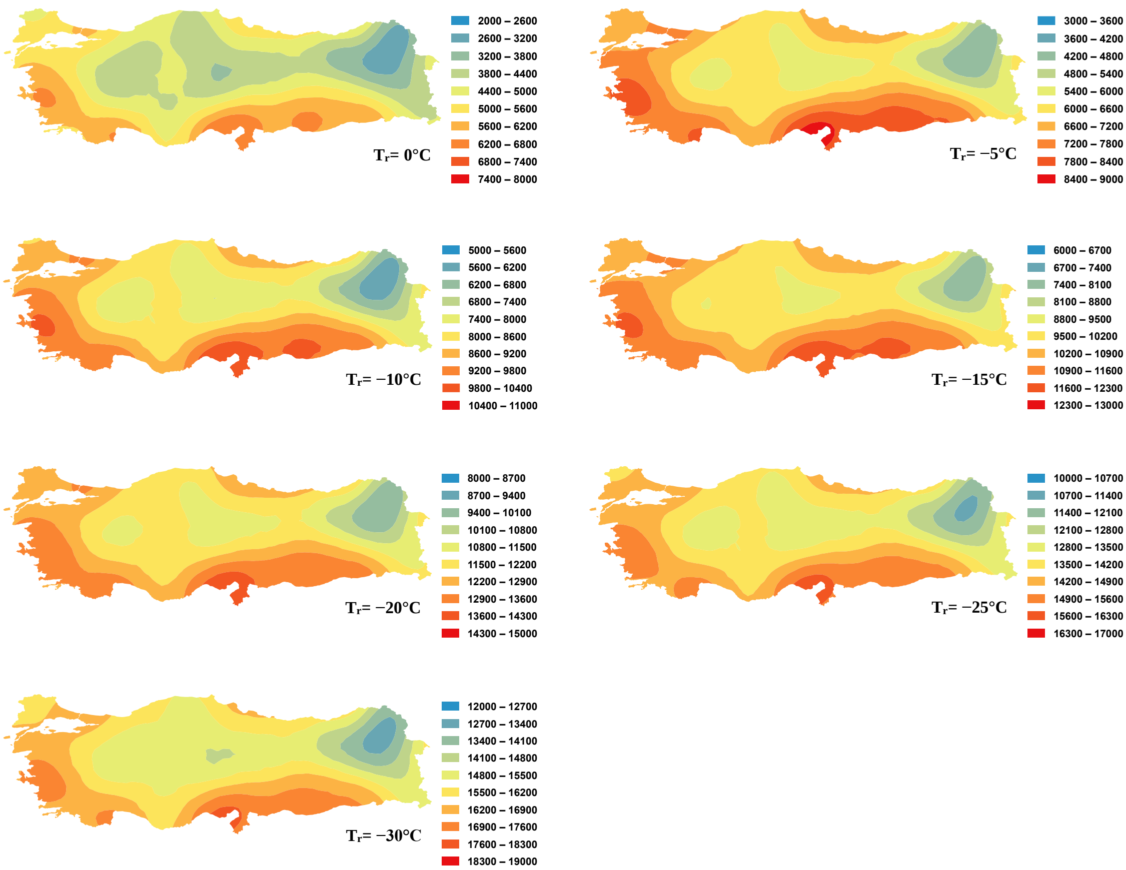

Figure 4. Spatial maps of the CDDs in all climate zones of Türkiye for selected reference temperatures (each of the maps has its own legend).

3.2. Optimum Insulation Thickness

Table 4 shows the optimum insulation thicknesses of cold storage exterior walls in selected Turkish provinces using XPS, EPS, RW, and PU as insulation materials. For Antalya, the optimum thicknesses of XPS, EPS, RW, and PU were calculated to be 0.029–0.068 m, 0.044–0.098 m, 0.068–0.137 m, and 0.020–0.049 m, respectively, depending on the reference temperatures. For Erzurum, the optimum thicknesses of XPS, EPS, RW, and PU were calculated to be 0.006–0.053 m, 0.013–0.077 m, 0.028–0.110 m, and 0.003–0.038 m, respectively, depending on the reference temperatures. These values indicated that PU performed best among the studied insulation materials in terms of optimum thickness.

Table 4. Optimum insulation thickness (m) at different reference temperatures of four insulation materials in the selected cities.

