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Optimal Combination of External Wall Insulation Thickness and Surface Solar Reflectivity of Non-Residential Buildings in the Korean Peninsula

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Abstract: To delay fossil energy depletion and implement the Paris Climate Change Accord, the South Korean government is attempting to reduce greenhouse gas emissions with the establishment of the 2030 Roadmap. The insulation performance of external walls is being continuously enhanced in the architectural domain. However, Korea's policy and construction market focuses only on the heat resistance of buildings' external walls to enhance the insulation performance, leading to an increased thickness of the insulation materials. In this study, the relationship between the surface reflectivity and insulation thickness of external walls was examined to formulate an effective insulation strategy for buildings in Korea. Office buildings of 12 regions in the Korean Peninsula were considered. The dynamic energy simulation program EnergyPlus was used to perform the heating and cooling load analyses. The present worth method was adopted to perform the economic analysis. The analysis of the cooling and heating loads indicated that a change occurred not only in terms of the latitude but also between the Eastern and Western regions. The energy consumption could be reduced by increasing the reflectivity in the Southern region and lowering the reflectivity in the Northern region, based on the total load. In addition, a higher latitude corresponded to a higher energy saving effect owing to the increased insulation thickness. In the case of Jeju Island and Busan, regions with a relatively large cooling load and small heating load, the total load is little affected by insulation thickness at high reflectivity. If the external skin was considered to have the optimal reflectivity, the regions for optimal insulation thickness could be divided into three categories: north, central and south.

Keywords: EnergyPlus; heating and cooling loads; insulation thickness; present worth method; reflectivity

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1. Introduction

Among OECD countries, South Korea ranks first in terms of the increase in greenhouse gas emissions [1] (increase of 113% since 1990). To prevent energy depletion and implement the Paris Climate Change Accord, the National Greenhouse Gas Reduction Goals 2030 Roadmap was formulated by the government of the Republic of Korea in 2016. The objective is to reduce 37% (domestic 32.5%, overseas 4.5%) of the emissions compared to those in business as usual (BAU) conditions in the industry, home, commerce, public, and transportation domains. According to the roadmap, the industrial domain requires the highest reduction in the emissions (from 481.0 to 382.4 million tons of CO_2), with a reduction rate of 20.5%. Nevertheless, the architectural domain requires the highest rate of reduction (from 197.2 to 132.7 million tons, 32.7%) compared to the BAU conditions [2] to minimize the impact on the social economy. Moreover, only limited approaches are available to enhance the energy efficiency after construction, and most buildings have a long life span. Therefore, the formation of buildings with a high energy efficiency has become a key administrative purpose for the nation [3].

Since September 2013, the Korean government has expanded the scope of the energy saving plan submission. It is mandatory to submit an application to obtain a building permit with a floor area of 500 m^2 or more, to change the use or report, or to change the contents of the building register. The energy saving plan of a building consisted of mandatory (21 items in the architectural, mechanical and electrical sectors) and recommendation aspects, along with the energy performance index (EPI) (40 items in the architectural, mechanical, electrical and renewable sectors). All the mandates were required to be met, and the recommendations required a score of 65 or higher (74 for public buildings) to obtain the approval of a building. Especially, insulation (one of different mandatory energy saving plans) has been strengthened the most so far because appropriate insulation can reduce the energy consumption by approximately 40% to 70% compared to non-insulation cases, depending on the region and climate [4,5]. The basic points (21–34) of the average thermal transmittance of the wall were allocated the largest proportion of the total points in the recommendation section. Thus, the applicant was encouraged to maintain a high insulation performance. The standard for the heat transmission rate of building sites by region was divided into four climates and applied accordingly (the divisions for the climate were increased from three to four in September 2018). Buildings in a higher latitude required a higher insulation performance. Figure 1 represents the insulation criteria for the external walls of non-residential buildings in the Korean Peninsula, in the central region. The x-axis indicates the revision year, and the y-axis shows the legal thermal transmittance criteria. The heat insulation criteria have become more stringent with time. Currently, Korea's standard for thermal transmittance has been revised to the level of passive house.

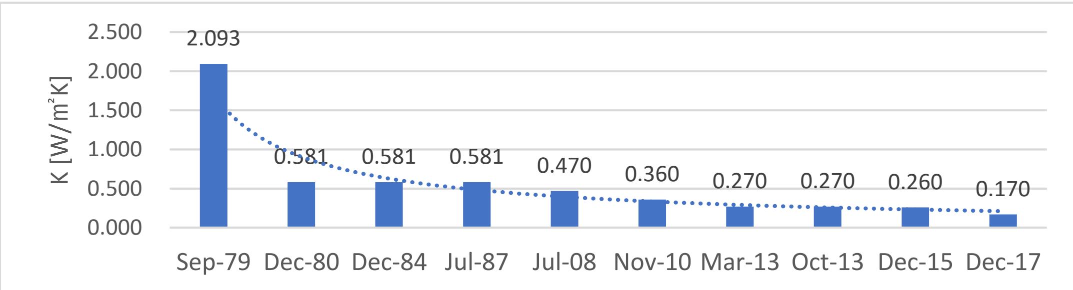


Figure 1. Changes in the insulation criteria of Korea: Central, non-residential, external wall (Source: Specification for energy-saving design of buildings, Ministry of Land, Infrastructure and Transport Notice, 2017-881).

The status of zero-energy building has become mandatory for public buildings since 2020 in Korea. Specifically, the primary energy output and primary energy consumption of the buildings are evaluated, and the buildings are assigned five grades according to the energy independence ratio. The Green Building Construction Support Act No. 16418, 2020.1.1. enforcement, is applied to public buildings subject to the submission of energy saving plans with a total floor area of 1000 m^2 or more, which are newly constructed, rebuilt, or annexed to public buildings. Moreover, although the foregoing is not applied to multi-family housing and dormitories, zero-energy conditions will be required for all private buildings after 2025 [6].

According to this background and policy situation, the importance of insulation performance, which accounts for the largest proportion of building energy saving factors, is expected to increase in Korea. However, to enhance the insulation property of external walls according to Korea's policy and construction market, most external walls are designed and produced with a focus on the heat resistance, which inevitably increases the thickness of the insulation. Although the performance enhancement of these resistive insulation materials can help effectively reduce the heating load, the cooling load cannot be reduced [7]. Consequently, alternatives must be adopted to reduce the cooling loads in summer. The cooling load can be reduced by using cooling colors and cold paint by increasing the solar reflectivity of the external surface [8]. Moreover, the reflectivity of the external surface, when suitably combined with the existing insulation, can help improve the indoor thermal comfort and effectively reduce heating and cooling loads [9].

Therefore, in this study, the changes in the cooling, heating and total loads in 12 regions of the Korean Peninsula due to changes in the thickness of the external wall insulation material and the reflectivity of the external wall surface were examined to identify the energy saving strategies for each region. These strategies are expected to be used efficiently in the building design stage. In addition, by performing an economic analysis based on the combination of the insulation thickness, reflectivity and energy consumption, the optimal combination of the external wall insulation thickness and reflectivity for each region was derived to facilitate the establishment of a unified insulation strategy for Korea.

Existing studies on the effect of the reflectivity and insulation thickness of buildings' external walls on changes in heating and cooling loads have been surveyed. Many studies have focused on roofs among the external surface of buildings, likely because the application to the roof is more effective than that to a wall [9].

The studies pertaining to the reflectivity and insulation thickness of roofs can be summarized as follows: Ascione et al. [8] considered the penalties during heating periods due to roof reflectivity in the Mediterranean climate. Materials with four reflectivity values were evaluated. EnergyPlus simulations were conducted on four typical offices in Lisbon (Portugal), Seville (Spain), Naples (Italy) and Athens (Greece) to examine the effects of the insulation thickness and reflectivity combinations. It was concluded that an insulation of 12 to 14 cm must be adopted in all cities to avoid penalties during heating periods. Sabe et al. [10] assessed the energy performance according to the insulation thickness and reflectivity (white or black) of the roof in hot, humid climatic conditions in Saudi Arabia. It was observed that if a white roof were applied to a building, the use of insulation on the roof could be reduced. These results were expected to help upgrade Saudi architecture codes. Saafi et al. [11] derived the optimal combination of the roof insulation and cooling through life cycle cost analyses for residential buildings in Tunisia. The annual energy requirement was obtained using EnergyPlus and considering two roof structures, three insulation materials and three reflective scenarios. In Tunisia, the benefits of increasing the roof reflectivity in summer were greater than winter penalties, and a higher reflectivity was desirable. Ramamurthy et al. [12] quantified the heat transmitted over a year through the roof in northeastern United States. The objective was to identify the optimal combination of the roof reflectivity and insulation thickness to minimize the energy consumption. For the New York Metro, the albedo was 0.6, and the ideal insulation thickness was 46 cm; the heating and cooling loads could be considerably reduced when adopting these specifications. The white-roofed winter penalty was insignificant compared to the summer benefits. However, increasing the thickness of the roof insulation was expected to increase the cost recovery period, and the authors indicated that the roof life (20 years) must be considered as well. If the thickness of a 5.08 cm (2 in.) insulation was doubled, 13 years were required to recover the additional costs incurred.

The research on exterior walls has been primarily focused on determining the optimal insulation thicknesses for each region and use case worldwide [13–27]: Ozel [15] studied the optimal insulation thickness for structural materials on the southern walls of buildings in Turkey. Dynamic simulations were performed considering five structural materials (concrete, briquet, brick, blokbims and autoclaved aeration) and two insulation materials (extruded polystyrene (XPS) and extended polystyrene (EPS)). In addition, an economic analysis of the energy consumption costs (10 years) was performed to determine the optimal insulation thickness. The optimal insulation thickness was 2–8.2 cm, leading to energy savings of 2.78 to 102.16 $/m^2 and payback periods of 1.32 to 10.33 per year. Daouas et al. [18] determined the optimal insulation thickness of the external wall of a Tunisian building. The most profitable specifications corresponded to stone/brick sandwich walls and foam polystyrene as the insulation material, and the optimal insulation thickness was 5.7 cm. Wati et al. [19] examined the effects of external shading on the optimal insulation thickness of building walls in tropical areas. Increasing the shading reduced the optimal thickness, which was dependent on the directions. For each 1% reduction of solar radiation, the optimal insulation thickness was reduced by 0.035–0.036 cm in the south, east, and west regions, and 0.029 cm in the north.

Furthermore, only a few studies attempted to analyze the cooling and heating loads through the external walls by correlating the reflectivity and insulation thickness: Ouarda Mansouri [26] investigated and analyzed the reflective coating effect and performance of external walls of residential buildings in the Mediterranean climate zone of Algeria with the TRNSYS analysis program. The results showed that the presence of insulation combined with a high solar reflectivity positively influenced the indoor air, thermal comfort levels and energy efficiency, providing a better environment for residents. The optimal combination corresponded to a wall of light-colored coatings with an albedo higher than 0.5 with insulation. Yuan [27] investigated the optimal reflectivity and insulation thickness by region in Japan. Based on the Japanese architectural market and economic analysis data, Yuan analyzed the changes in the cooling and heating loads according to the insulation thickness and reflectivity of each region and derived the optimal combination of the insulation thickness and reflectivity by region considering the cost. The results were Naha 0–10 mm, 0.7–1.0; Fukuoka 50 mm, 0.5–0.6; Osaka 60 mm 0.5–0.6; Nagoya 60 mm, 0.5–0.6; Tokyo 70 mm, 0.4–0.5; Sapporo 100 mm, 0–0.1. In this work, the study of Yuan was referenced, and the differences between this work and Yuan's research are summarized in Table 1.

