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Research Note

Developing a New Model to Optimize Thermal Insulation Thickness for Building Energy Efficiency

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A B S T R A C T

Building insulation stands out as one of the most widely employed strategies to enhance energy efficiency in the building sector. Increasing the thickness of thermal insulation is a conventional approach to meet the design requirements of these structures. In this study, a novel approach to augment the thermal resistance of external building walls is explored by simultaneously employing multiple thermal insulation materials, comparing this with a single-layer insulation setup. Three typical insulation materials with varying thicknesses are utilized to create a three-layer insulation system, which is applied to a case study involving a house-like cubicle situated in the 3B climate zone per ASHRAE 169-2006. The findings indicate that merely increasing the thickness of a single-layer insulation does not invariably yield optimal solutions. The results emphasize that the consideration of multi-layer insulation systems can establish a continuous decision-making space, enabling the identification of at least one insulation scenario aligned with design requirements. To facilitate designers in the initial stages of thermal insulation design, a rapid and simplified design model has been developed based on the results. The methodology proposed in this study is generalizable and can be applied to all climate zones, offering a comprehensive design tool without the need for intricate calculations.

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1. INTRODUCTION

Global warming and climate change are identified as the most important challenges of this century and a threat to human survival (Arregi et al., 2020; Amani and Reza Soroush, 2020). Building performance can be improved by employing energy efficiency strategies, such as building insulation (Carreras et al., 2015). Thermal insulation materials are recognized as the most crucial components of a building's envelope to reduce its energy demand and carbon emissions. However, applying thicker insulation materials to external walls and roofs has energy, environmental, and economic consequences. Optimizing insulation thickness is essential to balance these aspects (Gonzalo and Bovea, 2017). Using more insulation than the economically viable thickness does not necessarily lead to energy conservation (Kayfeci et al., 2013). In the initial stages of designing thermal insulation systems, there are no standard tools for choosing the optimal option. Generally, designers determine the type and thickness of the insulation system based on previous studies or their experiences, followed by analysis using simulation software. Comparisons between these results and design requirements necessitate refining the initial option to meet design criteria, leading to time and cost-consuming processes that may be unnecessary and could overlook viable alternatives. With increasing environmental threats, exploring new scenarios could uncover more sustainable and environmentally friendly options. Therefore, this study investigates the simultaneous use of three types of thermal insulation in three layers within the building envelope. Comparisons between the results of applying single-layer and three-layer insulation materials are conducted using a three-criteria approach. Additionally, to find the nearest option to design requirements, a new fast estimating model based on one of the ASHRAE climate zones (3B) has been developed. Implementing this model in the initial design stages could result in significant time savings and provide easy access to more accurate estimations for selecting insulation materials. The objective of this study is to determine the optimal thicknesses of multi-layer insulation and compare them with single-layer alternatives. After outlining the problem statement and research purpose, the literature review in this field is discussed. Subsequently, a new model is developed in three main phases: (1) creating a database; (2) multi-objective optimization; and (3) proposing a new fast designing model. Finally, the study findings are discussed.

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2. LITERATURE REVIEW

Determining optimal insulation thickness has become an outstanding factor in energy efficient building design (Rosti et al., 2020). An optimum thickness of insulation suggests maximum energy savings and minimum insulation material costs (Nematchoua et al., 2015). Many studies in material selection have considered the environmental impacts of insulation materials using life cycle assessment (LCA) and Life Cycle Costing methodologies (Carreras et al., 2015; Gonzalo and Bovea, 2017; Ozel, 2012; Sharif and Hammad, 2019). It is demonstrated that heat transmission load decreases with thicker insulation. However, the cost and environmental impacts of insulation increase linearly with its thickness. Therefore, there should be an optimum insulation thickness where the cost and environmental impacts of the insulation material are minimized (Ozel, 2012), and the energy savings over the building's lifetime are maximized. The designation of the optimum thickness for insulation can be based on each of the three above-mentioned criteria. However, optimization based on all three criteria simultaneously is more trustworthy. Numerous studies have been conducted to distinguish the material and optimum thickness of insulation in various countries, considering specific economic and climatic conditions to maximize or minimize conflicting objectives such as environmental impacts, energy savings, material costs, and total costs (Rosti et al., 2020). Carreras et al. (2015) determined the optimal insulation thickness based on multi-objective optimization for three different insulation materials separately (PU, EPS, and MW). Results showed that PU with a thickness of 8 cm is the optimal selection for walls. Gonzalo and Bovea (2017) considered 12 different insulation materials in a thickness optimization study, illustrating that the alternative with the minimum thickness and maximum energy saving is PUR with a thickness of 25 cm. Rosti et al. (2020) calculated optimum insulation thickness of external walls in different climate zones. Results showed that the optimal insulation thickness varied between zero and 4 cm. In a study on economical and optimum thermal insulation thickness, Nematchoua et al. (2015) found that the lowest value of optimum insulation thickness was for extruded polystyrene with a thickness of 9 cm. Mahlia et al. (2007) examined six different insulation materials to determine optimum thermal insulation thickness, with results showing that Fiberglass (rigid) with a thickness of 4.7 cm is the lowest value of insulation thickness. Kayfeci et al., (2013) calculated the optimum insulation thickness of external walls, with the results indicating that Glass wool with a thickness of 4.09 cm is the thinnest alternative among other optimum results. In a study by Ozel (2012), optimum thickness of different insulation materials was investigated by using life cycle cost analysis. This study demonstrated that the optimum thickness for XPS, EPS, RW, and GW was 0.082, 0.12, 0.054, and 0.192 m, respectively. According to a study by Dombayci et al. (2020), the optimum thermal insulation thickness for Glass wool and Rock wool was 0.4 and 0.18 m, respectively. Combined Economic and Environment Method (CEEM) was used by Açıkkalp and Kandemir (2019) and the results of this method were compared with those of two other methods. Optimum insulation thickness by using CEEM was 0.185 m for Glass wool. Results of a study by Zhua et al. (2011) showed that optimum thickness of EPS in different climate zones varied between 11.6 and 21.6 cm. Glass wool with a thickness between 10.5 and 17.3 cm is the optimum insulation thickness for external walls based on cooling and heating loads based on life cycle cost analysis (Aydin and Biyikoğlu, 2020). Polystyrene with a thickness between 5.3 and 12.4 cm is the optimum insulation thickness depending on fuel types (Kaynakli, 2008). Gounni et al. (2020) in order to find the optimum thickness of EPS and RW to use in external walls. The results showed that the optimum thermal insulation depended on climate zones and insulation types and the optimum thickness of EPS was between 0.056 and 0.085 m. In addition, there is RW with optimum thickness between 0.078 and 0.119 m.

Many studies have been done to determine the optimum thickness of thermal insulation materials. These studies can be classified according to the following items.

