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Article

The use of LCC and optimisation in determining optimum insulation thickness: Case of Ankara, Turkey

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ABSTRACT

In energy-efficient design, the thickness of the building's insulation is a critical factor. Because the material is thicker than the optimum level, the initial investment costs of the structure rise, whereas the running costs of the building rise if the level is thinner. For this reason, the thickness of the optimum insulation must be calculated correctly in the early design process. Previous research attempted to solve this problem by calculating the optimum insulation thickness for a 10-year period while only considering the external wall. However, structures should be addressed as a whole, and the economic life cycle for residential buildings has been specified as 30 years in Article 2 (14) of the Energy Performance of Buildings Directive. This study aims to uncover the most optimum insulation thickness with the correct lifespan in terms of life cycle cost by addressing the entire building and demonstrating the inaccuracy of prior studies with the novel methodology based on life cycle costing and optimization algorithms. In the study, thirty different insulation thicknesses and two different materials have been used. The new methodology has been applied to the mass housing unit constructed in Ankara in the last 10 years to give information about insulation thicknesses used in the Turkish housing environment. Optimum insulation thicknesses based on the third climate zone for a period of 30 years are calculated as 0.12 m for the external walls. This study reveals that accurate calculations using the right lifespan will result in huge savings in energy and cost. In the case study, which was selected by applying the optimum insulation thickness, the annual energy expenses are decreased by 13%. These findings have indicated that for buildings constructed in the third climatic zone, the optimal insulation thicknesses should be reviewed. The results of the methodology may be utilized as important inputs throughout the decision-making processes of the construction sectors.

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INTRODUCTION

Energy is the most basic resource that humans require in all aspects of their lives. As a result, it is the most essential factor influencing economic and social progress. Energy consumption is quickly increasing as a result of urbanization, fast industrialization, and technological advancements. The rise in energy consumption results in the decrease of resource limits and in the rapid expansion

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of environmental concerns such as pollution and global warming. Efforts are undertaken to efficiently employ current resources to address the growing demand for energy. The sustainability of the world is mostly dependent on three factors: energy efficiency, the use of renewable energy, and energy savings (Morales et al., 2016). Since the 1973 energy crisis, energy conservation has been a crucial aspect of domestic energy policies. For the developing countries, this is extremely important since they largely import energy from overseas to fulfil their energy demands. The construction sector is the dominant factor in the worldwide primary energy consumption with a steady rise since the 1960s. The sector accounts for 30–40% of global consumption of energy (Huovila et al., 2007), and around 40% of global greenhouse gas emissions (UNEP, 2019). The energy consumption for this industry might climb by 50% by 2060, according to UNEP (2019), if no steps are adopted. The sector, therefore, has enormous potential for reducing energy consumption and greenhouse gas emission. Due to the fact that residential energy demand accounts for a larger percentage of total energy demand, with residential heating and cooling representing 75% of this share, thermal insulation has garnered a lot of attention and priority for developed and developing countries.

Several studies have been conducted to determine energy requirements in buildings as well as the impacts of insulation on the heating and/or cooling load. For calculating the optimum insulation thickness, Hasan (1999) use the degree day approach for residential structures in Palestine. In his analysis, he projected that energy savings of roughly $21/m^2 over a 10-year period were possible with the optimum insulation thickness for the external walls. Mohsen and Akash (2001) carried out a study to assess the energy-saving benefit of thermal insulation. They observed energy savings on air gap polystyrene and rock wool at 5.4%, 36% and 34% correspondingly for the heating in Jordan. Çomaklı and Yüksel (2003) studied the optimal insulation thickness for Turkey's coldest cities, including Erzurum, Kars, and Erzincan. They discovered that the savings in cold cities can amount to as much as $12.13/m^2 of wall area over a 10-year period. Al-Sanea and Zedan (2002) evaluated a variety of insulation materials in order to establish the most cost-effective type and its optimal thickness over the course of a year. Dombaycı et al. (2006) evaluated the optimal thickness of insulation in Denizli using various insulation materials. They discovered that energy-saving, and payback period were corresponding $14.09/m^2 and 1.43 years over a lifetime of 10 years. Sisman et al. (2007) investigated optimum thickness insulation for 10 years in several locations of Turkey using LCC; similarly, Bolattürk (2006) have evaluated it for 16 cities in four Turkey climates. Gurel and Dasdemir (2011) has computed for four select cities in different climate areas of Turkey the optimum insulation thickness and energy savings for heating and cooling load. The optimal thickness of the insulation ranges within 0.036 m and 0.1 m and energy savings range from 12.08 (Turkish Lira, TL)/m^2 to 58.28 TL/m^2 based on the material of the insulation and the chosen city. Similarly, Inalli et al. (2011) used the TS 825 standard to estimate optimal isolation thicknesses for four regions in four different degrees day areas. The optimal thicknesses in insulation for the external wall were estimated between 0.038 m and 0.144 m. Ozel (2013) computed an optimal isolation thickness, energy-saving and payback period for three distinct types of fuel for the province of Elazıg. As a consequence, she determined the optimal outer wall insulation thicknesses for natural gas, imported coal, and fuel oil as 0.040, 0.045, and 0.075 m, respectively. Kurekci (2016) has identified optimum insulation thicknesses In Turkey's 81 provincial centres. Four alternative fuels and five different insulating materials were calculated for each of the computations. The optimal thickness of insulation to be applied to external walls was examined by Işık and Tugan (2017) using the degree-day approach in three provinces. For a lifetime of 10 years, they estimated optimal insulation thicknesses depending on heating demand. When the current literature is studied, the degree day technique is typically utilised in the studies done, the lifetime is calculated for a period of 10 years, and the calculation of the optimal thickness is taken into account based on the heating load for the outer walls.