Table 1. Differences in this work and the research of Yuan.

Aspect		Present Study	Yuan [27]
Analysis program		ENERGY+	HASP/ACLD-B
Climatic data		IWEC, Korean Peninsula (Latitude 33–43° N)	Japan (Latitude 26–43° N)
Simulation model	Purpose	Standard Building Office (medium size)	- Office
	Conditioned area	582 m^2	605 m^2
Parameter value	Insulation	10 to 150 mm (10 mm spacing)	10 to 100 mm (10 mm spacing)
	Reflectivity	0.1–0.9 (0.1 interval)	
Applicable law		Korea (Energy Saving Design Criteria): Central 1 (Wall: 0.17 and Window: 1.3)	Japan (Act on the Rational Use of Energy)
Economic analysisdata	Material price	Korea Market (2020) Including labor	Japan Market (2015) -
	Electricity cost	Summer: 0.08 $/kWh Winter: 0.07 $/kWh (2019)	0.18 $/kWh (2015)
	Inflation rate	Rise of inflation: 1.72% (IMF 2010–2019)	Energy cost increase rate: 0.73% (IMF)
	Interest rate	2.05% (Korea Bank, 2010–2019)	2.4% (Cooperative Association DDK)
	Period	40 y	10 y

2. Materials and Methods

The cooling and heating loads of buildings for each region were determined using EnergyPlus after selecting representative cities from low to high latitudes of the Korean Peninsula.

After collecting the simulation results and data, an economic analysis was conducted using the present worth method. Figure 2 shows the process flow of this study.

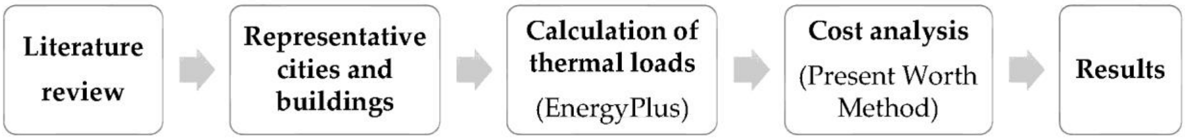


Figure 2. Process flow of the study.

2.1. Selection of Representative Cities and Buildings for Simulation

2.1.1. Representative City

Each region has different climatic characteristics depending on the latitude and surrounding environment. This aspect directly influences the energy load of a building. To reflect the diversity of the entire Korean Peninsula, 12 cities—from Jeju Island, located at a low latitude, to Chongjin, at a high latitude—were selected as representative cities (in the order of population size). Figure 3 shows the location of the cities selected on the map of the Korean Peninsula.

Figure 3. Representative cities of the Korean Peninsula (12 locations).

- Jeju Island: The largest island in South Korea (low latitude).
- Busan: A metropolitan government located in the southeastern part; the second largest city in South Korea and a port city.
- Kwangju: A metropolitan government located in the southwestern region; the largest city in southwestern Honam Province.
- Daegu: A metropolitan government located in central Gyeongsang-do; the third largest city in South Korea.
- Daejeon: A metropolitan government located in the central region; a key transportation location.
- Seoul: The capital of South Korea, having the largest population, located in the center of the Korean Peninsula.
- Gangneung: Located in the eastern region; the largest city in Gangwon Province.

- Kaesong: A large city in North Korea, adjacent to South Korea.
- Pyongyang: The capital and largest city in North Korea.
- Hamhung: The second largest city in North Korea, and an industrial city.
- Sinuiju: A city located in the northwestern region, adjacent to the Chinese border.
- Chongjin: The third largest city in North Korea, located in the northern region (high latitude).

The Korean Peninsula is situated in the temperate climate zone of the mid-latitude region and exhibits four distinct seasons: spring, summer, fall and winter. Winter is cold and dry and influenced by the dry continental high pressure. In summer, the hot weather is affected by the hot and humid North Pacific high pressure. Spring and fall show many clear and dry days due to the influence of the migratory anticyclone. The geographical information and detailed weather characteristics of each region of the Korean Peninsula are summarized in Table 2, according to the Korea Meteorological Administration data [28] and a literature survey [29–32].

Table 2. Climate details of the representative cities.

City	Latitude (°N), Longitude (°E)	Climate	Temperature (°C)				
			Mean	Max (Aug)		Min (Jan)	
				Av	Hi	Av	Lo
Jeju	33.30, 126.31	Humid subtropical climate. Winters are cool and dry, while summers are hot, humid and sometimes rainy. Usually windy.	15.5	18.7	35.5	12.4	−5.8
Busan	35.06, 129.01	Cooler version of a humid subtropical climate. Extremely high or low temperatures are rare.	14.7	18.9	37.3	11.3	−10.2
Daegu	35.53, 128.37	Cooler version of a humid subtropical climate. Warm temperate, moist forest climate. Basin climate characteristics in summer.	14.1	19.5	38.1	9.5	−13
Kwangju	35.10, 126.53	Close to the west coast. In winter, snowfall occurs because of west-north or west winds.	13.8	19.1	37.2	9.5	−11.7
Daejeon	36.22, 127.22	Monsoon-influenced, humid subtropical and humid continental climatic regimens.	13.0	18.4	37.6	8.3	−17
Seoul	37.34, 126.57	Humid subtropical climate influenced by the monsoons.	12.5	17	36.6	8.6	−18
Gang-neung	37.45, 128.53	Humid subtropical climate with cool to cold winters and hot, humid summers. Because this is a coastal city, generally milder winters and relatively cooler summers than the rest of Korea are experienced. Warmer than the west coast at the same latitude in winter.	13.1	17.5	35.5	9.2	−14.7
Kaesong	37.58, 126.34	Humid continental climate, with cold, dry winters and hot, humid summers with abundant rainfall.	11.0	16.3	35.5	6.6	−17.9
Pyong-yang	39.02, 125.47	Hot-summer humid continental climate, featuring warm to hot, humid summers and cold, dry winters. Cold, dry winds can blow from Siberia in winter, making conditions extremely cold.	10.6	15.9	34.4	6.0	−18.8

Table 2. *Cont.*

City	Latitude (°N), Longitude (°E)	Climate	Temperature (°C)				
			Mean	Max (Aug)		Min (Jan)	
				Av	Hi	Av	Lo
Hamhung	39.56, 127.33	Humid continental climate, with warm, humid summers and moderately cold, dry winters.	10.3	16.0	35.9	5.4	−20.4
Sinuiju	40.06, 124.23	Monsoonal humid continental climate with hot, humid and stormy summers and cold, dry winters with little snowfall.	9.8	15.0	35.5	5.6	−20
Chongjin	41.47, 129.49	Humid continental climate with cold, dry winters and warm, rainy summers.	8.4	12.7	32.4	4.5	−14.3

The average annual value for the Korean Peninsula between 1981 and 2010 was used. The highest/lowest temperature data corresponded to the 2016 values.

It can be noted that the average annual temperature (based on the average values from 1981 to 2010) decreased toward higher latitudes. (Gangneung, which faces the east coast and is affected by coastal climate, was not considered). The highest average temperature, 19.5 °C, corresponded to Daegu, which has the characteristics of a basin. The lowest average temperature, 4.5 °C, corresponded to Chongjin, which is located in the high latitude of the Korean Peninsula. As of 2016, the highest temperature in most cities in the Korean Peninsula occurred in August (Jeju in July) and the lowest temperature occurred in January.

2.1.2. Selection of Simulated Buildings

The simulation buildings were selected as medium-sized standard buildings for non-residential work facilities [33], as extracted from the 2019 Energy Efficiency Rating DB Analysis (2016–2018). The selected standard building has a floor area of 6147 m^2, five stories above ground, two basement floors with reinforced concrete and a southward-facing orientation. The details of the building are presented in Figure 4 and Table 3. Figure 4 is a simplified zone layout for the middle floor based on the standard model of reference [33]. The zone ratio is given in Table 3. For the zone ratio in Table 3, others include spaces for the office occupants, such as restrooms, rest area, etc. The first floor usually houses generally convenient facilities for the neighborhood.

Table 3. Details of a standard office (medium-sized) building model in Korea [33].

Item	Detail	
Building scale	Total floor area: 6147 m^2 (five floors above ground, two basement levels)	
Orientation	South	
Construction material	Reinforced concrete	
Aspect ratio	1.46	
Mid-level floor area	786 m^2 (air-conditioned area)	
Core position	Side	
Floor height	4.02 m (Ceiling height: 2.7 m)	
Window to wall ratio	East: 22%, West: 25%, South: 31%, North: 19%	
Zone ratio	Office 38.5%, Meeting 3.8%, Storage 5.1%, EV and Corridor 26.9%, Others 25.7%	
Insulation	Wall	PF board (0.232 W/m^{2}K)
	Roof	Rigid polyurethane (0.127 W/m^{2}K)
	Floor	Rigid polyurethane (0.173 W/m^{2}K)

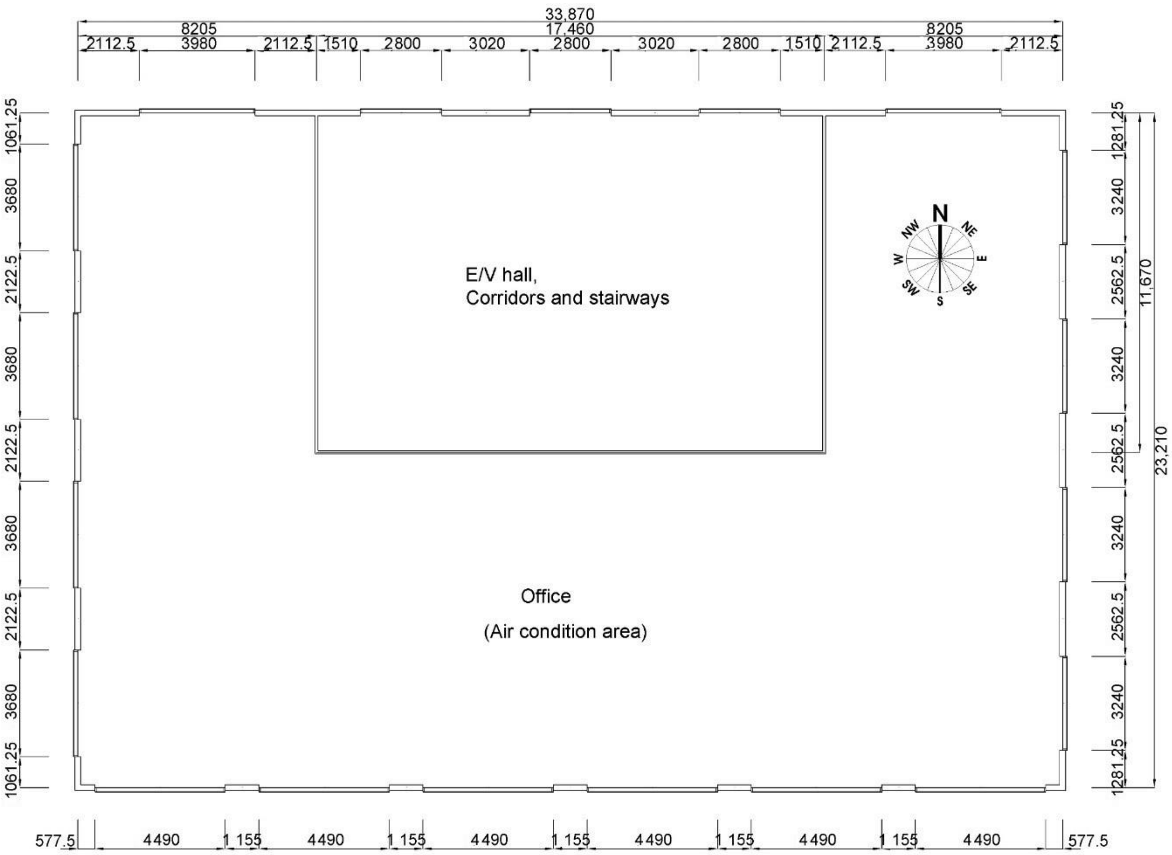


Figure 4. Floor plan of standard office building (middle size) in Korea (air-conditioned area: 582 m^2).

