Impact of the different life cycle cost models on design decisions for insulation

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Abstract

The building envelope represents one of the most effective variables against thermal losses and thus it is necessary to have the best design of this envelope to operate as a passive system all over the lifetime. Commonly, insulation materials with low conductivity are used. However, it was noticed that different external factors have large effects on the insulation performance, due to aging and uncertainties that badly affect the effective conductivity. As considering uncertainty scenarios is related to the design decision, it is proposed in this paper to consider both the aging scenarios and the data uncertainties while looking at the optimum thickness of insulation to be used for design. For this reason, a reliability-based design optimization is applied, considering the classical life cycle cost formulation based on the investment and energy costs only. Finally, the optimum thickness is obtained using a new cost formulation that considers the indirect costs.

Keywords: Insulation, Uncertainties, Reliability, Optimization, Life cycle cost.

1. Introduction

The energy demand is increasing worldwide because of the increase of population and the improvement of living standards [1]. In Europe, the building sector is currently the largest energy consumer, much more than industry and transport sectors [2], leading to continuously increasing impacts on the environment. It consumes about 40% of natural resources extracted in industrialized countries, with nearly 70% of electricity and 12% of potable water, and produces between 45 and 65% of the waste disposed in landfills. Moreover, it is responsible for a large amount of harmful emissions, accounting for 30% of greenhouse gases, due to their operation, with additional 18% caused indirectly by material exploration and transportation [3].

Depending on the different climatic conditions of in various regions, a substantial share of energy goes to heat. This heating load can be reduced by many means, mainly by increasing the thermal resistance of outer walls through thermal insulation. This topic has gained a lot of engineering interest, through the determination of both the type of thermal insulation material and the economic thickness of the material to be used in the building envelope [4].

In the scientific literature, several works have dealt with building envelope, in order to determine the optimum insulation thickness [5,6], the insulation layers sequence [7,8] and the best insulation materials to be used [8,9].

Although these works have shown the importance of envelope design, they are mainly based on deterministic assumptions and data from survey and experimental measurements. However, all these data are often uncertain due to the intrinsic variation of properties, unavoidable measurement errors, random errors, non-representativeness of sample data, etc. [10].

The aim of this paper is to show the impact of these uncertainties on the decision making process concerning the optimal thickness to use for insulation. Firstly, it is proposed to show the impact of uncertainties on the conventional insulation thickness in terms of insulation reliability. Secondly, an optimization procedure based on reliability assessment is applied to determine the optimal thickness to be used, under uncertainty considerations. Finally, as it was noticed that the life cycle cost used in optimization considers only the investment and energy costs, the other costs related to the building location are investigated and their effect on the decision making process is clearly shown. The optimum thickness based on this formulation is then calculated in order to show the interest of considering all the involved costs.

2. Thermal insulation and uncertainties

As said previously, increasing the thermal resistance of outer walls by using a thermal insulation is the most effective mean to reduce the heat transmission load. Thermal insulation and thermal mass have been used by building envelope designers for years to achieve the above goal. However, this view was based upon thermal properties and behaviour of buildings and insulation materials under static (steady state) conditions. It assumes that outdoor and indoor conditions do not change with time, which is not the case in reality [1].

Thermal insulations are defined by the combination of materials that are used primarily to provide resistance to heat flow. One feature shared by all insulating materials used in building applications is their low thermal conductivity λ, usually lower than 0.1 W/m.K. Since insulating materials act as barriers for heat flow, it is obvious that insulation plays an important role in energy savings.

Although the design lifetime of a building usually varies from 50 to 100 years, the average lifetime of insulation is 10 years depending on the degree of deterioration of the used materials. In addition to aging, uncertainties related to physical properties of materials have a negative incidence on the useful thermal conductivity of the outer walls, and thus on their thermal resistance. In general, uncertainties on physical properties of materials are always present as they are related to thickness, density, thermal conductivity, etc. These uncertainties arise from a variety of sources, such as the lack of information, the measurement errors and the non-representativeness of the sample, as well as the various random errors and uncontrolled factors related to manufacturing processes and raw material properties. However, these uncertainties are often largely undervalued in energy or thermal comfort simulations. Although it is still difficult to have accurate quantification of these uncertainties, *Burhenne et al.* [11] pointed out that quantification of the input uncertainty can be based on measurements, estimates, expert judgment, physical bounds, output form simulations and analogies to similar simulation input.