In addition to that, there are studies in the literature on optimal insulation that take 30 years of lifespan into account, albeit in a small number of cases. Daouas (2011) has stated that in Tunisian buildings, the life cycle cost analysis is based on cooling and heating transmission loads calculated over 30 years and the optimal insulation thicknesses of 0.10 cm and payback periods of 3.29 years. By using EnergyPlus, Saglam et al. (2017) estimated the energy requirements of structures. As a consequence, they discovered that if insulation is installed in high-rise apartments with the optimum insulation thickness, energy savings of 70–80% can be realized over a 30-year period, depending on user behaviour. However, the tool used by these studies is "black boxes" with limited capacity to discover potential causal relationships. In other words, in choosing decision variables and objective functions, they encounter restrictions. These approaches tend to converge to a local minimum without ensuring optimal solutions because all the characteristics of the black box programs can't be totally controlled. In order to determine the optimum insulation, all the characteristics of the simulation program must be fully managed.

The substantial body of research on optimum insulation thickness in the literature indicated a 10-year lifetime. However, according to the EPBD, the lifespan of the building is determined as 30 years for residences. With calculations that take into consideration 10 years, the so-called "optimum" insulation thickness is far from optimum. Similarly, the optimal option cannot be achieved in research over a lifespan of 30 years because of the off-shelf software limitations. In addition to that, in the literature research, several factors, such as orientation and window frame, are disregarded. Structures should be addressed as a whole. This study aims to uncover the most optimum insulation thickness with the correct lifespan in terms of life cycle cost by addressing the entire building and demonstrating the inaccuracy of prior studies with the novel methodology based on life cycle costing and optimisation algorithm.

RESEARCH METHODOLOGY

The novel method proposes the optimum insulation thickness based on an optimisation algorithm in relation to the life cycle costs of new and existing buildings. The technique combines the open box life cycle costing model with the R programming optimisation tool. The life cycle costing model has been designed as a BPS tool, as the model enables complete control and hence, unlike other off-shelf software, there are no limits to the choice of decision factors and objective functions. The R software was chosen for two primary reasons; a) R, with extremely strong capacity and open source, permits the optimisation and automated starting of the LCC model, b) also operates input files and output files that are in keeping with the life costing model.

The decision support tool (DST) has been designed to identify the optimal thickness of insulation by reducing LCCs under specific design limitations. DST is divided into two components. The first component of the created decision support tool, the LCC phase, is a software that calculates total building LCC using standards, rules, and literature. The second step of the optimisation program calculates all linear dependent variables and then determines which solution set is the most optimum in terms of building life cycle cost (Figure 1).

Life Cycle Costing Part

Life cycle costing is a method of assessing projects involving all the costs connected with the project's construction, operation, maintenance and final disposal. The LCC approach is used to estimate the cost of building cycles and energy consumption in the early phases of the design of buildings. The following is a mathematical representation of the generic life cycle costing formula (Kneifel and Webb, 2020).

$$LCC = IC_0 + (OC + MC).PV_{sum} + D.PV \quad (1)$$

Where

$$PV_{sum} = \frac{(1+r)^t - 1}{r(1+r)^t} \quad (2)$$

and

$$PV = \frac{1}{(1+r)^t} \quad (3)$$

IC_0 is investment cost consists of construction cost
OC is operation cost including annual cost (*i.e.* energy)
MC is maintenance cost including annual cost (*i.e.* cost for replacement)
DC is disposal cost
PV is present value
t is time variable
r is discount rate

In this study, the method is used to estimate the optimum insulation thickness in order to account for changes in interest rates and inflation, which have a direct impact on the cost of insulation materials and fuels. Since this method takes into account the lifetime of the building, it allows the building to be considered together with ten variables (i.e. orientation, heating system, fuel type, window frame, window glass) that can directly or indirectly affect the cooling and heating load. Figure 2 designated phases of the LCC part.

The life cycle costing phase is divided into three parts:

- The first part is known as the initial cost. The term "initial cost" refers to the total cost of the asset prior to occupation. All expenditures paid by the customer, including consulting fees, infrastructure charges, licensing, and licenses, marketing expenses, lighting expense rights and project risk record contingency, are included in the initial costs according to ISO 15686-5 (2000). Since most of these fees/charges even differ from one city to the next, only construction costs were

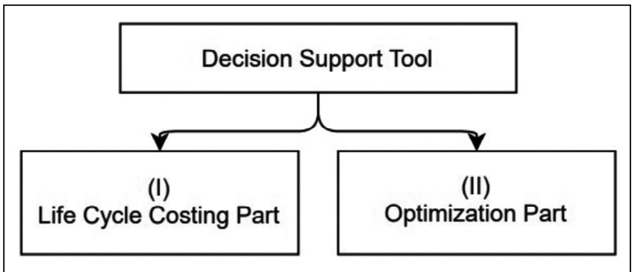

Figure 1. The decision support tool.