The external wall structure is based on the reinforced concrete structure of the standard building. The external wall finish reflects the exterior insulation finishing system and involves an aluminum sheet finish. Currently, such buildings are widely used as non-residential office facilities in Korea. The detailed composition of the external wall structure is illustrated in Figure 5.

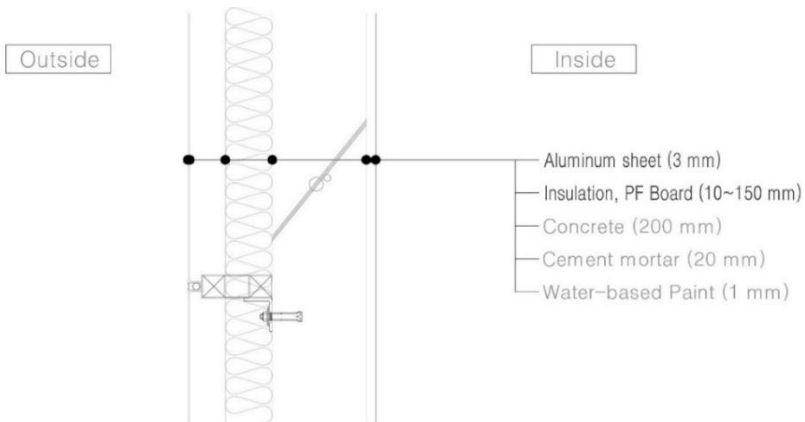


Figure 5. Exterior wall structure of the simulation model.

2.2. Analysis Methods and Conditions

2.2.1. Energy Simulation

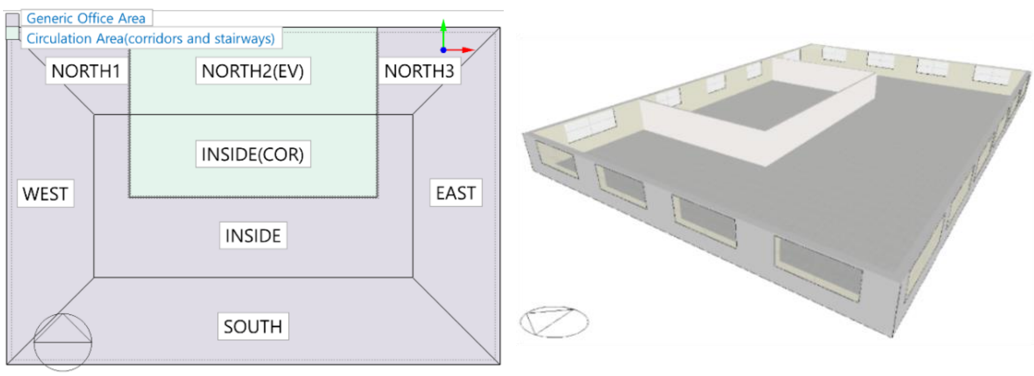
A total of 1620 simulations (135 times per region) were performed using EnergyPlus ver. 8.9, a dynamic energy simulation program, for the selected standard buildings, considering 12 regions of the Korean Peninsula, to calculate the cooling and heating demand and the energy consumption. The simulation conditions are summarized in Table 4.

In general, the heat transfer through the external wall must be calculated to determine the optimal insulation thickness [34,35]. In most studies, this analysis is performed using the degree-time method (degree-day or degree-hour). This approach is a simple technique pertaining to the steady state [20,36–42]. However, the degree-time method, in most cases, does not take into account the non-constant operation schedule (lighting, occupancy and equipment), the heat storage effect of walls and the characteristics of the heating and cooling system in the calculation of the heat transfer through the external wall [43]. In this regard, a dynamic heat transfer simulation program can calculate the building energy consumption more accurately.

The EnergyPlus software is a powerful dynamic energy simulation engine, which was used to realize the official thermal modeling of the US Department of Energy. Moreover, Design Builder (6.1.4.006) was used for building modeling. The accuracy of EnergyPlus has been demonstrated by the International Energy Agency in accordance with the Building Energy Simulation TEST (BESTest) procedure [44]. To calculate the amount of energy required to satisfy the heating and cooling demand in the simulation building, the EnergyPlus software utilized many program modules that operated simultaneously. This software calculates the heat load according to the thermal balance method, which can take into account the climatic characteristics over time, thereby considering the complete thermal balance of the inner and outer surfaces and the transient heat conduction through the building [45,46]. In this study, the time step was set as 30 min. The detailed equations and more information are available in the EnergyPlus Engineering Reference Document [47].

The climate data were based on data from TMYx (Typical Meteorological Years 2004–2018) for 12 regions of the Korean Peninsula. The TMYx file involves the typical metering data derived from hourly meteorological data from the US NOAA's Integrated Surface Database through 2018, by using the TMY/ISO 15927-4: 2005 methodology, and currently provides more than 13,550 TMYx locations [48]. The goal is to provide a standardized weather file format for solar system calculations. The basic logic of the TY type weather file is that it represents long-term weather conditions with data containing the least weather points, and thus the data correspond to the weather data closest to the long-term average of the climate [49]. Therefore, the typical year type weather files are used to estimate the average energy consumption [50].

The influence of the surrounding buildings affects the heating and cooling loads of buildings. However, it was difficult to generalize this effect, and it was not reflected in this study. Moreover, because the simulations were conducted considering the middle floor of the building, the upper and lower floors were set as adiabatic. Figure 6 show the 3D modeling of the simulated space.



(**a**) Plane (**b**) 3D

Figure 6. Simulation modeling of the building (Design Builder).

The simulation parameters include the reflectivity and insulation properties of the external wall. The reflectivity and insulation properties of the buildings in each region were changed for the external walls of the east, west, south and north. For the input range, the reflectivity was varied in nine steps from 0.1 to 0.9 in intervals of 0.1. Moreover, the insulation was varied in 15 steps from 10 mm to 150 mm in 10 mm intervals. The input conditions for the simulation are summarized in Table 4. Except for these values, the default values were used.

Table 4. Energy simulation conditions for the thermal load calculation.

Item		Detail
Weather data (External condition)		TMYx (2004–2018): South and North Korea (Jeju, Busan, Seoul, Pyongyang, Sinuiju Chongjin, etc.) [48]
Ground reflectivity		0.2 (constant, default)
Activity schedule		Monday to Friday (9:00–18:00), 9 h [51]
Internal heat gain	Occupant	131 W/person (latent and sensible heat) Occupancy density: 0.2 (person/m^2) [52]
	Lighting	25 W/m^2 (latent heat) [53] Mean radiant fraction: 46%
	Office equipment	14 W/m^2 [54]
Setting point [53]	Heating (Nov–Feb)	20 °C, RH 40%
	Cooling (Jun–Aug)	26 °C, RH 60%
	Mid-term (Mar–May, Sep–Oct)	20–26 °C, RH 40–60%
Insulation	External wall	PF board (0.019 W/m·K) 10–150 mm (no air gap between aluminum sheet and insulation)
	Roof and floor	Adiabatic
Wall reflectivity		East, West, North, and South: 0.1–0.9
Outer surface emissivity (paint coating)		0.9
Infiltration		1.5 ACH [54]
Windows	U-value	1.3 W/m^2·K, Steel frame [Legal criteria (Central 1)]
	SHGC	0.58 [33]
Heating and cooling		EHP (heating COP 3.0, cooling COP 3.5)
Ventilation		2.15 ACH [55]
Annual operating days		250 d [51]

2.2.2. Cost Analysis

For the cost analysis, the present worth method was used, in which all future costs are compared and analyzed by converting them into current costs. The total cost consists of the insulation cost (C_i), reflectivity material cost (C_r) and present value (C_e) of the energy cost over the life of the building and can be calculated as a sum of all these costs [56] as follows:

$$C_t = C_i + C_r + C_e \quad (1)$$

C_i was calculated by multiplying the cost per unit area (C_{im}) of the insulation by the required area (A_i). C_r was calculated by multiplying the cost per unit area (C_{rm}) of the reflector by the required area (A_r).

$$C_i = C_{im}\ A_i \quad (2)$$

$$C_r = C_{rm}\ A_r \quad (3)$$

The cost survey of insulation and reflective materials was conducted considering the Korean architectural market. The costs included material and labor. Specifically, the survey was conducted based on the information of commodity prices, Korea's price information and company estimates, and the lowest price among these aspects was selected. In addition, the advice of a construction specialist was sought to obtain a unit cost of the external wall construction.

Labor costs were divided into two categories based on 100 mm, and each sector corresponded to a certain cost. Specifically, sectors over 100 mm costed an additional $1.76

per m^2, due to the increase in the material weight and volume. The expenses were 1% of the workforce cost based on the standard calculation of the construction works and the external insulation work method published in 2019 [57].

According to an investigation by curtain wall experts and companies, the reflectivity of 0.1–0.7 of the external wall can be adjusted by painting the aluminum sheet surface without any additional cost. However, the reflectivity of 0.8 or higher is difficult to implement using pure aluminum materials or paint alone, as this process is expected to incur additional costs. In this study, this range was excluded from the cost analysis because the reflectivity of 0.8 or higher is rarely used in the Korean construction market as an outer finish material, and the market prices are not available.