3. Optimal design and evaluation criteria

The first step to consider in uncertainty propagation analysis is to choose a mathematical representation for uncertainty. The second step is to identify what elements of the problem will be considered uncertain and quantify their dispersion. After that, the uncertainties are propagated through the model to determine the dispersion of the outputs. Finally, the sensitivity analysis is carried out to identify the subset of input factors that mainly drive the uncertainties in the results [12].

In this work, uncertainties related to thermal conductivity are considered and will be characterized by probability distributions. As an example, figure 1 illustrates the evolution of thermal conductivity of polyurethane. Two probability distributions are plotted for the 2nd and the last year, in order to show the effect of uncertainty on the thermal conductivity. It is hypothesized that the degree of dispersion in the last year is much higher than for new insulation materials.

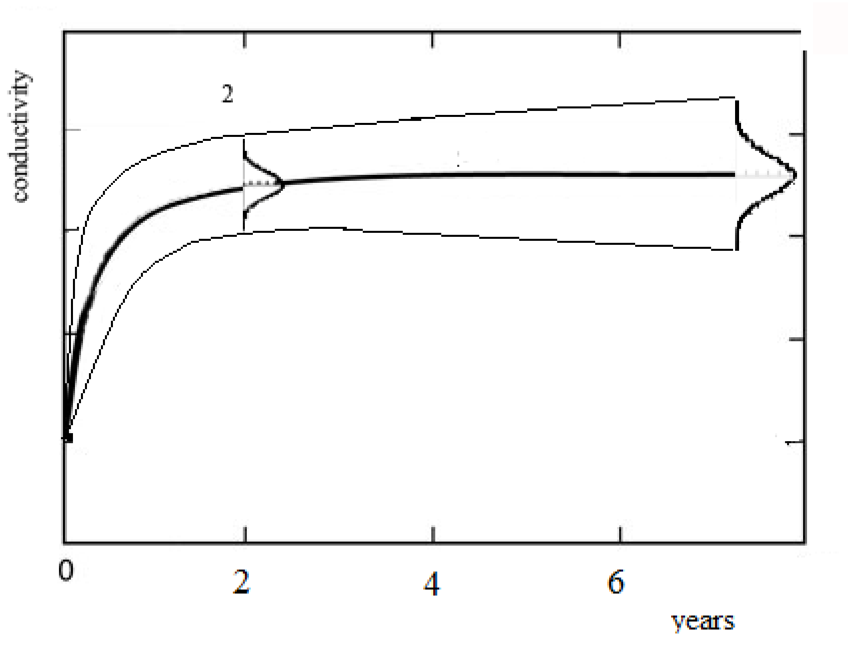

Figure.1. Deterioration of the thermal conductivity and expected uncertainty according to age.

In this work, a conventional wall is studied, as illustrated in figure 2. It has a composite structure made of 1.5 cm inner and outer plaster, 20 cm of hollow brick and internal insulation. In this study, two kinds of insulation materials were chosen: expanded polystyrene and mineral wool. The different values used for calculations are given in table I.

The thermal insulation used in the external walls of buildings aims at reducing the heating loads in winter and the cooling loads in summer, in order to reduce the energy consumption. *Dombayci* [13] gives the heat loss per unit surface q of an external wall as following:

$$q = \frac{\Delta T}{R_w} \tag{1}$$

He also gives the annual heat loss for unit surface q_A that can be calculated using equation (2).

$$q_A = \frac{86400\ DD}{R_w} \tag{2}$$

where DD are the degree-days for the considered year, corresponding to the sum of all the difference of temperatures obtained during all the heating days of the year, and R_w is the resistance of the insulated wall obtained by summing all the internal resistances of the different insulation layers in addition to the surface resistance. The *DD*-value simplifies the calculations by avoiding the calculation of the heat flows for each second of the day using the internal and the external temperatures. The annual consumption M_F is then given by:

$$M_F = \frac{86400\ DD}{R_w\ \eta\ H_u} \tag{3}$$

where ΔT is the difference of temperature between outer and inner environments, the factor η is the efficiency of the space heating system and H_u is the heating value.