T_r (°C)	Insulation Material	Antalya	Samsun	Ankara	Erzurum
0	XPS	0.029	0.022	0.016	0.006
	EPS	0.044	0.034	0.026	0.013
	RW	0.068	0.054	0.045	0.028
	PU	0.020	0.014	0.010	0.003
−5	XPS	0.037	0.031	0.026	0.015
	EPS	0.055	0.046	0.040	0.025
	RW	0.082	0.070	0.062	0.043
	PU	0.026	0.021	0.018	0.009
−10	XPS	0.044	0.038	0.034	0.024
	EPS	0.065	0.057	0.051	0.037
	RW	0.095	0.084	0.077	0.058
	PU	0.031	0.027	0.024	0.016
−15	XPS	0.051	0.046	0.042	0.032
	EPS	0.074	0.067	0.062	0.049
	RW	0.106	0.097	0.090	0.073
	PU	0.036	0.032	0.029	0.022
−20	XPS	0.057	0.052	0.049	0.040
	EPS	0.083	0.076	0.071	0.059
	RW	0.117	0.108	0.102	0.087
	PU	0.040	0.037	0.034	0.028
−25	XPS	0.063	0.058	0.055	0.047
	EPS	0.091	0.084	0.080	0.069
	RW	0.127	0.119	0.113	0.099
	PU	0.045	0.041	0.039	0.033
−30	XPS	0.068	0.064	0.061	0.053
	EPS	0.098	0.092	0.088	0.077
	RW	0.137	0.129	0.123	0.110
	PU	0.049	0.045	0.043	0.038

In studies conducted in different regions of the world, it was reported that the optimum insulation thickness primarily depends on the cost of insulation material and its thermal conductivity [18,21,24,61]. Therefore, the optimum insulation thickness is expected to be lower when the insulation material's thermal conductivity and price are lower for the same CDD value [16].

The spatial distributions of the optimum insulation thicknesses in all climatic zones of Türkiye at a reference temperature of −20 °C are presented in Figure 5. The spatial patterns are similar for XPS, EPS, RW, and PU. Higher values of optimum insulation thickness were found in the provinces near the coast (e.g., Mersin, Antalya, Hatay, and İzmir), where the CDD value was higher, while lower values of optimum insulation thickness were found in the provinces in central and eastern areas (e.g., Ardahan, Kars, Erzurum, and Yozgat), where the CDD value was lower (Supplementary Material, Table S2).

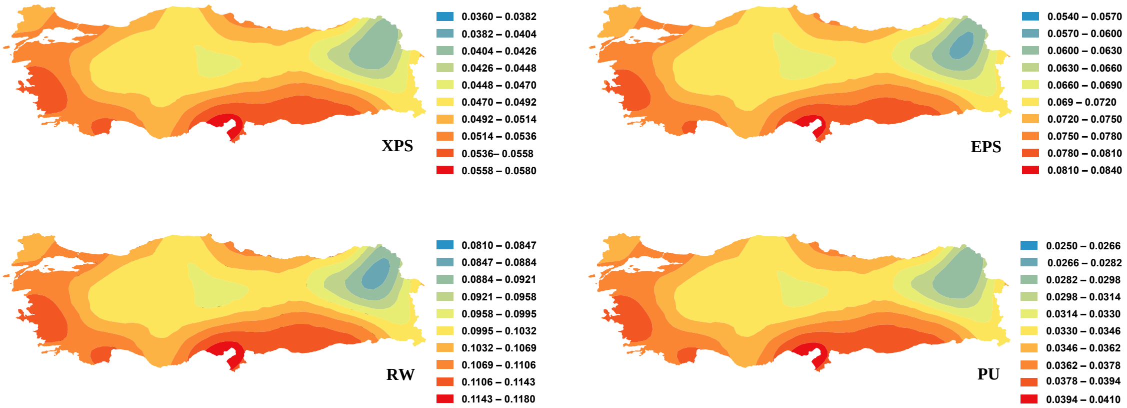

Figure 5. Spatial maps of the optimum insulation thickness in all climate zones of Türkiye at −20 °C reference temperature for four insulation materials (each of the maps has its own legend).

3.3. Insulation, Electricity, and Total Costs

Figure 6 illustrates insulation, electricity, and total costs depending on the PU thickness and T_r = −20 °C of cold storage in Ankara. With the increase in insulation thickness, the cost of insulation rose exponentially, while the cost of electricity fell. As the insulation thickness increased, the total cost declined; however, the cost continued to rise once the optimum insulation thickness was reached. An additional layer of insulation increased the insulation cost and decreased the cooling cost, thus increasing the total cost [62,63]. Similar trends were observed in other provinces with a similar pattern of using different insulation materials.