The present value (C_e) of the energy costs during the lifetime of a building can be calculated by multiplying the total energy cost (E_t) per unit area per year by the target floor area (A_f) and a present worth factor (PWF), as expressed in Equation (4).

$$C_e = E_t\ A_f\ \mathrm{PWF} \tag{4}$$

E_t can be obtained as the sum of the cost of cooling energy per unit area and heating energy per unit area per year (Equation (5)). The cost of cooling energy per unit area per year was calculated by multiplying the annual cooling energy consumption (E_c) per unit area, calculated by an energy simulation, and the 2020 Korean electricity fee (summer) (F_s). The annual heating energy cost per unit area was calculated by multiplying the annual heating energy consumption (E_h) per unit area, calculated by an energy simulation, and the 2020 Korean electricity fee (winter) (F_w). The annual cooling and heating energy consumption per unit area were calculated through the simulation by reflecting the cooling and heating coefficient of performance (COP) of the EHP according to the demand for heating and cooling.

$$E_t = E_c\ F_s + E_h\ F_w \tag{5}$$

The PWF was calculated based on the building's life (n), inflation rate (I_f) and interest rate (I_t). The basic expression is given as Equation (6), where r can be obtained in terms of the interest rate and inflation ratio as the actual interest rate. If the interest rate is greater or smaller than the inflation, Equations (7) and (8) are used, respectively. Equation (9) may be used when the two values are identical [18–20,39,56,58–60]. In this study, Equation (7) was used because the interest rates were higher than the inflation rates, and the cost analysis period was considered to be 40 y, based on the standard life of the Korean corporate tax law buildings. Table 5 summarizes the conditions considered for the cost analysis in this study.

$$PWF = \frac{(1+r)^n - 1}{r(r+1)^n} \tag{6}$$

$$r = \frac{I_t - I_f}{1 + I_f}\ \text{for}\ \mathrm{I_t} > \mathrm{I_f} \tag{7}$$

$$r = \frac{I_f - I_t}{1 + I_t}\ \text{for}\ \mathrm{I_t} < \mathrm{I_f} \tag{8}$$

$$\text{For}\ \mathrm{I_t} = \mathrm{I_f},\ PWF = \frac{n}{1 + I_t} \tag{9}$$

Table 5. Parameters for the cost calculation.

Parameter		Unit Cost	Remark
Cost of insulation material (C_{im})	10 mm	8.37 $/m^2	PF board, semi-nonflammable
	20 mm	10.29 $/m^2	
	30 mm	12.62 $/m^2	
	40 mm	14.99 $/m^2	
	50 mm	15.49 $/m^2	
	60 mm	17.49 $/m^2	
	70 mm	19.49 $/m^2	
	80 mm	21.49 $/m^2	
	90 mm	23.49 $/m^2	
	100 mm	27.27 $/m^2	
	110 mm	29.27 $/m^2	
	120 mm	31.27 $/m^2	
	130 mm	33.27 $/m^2	
	140 mm	35.27 $/m^2	
	150 mm	37.27 $/m^2	
Cost of reflective material (C_{rm})	0.1~0.7	88.84 $/m^2	Aluminum sheet (coating)
Electricity fee (F_s, F_w) [61]		Summer: 0.08 $/kWh, Winter: 0.07 $/kWh	Korea Electric Power Corporation 2020, General Electric Power (A)
Inflation rate (I_f) [62]		1.72%	2010–2019 Korean average consumer inflation rate
Interest rate (I_t) [63]		2.05%	2010–2019 Standard interest rate average
Analysis period (n) [64]		40 y	Corporate Tax Act Enforcement Rule [Attachment 5] Standard useful life for buildings, etc.
Heating and cooling energy demand and consumption (E_c, E_h)		EnergyPlus	

1$ = 1250 Won (as of March 2020).

3. Results and Discussion

3.1. Analysis of Energy Saving Methods for Heating and Cooling

Table 6 shows the HDD (Heating degree day) and CDD (Cooling degree day) of representative cities based on a temperature of 18.3 °C. These values can approximately quantify the demand of energy needed to heat or cool buildings for each location.

Table 6. Heat and cool degree-days of representative cities.

City	Latitude (°N)	Longitude (°E)	Elevation (m)	Heat/Cool Degree-Days (°C d) HDD 18.3	CDD 18.3
Busan	35.100	129.033	71	1862	717
Daegu	35.883	128.617	61	2185	862
Daejeon	36.300	127.400	78	2682	696
Jeju	33.517	126.533	23	1647	823
Kwangju	35.167	126.900	74	2261	812
Seoul	37.567	126.967	87	2684	736
Chongjin	41.783	129.817	43	3776	232
Hamhung	39.933	127.550	22	3187	423
Kaesong	37.967	126.567	70	3061	1026
Pyongyang	39.224	125.670	36	3243	619
Sinuiju	40.100	124.383	7	3481	525

Source: ASHRAE Handbook Fundamentals 2017, Appendix: Design conditions for selected locations.

The thermal load was calculated by reflecting the climate of 12 regions by using EnergyPlus for the middle floor of the building, which occupies a relatively large portion of the building. The heat load changes due to the change in the insulation thickness and the reflectivity of the external walls could be clarified, as follows.

3.1.1. Cooling Load Results

The analysis results for the cooling load are as follows:

- In general, the cooling load decreases as the latitude increases, although certain differences were observed between the east and west regions of the Korean Peninsula, (East region: Busan, Daegu, Gangneung, Hamhung and Chongjin. West Region: Jeju, Kwangju, Daejeon, Seoul, Kaesong, Pyongyang and Sinuiju)
- Even when the cities are located at a similar latitude, less cooling load occurs in the east than that in the west. For example, Kwangju and Busan, Seoul and Gangneung and Sinuiju and Hamhung are located at similar latitudes, but there are less cooling loads in the east compared to the west, likely because of the coastal climate effects in the east.
- As the reflectivity increases, the cooling load decreases [10,11,65]. This phenomenon occurs because the increase in the reflectivity of the solar radiation energy prevents the temperature rise of the external wall, thereby reducing the amount of heat transfer to the indoor space [24,25].
- As the thickness of the insulation material increases, there exists a sector in which the cooling load increases. This phenomenon occurs because increasing the thickness of the resistive thermal insulation results in less heat loss to the outside that was generated internally by the equipment, the lighting, the human body and solar radiation [66–70]. These phenomena can be identified by the change in the cooling load, i.e., the slope, against the change in the insulation thickness. In this study, the change of insulation thickness for each reflectivity was constant at 10 mm; therefore, if the change in the cooling load was greater than zero, then this sector could be considered as one in which the cooling load increases with increasing insulation thickness. The reflectivity values at which this change-over starts are as follows: Jeju 0.1, Busan 0.1, Daegu 0.1, Kwangju 0.2, Daejeon 0.3, Seoul 0.2, Gangneung 0.3, Kaesong 0.2, Pyongyang 0.2, Hamhung 0.2, Sinuiju 0.2, Chongjin 0.1.
- In all the regions, an increase in the reflectivity increases the change-over interval. In other words, the sector in which the increase in the insulation thickness results in an increase in the cooling load is broadened.
- The changes in the cooling load occur over a larger range as the insulation thickness decreases in a thin sector (approximately 10 to 40 mm) and the reflectivity of the external wall increases.
- As the reflectivity of the exterior wall of the building increases, the region with a relatively large reduction in cooling loads pertains to the low latitudinal region. Therefore, the cooling load can be effectively reduced by increasing the external wall reflectivity at low latitudes.

To reduce the cooling load, it is necessary to increase the surface reflectivity of the external wall in the same way as Ouarda Mansouri's study [26] of the Mediterranean climate zone of Algeria and adopt an appropriate insulation thickness to achieve the corresponding reflectivity. To reduce the cooling load for each region in the Korean Peninsula, Figure 7 indicates the appropriate insulation thickness according to the reflectivity of the external wall surface.

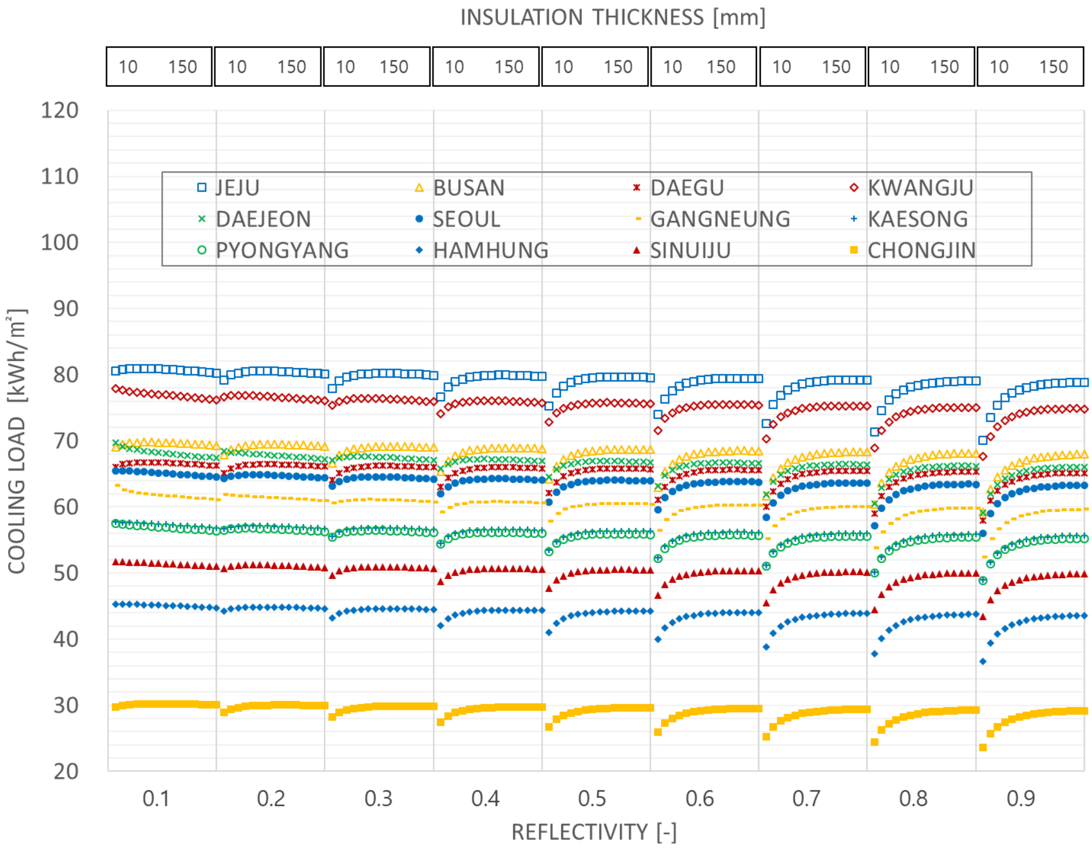


Figure 7. Changes in the cooling load depending on the insulation thickness and reflectivity of the external wall (12 regions in the Korean Peninsula).

3.1.2. Heating Load Results

The results of the analysis of the heating load are as follows.