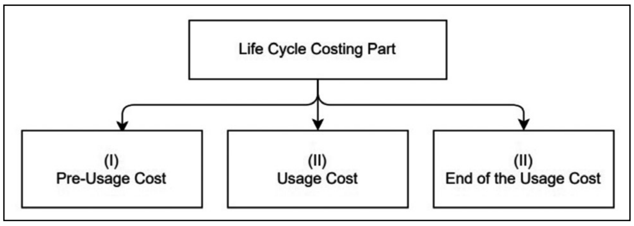

Figure 2. Phases of the LCC.

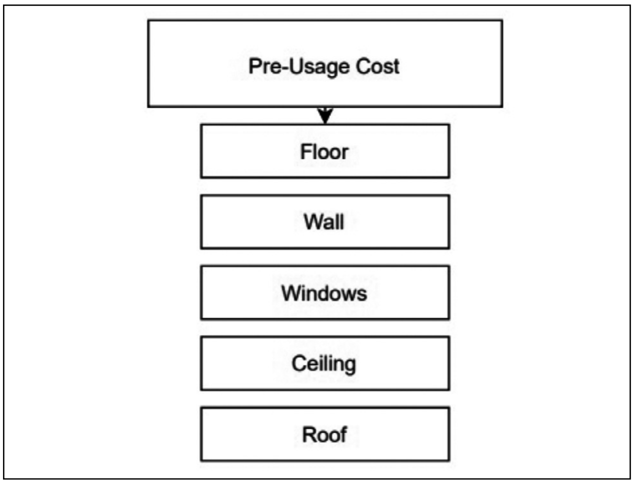

Figure 3. Cost components of the pre-usage part.

considered in this section to get a broad conclusion. The cost of construction includes the execution of the project, construction or assembly of the infrastructure. It can be characterised as the conversion into the reality of paper or computer drawings (Kirk and Dell'isola, 1995). This section was created on the basis of the construction components shown in Figure 3.

The computation framework is established by standards and regulations. The relevant standards and regulations (see Table 1) were adjusted in a way to construct the mathematical model.

The "2020 Unit Prices for Construction and Facilities Book," which is issued annually by the "Ministry of Environment and Urbanization" was utilised for the cost variable when the mathematical infrastructure was established.

- The second parts is the usage cost, which includes two major costs: (1) operational cost and (2) maintenance cost (Figure 4).

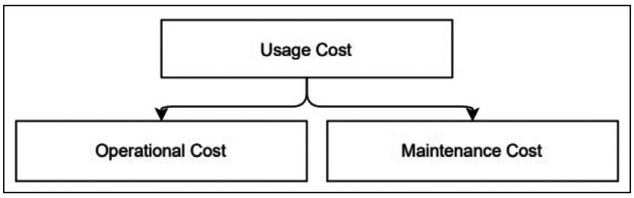

Figure 4. Usage part.

According to the BCIS and BSI published paper "Standardized Method of Life Cycle Costing for Construction," (2013) operation costs are defined as all expenditures associated with operating the building excluding maintenance costs. Operation costs are periodic costs that include heating energy, cooling energy, hot water energy, and water usage. This part was constructed using the components depicted in Figure 5.

Standards and regulations define the mathematical framework of this part. The fundamental principle is to compute the building's net energy demand. For this purpose, heat loss and heat gains are determined in the building and subtracted from one another in order to establish the net energy requirements according to TS EN ISO 13790 and the BEP Regulation. Building features, external climate conditions, internal climate conditions, characteristics of the heating/cooling system, solar energy internal heat gain sources are the factors that affect the energy demand of the building. This approach takes into account heat losses caused by transmission, convection, and ventilation, as well as internal heat gains and solar energy gains. The net output of the heating system is referred to as the heating energy demand. Because certain heat losses may occur during distribution, the heating system's conversion efficiency will be less than 1.00. The heating system efficiency was determined according to TS EN 15316-1. The calculating approach considers net internal heat gains and net solar energy gains.

Table 1. Computational background of pre-usage part

Building Part		Standards, Law, and Regulations
Roof	Ceiling & roof	ISO 7345 ISO 7726 ISO 9869
	Flat roof	EN ISO 10211 EN ISO 10456
	Conditioned inclined roof	EN ISO 13370 EN ISO 13789
	Unconditioned in-clined roof	EN ISO 13792 EN ISO 14683 TS 825 TS EN 832 TS EN 12524 TS EN ISO 6946
Ceiling		BEP Regulation
Windows		TS EN ISO 10077-1 TS EN ISO 10077-2 ISO 15099 TS 825 TS EN 12207 TS EN ISO 14438
Wall		TS EN ISO 10456, TS 6874 EN ISO 9251, TS EN 832, TS825, TS EN ISO 13789, TS EN ISO 10456, TS EN ISO 13788
Floor	Basement	ISO 7345 ISO 7726 ISO 9869
	Conditioned	EN ISO 10211 EN ISO 10456
	Unconditioned	EN ISO 13370 EN ISO 13789
	No basement	EN ISO 13792 EN ISO 14683 TS 825, TS EN 832 TS EN 12524 TS EN ISO 6946