1. Optimization objectives such as minimizing the environmental impacts, minimizing the energy cost, minimizing the material cost, minimizing the LCA costs, and maximizing the energy savings (Liu et al., 2020; Dombayci et al., 2020; Kumar et al., 2019).
2. Methodology including multi-objective optimization (Sharif and Hammad, 2019), thermal modeling by using simulation tools such as EnergyPlus, DesignBuilder, TRANSYS, Energy-10, eQuest, DOE-2, IDAICE and MIT Design Advisor (Azari et al., 2016), scenario-based methodologies and comparison between scenarios. Numerical and mathematical formulation (Nematchoua et al., 2015) methodologies such as Transmission load through the wall (Rosti et al., 2020), thermal transmission process (Dombayci et al., 2020), heat loads calculations (Kayfeci et al., 2013), dynamic simulations, dynamic thermo-physical analysis (Stazi et al., 2013), the transient one-dimensional heat conduction (Ozel, 2012), heat transfer rate (Açıkkalp and Kandemir, 2019), the degree-days method (Canbolat et al., 2020), the heat loss from walls (Comaklı and Yuksel, 2003), and LCA based methodologies (Hasan, 1999; Annibaldi et al., 2019).
3. Climate zones including wet and hot tropical climate (Nematchoua et al., 2015), hot and cold climate (Canbolat et al., 2020), cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and warm zone (Zhua et al., 2011).
4. Case studies including Modeled cubicles (Carreras et al., 2015), Single-family house (Gonzalo and Bovea, 2017), Multi-story buildings (Stazi et al., 2013), Multipurpose university building (Sharif and Hammad, 2019), Multi-story residential building (Mahlia et al., 2007), and three-story office building (Amiri Rad and Fallahi, 2019).
5. The common feature among the previous studies on optimization thermal insulation thickness is the use of only one insulating layer in the building's envelope and optimal thickness is determined by changing the thickness of this layer. However, there are a few studies in which more than one-layer insulation materials are investigated (Amani and Kiaee, 2020).

Table 1 shows the review of selection studies on optimization thermal insulation thickness in buildings.

Table 1. Review of selection studies in the literature

	Table row Reference	1 Carrerasa et al., 2015	2 Gonzalo and Bovea, 2017	3 Kayfeci et al., 2013	4 Rosti et al., 2020	5 Nematchoua et al., 2015	6 Ozel, 2012	7 Sharif and Hammad,2019	8 Mahlia et al., 2007	9 Dombayci et al., 2020	10 Acikkalp and Kandemir, 2019	11 Zhua et al., 2011	12 Liu X, Chen X and Shahrestani M,2020	13 Kumar et al.,2019	14 Azari et al., 2016	15 Canbolat et al., 2020	16 Comakli and Yuksel, 2003	17 Hasan, 1999	18 Annibaldi et al., 2019	19 stazi et al., 2013	20 amani and Kiaee
Purpose	Environmental analysis	🟩	🟩		🟩		🟩	🟩		🟩	🟩		🟩	🟩	🟩		🟩		🟩		🟩
	Cost analysis	🟩	🟩				🟩	🟩	🟩		🟩		🟩			🟩			🟩		🟩
	Energy analysis		🟩			🟩		🟩	🟩			🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩
Isulation materials analyse	Mineral wool (MW)	🟩	🟩	🟩			🟩			🟩	🟩			🟩				🟩	🟩		🟩
	Glass wool (GW)		🟩	🟩			🟩			🟩	🟩			🟩							🟩
	Expanded Polystyrene (EPS)	🟩	🟩		🟩		🟩		🟩			🟩	🟩	🟩					🟩	🟩	🟩
	Extruded Polystyrene (XPS)		🟩			🟩	🟩					🟩		🟩							🟩
	Polyurethane (PUR)	🟩	🟩						🟩									🟩			🟩
	Cork (c)		🟩																🟩		
Layers	Number of insulation layers	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
Optimization objectives	Minimizing the environmental impacts	🟩					🟩	🟩			🟩										🟩
	Minimizing the cost	🟩					🟩	🟩			🟩										
	Minimizing the LCA cost		🟩					🟩													
	Maximizing the energy savings		🟩		🟩	🟩	🟩					🟩									🟩
	Optimizing the thickness of insulation materials	🟩	🟩	🟩	🟩	🟩				🟩	🟩	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩
Methodology	Multi-objective optimization	🟩						🟩							🟩				🟩		🟩
	Thermal modeling by using simulation tools		🟩			🟩		🟩				🟩									
	Numerical and mathematical formulation					🟩			🟩		🟩	🟩				🟩					
	Transmission load through the wall				🟩																
	Dynamic simulations																			🟩	
	The transient one-dimentional heat conduction						🟩														
	Heat transfer rate								🟩												
	The degree-days method									🟩				🟩				🟩	🟩		
	The heat loss from walls			🟩													🟩				
	LCA based methodologies							🟩		🟩	🟩		🟩	🟩	🟩		🟩	🟩	🟩		
Climate zones	Wet and hot tropical climate					🟩					🟩										
	Hot and cold climate															🟩					
	Cold zone				🟩			🟩				🟩					🟩				
	Hot summer and cold winter zone				🟩							🟩	🟩								🟩
	Hot summer and warm winter zone											🟩									
Case studies	Modelled cubicles	🟩																			
	Single family house		🟩																		
	Multi-story residential buildings												🟩							🟩	
	University building							🟩						🟩							
	Office buildings														🟩						

As mentioned in the literature, a black box is a device, system, or object that produces useful information without revealing any information about its internal working. Therefore, the properties of the insulation materials were applied as input to the black box (energy analysis programs and environmental impacts). We assumed the generated outputs as the values of the objective functions and optimization has been done based on a trade-off between them. Using this model in the initial design stages could lead to massive savings in the design time. Also, this model provides easy access to more accurate estimations to select insulation materials. The objective of this study is to find the optimal thicknesses of multi-layer insulation and to compare them with single-layer ones.

3. METHOD

3.1. Methodology

The model is developed in three main phases, as shown in Figure 1: (1) creating data base; (2) multi-objective optimization; and (3) proposing a new fast designing model.

The first phase relies on a simulation model of the building to create a varied and accurate data base. The model is created by using DesignBuilder v 6.1.6.005 (DesignBuilder, 2018) and the energy loads are calculated by EnergyPlus 8.9 (EnergyPlus, 2014), a software package for energy simulations in buildings. The properties of each insulation scenario are applied to the building's model, and the total source energy (the metric used in the ENERGY STAR Score) is recorded as the value of the first objective function. The global warming potential (GWP) of each scenario is calculated using SimaPro (SimaPro, 2020) and the IPCC2013 method, recorded as the value of the second objective function. Finally, the cost of insulation materials used in each scenario is calculated by using their prices according to their thickness and recorded as the value of the third objective function. Thus, the database is a three-dimensional decision-making space, and each scenario has three vector components (P_1, P_2, P_3). The second phase aims to make a comparison between one-layer and three-layer insulation alternatives; therefore, a multi-objective optimization approach is used to determine non-dominated solutions.

3.2. Objectives of the Current Optimization

Objective 1: Minimizing the total source energy of the case study over a year (f1).

Objective 2: Minimizing global warming potential of the insulation system (f2).