- There exist certain differences between the eastern and western regions of the Korean Peninsula; however, in general, the heating load decreases at lower latitudes.
- The heating load is smaller in the eastern than in the western region of the Korean Peninsula. For example, Chongjin, Hamhung, Gangneung and Busan, located in the east, are located at a higher or almost identical latitude than Sinuiju, Pyongyang, Daejeon and Kwangju, which are located in the west, but exhibit a smaller heating load. This phenomenon likely occurs because the western part of the Korean Peninsula is affected by the continental climate, and the eastern part has the characteristics of the coastal climate caused by the Kuroshio current [28].
- As the reflectivity increases, the heating load increases. This phenomenon occurs because as the external wall reflectivity increases, the solar radiation energy absorbed by the external wall decreases.
- The increase in the insulation thickness decreases the heating load because less heat is lost to the outside [71–73].
- The heating load changes considerably in the thin sector (10 to 40 mm) of the insulation. As the thickness of the insulation increases, this value decreases rapidly. As the reflectivity increases or the thickness of the insulation decreases, the heating load increases.
- The change in the amount of reduction in the heating load due to the increase in the insulation material increases as the latitude increases. Therefore, the heating load reduction effect pertaining to the increase in the insulation thickness is more notable at higher latitudes than that at lower latitudes.

To reduce the heating load, one must reduce the reflectivity of the external wall and increase the insulation thickness. To reduce the heating load for each region, Figure 8 shows the insulation thickness suitable for a certain reflectivity of the external wall.

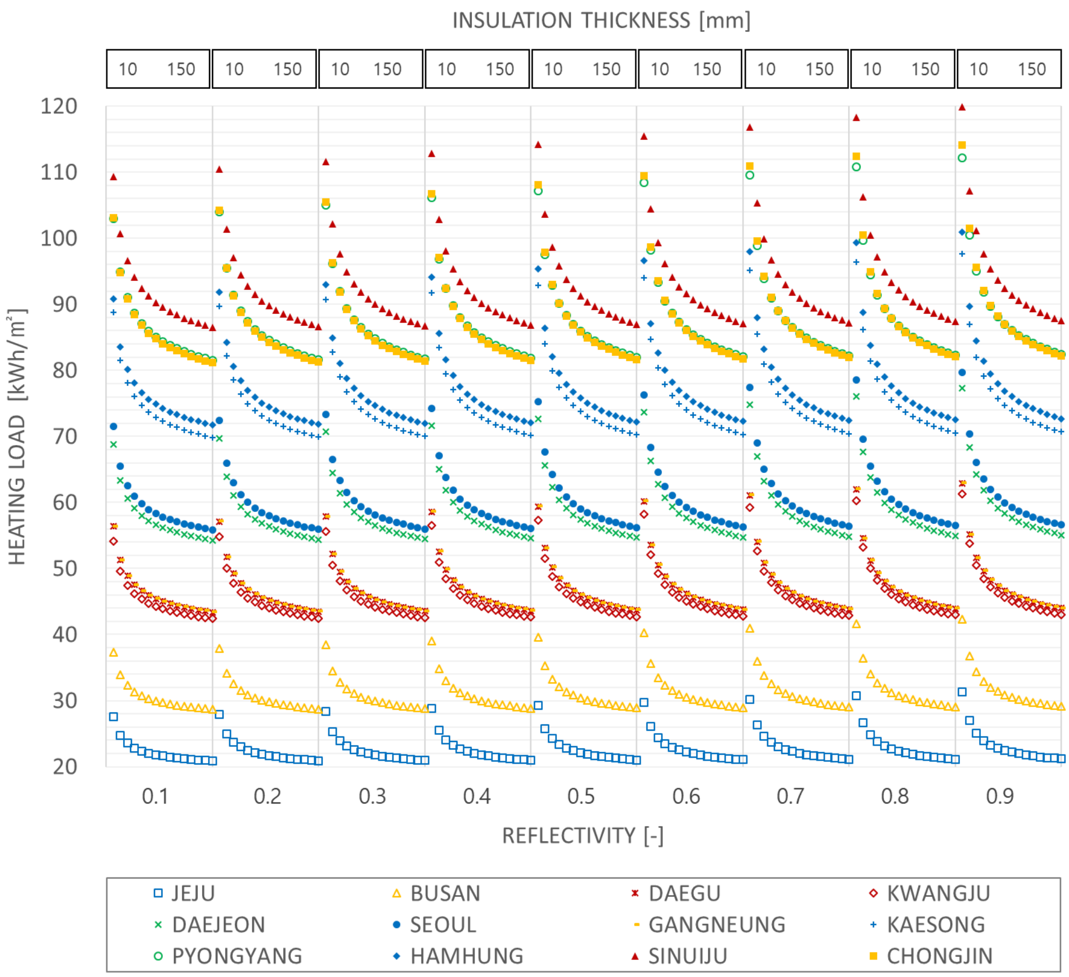


Figure 8. Changes in the heating load depending on the insulation thickness and reflectivity of the external wall (12 regions in the Korean Peninsula).

The cooling and heating load analysis shows that insulation thickness and reflectivity yield different results. Therefore, the total amount of heating and cooling loads must be evaluated on a yearly basis, as explained in the following section.

3.1.3. Total Load Results

The regional cooling and heating loads described in the previous section indicate that the regions in which the annual cooling load is higher than the heating load are Jeju, Busan, Daegu, Kwangju, Daejeon and Gangneung, which are located at low latitudes or are strongly affected by the coastal climate. Moreover, the regions in which the annual heating loads are higher than the cooling loads are located at a high latitude or strongly affected by coastal climate, such as Seoul, Kaesong, Pyongyang, Hamhung, Sinuiju and Chongjin. To reduce the load on buildings, a larger amount of solar radiation should be absorbed in winter, and a high reflectivity should be maintained in summer [25,74–76]. Therefore, this section clarifies the optimum insulation thickness and reflectivity through the total load on a yearly basis. Figure 9 shows the total changes in the cooling and heating loads by region according to the reflectivity and insulation thickness.

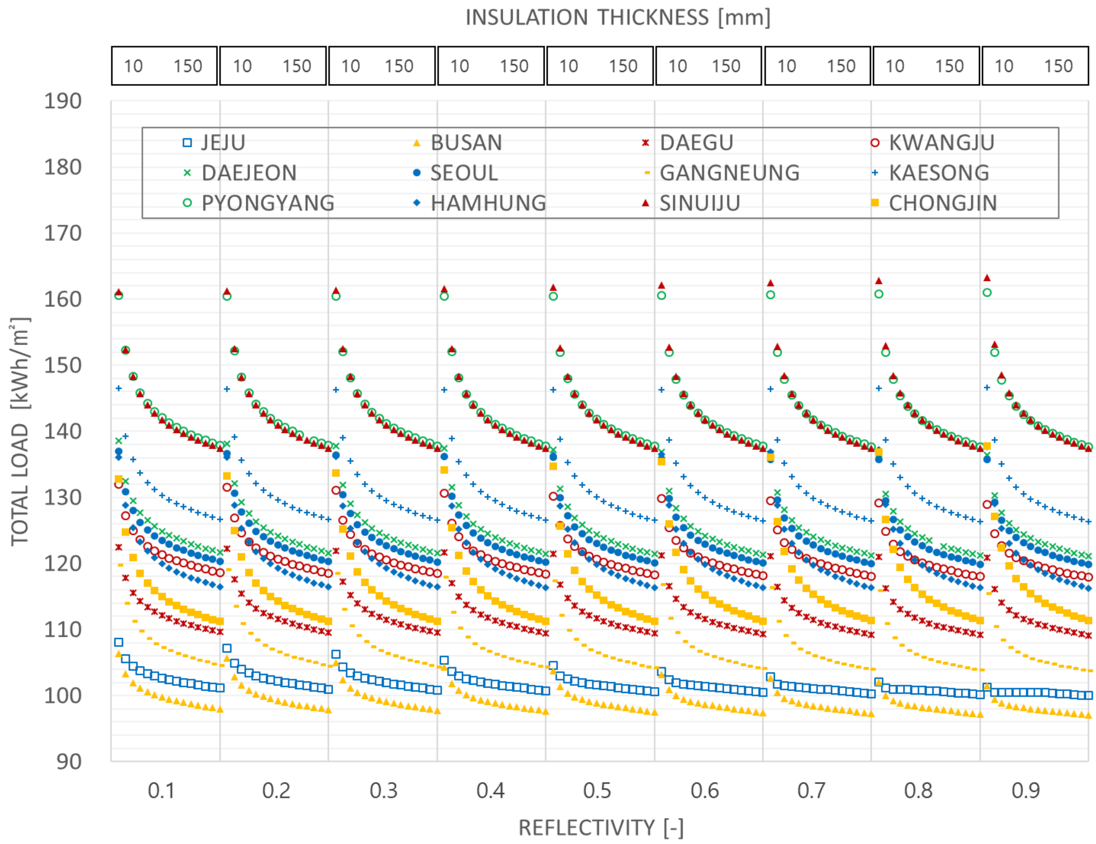


Figure 9. Changes in the total load depending on the insulation thickness and reflectivity of the external wall (12 regions in the Korean Peninsula).

The following key findings could be derived:

- The total load of each region can be clearly divided into the western part of the Korean Peninsula (Pyongyang, Sinuiju, Kaesong, Daejeon, Seoul, Kwangju) and the eastern part (Hamhung, Chongjin, Daegu, Gangneung, and Busan), with the western part occupying a larger portion. This finding occurs because the eastern part of the Korean Peninsula is affected by the coastal climate, involving a small daily temperature range and a mild climate.
- The increase and decrease in the reflectivity are based on the different total loads by region. With an increased reflectivity, Chongjin, Sinuiju, Hamhung, Pyongyang and Kaesong exhibited an increased total load, while Jeju, Busan, Gangneung, Kwangju, Daejeon, Daegu and Seoul exhibited a decreased total load. The regions are listed in order of the increase and decrease in the load. Specifically, the regions with high heating load should have lower reflectivity and the regions with high cooling loads higher reflectivity, to reduce each load. In other words, energy saving can be achieved by increasing and decreasing the reflectivity in the southern and northern regions, respectively.
- In all the regions, the total load decreases as the insulation thickness increases.
- A higher latitude corresponds to a greater total load change due to the change in the insulation thickness. In other words, a higher latitude corresponds to a significant effect of the insulation thickness.
- Lower-latitude regions correspond to a reduced total load variation against the change in the insulation thickness.
- The total load is highly dependent on insulation thickness in the thin insulation thickness sector, but becomes less dependent in the thick sector.
- In the case of Jeju Island and Busan, regions with relatively large cooling load and small heating load, the total load is little affected by insulation thickness at high reflectivity.

Figure 9 can help select the appropriate insulation thickness depending on the reflectivity of the external wall to reduce the total load of each region.

The abovementioned load analysis indicated that relatively large variations in the load occur in the thin sector (10–40 mm) of the insulation [77–79]. Therefore, the optimal insulation thickness and reflectivity analysis must be performed considering the total cost of the whole year. This aspect is further evaluated in the following sections.

3.2. Optimal Insulation Thickness and Reflectivity Considering Economics

The optimal insulation thickness and reflectivity for each region refer to a combination of the reflectivity and the insulation thickness with the lowest total cost. The high-latitude-lying Chongjin, mid-latitude-lying Seoul, and low-latitude-lying Jeju are considered as the representative regions of each latitude in the Korean Peninsula. Figures 10–12 show the optimum insulation thickness and reflectivity considering the total cost by region, exterior wall insulation and graph of the total cost change with the reflectivity change.