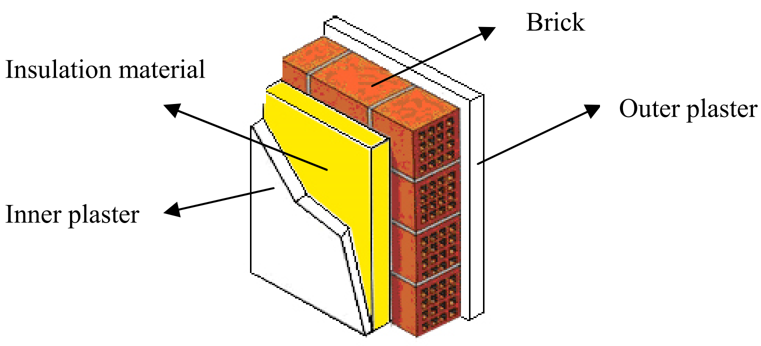

Figure.2. Structure of the studied wall.

Table I: Parameters used for calculations.

Parameter	**Value**
DD-value Mediterranean regions	1627 K
DD-value Mountain regions	2509 K
Efficiency of electricity η	99 %
Heating value H_u	3.599 x 10^6 J/kWh
Lifetime L_T	15 years
Brick thermal conductivity k_{Brick}	0.620 W/m.K
Plaster thermal conductivity $k_{plaster}$	0.720 W/m.K
Polystyrene thermal conductivity k_{ins1}	0.034 W/m.K
Mineral wool thermal conductivity k_{ins2}	0.040 W/m.K

3.1. Impact of uncertainties and reliability requirement

The aging of the insulation material is related to the evolution of its thermal conductivity with time *k(t)*. The main difficulty lies in the prediction of the deterioration process allowing to define the effective thermal conductivity as a function of the insulation age.

When the material is new, the thermal conductivity is supposed to be almost equal to the default value given by the manufacturer. We believe that the uncertainty on this value is small. However, when installing insulation, unavoidable defects and singularities may appear. In addition, the climate changes and the moisture content are often uncontrollable, and the related uncertainties are supposed to increase with time.

In the case of 8 cm of expanded polystyrene and mineral wool insulations, Figure 3 shows the impact of uncertainties on the total energy consumption over the lifespan. This case represents the conventional insulation thickness used generally with bricks or Hollow Blocks.

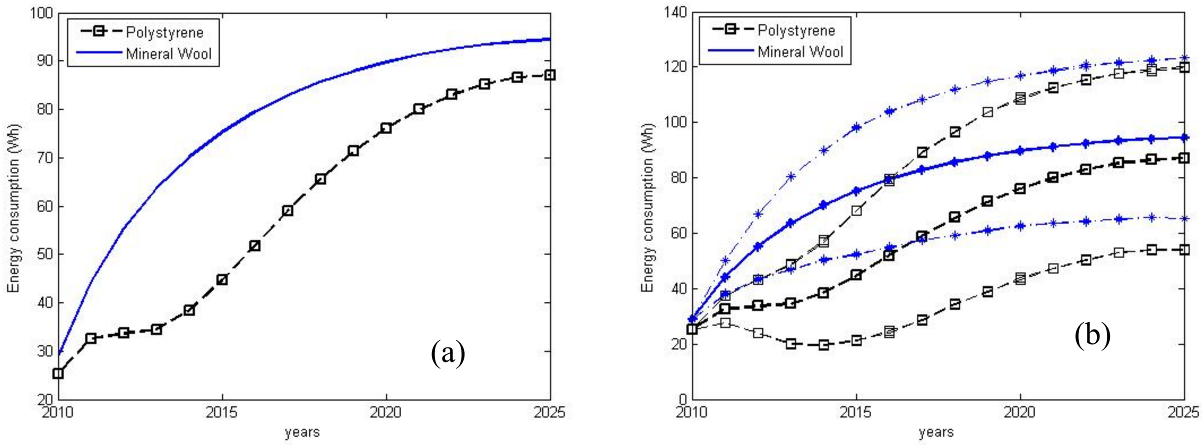

Figure.3. a. Evolution of the average energy consumption.
b. Evolution of the total energy consumption according to uncertainties.

For the first 15 years after installing the insulation, Figures 3.a and 3.b represent respectively the evolution of the average and the uncertainty related to energy consumption of polystyrene and mineral wool materials. Both insulations are subjected to external factors that affect their thermal conductivity over the lifespan and then a growing uncertainty level is observed each year. In both cases, it is seen that using mineral wool provides more consumption than polystyrene, which is related to their thermal conductivity. The two curves have different shapes due to the degradation model for each material.