Objective 3: Minimizing the insulation material cost (f3).

Therefore, Pi is the value of objective function i.

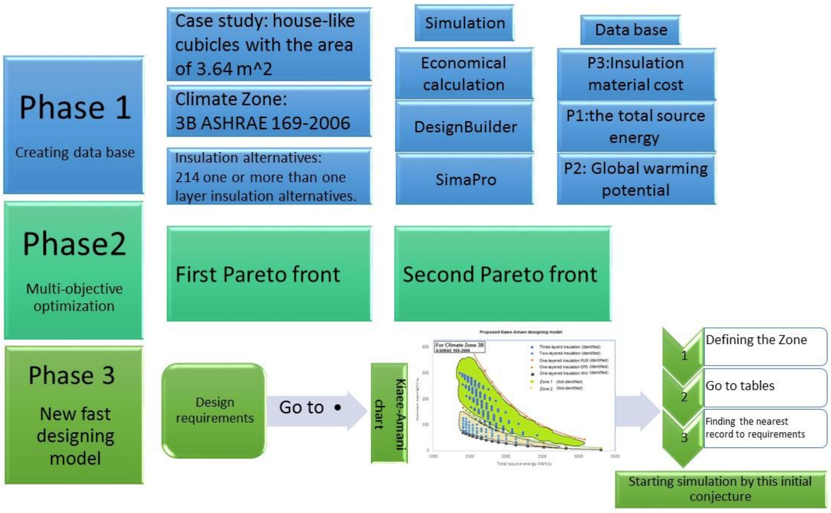


Figure 1. Research methodology framework

3.3. Optimization

In this study, selecting the optimum scenario requires that a compromise be stuck between 3 objectives. The problem is complicated because the decision space is large. Sirisalee et al. (2003) found that trade-off surfaces facilitate visualizing the alternative compromises, which is why an algorithm was suggested to address this problem. This algorithm is adopted based on our study conditions to find the Pareto front or non-dominated solutions as follows:

Algorithm:

Consider the following simplified example. We define P1, P2, and P3 values for solution A-E. The selection procedure starts by seeking non-dominated solutions and it is assumed that all objectives should be minimized.

If all the objective values *Pi* for solution ‘A’ are equal to or less than those for solution ‘B,’

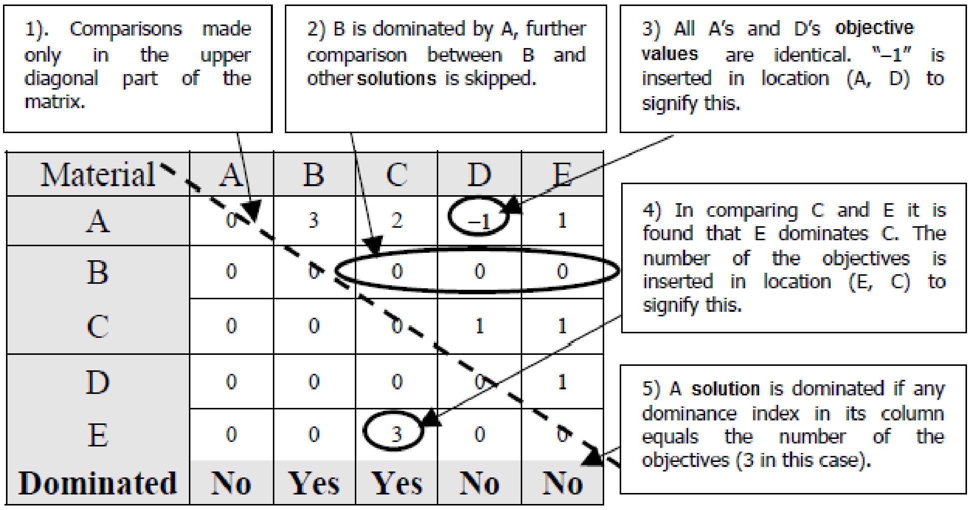
and there is at least one objective value for solution A that is less than that for solution B

then solution A dominates solution B

The dominance matrix is a square matrix in which the set of comparisons can be shown. The size of this matrix is equal to the number of solutions in the database. The number of objectives P_i for that row solution that have values equal to or less than those for the solution of the corresponding column is defined as the dominance index. The cells of the matrix contain the dominance index. If the dominance index equals the number of objectives (here= 3) and all the objective values are not identical, the solution corresponding to that row dominates the one for the corresponding column. The non-dominated solutions are the ones whose columns do not contain any dominance index equal to the number of objectives.

Table 2. Hypothetical data set for the example shown in Figure 2. (Sirisalee et al., 2003)

Solution	P_1	P_2	P_3
A	2.0	5.0	3.0
B	10.0	8.0	7.0
C	6.0	4.0	8.0
D	2.0	5.0	3.0
E	5.0	4.0	2.0



1). Comparisons made only in the upper diagonal part of the matrix.

2) B is dominated by A, further comparison between B and other solutions is skipped.

3) All A's and D's objective values are identical. "−1" is inserted in location (A, D) to signify this.

4) In comparing C and E it is found that E dominates C. The number of the objectives is inserted in location (E, C) to signify this.

5) A solution is dominated if any dominance index in its column equals the number of the objectives (3 in this case).

Material	A	B	C	D	E
A	0	3	2	−1	1
B	0	0	0	0	0
C	0	0	0	1	1
D	0	0	0	0	1
E	0	0	3	0	0
Dominated	**No**	**Yes**	**Yes**	**No**	**No**

Figure 2. An example of a dominance matrix (Sirisalee et al., 2003)

After determining the first Pareto front to ensure a better comparison between multi-layer and single-layer solutions (Elbeltagi et al., 2010), the first Pareto front is set apart and the remaining solutions are compared to identify a new set of non-dominated solutions (second Pareto front).

The major task of Phase 3 is to produce a new designing model to evaluate the nearest possible alternatives to the design requirements. This model is proposed based on the climate zone 3B according to ASHRAE 169-2006 and the data base provided in Phase 1. The relationship between the two important designing requirements is illustrated by using a chart.

3.4. Case study

In order to find optimum insulation thickness and compare single-layer insulation alternatives with multi-layer ones, without loss of generality, a house-like cubicle (Carreras et al., 2015; Cabeza et al., 2010; Menoufi et al., 2013) model was created in DesignBuilder, as shown in Figure 3. We assumed that this cubicle was situated in the 3B climate zone according to ASHRAE 169-2006 standard (Coma et al., 2017) since it is a standard classification and it is possible to follow the presented methodology in all other climate zones. Climate Zone 3B is defined as follows:
Dry with IP Units 4500 < CDD50ºF ≤ 6300 and SI Units 2500 < CDD10ºC < 3500 (Climate Zone 3B, 2021).

This cubicle has no insulation material in its external walls, but it is insulated by 9 cm PUR in the roof. A construction profile is depicted in Figure 4. Details of the cubicle configuration are provided in Table 3. The cubicle has identical dimensions (2.4 m × 2.4 m × 2.4 m), and the area of walls, roof, and ground floor are 22.96, 5.76, and 5.76 m2, respectively.