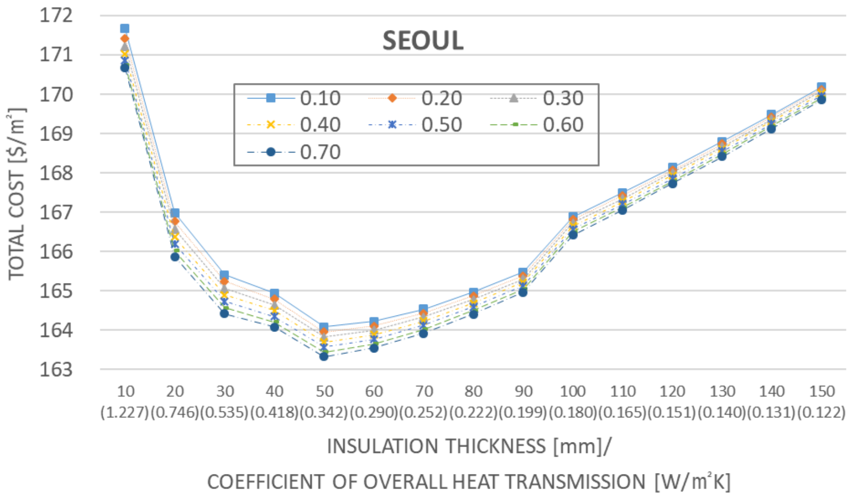


Figure 10. Changes in the total cost depending on the insulation thickness and reflectivity of the external wall (Jeju, low-latitude region in the Korean Peninsula).

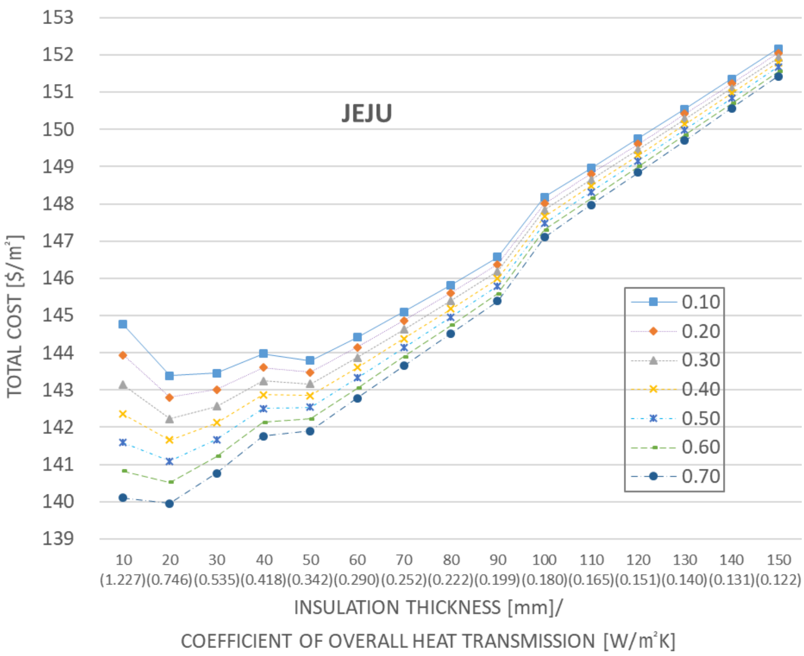


Figure 11. Changes in the total cost depending on the insulation thickness and reflectivity of the external wall (Seoul, mid-latitude region in the Korean Peninsula).

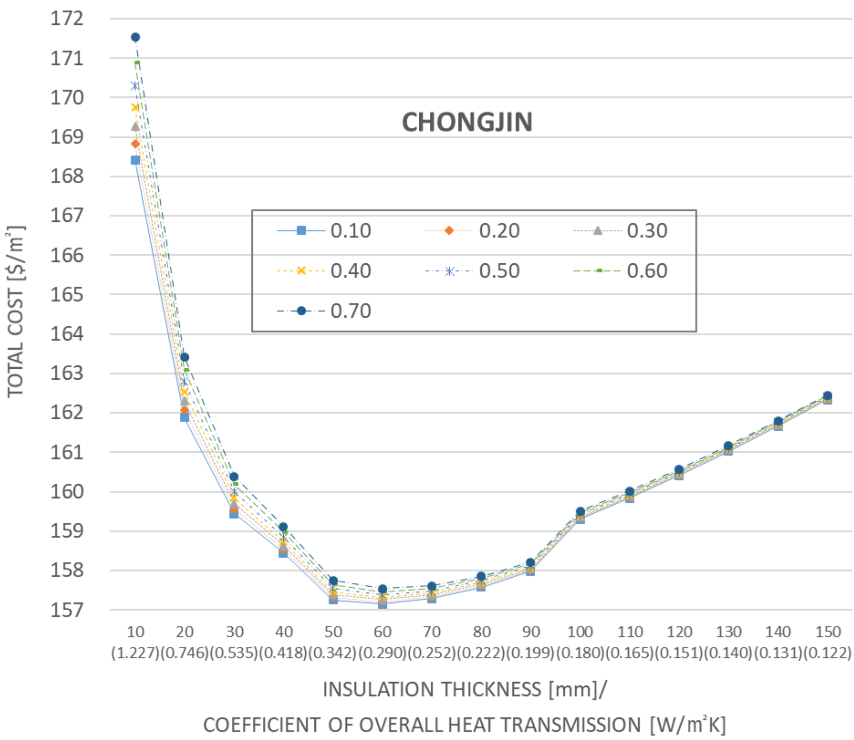


Figure 12. Changes in the total cost depending on the insulation thickness and reflectivity of the external wall (Chongjin, high-latitude region in the Korean Peninsula).

Figure 10 corresponds to Jeju, which is a representative region for low-latitude regions, and the following findings can be derived:

- The total cost mimics the shape of a proportional graph.
- Except for the insulation thickness of 10–20 mm, a thicker insulation corresponds to a higher total cost.
- The change in the total cost for changes in the reflectivity at an arbitrary insulation thickness is relatively large compared to that in the other regions. High reflectivity corresponds to a minimum total cost for all insulation thicknesses. In particular, a thinner insulation corresponds to a greater change in the total cost.
- The lowest total cost combination pertains to an insulation thickness and reflectivity of 20 mm and 0.7, respectively, for Jeju.

Figure 11 corresponds to Seoul, which is a representative region for mid-latitude regions, and the following findings can be derived:

- The shape of the total cost graph is similar to a U-shape.
- The total cost is reduced as the insulation thickness increases from 10 to 50 mm; however, the cost in the subsequent sector increases.
- The cost changes due to the changes in reflectivity are not as large as those in low latitudes. However, the thin sector of the insulation exhibits a relatively large change compared to that in the thick sector.
- The lowest total cost combination pertains to an insulation thickness and reflectivity of 50 mm and 0.7, respectively.

Figure 12 corresponds to Chongjin, which is a representative region for high-latitude regions, and the following findings can be derived:

- The shape of the total cost graph is close to the L-shape.
- The total cost decreases as the insulation thickness increases to 60 mm; however, it increases at higher thicknesses.
- The change in the total cost with the change in reflectivity decreases as the thickness of the insulation increases. In particular, a relatively large change can be observed

for the insulation thickness of 10–20 mm. In contrast to the low latitude case, a lower reflectivity corresponds to a lower total cost.

- The lowest total cost combination pertains to an insulation thickness and reflectivity of 60 mm and 0.1, respectively.

The analysis of the optimal insulation thickness and reflectivity for each region considering the total cost yielded the following trends according to the change in latitude.

- High-latitude regions correspond to a higher shift to the right of the optimal insulation thickness.
- The range of total cost due to changes in the insulation thickness varied for the high (approximately 157–172 $\$/m^2$), low (approximately 140–152 $\$/m^2$) and mid (approximately 163–172 $\$/m^2$) latitudes. Therefore, if the high-latitude region, the building is assigned an optimum insulation thickness, and the insulation thickness for the low-latitude building is not larger than the one required, and a relatively large energy saving effect can be expected compared to that in the mid-latitude.
- In all the regions, the total cost changes are significant due to changes in reflectivity in the regions with a thin insulation thickness. This aspect can increase the energy savings in terms of the surface reflectivity in low-latitude regions, as the optimal insulation thickness occurs in sectors thinner than that in the other regions.
- In the low latitude and mid latitude regions, a higher reflectivity corresponds to a lower total cost. However, in high latitudes, a lower reflectivity corresponds to a lower total cost.

Finally, for the 12 regions, the optimal insulation thickness and reflectivity can be derived, as illustrated in Figure 13.

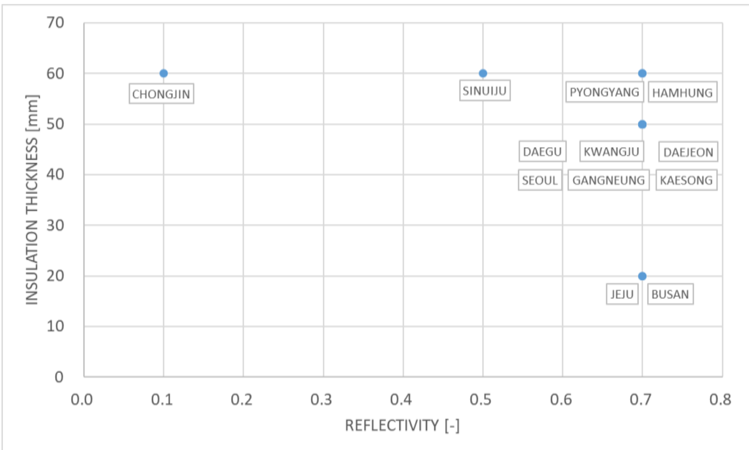


Figure 13. Optimal insulation thickness and reflectivity of the external wall considering the total cost (12 regions in the Korean Peninsula).

- All the regions except Chongjin (reflectivity 0.1) and Sinuiju (reflectivity 0.5), which are located at high latitudes, exhibited the lowest cost when the reflectivity was high (reflectivity 0.7). Moreover, high-latitude regions with an optimal reflectivity of 0.7 corresponded to a larger optimal insulation thickness.
- Comparing the optimal reflectivity values of the two countries based on Yuan's research data [27], regions close to the poles had optimal values in the range of low reflectivity, and regions close to the equator had optimal values in the range of high reflectivity. For the central region, the optimum reflectivity was 0.7 in the Korean Peninsula and 0.4–0.6 in Japan, although the two countries are located in similar latitudes.
- When the regions are sorted in order of large cooling loads, in most regions, the optimum reflectivity is high in the order of large cooling loads. However, although

Sinuiju exhibited a higher cooling load than Hamhung, it required a lower optimal reflectivity. In terms of the cooling load, Sinuiju exhibited values one step larger than those of Hamhung, but in terms of the heating load, Sinuiju exhibited values three step larger. Therefore, in the case of Sinuiju, the thickness of the insulating materials must be increased, and the reflectivity must be reduced to lower the heating load.