The concept of economic thermal insulation thickness considers the initial cost of the insulation system, in addition to the ongoing value of energy savings over the expected insulation lifetime [4]. This cost analysis is generally based on deterministic assumptions, using different defect values. As a result, the owners generally expect to recover their investment within a period of 3 to 5 years. However, the previous uncertainties can impact the expected insulation reliability, leading to unexpected additional consumptions and therefore to longer recovery periods.

To determine the reliability of insulation, it is necessary to use both physical and probabilistic models, in order to assess the reliability related to the performance function which is affected by the random variable representing the thermal conductivity. In this study, the performance function is defined by the difference between the reference and the effective energy consumptions:

$$G(x) = Q_{ref} - Q(x) \tag{4}$$

where x is the vector of random variables, Q_{ref} is the reference yearly heat losses and Q the yearly heat losses considering uncertainties. This function defines the safety area when $G(x) > 0$ whereas it defines the failure area when $G(x) \leq 0$. In our case, the failure mode is described in terms of heat losses, as the insulation is considered reliable when the annual heat losses are lower than the reference heat losses imposed by regulations.

The failure probability is evaluated by using the First Order Reliability Method (FORM). This method, which is among the most widely used techniques, is appropriate in most cases due to its effectiveness in terms of ratio between computation time and accuracy [14,15]. This method is based on the computation of the reliability index, which is evaluated by an optimization algorithm, such as the Rackwitz- Fiessler algorithm [14]; the probability of failure is then calculated by first order approximations.

Figure 4 shows the evolution of the reliability index of the insulation as a function of time, for both insulation materials. These reliabilities are computed for 8cm of insulation thickness.

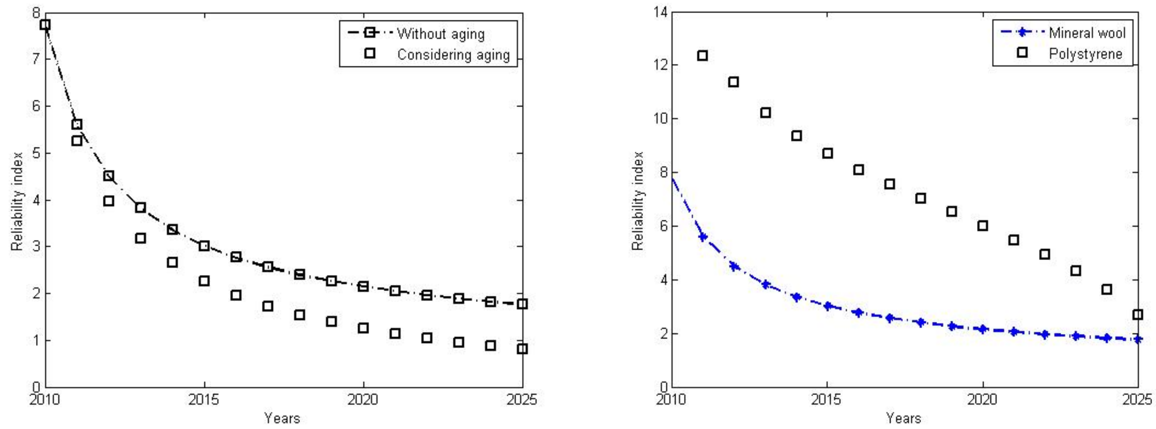

Figure.4.a. Reliability of polystyrene while considering material degradation or not.
b. Comparison between the annual reliabilities of Polystyrene and Mineral wool considering aging.

Figure 4.a shows the decrease of reliability index of insulation using polystyrene, where the impact of degradation is clearly observed over the insulation lifespan. In reality, the degree of uncertainty is related to different external factors such as climate aggressiveness and man-kind impacts. The difference between the two curves allows us to appreciate the effect of polystyrene aging. It is clear that more the insulation is deteriorating more the degree of uncertainty on its thermal conductivity is growing and thus the thermal reliability decreasing.

Figure 4.b. shows the evolution of the reliability index for polystyrene and mineral wool, respectively. In both cases, the same annual uncertainty level is considered. We can notice that the reliability of mineral wool decreases faster and this is due to two facts:

- The mineral wool has a higher thermal conductivity than polystyrene, leading to higher thermal losses and thus to lower reliabilities;
- The mineral wool is vapour permeable, and its thermal performances are greatly reduced by moisture. Actually, while considering deteriorating scenarios, we assumed that the degree of moisture present in the material grows gradually until reaching 10% at the end of the lifespan. In this case, the thermal conductivity of mineral wool is more affected by moisture than the conductivity of polystyrene affecting sooner the insulation reliability.