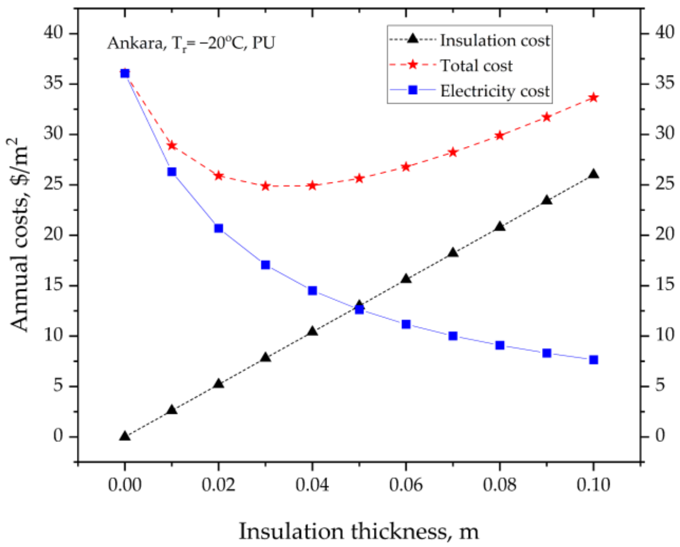

Figure 6. Electricity, insulation, and total costs at −20 °C reference temperature for PU insulation material in Ankara.

3.4. Annual Net Energy Savings

Net annual energy savings were calculated using cooling costs for insulated and uninsulated walls. Figure 7 depicts the savings for the PU when the optimum insulation thickness was employed for cold storage walls at 0 and −30 °C at four different locations in Türkiye. As can be seen from the graph, the energy savings increased as the insulation thickness was reduced until the highest value of optimum insulation thickness was reached. Beyond the optimum insulation thickness, the energy savings decreased as the insulation thickness increased. All results show that higher savings can be achieved at the lowest reference temperature. Compared with all other insulation materials tested, the highest annual energy savings with RW at a reference temperature of −30 °C were 6.819, 6.136, 5.710, and 4.709 USD/m^2 in Antalya, Samsun, Ankara, and Erzurum, respectively (Table 5). In contrast, the lowest energy savings were achieved with PU, which can be explained by its higher price compared with the other insulation materials.

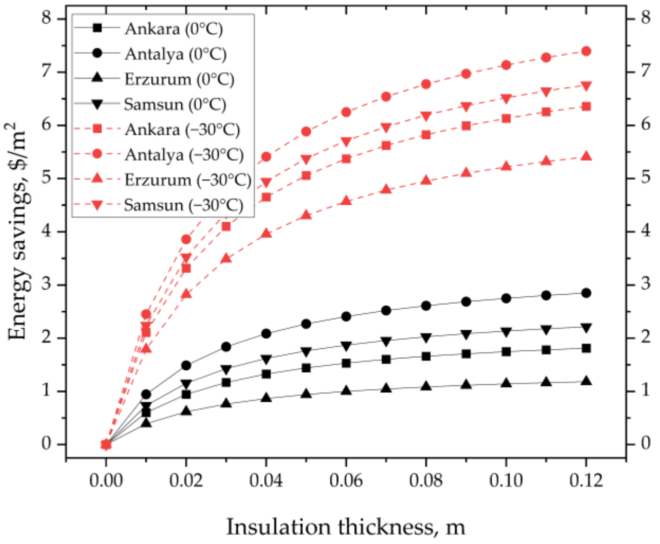

Figure 7. Annual energy saving results for PU, which would achieve optimum insulation thickness for the cold storage walls at 0 and −30 °C in four locations in Türkiye.

Table 5. Energy savings (USD/m^2) at different reference temperatures for four insulation materials in selected cities.