- The high reflectivity of the external wall may reflect sunlight according to the reflective characteristics, creating a glare around the building and vehicle drivers [80,81]. Therefore, a high reflectivity of the exterior walls of the buildings must be accompanied by an environmental impact assessment considering the surrounding environment.
- Sinuiju is located at a lower latitude than Chongjin but requires an optimal insulation thickness larger than that of Chongjin. This phenomenon is likely accompanied by an increase in insulation thickness because Sinuiju has a larger heating load than Chongjin.
- In all regions, the thickness of the optimal insulation material increased in the order of the large heating loads.
- Assuming that the optimal reflectivity is applied to the external wall, the regions for the optimal insulation thickness can be divided into three categories: Jeju and Busan (20 mm); Daegu, Kwangju, Daejeon, Seoul, Gangneung and Kaesong (50 mm); Chongjin, Sinuiju, Pyongyang and Hamhung (60 mm).

4. Conclusions

By selecting 12 representative cities and the office building in the Korean Peninsula, this study was aimed at examining the changes in the cooling and heating loads due to the changes in the insulation thickness and reflectivity and at deriving the optimal insulation thickness and reflectivity considering the total cost. The cooling and heating load were calculated using the dynamic simulation program EnergyPlus. Moreover, a cost analysis was performed using the present worth method. The total cost includes the initial investment and energy cost during the analysis period.

The results of the analysis can be divided into three main categories: analysis of cooling and heating loads by region, analysis of total cost changes according to the optimal insulation thickness and reflectivity, and derivation of the optimal insulation thickness and reflectivity.

- According to the analysis of heating and cooling loads in the Korean Peninsula, certain changes were observed in the eastern and western regions as well as the latitude.
- To reduce the cooling load, it is necessary to increase the reflectivity of the external wall and adopt an insulation thickness suitable for that reflectivity. Figure 7 illustrates the appropriate insulation thickness according to the reflectivity of the external wall of the building.
- To reduce the heating load, one must reduce the reflectivity of the external wall and increase the insulation thickness. Figure 8 presents the insulation thicknesses suitable to match the reflectivity of the exterior walls by region.

The cooling and heating load analysis shows that the load reduction methods lead to certain variations. Therefore, it is necessary to analyze the total amount of heating and cooling loads on a yearly basis. The key results are as follows:

- To reduce the total load, energy can be saved by increasing and decreasing the reflectivity in the southern region (South Korea) and northern region (North Korea), respectively.
- The total load decreases as the insulation thickness increases in all regions. In particular, high-latitude regions present greater total load changes due to the change in the insulation thickness.
- However, in the case of Jeju Island and Busan, which have relatively large cooling loads and small heating loads, a high reflectivity of the external walls corresponds to a small effect by the increase in the insulation thickness.

The optimal combination of insulation thickness and reflectivity based on the total cost, including the initial installation and energy costs, was studied. High-latitude Chongjin, mid-latitude Seoul and low-latitude Jeju were designated as representative regions for each latitude in the Korean Peninsula. For the minimum total cost, the combinations of insulation thickness and reflectivity are 20 mm, 0.7; 50 mm, 0.7 and 60 mm, 0.1 for Jeju, Seoul and Chongjin, respectively.

When the market price of the 0.8–0.9 sector of reflectivity is available in the Korean architectural outer finish market, an economic analysis of the high-reflection sector must be incorporated through additional cost investigations. Moreover, further research is needed for residential buildings because the building envelope of residential buildings is more important than that of the office buildings.

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Abbreviations

Symbols

A_f	Floor area of simulation, m^2
A_i	Applied area of insulation material, m^2
A_r	Applied area of reflectivity material, m^2
ACH	Air change per hour, 1/h
C_e	Cost of energy consumption over the building life time, $
C_i	Insulation material cost, $
C_{im}	Cost of insulation material per square meter, $/$m^2$
C_r	Reflectivity material cost, $
C_{rm}	Cost of reflectivity material per square meter, $/$m^2$
C_t	Total cost, $
CDD	Cooling degree day, base 18.3 °C, °C-day
COP	Coefficient of performance
E_c	Cooling energy consumption per square meter per year, kWh/m^2·y
E_h	Heating energy consumption per square meter per year, kWh/m^2·y
E_t	Total energy cost per square meter per year, $/$m^2$·y
EHP	Electric heat pump
F_s	Electricity fee in summer of Korea, $/kWh
F_w	Electricity fee in winter of Korea, $/kWh
I_t	Interest rate, %
n	Life time of a building, y
PF	Phenolic foam
PWF	Present worth factor
r	Actual interest rate, %
RH	Relative humidity, %
TMY	Typical meteorological year

References

1. Key World Energy Statistics. 2016. Available online: https://www.oecd-ilibrary.org/energy/key-world-energy-statistics-2016_key_energ_stat-2016-en (accessed on 18 November 2020).
2. 2030 Greenhouse Gas Reduction Roadmap Revised and 2018–2020 Emission Rights Allocation Plan Confirmed. Available online: http://www.me.go.kr/home/web/board/read.do?pagerOffset=1170&maxPageItems=10&maxIndexPages=10&searchKey=&searchValue=&menuId=&orgCd=&boardId=886420&boardMasterId=1&boardCategoryId=&decorator= (accessed on 18 November 2020).
3. Yi, D.-I. A Study on the Energy Saving System: Focusing on the Energy Saving System in Building Sector. Master's Thesis, ChungAng University, Seoul, Korea, 2010.
4. Kim, P.-W. Architecture and Energy: A System for Energy Saving in Buildings—Focused on Regulatory and Promoting Methods. *Rev. Arch. Build. Sci.* **1986**, *30*, 58–60.
5. IEA. *Technology Roadmap Energy Efficient Building Envelopes 2013*; IEA: Paris, France, 2013.
6. Zero Energy Building Mandatory Detailed Road Map. Available online: https://zeb.energy.or.kr/BC/BC02/BC02_02_001.do (accessed on 18 November 2020).
7. Seo, S.-M.; Park, J.-C.; Rhee, E.-K. An Analysis of Thermal Loads Depending on Korea Building Insulation Standard and the Optimum Insulation Standard. *J. Korean Sol. Energy Soc.* **2011**, *31*, 146–155. [CrossRef]
8. Ascione, F.; De Masi, R.F.; Santamouris, M.; Ruggiero, S.; Vanoli, G.P. Experimental and numerical evalua-tions on the energy penalty of reflective roofs during the heating season for Mediterranean climate. *Energy* **2018**, *144*, 178–199. [CrossRef]
9. Mansouri, O.; Bourbia, F.; Belarbi, R. Influence de la réflectivité de l'enveloppe sur la demande énergétique des bâtiments et sur le confort thermique. *Fundam. Eng. Sci.* **2018**, *18*, 33–42.
10. Saber, H.H.; Maref, W. Energy Performance of Cool Roofs Followed by Development of Practical Design Tool. *Front. Energy Res.* **2019**, *7*. [CrossRef]
11. Saafi, K.; Daouas, N. A life-cycle cost analysis for an optimum combination of cool coating and thermal insulation of residential building roofs in Tunisia. *Energy* **2018**, *152*, 925–938. [CrossRef]
12. Ramamurthy, P.; Sun, T.; Rule, K.; Bou-Zeid, E. The joint influence of albedo and insulation on roof performance: A modeling study. *Energy Build.* **2015**, *102*, 317–327. [CrossRef]
13. Ucar, A.; Balo, F. Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls. *Renew. Energy* **2010**, *35*, 88–94. [CrossRef]
14. Yu, J.; Yang, C.; Tian, L.; Liao, D. A study on optimum insulation thicknesses of external walls in hot summer and cold winter zone of China. *Appl. Energy* **2009**, *86*, 2520–2529. [CrossRef]
15. Ozel, M. Thermal performance and optimum insulation thickness of building walls with different structure materials. *Appl. Therm. Eng.* **2011**, *31*, 3854–3863. [CrossRef]
16. Kaynakli, O. A study on residential heating energy requirement and optimum insulation thickness. *Renew. Energy* **2008**, *33*, 1164–1172. [CrossRef]
17. Nematchoua, M.K.; Raminosoa, C.R.R.; Mamiharijaona, R.; René, T.; Orosa, J.A.; Elvis, W.; Meukam, P. Study of the economical and optimum thermal insulation thickness for buildings in a wet and hot tropical climate: Case of Cameroon. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1192–1202. [CrossRef]
18. Daouas, N.; Hassen, Z.; Aissia, H.B. Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia. *Appl. Therm. Eng.* **2010**, *30*, 319–326. [CrossRef]
19. Wati, E.; Meukam, P.; Nematchoua, M.K. Influence of external shading on optimum insulation thickness of building walls in a tropical region. *Appl. Therm. Eng.* **2015**, *90*, 754–762. [CrossRef]
20. Dombaycı, Ö.A.; Gölcü, M.; Pancar, Y. Optimization of insulation thickness for external walls using different energy-sources. *Appl. Energy* **2006**, *83*, 921–928. [CrossRef]
21. Kayfeci, M.; Keçebaş, A.; Gedik, E. Determination of optimum insulation thickness of external walls with two different methods in cooling applications. *Appl. Therm. Eng.* **2013**, *50*, 217–224. [CrossRef]
22. Çomaklı, K.; Yüksel, B. Environmental impact of thermal insulation thickness in buildings. *Appl. Therm. Eng.* **2004**, *24*, 933–940. [CrossRef]
23. del Coz Díaz, J.J.; García Nieto, P.J.; Betegón Biempica, C.; Prendes Gero, M.B. Analysis and optimization of the heat-insulating light concrete hollow brick walls design by the finite element method. *Appl. Therm. Eng.* **2007**, *27*, 1445–1456. [CrossRef]
24. Al-Khawaja, M.J. Determination and selecting the optimum thickness of insulation for buildings in hot countries by accounting for solar radiation. *Appl. Therm. Eng.* **2004**, *24*, 2601–2610. [CrossRef]
25. Ozel, M. The influence of exterior surface solar absorptivity on thermal characteristics and optimum insulation thickness. *Renew. Energy* **2012**, *39*, 347–355. [CrossRef]
26. Mansouri, O.; Belarbi, R.; Bourbia, F. Albedo effect of external surfaces on the energy loads and thermal comfort in buildings. *Energy Procedia* **2017**, *139*, 571–577. [CrossRef]
27. Yuan, J.; Farnham, C.; Emura, K.; Alam, M.A. Proposal for optimum combination of reflectivity and insulation thickness of building exterior walls for annual thermal load in Japan. *Build. Environ.* **2016**, *103*, 228–237. [CrossRef]
28. Domestic Climate Data of Korea. Available online: http://www.weather.go.kr/weather/climate/average_regional.jsp (accessed on 18 November 2020).