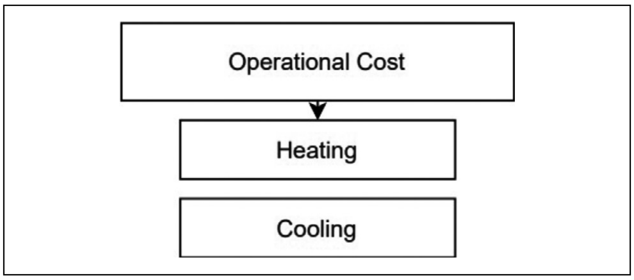

Figure 5. Components of the operational cost.

Therefore, the total of the gains is multiplied by the “heat gain usage factor”. Similarly, the energy required for space cooling is equal to the difference between total heat gains and total heat transfer, adjusted for heat losses using a dimensionless utilisation factor. Regarding climatic data, according to TS EN 15927-46, a typical climatic year (reference year) should be created for use in all energy efficiency evaluations of buildings. In addition, typical weather data sets, rather than average values, are recommended by Crawley et al. (2008), and such weather data sets can be generated on a national level or by international organizations. Therefore, in this study, outside temperature data are provided by the Turkish State Meteorological Service (DMI) on its official website for all cities in Turkey. The Service also provides average temperatures throughout a wide range of historical periods, beginning in the 1970s and ending in the present. Furthermore, the temperature set points and temperature variances between the outside and inside of a building have a significant impact on its energy efficiency. According to BEP Regulation, the internal set-point temperature for heating is 20°C while the value is accepted as 26°C for cooling. The same values were used for the computations. The necessary standards and regulations (see Table 2) were modified to allow for the construction of the mathematical model.

The maintenance cost, which forms the second part of the usage phase comprises routine expenditures for keeping the facility in good working order (Woodward, 1997). However, there is no specific information on maintenance expenses in the standards and regulations. As a result, building maintenance costs account for around 1% of the total investment cost (Bejrum, 1991; Bejrum et al., 1986; Johansson and Öberg, 2001; Sterner, 2002).

Future expenses are translated to a current cost value in operational and maintenance cost computation. During this phase, net present value calculation was employed. According to the 2020 data, assumptions that are interest, inflation and dependently discount rates have been provided. Thirty years was considered to be the life cycle for the structure as indicated in EPBD recast.

- The third part is the end of the usage cost known as the disposal costs at the end of its life cycle. According to the BCIS and the British Standards Institute (2013), it is defined as *“the net worth of a building or building system at the end of the LCC study period”*. However, the standards and regulations do not provide precise information about the cost. Since the only value required to find the net value of a building is provided by the General Directorate of Highways, the cost of disposal is estimated on the basis of the unit price of the General Directorate of Highways. The cost of the unit comprises loading, unloading, work of every kind, costs of equipment and tools, the overall expenses of contractors, and profits for 1 m^3 of the destruction of concrete.

Optimisation Part

The section is designed to identify the optimal thickness of insulation by minimising LCC’s under specific design limitations. Mathematically the optimisation is presented as follows.

$$\min.\ f(x,y,z\ ...)$$
$$\text{s.t. } x \in \Omega_1,\ y \in \Omega_2,\ z \in \Omega_3, ...$$

f: objective function

Ω: feasible set

In this study, the objective function refers to building life cycle costs. A letter (x,y,z, etc.) is represented for each design variable consisting of wall, window (glass and frame), orientation, heating system, fuel type, number of floors. The feasible set is known as *constraints*. Ω (1,2,3…) signifies for each design variable the number of finite possibilities.

An optimum solution f (x,y,z...) is the answer to the following problem

$$f(x,y,z\ldots) * \le f(x,y,z\ldots),\ \forall x \in \Omega_1,\ \forall y \in \Omega_2,\ \forall z \in \Omega_3\ldots$$

Table 2. Computational background of usage part

Heating	TS EN ISO 13790 TS 825 TS EN 832 TS EN 14336 TS EN 14337 TS EN 15265 TS EN 15316-1 TS EN 15316-2-1 TS EN 15316-4-5 TS EN 15377-3 TS EN 15450
Cooling	TS ETS EN 15316-3-1 TS EN 15316-3-2 TS EN 15316-3-3 TS EN 15316-4-3 TS EN 15316-4-4N 15255 TS EN 15265 EN ISO 13790
Ventilation	EN ISO 13789 TS 825 TS 3419 TS 5895 TS CR 1752 TS EN 832 TS EN 13141-6 TS EN 13142 TS EN 15243

In R programming, an algorithm has been developed to compute the optimal insulating thickness. The R program was chosen since it is open source and suitable for extremely sophisticated numerical and graphical computations. The optimisation process determines the optimum insulation thickness by accounting for all relevant factors. The pseudocode for the optimisation process algorithm is shown in Table 3.