T_r (°C)	Insulation Material	Antalya	Samsun	Ankara	Erzurum
0	XPS	1.594	1.038	0.706	0.226
	EPS	1.753	1.179	0.834	0.329
	RW	2.100	1.484	1.110	0.552
	PU	1.485	0.942	0.619	0.156
−5	XPS	2.285	1.701	1.346	0.631
	EPS	2.464	1.864	1.497	0.755
	RW	2.854	2.218	1.826	1.024
	PU	2.162	1.590	1.242	0.547
−10	XPS	2.999	2.396	2.025	1.180
	EPS	3.197	2.579	2.198	1.326
	RW	3.625	2.975	2.572	1.642
	PU	2.864	2.272	1.908	1.081
−15	XPS	3.732	3.114	2.732	1.851
	EPS	3.946	3.315	2.923	2.019
	RW	4.410	3.749	3.338	2.382
	PU	3.586	2.978	2.602	1.737
−20	XPS	4.478	3.849	3.458	2.552
	EPS	4.708	4.066	3.667	2.739
	RW	5.205	4.536	4.118	3.143
	PU	4.322	3.701	3.316	2.425
−25	XPS	5.236	4.598	4.200	3.274
	EPS	5.480	4.829	4.424	3.478
	RW	6.008	5.332	4.909	3.920
	PU	5.070	4.440	4.047	3.135
−30	XPS	6.004	5.357	4.954	4.012
	EPS	6.261	5.603	5.193	4.232
	RW	6.819	6.136	5.710	4.709
	PU	5.828	5.189	4.791	3.862

Figure 8 presents the spatial distribution of annual net energy savings at the −20 °C reference temperature for all climate zones in Türkiye. The spatial patterns were similar for all insulation materials examined in this study. Energy savings depend on geographical and climatic conditions and are more important in hot climatic zones [64,65]. For example, Antalya, which is located in a hot region, saves more energy than provinces in a cold region (e.g., Erzurum and Ardahan) (Supplementary Material, Table S3). In addition, RW had the highest energy savings among all insulation materials examined in the study.

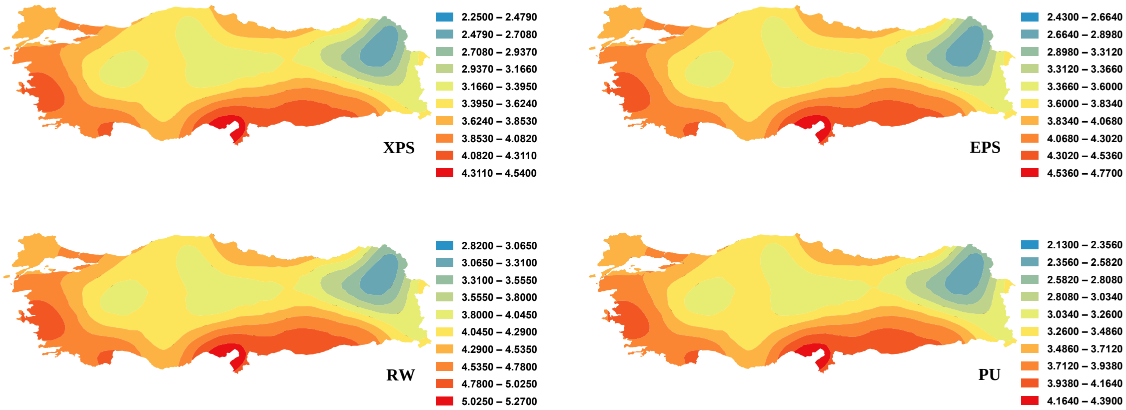

Figure 8. Spatial maps of energy savings in all climate zones of Türkiye at −20 °C reference temperature for four insulation materials (each of the maps has its own legend).

3.5. Payback Periods

Table 6 presents the values of payback periods considering optimum insulation thicknesses and different base temperatures for various insulation materials in the chosen provinces. For all insulation materials, it was found that the payback period shortened when the cold storage reference temperature decreased. In addition, the payback period shortened as the energy savings increased, and the maximum values were found in the coldest regions. Of the four provinces studied, Erzurum at 0 °C with PU had the most prolonged payback period (5.42 years), while Antalya at −30 °C with RW had the shortest one (1.50 years). In contrast to this study, Al-Sallal [66] discovered that the payback period was shorter in cold regions than in warm regions. The primary reason for this was that high base temperatures were used in their study, unlike in our research study.