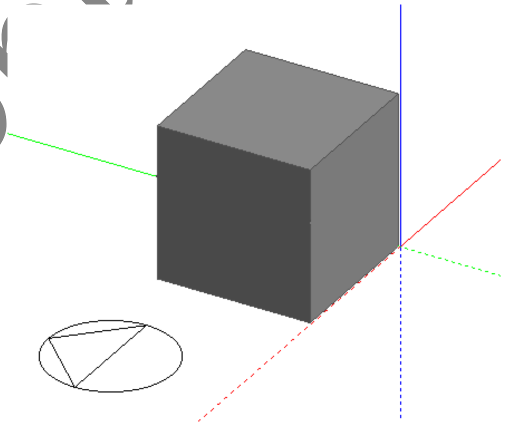


Figure 3. A house-like cubicle model

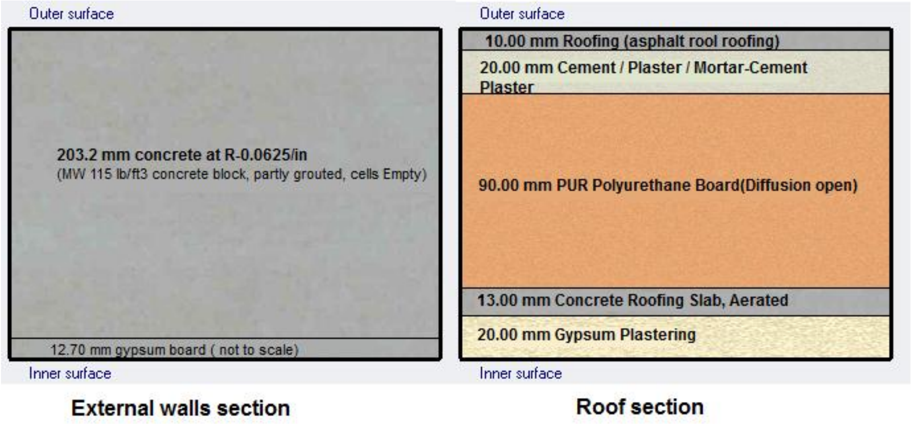


Figure 4. The cross section of the external walls and the roof of the cubicle

Table 3. Details of the cubicle configuration

External walls (22.96 m2)					
Material	Concrete		Gypsum Board		
Thickness(mm)	203.20		12.70		
U-value(W/m^2K)	3.64				
Roof (5.76 m2)					
Material	Asphalt roof roofing	Cement plaster	Polyurethane Board (diffusion open)	Concrete Roofing slab, Aerated	Gypsum plastering
Thickness(mm)	10.00	20.00	90.00	13.00	20.00
U-value(w/m^2K)	0.264				
Opening	Without opening				
Heating system	Fan Coil Unit (4-Pipe), Air cooled Chiller				
Lighting system	Reference				
Occupancy density (People/m2)	0; The cubicle assumed without any occupants.				
Use of building	Generic Office Area				
District Heating	712.55				kWh/year
District Cooling	771.15				
Lighting	242.65				
Water system	12.91				
Net source energy	4203.92				

3.5. Model specifications

As mentioned before, our main goal is to find a simple and fast tool to determine the initial guess for thermal insulation systems. The model conditions involve several simplifications (Carreras et al., 2015), which facilitate the analysis of the system without a loss of generality. Additionally, using this model in future studies for various climate zones could encompass all zones, making it possible to have a comprehensive tool. The specifications of the model are listed below:

- Heating set point temperature of 22 ◦C and cooling set point temperature of 24 ◦C are fixed for the whole year.
- Neither windows nor doors are considered (i.e., cubicles without openings). The aim is that the simulated configuration will be as close as possible to the real one.
- There is no internal mass and no human occupancy.
- Only thermal insulation of the walls is changed during energy loads simulations and all other specifications are left without any changes.

3.6. Solution procedure

To create a diverse data base, a range of thicknesses of different insulation materials are considered as decision variables. Figure 5 illustrates two main scenarios to use insulation materials in the walls in this study. Scenario A implies a monolayer insulation system in which only one layer of insulation materials (PUR or GW or EPS) with different thicknesses between 1 and 15 cm is used. Scenario B is a combination of different materials in the same model, as shown in Figure 5, considering a multi-layer insulation system including three different insulation materials (As used in Scenario A) with different thicknesses between 1 and 5 cm for each insulation material. The study begins by analyzing each single objective separately and then, looks for the set of Pareto solutions representing the optimal tradeoff between three objectives. Table 4 illustrates the properties of insulation materials used in this study. Scenarios A and B provide 45 and 169 different alternatives, respectively, as represented in Appendix A.

Table 4. The properties of insulation materials

Insulation material	l (W/mK)	r (kg/m3)	Cost for 1 cm ($)
PUR	0.028	35	4.78
MW	0.04	12	0.245
EPS	0.04	15	1.15

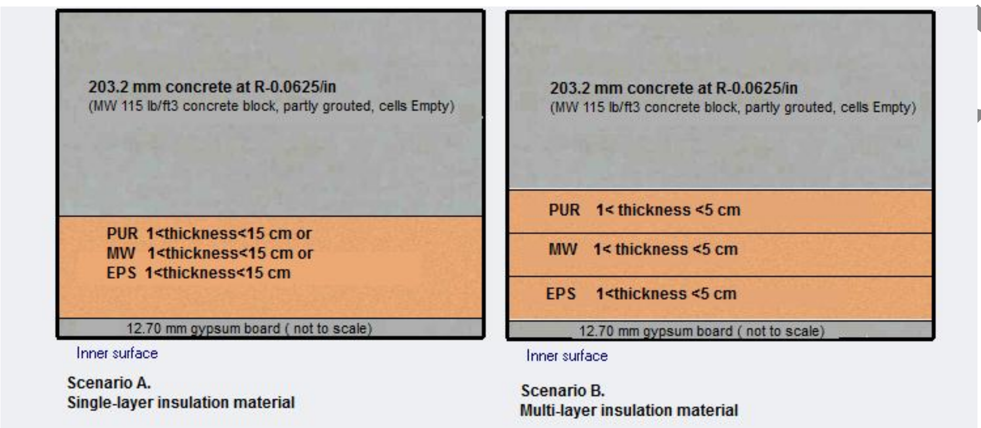


Figure 5. Two main scenarios of using insulation materials in the cubicle’s walls

4. RESULTS AND DISCUSSION

Appendix A represents all alternatives and the results of energy loads analyses, environmental impact, and cost of insulation materials corresponding to each alternative. For example, the alternative number 6 corresponds to an insulation system in which PUR, MW, and EPS with thicknesses of 2,1, and 1 cm respectively used as insulation layers. If this alternative is used in the cubicle's walls, the annual total source energy will be 2173.27 kWh, the global warming potential of insulation materials will be 104.29 kgCO2 eq, and the cost of these insulation materials will be 252.4 $.