Figure 6 depicts the data model, which is an abstract model that organises elements of data and standardises how they connect to one another.

Assumptions and Limitations

The tool has a highly sophisticated calculating algorithm. Limitations and assumptions in the tool are established to allow computations. The following are the assumptions.

- The cost and energy necessary to produce construction materials are not included in this computation.
- Salvage value is neglected since the costs represent a relatively small proportion of the total cost of the structure.
- An interest rate of 10% and an inflation rate of 8% are assumed.

Table 3. Pseudocode

Algorithm: identifying optimum insulation thickness

Result: optimum insulation thickness

```
set design variables;
read ISO constant.xlsx;
read price.xlsx;
read weather.xlsx;
read solar radiation.xlsx;
while (is there any alternative not tried) do
   set new insulation thickness
   calculate LCC of the building unit;
      calculate IC of the building unit;
      calculate OC of the building unit;
         calculate energy demand;
         calculate costs
         calculate present value
      calculate MC of the building unit;
         calculate present value
      calculate DC of the building unit;
         calculate present value
   if calculated LCC< minimum LCC then
         set new minimum LCC
   else
         do not change minimum;
   end
   iterate insulation thickness
end
return minimum LCC and associated insulation thickness
```

Case Study

The developed tool was tested in a representative building unit in a multi-story building to assess the capability and efficiency of the suggested optimisation approach to investigate the influence of lifespan on optimum insulation thickness in the Ankara climatic zone. A typical building unit was chosen from mass housing, and it was aimed to create a reference model for the building types to be produced in the future by using these architectural configurations throughout the country. According to the EPBD Recast, the economic life of the building was regarded as 30 years.

Mass Housing Projects in Turkey

The Housing Development Administration of Turkey (TOKI), a leading figure in Turkey's housing sector, makes substantial efforts to close the housing gap. According to TOKI, it meets 5–10% of Turkey's housing demands, resulting in around 50,000 housing units per year (TOKI, 2020).TOKI has constructed 837,572 dwelling units since 1983 (TOKI, 2018). The lack of flexibility in design leads in uniformity due to rapid production; regional and climatic variables are not taken into consideration in their utilisation. As a result, the same plan scheme and architectural configuration are used across the country.

Description of the Sample Projects

Real housing projects were selected as case studies in this research. The medium-high income category was chosen because of its large representation of 44.7% in social housing projects (TOKI, 2018). The following are displayed plans and fundamental characteristics of the sample project (Figure 7).

Sample projects constructed with tunnel formwork systems in the recent decade have been analysed. The unit is 154.00 m^2. The case study was selected from the intermediate level of the building to more clearly demonstrate the influence of insulation thickness and lifespan on the building energy consumption and life cycle cost and to compare them in related studies (Table 4).

RESULTS

Identifying the optimum insulation thickness is critical in terms of the building's energy requirements. Excess insulation raises the initial cost unnecessarily, whereas insufficient insulation can lead to an increase in the usage cost. In establishing the thickness of optimum insulation, it is also necessary to calculate the right lifespan. The study aims to find an optimum insulation thickness with the right insulation material in terms of life cycle cost with the help of the novel methodology and to compare real housing project that reflects the Turkish housing environment. In this study, contrary to prior studies, the optimum thickness was investigated for 30 years. The findings are as follows.