3.2. Optimization procedure and Life Cycle Cost

The insulation materials are the key tool in designing and constructing energy thrifty buildings and this is demonstrated by the increasing thicknesses used in buildings [16] and the increasing number of new insulation materials that appear with very low thermal conductivity. Actually, more the insulation thickness adopted is high, less will be the heat transmission loads. Although it was noticed that the investment cost is linearly proportional to the amount of insulation, there is a point for each type of material, beyond which the saving in energy consumption will not balance the extra cost of insulation. In other words, there is an optimum insulation thickness at which the total cost of the insulation material, combined with the present worth of energy consumption over the lifetime of the building, is minimum [17].

In this study, to ensure the quality assurance all over the expected lifetime of insulation, a reliability-based design optimization (RBDO) is applied to determine the optimum thickness considering uncertainties. The optimal thickness corresponds to the minimal total life-cycle cost, such that the annual failure probability satisfies the prescribed failure probability:

$$\begin{aligned} & Min \quad C_{tot} \\ & under \begin{cases} P_{fi}(d,x) \leq P_{f0} & \\ g_j(d,x) \geq 0 & j = 1,..,n \end{cases} \end{aligned} \tag{5}$$

where C_{tot} is the total cost of the insulated wall, d is the vector of design variables, x is the vector of random variables, P_{f0} is the allowable annual failure probability and P_{fi} is the annual failure probability of the insulation computed as described in section 3.1.

Ozel [18] and *Al-Sanea and Zedan* [5] defined the classical cost model which considers the fuel cost C_{enr} and the investment cost C_{inv}, as following:

$$C_{tot} = C_{inv} + C_{ad} + C_{enr} = t_{ins} C_i + C_{ad} + C_e PWF \tag{6}$$

where t_{ins} is the insulation thickness, C_i is the cost of insulation material per unit volume, C_e is the yearly cost of energy consumption ($/m²/year), PWF is the present worth factor and C_{ad} is the additional cost for insulation.

It was noticed that other costs related to the local regions may influence the decision-making process. These additional costs are mainly related to the environment, such as the cost of pollution with the application of the carbon tax and other costs related to socio-economic factors such as the housing value of the region. Hence, a new life cycle cost model considering these indirect costs is proposed herein as follows [18]:

$$C_{totN} = C_{ins} + C_{ad} + C_{enr} + C_{CO_2} + C_{surf} \tag{7}$$

where C_{CO2} is the amount of money that should be paid because of pollution while C_{surf} is the cost of the surface lost because of the internal insulation system. These costs are given by:

$$\begin{cases} C_{CO_2} = E_c \; C_{tax/kWh} \\ C_{surf} = (t_{ins} \; L_{ins}) \; C_{m^2/house} \end{cases} \tag{8}$$

where $C_{tax/kWh}$ is the carbon tax applied to 1 kWh of energy consumed. C_{surf} represents the cost of the lost indoor floor surface which depends on the insulation thickness t_{ins}, the length of the wall L_{ins} and the housing value $C_{m^2/house}$ that depends on the considered city/region.

The effective integration of uncertainty analysis for design information and quality assurance is of high importance. Therefore, it is firstly proposed to compare the optimal insulation thickness conventionally used (i.e. 8 cm) with the optimal thickness to be used when considering uncertainties. Then, it is proposed to compare the conventional costs obtained with the classical cost model (Eq. 6) to the new cost (Eq. 7) computed by considering indirect costs.

Table II: Economic parameters used for calculations.

Parameter	**Value(*)**	
$C_{m2/house}$ - Mediterranean region	3550.50	$ / m²
$C_{m2/house}$ - Mountain region	2390.85	$ / m²
$C_{tax/kWh}$	0.027	$/ kWh
C_e	0, 1611	$ / kWh
C_{Laying} –*ITI*	43.55	$ for 10 cm thickness
C_{ins} - Polystyrene	13.4	$/m²for 10 cm thickness
C_{ins} – Mineral Wool	8.14	$/m²for 10 cm thickness

*Average values according to what is found in the French market.

Table III: Impact of uncertainties and region on the optimal thickness of polystyrene.