Table 5 represents the results of single-objective optimization. The best alternative for minimizing energy demand of the cubicle is the alternative number 140 with one-layer PUR with a thickness of 15 cm. As can be seen, this alternative has the highest environmental impact value of 662.86 kgCO2 eq. Alternative 141, with a 1 cm microwave (MW), minimizes the second and third objectives. However, this alternative has the lowest energy savings compared to other alternatives.

Table 5. Single-objective optimization results

Objectives	Alternative number	Layer 1	Thickness (m)	Layer 2	Thickness (m)	Layer 3	Thickness (m)	The value of f1 (kWh)	The value of f2 (kg CO2 eq)	The value of f3 ($)
Minimizing the first objective f1: total source energy of the case study over a year	140	PUR	0.15	-	0	-	0	1297.38	662.86	1651.97
Minimizing the second objective f2: Global warming potential of the insulation system.	141	-	0	MW	0.01	-	0	3306.46	4.64	5.64
Minimizing the third objective f3: insulation material cost.	141	-	0	MW	0.01	-	0	3306.46	4.64	5.64

The results of multi-objective optimization, comprising non-dominated solutions or the Pareto Front of this study, are presented in Table 6. According to these findings, alternatives numbered 120, 124, and 125 are associated with scenario B (three-layer insulation), while all other alternatives are linked to scenario A. The results indicate that the conventional approach of augmenting the thickness of insulation material to achieve a lower U-value is only applicable to MW. Despite the fact that increasing the thickness of MW (from 1 to 15 cm) results in an escalation of environmental impact and material cost, none of its thicknesses has been surpassed by other solutions. Among the optimal solutions, two alternatives pertain to PUR with thicknesses of 14 and 15 cm.

Table 6. Multi-objective optimization results (The first Pareto front)

alternative number	Layer 1	Thickness (cm)	Layer 2	Thickness (cm)	Layer 3	Thickness (cm)	Total thickness (cm)	The value of f1 (kWh)	The value of f2 (kg CO2 eq)	The value of f3 ($)
120	PUR	4	MW	5	EPS	4	13	1409	256	601
124	PUR	5	MW	5	EPS	4	14	1399	289	648
125	PUR	5	MW	5	EPS	5	15	1363	300	711
139	PUR	14	MW	0	EPS	0	14	1333	618	1541
140	PUR	15	MW	0	EPS	0	15	1297	662	1651
141	PUR	0	MW	1	EPS	0	1	3306	4.64	5.64
142	PUR	0	MW	2	EPS	0	2	2828	9.28	11.28
143	PUR	0	MW	3	EPS	0	3	2551	13	16
144	PUR	0	MW	4	EPS	0	4	2302	18.57	22
145	PUR	0	MW	5	EPS	0	5	2136	23	28
146	PUR	0	MW	6	EPS	0	6	2005	27	33
147	PUR	0	MW	7	EPS	0	7	1898	32	39
148	PUR	0	MW	8	EPS	0	8	1808	37	45
149	PUR	0	MW	9	EPS	0	9	1730	41	50
150	PUR	0	MW	10	EPS	0	10	1662	46	56
151	PUR	0	MW	11	EPS	0	11	1601	51	62
152	PUR	0	MW	12	EPS	0	12	1547	55	67
153	PUR	0	MW	13	EPS	0	13	1496	60	73
154	PUR	0	MW	14	EPS	0	14	1551	65	79
155	PUR	0	MW	15	EPS	0	15	1410	69	84

In order to further examine the alternatives of scenario B, after removing Pareto 1, non-dominated solutions are sought again. Table 7 shows the second Pareto front for this study. These results demonstrate that there are 8 alternatives related to scenario B. These findings confirm that multilayer insulation can be among the optimal and semi-optimal solutions.

Comparing the two non-dominated solutions, 125 and 140, with the same thickness of 15 cm, it is concluded that energy savings for both alternatives are about 70 percent compared to the base model without wall insulation. While the environmental impact of the three-layer solution is 45%, and its price is 43% lower than the single-layer solution. Additionally, a comparison between 10 cm thickness alternatives 104, 165, and 135 showed that all three alternatives have the same energy savings, but the price and environmental impact of alternative 135 are four times higher.

Table 7. The second Pareto front

alternative number	Layer 1	Thickness (cm)	Layer 2	Thickness (cm)	Layer 3	Thickness (cm)	Total thickness (cm)	The value of f1 (kWh)	The value of f2 (kg CO2 eq)	The value of f3 ($)
51	PUR	1	MW	3	EPS	1	5	2084	69	153

76	PUR	1	MW	4	EPS	1	6	1964	74	159
100	PUR	5	MW	4	EPS	5	14	1400	295	705
101	PUR	1	MW	5	EPS	1	7	1865	78	164
102	PUR	1	MW	5	EPS	2	8	1781	89	191
103	PUR	1	MW	5	EPS	3	9	1707	101	217
104	PUR	1	MW	5	EPS	4	10	1643	112	244
105	PUR	1	MW	5	EPS	5	11	1585	123	270
138	PUR	13	MW	0	EPS	0	13	1372	574	1431
156	PUR	0	MW	0	EPS	1	1	3306	11	26
157	PUR	0	MW	0	EPS	2	2	2828	22	52
158	PUR	0	MW	0	EPS	3	3	2521	33	79
159	PUR	0	MW	0	EPS	4	4	2302	45	105
160	PUR	0	MW	0	EPS	5	5	2137	56	132
161	PUR	0	MW	0	EPS	6	6	2006	67	158
167	PUR	0	MW	0	EPS	12	12	1548	135	317
168	PUR	0	MW	0	EPS	13	13	1497	146	344
169	PUR	0	MW	0	EPS	14	14	1453	157	370
170	PUR	0	MW	0	EPS	15	15	1411	168	397

The results show that applying a multi-layer insulation system could be considered a competitive approach to finding optimum solutions. However, the number of non-dominated solutions for one-layer scenarios is greater than that for multi-layer solutions. Also, it is observed that by using multi-layer insulation scenarios, it will be possible to have a more comprehensive database so that decision-makers will be able to choose from more options. In general, previous studies did not pay attention to multi-layer insulation systems, and their approaches are based on removing dominated solutions to find optimum scenarios, while these approaches could lead to an ignorance of multi-layer's advantages, such as having lower thickness.

Using multi-objective optimization methodologies is usually based on objective functions, and the dominance procedure is done according to a fitness function. So, if one of these objectives changes, it will be possible that some dominated solutions change to non-dominated. Whereas designing requirements could be different according to climate zones, types of buildings, etc. For example, in regions with a higher land price, lower thickness of insulation systems might be the first criterion. Therefore, achieving a comprehensive tool for a wider range of criteria is necessary, and the methodology presented in this study could cover these problems.