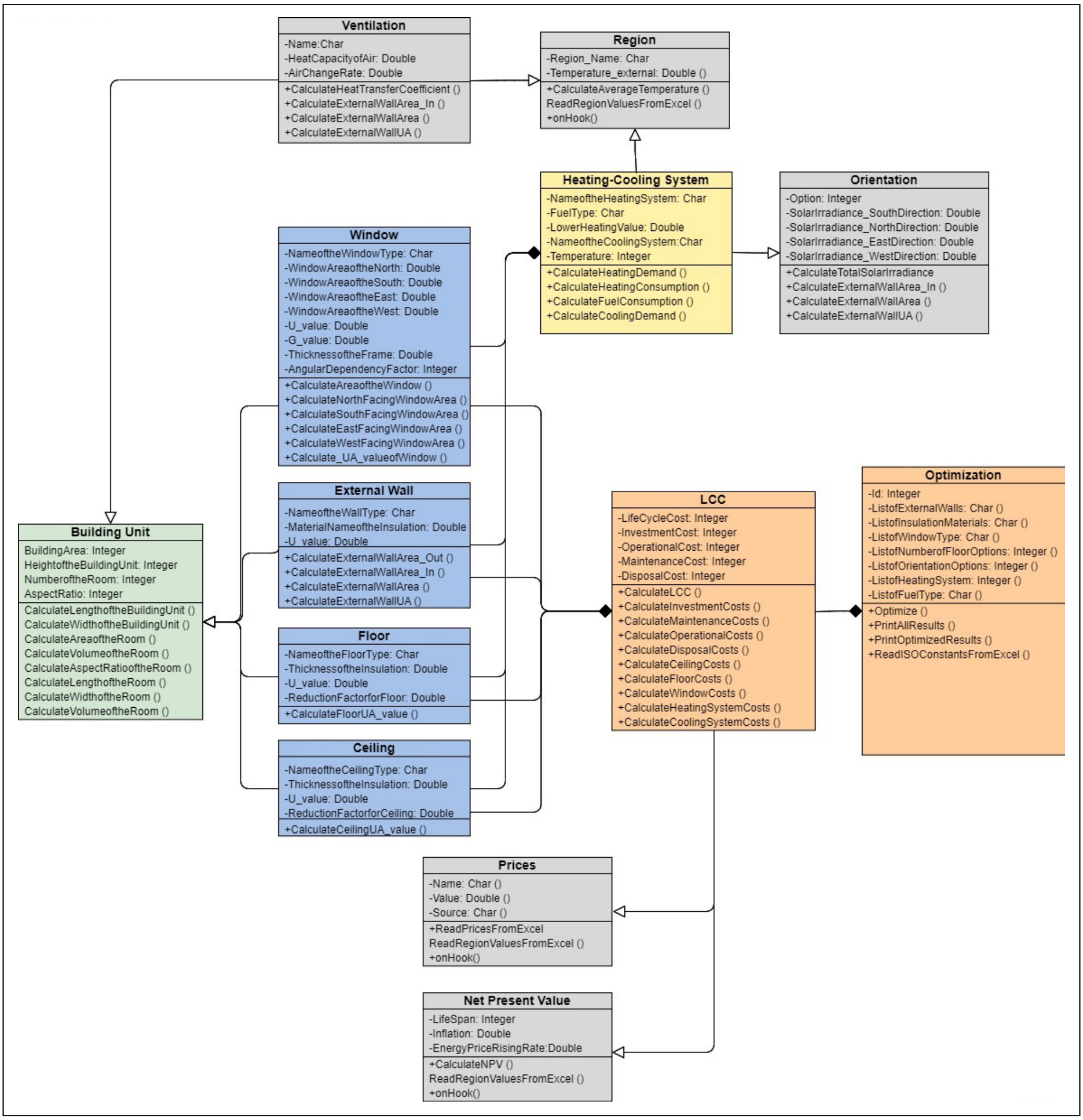

Figure 6. Data model.

In the study, thirty different insulation thicknesses have been used. It is apparent that neither excessive nor inadequate insulation is economically advantageous. Excessive insulation reduces life cycle energy costs but necessitates too much investment cost, whereas lack of insulation requires a less initial investment but a higher life cycle energy cost. As seen in Figure 8, the insulation thickness chosen for the case study is far from optimum. The use of optimum insulation in conjunction with the same architectural configurations considerably decreases the building's life cycle cost.

When the life cycle cost breakdown is analysed, it is discovered that since increasing the insulation thickness reduces the heat loss, it decreases the amount of energy demanded accordingly, thus declining the operational cost. On the other hand, increasing the thickness rises the investment cost as it imposes a burden on the initial cost. But the situation continues to such a point where the increase in the investment cost will no longer be able to compensate for the decrease in the operational cost. After this point, the life cycle cost begins to increase. The curve for the insulation cost for different thicknesses is given in Figure 9.

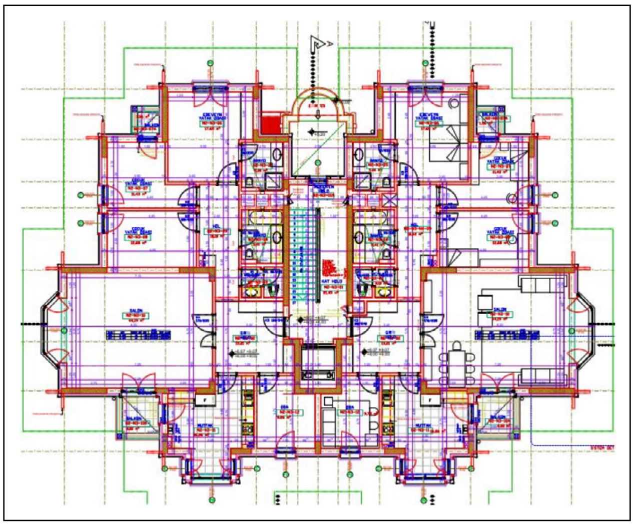

Figure 7. Building unit plan.

Table 5 shows the optimum insulation thickness for the case study by using proposed methodology with the parameters in Table 4.

Figure 10 depicts the impact of energy consumption on the LCC. When the optimum insulation thickness is applied to external walls, considerable energy savings can be realized. Thicker insulation saves more energy but needs more LCC. The essential finding is that the optimal scenario has a lower LCC and uses less energy than the case study.

When the optimal insulation thickness is applied to external walls, considerable energy savings can be realised. Figure 11 depicts the energy savings achieved in this research.