Uncertainties	**Mountain region**		**Mediterranean region**	
	Thickness	Cost	Thickness	Cost
COV max = 8%	13.51 cm	316.10 $	13.51 cm	283.95 $
COV max = 10%	13.27 cm	318.10 $	13.27 cm	285.09 $
COV max = 15%	11.88 cm	331.01 $	11.87 cm	292.65 $
COV max = 20%	10.95 cm	341.06 $	10.95 cm	298.67 $
COV max = 40%	10.69 cm	344.12 $	10.54 cm	301.62 $

Table III presents the different optimum thicknesses obtained using the classical cost model. These thicknesses are obtained by considering uncertainties, for two regions with different climatic conditions. It can be noticed that the optimal thickness obtained in all cases are approximately the same, these are set according to the reliability constraint. However, we can notice that the costs are higher in the mountain region, due to cold climatic conditions implying more energy consumption. Regarding the uncertainty level, when the uncertainty increases, the thickness decreases, which is explained by the total cost of insulation. From table III, it can be seen that the total cost of insulation increases according to the uncertainty level, trying to find a compromise between energy and investment costs.

Table IV: Impact of uncertainties on the optimal thickness of both insulations.

Uncertainties	**Polystyrene**		**Mineral Wool**	
	Thickness	Cost	Thickness	Cost
COV max = 8%	13.51 cm	316.10 $	28.28 cm	325.04
COV max = 10%	13.27 cm	318.10 $	28.66 cm	324.64

COV max = 15%	11.88 cm	331.01 $	29.35 cm	324.03
COV max = 20%	10.95 cm	341.06 $	19.58 cm	349.04
COV max = 40%	10.69 cm	344.12 $	17.47 cm	361.76

Table IV shows the different optimum thicknesses obtained for the two insulation materials. To ensure the same reliability target, the optimum thicknesses obtained for polystyrene are much lower than those for mineral wool. This is of course due to the higher conductivity of mineral wool as well as its deterioration model. However, it is seen that using such high thicknesses can provide approximately the same total costs as those of polystyrene.

Table V: Optimum thicknesses computed using the classical and the new cost formulations and considering uncertainties (Cov 20%).

Region	**Insulation material**	**Classical formulation**		**New formulation**	
		Thickness	Cost	Thickness	Cost
Mediterranean	Polystyrene	10.95 cm	298.67 $	10.55 cm	678.54 $
	Mineral wool	19.59 cm	304.18 $	18.91 cm	986.19 $
Mountain	Polystyrene	10.95 cm	341.06 $	10.55 cm	604.89 $
	Mineral wool	19.58 cm	349.08 $	18.91 cm	817.59 $

Finally, table V presents the optimum thicknesses obtained using the classical cost and the new cost models (i.e. equations 6 and 7 respectively). It is noticed that using the new cost formulation gives approximately the same optimum thicknesses as those obtained by considering the conventional formulation. However, we can notice that the total costs go far beyond the conventional expectations.

As regards to regions, when considering polystyrene, the total cost in the mountain region is 12% lower than the cost of the wall in the Mediterranean region whereas the mountain region is colder and thus consumes more than the Mediterranean region. This difference of costs is related to the indoor surface loss. Although the used insulation thickness is the same, the housing value in the Mediterranean region is higher than the housing value in the mountain region.

As regards to materials, it can be noticed that in the same region, the difference in insulation thickness is very large and this is mainly related to the thermal performance of the insulation material and the evolution of its deterioration with time. Comparing costs, it can be seen that when using the classical cost formulation the difference in cost between polystyrene and mineral wool is often low. However, when considering the new cost formulation, the difference in cost approaches 36% in the mountain region.

These results show the importance of considering all the different indirect effects related to insulation in addition to uncertainties and aging scenarios, when looking for the optimal design.

4. Conclusion

This paper aims at showing the importance of considering system uncertainties to support the design process when insulating the building envelope. The analysis showed that the energy consumption and the reliability of the insulation are related to the effectiveness of the used insulation material as well as to its uncertainty level. The optimum thickness is then determined using the reliability-based design optimization. Under a given reliability target, the different degrees of uncertainty have been considered to show their impact on the optimum insulation thickness.

The study showed also the importance of considering direct and indirect factors related to insulation. Two cost models have been considered in computing the optimum thickness. The new cost model considered the indirect impacts of insulation, in addition to the conventional used costs related to energy and materials. The optimum thicknesses were computed considering uncertainties, in the case of two regions with different climatic conditions. The results showed that the difference in the optimum thickness is not very important, but the total cost is largely influenced by the type of region and the related indirect impacts.

On the basis of these results, it has be noticed that the integration of uncertainties for design quality assurance is very important and has provided additional information about the insulation reliability and the optimal design.

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