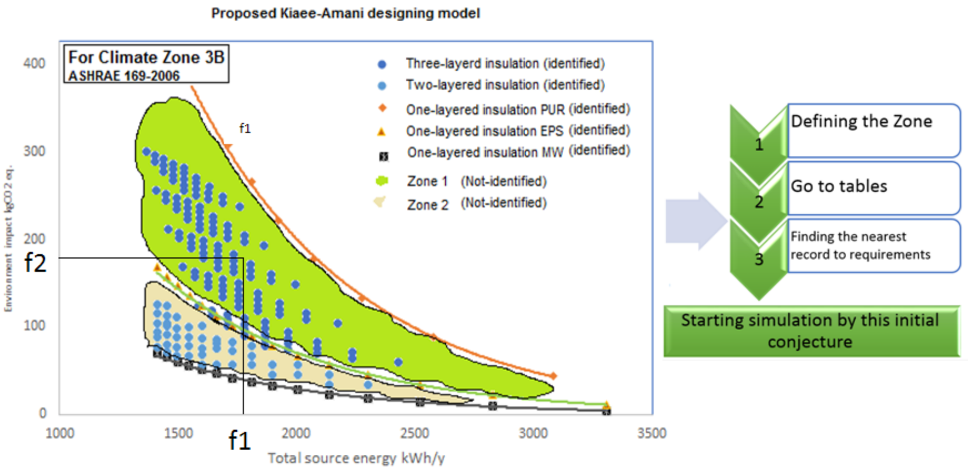


Figure 6. (a) Scatter chart of all alternatives according to their environmental impact and total source energy of the building; (b) Procedure of finding an initial conjecture scenario

Figure 6 illustrates the proposed design model resulting from phase one of this study. The figure comprises two distinct parts, denoted as Figure 6(a) and (b). While Figure 6(a) represents a scatter plot of the values of the two main objectives (f1 and f2) for all identified solutions within the database, Figure 6(b) outlines a procedure necessary to determine an initial conjecture scenario. According to Figure 6(a), it is evident that the values of the first objective (the total source energy of the building over a year) are plotted against their corresponding values of the second objective (environmental impact of the insulation systems). This chart depicts the database resulting from phase 1 for climate zone 3B, as per ASHRAE 169-2006.

Two major classifications are apparent on this chart: identified solutions (the scenarios investigated in this study), such as one, two-, and three-layer solutions, and not-identified zones implying probable scenarios not investigated in this study (Zone 1 and 2). One-layer scenarios using MW lie at the bottom of the chart as non-dominated solutions. In the middle are one-layer scenarios using EPS, and at the top are PUR one-layer scenarios. The area between one-layer scenarios is filled by multi-layer solutions, with Zone 1 situated between EPS and PUR, and Zone 2 between MW and EPS. The spots in these zones represent the multi-layer solutions investigated in this study.

This chart facilitates answering the study's questions. The decision-making space for choosing thermal insulation systems becomes continuous when considering multi-layer scenarios. It is also possible to find at least one scenario based on any design requirements. The use of a multi-layer insulation system fills the vacant space between one-layer solutions. Our approach in this study is based on identifying all possible solutions to provide a continuous decision-making space, and no solutions were eliminated due to dominance procedures. This provides decision-makers and designers with a flexible selection space that offers a wide range of scenarios according to their requirements.

Figure 6(b) depicts the process of finding an initial conjecture scenario. Using two design requirements, for example, f1 and f2, it is evident that the first option is in Zone 1, corresponding to three-layer insulation scenarios. In the second step, one should refer to Appendix A to find the nearest solution corresponding to the design requirements. This option can play a crucial role in the initial stages of designing thermal insulation systems.

Table 8 illustrates alternatives with the results of their energy, environmental impact, and cost analysis. These alternatives have been selected based on the closest total source energy to 1400, 1500, and 1600 kWh/y as a Hypothetical Design criterion among all alternatives reported in Appendix A. One-layer, two-layer, and three-layer alternatives are reported for each specified total source energy value.

For the energy range of about 1400 kWh/y, One-layer insulation alternative number 155 (MW) with a thickness of 15 cm exhibits the minimum values of environmental impact and material price, while the minimum thickness goes to alternative number 209 with a thickness of 10.8 cm. A comparison of these two options reveals that if two-layer insulation is used, the total thickness will be reduced by 28%, but the environmental impacts and material price increase by 9.21% and 41%, respectively. The results also indicate that the use of three-layer insulation does not improve the values of the other two criteria.

Similarly, for the energy levels of 1500 kWh/y, the best alternative is the single-layer insulation number 152 (MW) with a thickness of 13 cm, and the minimum thickness goes to alternative number 193 with a thickness of 9.8 cm.

The objective functions of this study were considered black-box, as it was necessary to assign candidate properties to energy and environmental simulation tools (DesignBuilder and SimaPro). This approach aimed to identify the impact of each scenario on energy consumption and the environment. Another limitation was the extensive number of possible scenarios, given the simultaneous use of three types of materials, involving variations in thickness and placement. Due to the sheer complexity, studying all conceivable scenarios was beyond the scope of this research, and only a limited number were investigated. Nonetheless, even with this restricted set, we were able to examine the significance and impact of multilayer insulation in buildings.

Table 8. Comparison table of alternatives with the closest total source energy to 1400, 1500, and 1600 kWh/y

	Insulation materials	PU (Polyurethane board)	MW (Glass Wool rolls)	EPS (Expanded Polystyrene standard)	Total thickness (cm)	Total Source Energy (kWh/y)	Global warming potential of insulation materials (kg CO2 eq)	Insulation material cost ($)
	Alternative number	First layer thickness (cm)	Second layer thickness (cm)	Third layer thickness (cm)				
Closest Total Source Energy to 1400 (kWh/y)	137	12	0	0	12	1414	530	1321
	155	0	15	0	15	1410	69	84
	170	0	0	15	15	1411	169	397
	209	0	6.8	4	10.8	1410	76	144
	100	5	4	5	14	1400	295	705
Closest Total Source Energy to 1500 (kWh/y)	135	10	0	0	10	1511	441	1101
	152	0	13	0	13	1547	55	67
	167	0	0	13	13	1548	135	317
	193	0	6.6	3.2	9.8	1547	66.24	121
	114	3	5	4	12	1504	200	464
	134	9	0	0	9	1569	397	991

Closest Total Source Energy to 1600 (kWh/y)	151	0	11	0	11	1601	51	62
	166	0	0	11	11	1603	123	291
	188	0	5	3	8	1601	57	107
	112	3	5	2	10	1606	178	411

5. CONCLUSIONS

The innovation of this study lies in the proposal to apply multi-layer insulation systems to meet various design requirements. Additionally, it presents a noteworthy result indicating that decision-making for thermal insulation systems exists in a continuous space, and the gap between single-layer insulation options is filled by multi-layer alternatives. A new design model was developed to assist designers in the initial stages of thermal insulation design, helping them find the nearest approximation to the design criteria.

One of the most common methods to reduce the U-value is to increase the thickness of the insulation. While this approach decreases the energy demand of the building, it also leads to increased environmental and economic effects. The results confirm that multi-layer insulation can be considered among the optimal and semi-optimal solutions. Comparing the two non-dominated solutions, 125 and 140, with the same thickness of 15 cm, it is concluded that energy savings for both alternatives are approximately 70 percent compared to the base model without wall insulation. Additionally, the environmental impact of the three-layer solution is 45%, and its price is 43% lower than the single-layer solution. A comparison between alternatives 104, 165, and 135, all with a thickness of 10 cm, reveals that all three alternatives provide the same level of energy savings, but the price and environmental impact of alternative 135 are four times higher.