Figure 12 compares the energy savings of all insulation materials investigated for a case study in which the heating need is exclusively supplied by natural gas as an energy source, using DST with the parameters listed in Table 4. When the savings begin to decrease as the thickness of the insulation material increases, the optimum insulation

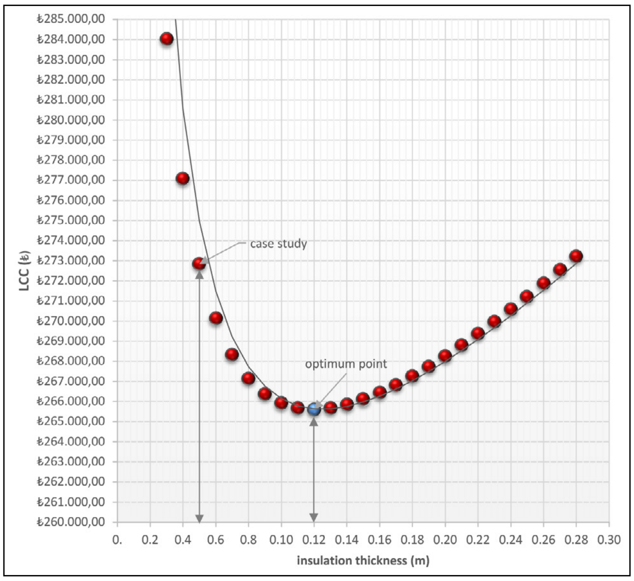

Figure 8. Effect of insulation thickness on life cycle cost.

thickness has been reached. The essential thing to remember is that each material has its own set of optimum points.

For 10 years, the optimum insulation thickness was estimated from previous studies. The building should, however, address it as a whole, and in Article 2(14) of the Energy Performance of Buildings Directive the economic life cycle for the residential buildings has been specified as 30 years.

Each lifespan has its own optimum insulation thickness, as shown in Figure 13.

According to Table 6, the thicknesses of optimum isolation and cost-saving vary depending on lifetime. Compared to 10-year studies, between estimations for the 30-year life cycle, savings are almost two times higher. This is crucial in determining optimum insulation for considering the right lifespan.

Table 4. Features of sample project

Building components	**Materials**
External wall	External plaster, reinforced concrete, internal plaster
External wall insulation material	XPS
External wall insulation thickness	0.05
Floor	Plastering screed concrete, light concrete
Ceiling	light concrete, screed concrete, PVC floor covering
Frame of window	Aluminium frame
Glass of window	Double glazing unit
Orientation	East North South direction
Heating system	Central heating system
Fuel type	Natural gas
Number of floors	13 floors

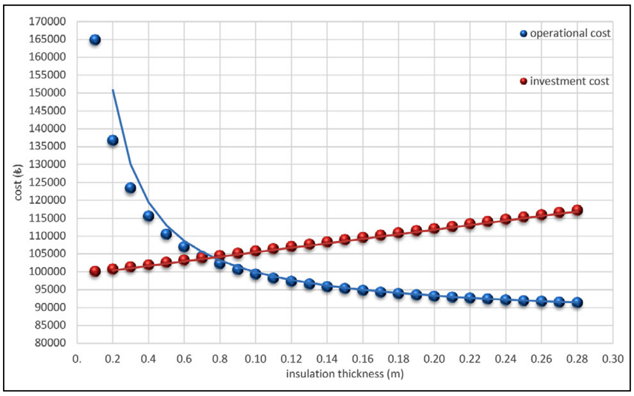

Figure 9. Life cycle cost breakdown.

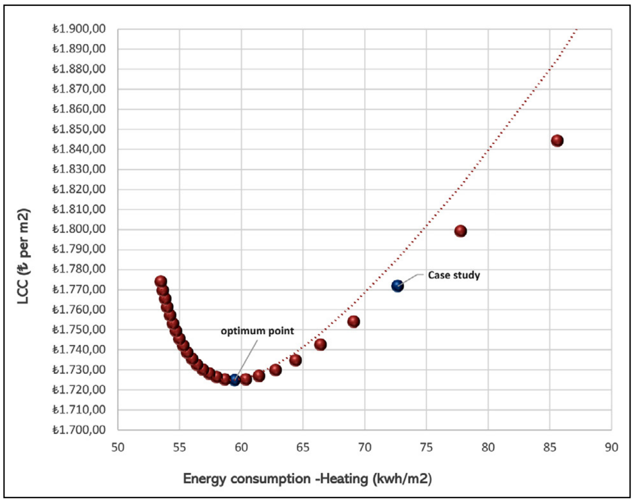

Figure 10. Effect of energy consumption on the LCC.

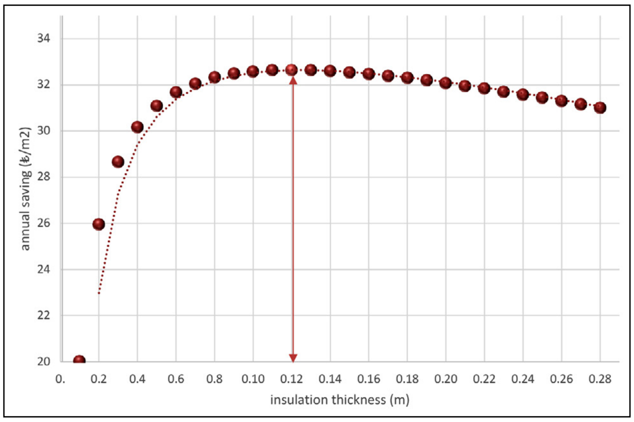

Figure 11. Annual saving and insulation thickness.