29. Korea Meteorological Administration. *1981~2010 the Climate Atlas of Korea*; Korea Meteorological Administration: Seoul, Korea, 2012.
30. Korea Meteorological Administration Seoul. *Annual Climatological Report of North Korea*; Korea Meteorological Administration Seoul: Seoul, Korea, 2016.
31. Korea Meteorological Administration. *30 Years of North Korean Meteorological (1981–2010)*; Korea Meteorological Administration: Seoul, Korea, 2012.
32. Climate Details. Available online: https://en.wikipedia.org/wiki/Climate_of_Seoul (accessed on 18 November 2020).
33. Korea Energy Agency. *A Study on the Improvement of the Total Energy Consumption Criteria in Korea*; Korea Energy Agency: Ulsan, Korea, 2019.
34. Kaynakli, O. A review of the economical and optimum thermal insulation thickness for building applications. *Renew. Sustain. Energy Rev.* **2012**, *16*, 415–425. [CrossRef]
35. Liu, X.; Chen, Y.; Ge, H.; Fazio, P.; Chen, G.; Guo, X. Determination of optimum insulation thickness for building walls with moisture transfer in hot summer and cold winter zone of China. *Energy Build.* **2015**, *109*, 361–368. [CrossRef]
36. Alsayed, M.F.; Tayeh, R.A. Life cycle cost analysis for determining optimal insulation thickness in Palestinian buildings. *J. Build. Eng.* **2019**, *22*, 101–112. [CrossRef]
37. Sagbansua, L.; Balo, F. Ecological impact & financial feasibility of Energy Recovery (EIFFER) Model for natural insulation material optimization. *Energy Build.* **2017**, *148*, 1–14. [CrossRef]
38. Kurekci, N.A. Determination of optimum insulation thickness for building walls by using heating and cooling degree-day values of all Turkey's provincial centers. *Energy Build.* **2016**, *118*, 197–213. [CrossRef]
39. Sisman, N.; Kahya, E.; Aras, N.; Aras, H. Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions. *Energy Policy* **2007**, *35*, 5151–5155. [CrossRef]
40. Bektas Ekici, B.; Aytac Gulten, A.; Aksoy, U.T. A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey. *Appl. Energy* **2012**, *92*, 211–217. [CrossRef]
41. Yu, J.; Tian, L.; Yang, C.; Xu, X.; Wang, J. Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of china. *Energy Build.* **2011**, *43*, 2304–2313. [CrossRef]
42. Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings. *Energy Build.* **2014**, *77*, 28–39. [CrossRef]
43. Fumo, N.; Mago, P.; Luck, R. Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. *Energy Build.* **2010**, *42*, 2331–2337. [CrossRef]
44. Henninger, R.H.; Witte, M.J.; Crawley, D.B. Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100–E200 test suite. *Energy Build.* **2004**, *36*, 855–863. [CrossRef]
45. Eskin, N.; Türkmen, H. Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey. *Energy Build.* **2008**, *40*, 763–773. [CrossRef]
46. Amiri Rad, E.; Fallahi, E. Optimizing the insulation thickness of external wall by a novel 3E (energy, environmental, economic) method. *Constr. Build. Mater.* **2019**, *205*, 196–212. [CrossRef]
47. U.S. DoE. *EnergyPlus Version 8.9.0 Documentation Engineering Reference, 2018*. Available online: https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.9.0/EngineeringReference.pdf (accessed on 12 March 2021).
48. Climate Data (TMYx 2004~2018). Available online: http://climate.onebuilding.org/WMO_Region_2_Asia/KOR_South_Korea/ (accessed on 18 November 2020).
49. National Climatic Data Center. *Typical Meteorological Year User's Manual TD-9734: Hourly Solar Radiation-Surface Meteorological Observations*; NCDC: Asheville, NC, USA, 1981.
50. Siu, C.Y.; Liao, Z. Is building energy simulation based on TMY representative: A comparative simulation study on doe reference buildings in Toronto with typical year and historical year type weather files. *Energy Build.* **2020**, *211*, 109760. [CrossRef]
51. Korea Energy Agency. *The revision of the Regulations on the Operation of Energy Efficiency Rating System for Buildings in Korea Energy Corporation*; Korea Energy Agency: Ulsan, Korea, 2016.
52. Minister of Land Infrastructure and Transport Korea. *Air Conditioning Load Calculation Design Criteria KDS 31 25 06*; Minister of Land Infrastructure and Transport Korea: Sejong, Korea, 2016.
53. Minister of Land, Infrastructure and Transport Korea. *National Construction Standards-2016 Design Criteria for Building Machinery Equipment*; Minister of Land Infrastructure and Transport Korea: Sejong, Korea, 2016.
54. Korea Energy Agency. *Detailed Guidelines for Energy Efficiency Rating of Buildings in Korea Energy Corporation*; Korea Energy Agency: Ulsan, Korea, 2020.
55. Rules on the Standards, etc. of Facilities in Buildings. Available online: http://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EA%B1%B4%EC%B6%95%EB%AC%BC%EC%9D%98%20%EC%84%A4%EB%B9%84%EA%B8%B0%EC%A4%80%20%EB%93%B1%EC%97%90%20%EA%B4%80%ED%95%9C%20%EA%B7%9C%EC%B9%99 (accessed on 18 November 2020).
56. Al-Sanea, S.A.; Zedan, M.F.; Al-Ajlan, S.A.; Abdul Hadi, A.S. Heat Transfer Characteristics and Optimum Insulation Thickness for Cavity Walls. *J. Therm. Envel. Build. Sci.* **2003**, *26*, 285–307. [CrossRef]
57. Minister of Land, Infrastructure and Transport Korea. Standard Product Estimation for Construction Projects 2019—Construction Technology Information System. Available online: https://www.codil.or.kr/helpdesk/read.do?bbsId=BBSMSTR_900000000202&nttId=11952&searchWrd= (accessed on 18 November 2020).

58. Aytaç, A.; Aksoy, U. The relation between optimum insulation thickness and heating cost on external walls for energy saving. *J. Fac. Eng. Archit. Gazi Univ.* **2006**, *21*, 753–758.
59. Bolattürk, A. Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Build. Environ.* **2008**, *43*, 1055–1064. [CrossRef]
60. Derradji, L.; Imessad, K.; Amara, M.; Boudali Errebai, F. A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness. *Appl. Therm. Eng.* **2017**, *112*, 975–985. [CrossRef]
61. Korea Electric Power Corporation. Electric Rates Table. Available online: http://cyber.kepco.co.kr/ckepco/front/jsp/CY/E/E/CYEEHP00101.jsp (accessed on 18 November 2020).
62. IMF. 2010–2019 Korea Average Consumer Price Growth Rate. Available online: https://tradingeconomics.com/south-korea/inflation-cpi (accessed on 18 November 2020).
63. Bank of Korea. 2010–2019 Base Rate Trend. Available online: https://www.bok.or.kr/portal/singl/baseRate/list.do?dataSeCd=01&menuNo=200643 (accessed on 18 November 2020).
64. Enforcement Rules of the Corporate Tax Act of the Ministry of Government Legislation, the Scope of the Standard Useful Life and the Scope of the Useful Life. Available online: http://www.law.go.kr/%EB%B2%95%EB%A0%B9/%EB%B2%95%EC%9D%B8%EC%84%B8%EB%B2%95%20%EC%8B%9C%ED%96%89%EA%B7%9C%EC%B9%99 (accessed on 18 November 2020).
65. Zhang, Y.; Long, E.; Li, Y.; Li, P. Solar Radiation Reflective Coating Material on Building Envelopes: Heat Transfer Analysis and Cooling Energy Saving. *Energy Explor. Exploit.* **2017**, *35*, 748–766. [CrossRef]
66. D'Orazio, M.; Di Perna, C.; Di Giuseppe, E. The effects of roof covering on the thermal performance of highly insulated roofs in Mediterranean climates. *Energy Build.* **2010**, *42*, 1619–1627. [CrossRef]
67. Kisilewicz, T. On the Role of External Walls in the Reduction of Energy Demand and the Mitigation of Human Thermal Discomfort. *Sustainability* **2019**, *11*, 1061. [CrossRef]
68. Chvatal, K.M.S.; Corvacho, H. The Impact of Increasing the Building Envelope Insulation upon the Risk of Overheating in Summer and an Increased Energy Consumption. *J. Build. Perform. Simul.* **2009**, *2*, 267–282. [CrossRef]
69. Mulville, M.; Stravoravdis, S. The Impact of Regulations on Overheating Risk in Dwellings. *Build. Res. Inf.* **2016**, *44*, 520–534. [CrossRef]
70. Overheating in Commercial Buildings—Waverley. Available online: https://www.waverley.co.uk/overheating-in-commercial-office-buildings-blinds/ (accessed on 2 March 2021).
71. Insulation. Available online: https://www.energy.gov/energysaver/weatherize/insulation (accessed on 2 March 2021).
72. Kameni Nematchoua, M.; Ricciardi, P.; Reiter, S.; Yvon, A. A Comparative Study on Optimum Insulation Thickness of Walls and Energy Savings in Equatorial and Tropical Climate. *Int. J. Sustain. Built Environ.* **2017**, *6*, 170–182. [CrossRef]
73. Aktemur, C.; Atikol, U. Optimum Insulation Thickness for the Exterior Walls of Buildings in Turkey Based on Different Materials, Energy Sources and Climate Regions. *Int. J. Eng. Technol. Ijet* **2017**, *3*, 72–82. [CrossRef]
74. Wang, C.; Guo, X.; Zhu, Y. Energy saving with optic-variable wall for stable air temperature control. *Energy* **2019**, *173*, 38–47. [CrossRef]
75. Hernández-Pérez, I.; Xamán, J.; Macías-Melo, E.V.; Aguilar-Castro, K.M. Reflective Materials for Cost-Effective Energy-Efficient Retrofitting of Roofs. In *Cost-Effective Energy Efficient Building Retrofitting*; Elsevier: Amsterdam, The Netherlands, 2017; pp. 119–139. [CrossRef]
76. Dominguez-Delgado, A.; Domínguez-Torres, H.; Domínguez-Torres, C.-A. Energy and Economic Life Cycle Assessment of Cool Roofs Applied to the Refurbishment of Social Housing in Southern Spain. *Sustainability* **2020**, *12*, 5602. [CrossRef]
77. Berardi, U.; Tronchin, L.; Manfren, M.; Nastasi, B. On the Effects of Variation of Thermal Conductivity in Buildings in the Italian Construction Sector. *Energies* **2018**, *11*, 872. [CrossRef]
78. Mahlia, T.M.I.; Taufiq, B.N.; Ismail; Masjuki, H.H. Correlation between Thermal Conductivity and the Thickness of Selected Insulation Materials for Building Wall. *Energy Build.* **2007**, *39*, 182–187. [CrossRef]
79. Yuan, J. Impact of Insulation Type and Thickness on the Dynamic Thermal Characteristics of an External Wall Structure. *Sustainability* **2018**, *10*, 2835. [CrossRef]
80. Lee, K.H.; Lee, H.S.; Lee, Y.G. A study on the environmental performance using the reflective glass as building envelope material. *J. Archit. Inst. Korea* **1994**, *10*, 167–173.
81. Choi, J.B. An Evaluation on the Reflected Sunlight Glare by Field Measurements and Surveys Analysis. Master's Thesis, Korea National University of Transportation, Choongbuk, Korea, 2019.