The proposed methodology in this study is generalizable; therefore, future studies could follow a similar approach based on other climate zones according to ASHRAE classification and explore additional insulation materials. Developing the proposed model in future studies would contribute to creating a comprehensive design tool.

6. ACKNOWLEDGEMENT

This study was done at the Department of Civil Engineering, Islamic Azad University in the years 2021-2022 as a research project.

Appendix A

All alternatives and the results of energy loads analyses, Environmental impact and cost of insulation materials corresponding to each alternative.

Insulation materials	PU (Polurethane board)	MW (Glass Wool rolls)	EPS (Expanded Polystyrene standard)	Total thickness (cm)	Total Source Energy (kWh/y)	Global warming potential of insulation materials (kg CO2 eq)	Insulation material cost ($)
Alternative number	First layer thickness (cm)	Second layer thickness (cm)	Third layer thickness (cm)				
Three-layered insulation (identified in Zone 1)							
1	1	1	1	3	2426.88	60.10	142.27
2	1	1	2	4	2234.03	71.37	168.77
3	1	1	3	5	2085.37	82.64	195.26
4	1	1	4	6	1965.32	93.90	221.76
5	1	1	5	7	1866.00	105.17	248.26
6	2	1	1	4	2173.27	104.29	252.40
7	2	1	2	5	2038.60	115.56	278.90
8	2	1	3	6	1928.08	126.83	305.40
9	2	1	4	7	1835.31	138.09	331.89
10	2	1	5	8	1756.12	149.36	358.39
11	3	1	1	5	1996.29	148.48	362.53
12	3	1	2	6	1893.99	159.75	389.03
13	3	1	3	7	1807.14	171.02	415.53
14	3	1	4	8	1732.12	182.28	442.02
15	3	1	5	9	1665.97	193.55	468.52
16	4	1	1	6	1862.85	192.67	472.67
17	4	1	2	7	1781.27	203.94	499.16

18	4	1	3	8	1710.27	215.21	525.66
19	4	1	4	9	1647.10	226.47	552.15
20	4	1	5	10	1590.47	237.74	578.65
21	5	1	1	7	1757.11	236.87	582.80
22	5	1	2	8	1689.29	248.13	609.29
23	5	1	3	9	1629.29	259.40	635.79
24	5	1	4	10	1574.74	270.66	662.28
25	5	1	5	11	1525.22	281.93	688.78
26	1	2	1	4	2233.82	64.75	147.92
27	1	2	2	5	2085.26	76.01	174.41
28	1	2	3	6	1965.27	87.28	200.91
29	1	2	4	7	1865.94	98.55	227.40
30	1	2	5	8	1781.46	109.81	253.90
31	2	2	1	5	2038.36	108.94	258.05
32	2	2	2	6	1927.85	120.20	284.54
33	2	2	3	7	1835.33	131.47	311.04
34	2	2	4	8	1756.03	142.74	337.54
35	2	2	5	9	1686.35	154.00	364.03
36	3	2	1	6	1893.69	153.13	368.18
37	3	2	2	7	1806.94	164.40	394.68
38	3	2	3	8	1731.98	175.66	421.17
39	3	2	4	9	1665.90	186.93	447.67
40	3	2	5	10	1606.89	198.19	474.16
41	4	2	1	7	1780.97	197.32	478.31
42	4	2	2	8	1709.96	208.59	504.81
43	4	2	3	9	1646.91	219.85	531.30
44	4	2	4	10	1590.35	231.12	557.80
45	4	2	5	11	1538.92	242.39	584.29
46	5	2	1	8	1688.95	241.51	588.44
47	5	2	2	9	1629.07	252.78	614.94
48	5	2	3	10	1574.54	264.04	641.43
49	5	2	4	11	1524.89	275.31	667.93
50	5	2	5	12	1480.47	286.58	694.43
51	1	3	1	5	2084.98	69.39	153.56
52	1	3	2	6	1965.19	80.66	180.06
53	1	3	3	7	1865.86	91.92	206.55
54	1	3	4	8	1781.40	103.19	233.05
55	1	3	5	9	1707.94	114.46	259.55
56	2	3	1	6	1927.49	113.58	263.69
57	2	3	2	7	1835.11	124.85	290.19
58	2	3	3	8	1755.79	136.12	316.68
59	2	3	4	9	1686.25	147.38	343.18
60	2	3	5	10	1624.58	158.65	369.68
61	3	3	1	7	1806.68	157.77	373.82
62	3	3	2	8	1731.82	169.04	400.32
63	3	3	3	9	1665.79	180.31	426.82
64	3	3	4	10	1606.76	191.57	453.31
65	3	3	5	11	1553.40	202.84	479.81
66	4	3	1	8	1709.64	201.96	483.96

67	4	3	2	9	1646.68	213.23	510.45
68	4	3	3	10	1590.18	224.50	536.95
69	4	3	4	11	1538.82	235.76	563.44
70	4	3	5	12	1492.17	247.03	589.94
71	5	3	1	9	1628.90	246.15	594.09
72	5	3	2	10	1574.33	257.42	620.58
73	5	3	3	11	1524.80	268.69	647.08
74	5	3	4	12	1480.23	279.95	673.57
75	5	3	5	13	1439.20	291.22	700.07
76	1	4	1	6	1964.95	74.04	159.21
77	1	4	2	7	1865.71	85.30	185.70
78	1	4	3	8	1781.29	96.57	212.20
79	1	4	4	9	1707.83	107.84	238.69
80	1	4	5	10	1643.21	119.10	265.19
81	2	4	1	7	1834.83	118.23	269.34
82	2	4	2	8	1755.67	129.49	295.83
83	2	4	3	9	1686.07	140.76	322.33
84	2	4	4	10	1624.44	152.03	348.83
85	2	4	5	11	1568.92	163.29	375.32
86	3	4	1	8	1731.48	162.42	379.47
87	3	4	2	9	1665.53	173.68	405.96
88	3	4	3	10	1606.54	184.95	432.46
89	3	4	4	11	1553.26	196.22	458.96
90	3	4	5	12	1504.71	207.48	485.45
91	4	4	1	9	1646.22	206.61	489.60
92	4	4	2	10	1590.09	217.88	516.10
93	4	4	3	11	1538.71	229.14	542.59
94	4	4	4	12	1492.07	240.41	569.09
95	4	4	5	13	1449.45	251.68	595.58
96	5	4	1	10	1574.04	250.80	599.73
97	5	4	2	11	1524.63	262.07	626.23
98	5	4	3	12	1480.04	273.33	652.72
99	5	4	4	13	1439.04	284.60	679.22
100	5	4	5	14	1400.08	295.87	705.72
101	1	5	1	7	1865.46	78.68	164.85
102	1	5	2	8	1781.15	89.95	191.35
103	1	5	3	9	1707.75	101.21	217.84
104	1	5	4	10	1643.15	112.48	244.34
105	1	5	5	11	1585.43	123.75	270.84
106	2	5	1	8	1755.37	122.87	274.98
107	2	5	2	9	1685.95	134.14	301.48
108	2	5	3	10	1624.21	145.41	327.97
109	2	5	4	11	1568.78	156.67	354.47
110	2	5	5	12	1518.26	167.94	380.97
111	3	5	1	9	1665.26	167.06	385.11
112	3	5	2	10	1606.48	178.33	411.61
113	3	5	3	11	1553.07	189.60	438.11
114	3	5	4	12	1504.47	200.86	464.60
115	3	5	5	13	1460.49	212.13	491.10