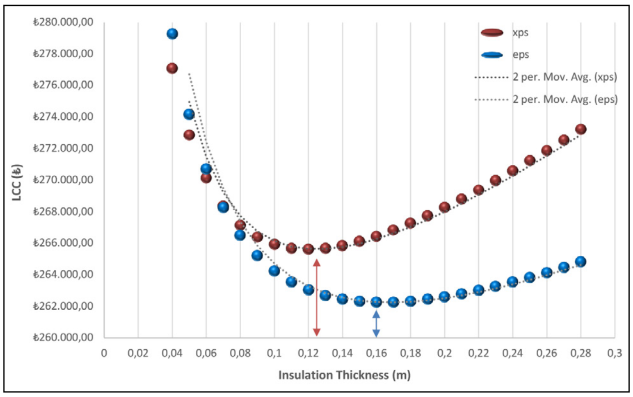

Figure 12. Comparison of energy and cost savings of all insulation materials.

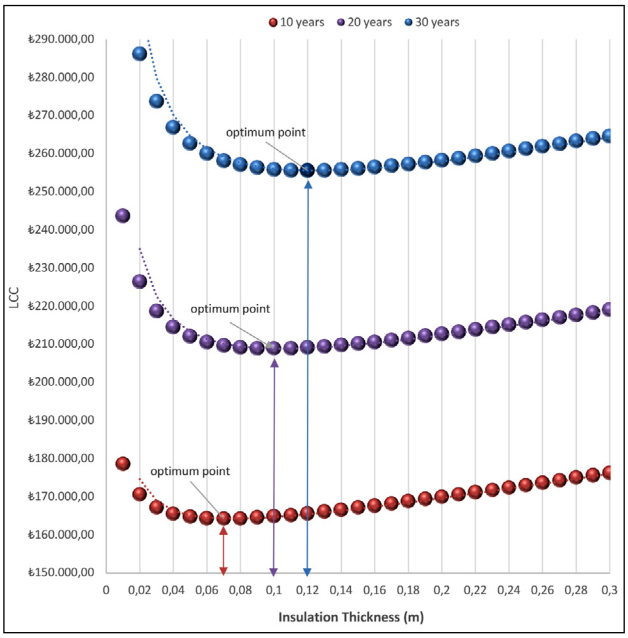

Figure 13. Comparison of different lifespans.

CONCLUSION

In this study, the suggested novel approach was used to evaluate the optimum insulation thickness, fuel savings, and payback period during a 30-year lifespan for a case study in Ankara, Turkey. A decision support tool has been developed to accurately determine the optimum insulation thickness. The tool combines the open box life cycle costing model with the R programming optimisation. The life cycle costing model was created as a BPS tool, because the model allows full control and hence there are no restrictions on the selection of decision variables and objective functions, unlike other software off-shelf. The building is evaluated as a whole in the calculations, and all components that affect the energy consumption of the structure, such as building orientation and window type, are included. The proposed methodology was tested on a real housing complex completed during the previous 10 years. The case study was chosen from among the most often used plan typologies in social housing projects in Turkey. In this selected case study, it is aimed to obtain information about insulation practices in Turkey.

According to the results,

- The insulation optimum thickness varies depending on the lifespan and the insulation material employed.

Table 5. Optimum insulation thickness, saving, and payback period for case study

	Optimum insulation thickness	Saving cost (₺/m²)	Payback period (years)
Case study	0.12	34.58	1.4

Table 6. Optimum insulation thicknesses and saving costs according to lifespans

Lifespan	Optimum insulation thickness	Saving cost (₺/m²)
10-year	0.7	10.18
20-year	0.10	21.92
30-year	0.12	34.58

- The building lifespan is at least as important as the insulation material and thicknesses to identify optimum insulation thickness.
- It is self-evident that neither excessive nor insufficient insulation is economically advantageous. Excessive insulation results in a lower life cycle energy cost but demands a disproportionate amount of capital investment, while inadequate insulation requires less capital investment but results in a higher life cycle energy cost.
- Until a certain value of insulation thickness is reached, the total cost begins to reduce gradually. Beyond this point, increasing the thickness of the insulation has the additional effect of raising the total cost. The important point is that each material has its own optimum points.
- Thicker insulations provide higher energy saving but at the same time they require more LCC. The important point is that the optimum point has both at least LCC and less energy consumption than the case study.
- Applying the optimum thickness of insulation to external walls results in considerable energy savings.
- Turkey as a country dependent on foreign energy has a big share in total energy demand, the insulation thickness used in the case study is far from the optimum thickness level.
- Insulation is also determinant in environmental problems, in order to reduce the amount of energy used for building and the consequent emissions of greenhouse gases into the environment.

As a consequence, identifying the optimum insulation thickness as the first step toward more efficient energy use in dwellings allows for the conservation of energy resources, the reduction of energy demand, and the protection of the environment by using energy wisely. Thermal insulation will become a significant subject in energy debates in the next years as a result of global warming, increased fossil fuel usage, rising energy demand, and energy price.

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