The spatial distribution maps of the payback periods at a reference temperature of −20 °C for the insulation materials of XPS, EPS, RW, and PU are shown in Figure 9. The payback period was shorter in provinces in coastal areas (e.g., Hatay and Izmir) and more prolonged in provinces in central and eastern regions (e.g., Ardahan, Kars, Ağrı, Sivas, and Yozgat), indicating that the use of insulation materials was more advantageous in hot areas than in cold regions (Supplementary Material, Table S4). Provinces with warmer climates likely benefit from shorter payback periods and higher energy savings at lower base temperatures than provinces with cooler climates.

Table 6. Payback periods (year) considering different reference temperatures and four insulation materials in selected cities.

T_r (°C)	Insulation Material	Antalya	Samsun	Ankara	Erzurum
0	XPS	3.304	3.750	4.144	5.129
	EPS	3.026	3.434	3.795	4.698
	RW	2.422	2.750	3.039	3.761
	PU	3.494	3.965	4.382	5.424

Table 6. *Cont.*

T_r (°C)	Insulation Material	Antalya	Samsun	Ankara	Erzurum
−5	XPS	2.936	3.236	3.480	4.255
	EPS	2.689	2.964	3.187	3.897
	RW	2.153	2.373	2.551	3.120
	PU	3.105	3.422	3.680	4.500
−10	XPS	2.669	2.889	3.058	3.617
	EPS	2.445	2.646	2.800	3.312
	RW	1.957	2.118	2.242	2.652
	PU	2.823	3.055	3.234	3.825
−15	XPS	2.464	2.633	2.760	3.149
	EPS	2.257	2.412	2.527	2.884
	RW	1.807	1.931	2.023	2.309
	PU	2.606	2.785	2.918	3.331
−20	XPS	2.300	2.436	2.535	2.826
	EPS	2.106	2.231	2.321	2.588
	RW	1.686	1.786	1.858	2.072
	PU	2.432	2.576	2.680	2.989
−25	XPS	2.165	2.277	2.357	2.586
	EPS	1.982	2.085	2.158	2.368
	RW	1.587	1.669	1.728	1.896
	PU	2.289	2.408	2.492	2.735
−30	XPS	2.051	2.145	2.212	2.398
	EPS	1.878	1.965	2.026	2.196
	RW	1.504	1.573	1.622	1.758
	PU	2.169	2.269	2.339	2.536

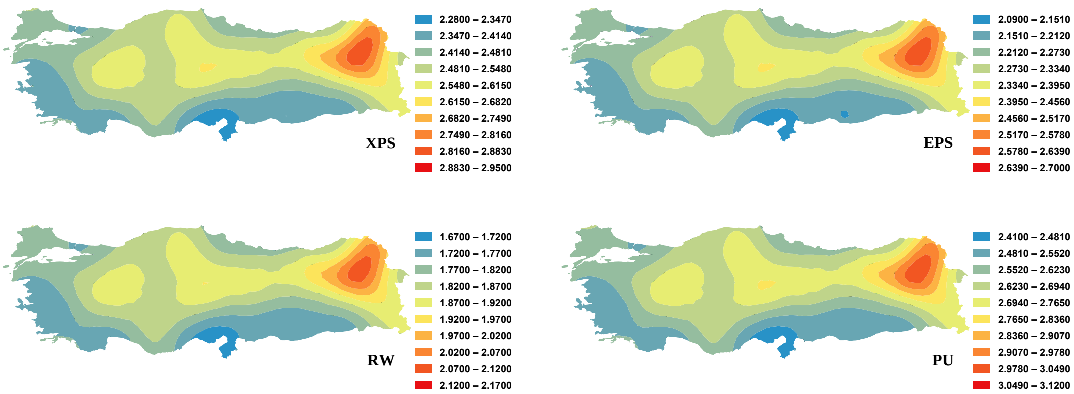

Figure 9. Spatial maps of the payback periods in all climate zones of Türkiye at −20 °C reference temperature for four insulation materials (each of the maps has its own legend).

4. Limitations and Future Research

It is important to note that this study had some potential limitations. (1) We conducted an analysis based on the Turkish economy for different insulation materials and energy prices. However, in some cases, prices may vary due to certain factors, such as different years, cities in Türkiye, and countries. (2) We used a simple example of wall construction to determine optimum insulation thickness, energy savings, and payback periods. Different wall constructions may change the results. (3) We employed the OK interpolation technique to determine the effects of insulation thickness on the energy and cost savings of exterior walls for cold storage. The geostatistical maps may differ somewhat if other interpolation techniques, such as inverse distance weighting and radial basis function, are used.