116	4	5	1	10	1589.77	211.25	495.24
117	4	5	2	11	1538.47	222.52	521.74
118	4	5	3	12	1491.80	233.79	548.24
119	4	5	4	13	1449.31	245.05	574.73
120	4	5	5	14	1409.64	256.32	601.23
121	5	5	1	11	1524.21	255.44	605.38
122	5	5	2	12	1479.73	266.71	631.87
123	5	5	3	13	1438.79	277.98	658.37
124	5	5	4	14	1399.85	289.24	684.86
125	5	5	5	15	1363.84	300.51	711.36
One-layered insulation PU (identified)							
126	1	0	0	1	3080.05	44.19	110.13
127	2	0	0	2	2574.75	88.38	220.26
128	3	0	0	3	2274.55	132.57	330.39
129	4	0	0	4	2072.56	176.76	440.52
130	5	0	0	5	1923.75	220.95	550.66
131	6	0	0	6	1808.46	265.14	660.79
132	7	0	0	7	1714.81	309.34	770.92
133	8	0	0	8	1636.70	353.53	881.05
134	9	0	0	9	1569.44	397.72	991.18
135	10	0	0	10	1511.81	441.91	1101.31
136	11	0	0	11	1460.74	486.10	1211.44
137	12	0	0	12	1414.26	530.29	1321.57
138	13	0	0	13	1372.35	574.48	1431.71
139	14	0	0	14	1333.33	618.67	1541.84
140	15	0	0	15	1297.38	662.86	1651.97
One-layered insulation MW (identified)							
141	0	1	0	1	3306.46	4.64	5.64
142	0	2	0	2	2828.50	9.29	11.29
143	0	3	0	3	2521.07	13.93	16.93
144	0	4	0	4	2302.03	18.58	22.58
145	0	5	0	5	2136.51	23.22	28.22
146	0	6	0	6	2005.84	27.87	33.87
147	0	7	0	7	1898.77	32.51	39.51
148	0	8	0	8	1808.25	37.16	45.16
149	0	9	0	9	1730.08	41.80	50.80
150	0	10	0	10	1662.21	46.45	56.45
151	0	11	0	11	1601.44	51.09	62.09
152	0	12	0	12	1547.03	55.74	67.74
153	0	13	0	13	1496.83	60.38	73.38
154	0	14	0	14	1451.33	65.03	79.03
155	0	15	0	15	1410.01	69.67	84.67
One-layered insulation EPS (identified)							
156	0	0	1	1	3306.50	11.27	26.50
157	0	0	2	2	2828.70	22.53	52.99
158	0	0	3	3	2521.42	33.80	79.49
159	0	0	4	4	2302.47	45.07	105.98
160	0	0	5	5	2137.22	56.33	132.48
161	0	0	6	6	2006.53	67.60	158.98

162	0	0	7	7	1899.50	78.87	185.47
163	0	0	8	8	1809.37	90.13	211.97
164	0	0	9	9	1731.16	101.40	238.46
165	0	0	10	10	1663.37	112.67	264.96
166	0	0	11	11	1603.04	123.93	291.46
167	0	0	12	12	1548.26	135.20	317.95
168	0	0	13	13	1497.97	146.47	344.45
169	0	0	14	14	1453.22	157.73	370.94
170	0	0	15	15	1411.81	169.00	397.44
Two-layered insulation (identified in Zone 2)							
171	0	1	3	4	2302.03	38.44	85.13
172	0	1	4	5	2136.51	49.71	111.63
173	0	1	5	6	2005.84	60.98	138.12
174	0	2	3	5	2136.51	43.09	90.78
175	0	2	4	6	2005.84	54.36	117.27
176	0	2	5	7	1898.77	65.62	143.77
177	0	3	4	7	1898.77	59.00	122.92
178	0	3	5	8	1808.25	70.27	149.41
179	0	5	4	9	1808.25	68.29	134.21
180	0	5	5	10	1808.25	79.56	160.70
181	0	4	5	9	1730.08	74.91	155.06
182	0	1	6	7	1730.08	72.24	164.62
183	0	1	7	8	1730.08	83.51	191.12
184	0	5	5	10	1662.21	79.56	160.70
185	0	2	6	8	1662.21	76.89	170.27
186	0	3	6	9	1662.21	81.53	175.91
187	0	4	6	10	1662.21	86.18	181.56
188	0	5	3	8	1601	57.02	107.71
189	0	5	4	9	1601	68.29	134.21
190	0	5.5	4.5	10	1601	76.25	150.28
191	0	5.5	5.5	11	1601	87.51	176.77
192	0	6	6.5	12.5	1601	101.10	206.09
193	0	6.5	3.2	9.7	1547	66.24	121.48
194	0	6.5	4.3	10.8	1547	78.64	150.62
195	0	6.5	5.2	11.7	1547	88.78	174.47
196	0	6.5	6.2	12.7	1547	100.04	200.97
197	0	6.6	3.2	9.8	1496	66.71	122.04
198	0	6.6	4.1	10.7	1496	76.85	145.89
199	0	6.6	5.1	11.7	1496	88.12	172.39
200	0	6.6	6	12.6	1496	98.26	196.23
201	0	6.6	7.1	13.7	1496	110.65	225.38
202	0	6.7	3.5	10.2	1451	70.55	130.56
203	0	6.7	4.3	11	1451	79.57	151.75
204	0	6.7	5.3	12	1451	90.83	178.25
205	0	6.7	6.2	12.9	1451	100.97	202.10
206	0	6.7	6.5	13.2	1451	104.35	210.04
207	0	6.7	7.2	13.9	1451	112.24	228.59
208	0	6.7	8.3	15	1451	124.63	257.74
209	0	6.8	4	10.8	1410	76.65	144.37

210	0	6.8	5	11.8	1410	87.92	170.86
211	0	6.8	5.6	12.4	1410	94.68	186.76
212	0	6.8	6.5	13.3	1410	104.82	210.61
213	0	6.8	7.5	14.3	1410	116.08	237.10
214	0	6.8	8.4	15.2	1410	126.22	260.95

NOMENCLATURE

LCA	Life Cycle Assessment
CEEM	Combined Economic and Environment Method
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
kWh	KiloWatt Hour
MW	MicroWave
kgCO2	Kilogram of Carbon Dioxide

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