To overcome the above limitations, in future work, we aim to use different combinations of wall constructions considering other thermal insulation materials to estimate the impact of insulation thickness on the energy efficiency and cost savings of cold storage facilities. To improve the model, we also aim to compare different periods and geographic locations to better account for the abovementioned price variations. Other spatial interpolation techniques should also be considered in future studies.

5. Conclusions

In Türkiye, energy demand continues to increase with rapid population growth. Therefore, energy conservation gains importance every day due to the country's limited energy resources and dependence on foreign resources. Significant energy savings could be achieved using appropriate insulation materials in buildings. In this work, economic analysis and geostatistics were combined to study the spatial distribution of optimum insulation thicknesses, energy savings, and payback periods for cold storage exterior walls in all climatic zones of Türkiye. The conclusions reported below were drawn from the results.

The highest values for optimum insulation thickness were obtained in the Mediterranean region and the lowest ones in Eastern Anatolia. The maximum values of energy savings were achieved in the Mediterranean region, which also had the shortest payback periods.

The application of geographic information systems was of great help to spatially determine insulation thickness, energy, and cost savings for cold storage. Interpolation techniques were particularly useful in evaluating investment opportunities in Türkiye, which is characterized by significant topographical differences.

It should be noted that the results obtained are specific to the case studies considered. Different model evaluations and economic parameters such as CDDs, energy, and insulation prices could produce different results. Based on this study, the investigation can be extended to other countries and presented in a further study.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr10112393/s1, Table S1: Cooling degree days for all the provinces of Türkiye, Table S2: Optimum insulation thickness of XPS, EPS, RW, and PU for all the provinces of Türkiye, Table S3: Energy savings of XPS, EPS, RW, and PU for all the provinces of Türkiye, Table S4: Payback periods of XPS, EPS, RW, and PU for all the provinces of Türkiye.

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Nomenclature

OIT	Optimum insulation thickness (m)
ES	Energy savings (USD/m^2)
PP	Payback period (year)
EPS	Expanded polystyrene
XPS	Extruded polystyrene
RW	Rock wool
PU	Polyurethane
CDD	Cooling degree day (°C)
N_c	Total number of cooling days
T_r	Cooling reference temperature (°C)
T_o	Monthly average outdoor temperature (°C)

ΔTD_c	Mean equivalent temperature difference between outdoor and base temperatures
U	Coefficient of total heat transfer (W/m^{2}K)
h_i, h_o	Inner and outer films' heat transfer coefficient, respectively (W/m^{2}K)
δ_{ip}, δ_{op}	Inner and outer films' thickness, respectively (m)
δ_{wm}, δ_{ins}	Wall and insulating materials' thickness, respectively (m)
k_{ip}, k_{op}	Inner and outer plasters' thermal conductivity, respectively (W/mK)
k_{wm}, k_{ins}	Wall and insulating materials' thermal conductivity, respectively (W/mK)
R_i, R_o	Inner and outer films' thermal resistance, respectively (m^{2}K/W)
R_{ip}, R_{op}	Inner and outer plasters' thermal resistance, respectively (m^{2}K/W)
R_{wm}, R_{ins}	Wall and insulating materials' thermal resistance, respectively (m^{2}K/W)
R_{tw}	Total thermal resistance of an uninsulated wall (m^{2}K/W)
E_C	Annual cooling energy requirement (kWh/m^2)
COP	Cooling performance coefficient
$C_{A,C}$	Annual cooling energy cost (USD/m^2 year)
$LCCA$	Life-cycle cost analysis
PWF	Present-worth factor
i, g	Interest and inflation rates, respectively (%)
N	Lifetime of the building (years)
C_e	Cost of electricity (USD/kWh)
k	Thermal conductivity of insulation material (W/mK)
C_{ins}	Cost of insulation material (USD/m^3)
x	Insulation thickness (m)
$E_{C,noins}$	Annual energy requirement for cooling uninsulated building (kWh/m^2)
$E_{C,withins}$	Annual energy requirement for cooling insulated building (kWh/m^2)
LCT_{noins}	Life cycle total cost for uninsulated building (USD/m^2)
$LCT_{withins}$	Life cycle total cost for insulated building (USD/m^2)
OK	Ordinary Kriging
$Z(x_0)$	Estimated values
$Z(x_i)$	Measured values
λi	Kriging weight
γ_{ij}	Variogram value between point i and point j
μ	Lagrange multiplier

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