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Cost model for optimum thicknesses of insulated walls considering indirect impacts and uncertainties

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ABSTRACT

Nowadays, insulation is increasingly used for houses and buildings for its economic and environmental advantages. The performance of an insulated construction depends mainly on the thickness and the properties of the used insulation material. However, this performance is subjected to various uncertainties related for instance to the manufacturing process of the material and to the different workmanship errors that affect the thermal resistance of the insulated construction. In practice, these uncertainties are still rarely considered in energy analysis. Nevertheless, beyond a given level of uncertainties, the insulation system does not perform as expected which induces additional unexpected costs related to energy and pollution. This work aims first, at showing the impact of these uncertainties on the reliability of the insulated construction and second, at developing a new formulation of the global cost for the design of insulation system considering additional costs related to user and environment. The proposed cost formulation allows us to provide a better estimation of the payback period. Three configurations are considered with different insulation schemes in order to show the impact of uncertainties and indirect costs on the insulation performance.

1. Introduction

The International Energy Agency (IEA) believes that it is crucial to reduce the energy demand of the building sector by making buildings much more energy efficient. In 2008, the building sector represented around 40% of the total primary energy consumption in most IEA countries [1] with approximately 60% of the consumed total energy dedicated to heating and cooling [2,3]. This percentage is going to rise in the coming years as the global population continues to increase, emerging economies continue to develop, climate changes lead to a greater demand for cooling buildings in warm climates and rising personal wealth pushed consumer demand for appliances even higher. A report of the IEA on the economic crisis of 2008, indicated that the global energy demand grew at a faster rate than the global economy [1], showing the importance of undertaking actions to develop energy-efficient equipment emitting less or even no CO_2.

After the alarming assessment of the energetic situation, the European Union established specific actions by introducing the EPBD (Energy Performance of Building Directives) dedicated to the building environmental issues [4]. These directives suggest to each EU state to target their own objectives. As a consequence, different projects of passive buildings emerged in Europe, such as PassivHaus in Germany, Minergie in Switzerland and Effinergie in France [5], leading to new thermal regulations to achieve more energy savings by using better insulations [6].

At present, the simulation of building energy performance is a mature field and the growing level of details in the available tools results in a large amount of parameters, all of them are uncertain to some extent [7]. These uncertainties arise from a variety of sources such as the lack of information, the random components and the approximations is the building mathematical and numerical models. Unfortunately, these uncertainties are large enough to make the results of the calculation very dependent on the assumptions about the input data [8]. In BPS (Building Performance Simulation), the improvement of quality assurance should consider uncertain configurations and should make the use of these tools more accessible [9]. It is therefore important to quantify to what extent the energy models are imperfect before using them in design, prediction and decision-making processes.

The aim of this paper is to study the impact of the uncertainties related to the insulation properties and the impact of cost estimation errors on the expected total cost of an insulated construction. In this framework, a new cost formulation based on direct and indirect

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costs is first proposed. Then, a design methodology that considers both uncertainties and the new cost formulation is presented and applied to three insulated wall configurations. Finally, the impact of uncertainties on the optimum insulation thickness is assessed and the effect of indirect costs on the payback period is estimated.

2. Literature review

2.1. Thermal insulation

Thermal insulation is known as the most effective way of building energy conservation for cooling and heating [2] by reducing the rate of heat transfer [3], it can be either installed on the external side (External Thermal Insulation, ETI) or on the internal side (Internal Thermal Insulation, ITI) of the building envelope. In general, ETI is commonly preferred [10], since it offers various significant advantages, such as prevention of moisture condensation, straightforward tackling of thermal bridges and use of the building thermal mass. However, ETI is associated with higher installation costs [11]. In special cases, such as historical, traditional or cultural heritage buildings, ETI is not allowed due to the resulting changes in the facade of the building. In contrast to ETI, the ITI configuration does not interfere with the facade and exhibits significantly lower installation costs [11]. However, ITI results in a non-negligible loss of indoor space (i.e. 5–15 cm for each insulated wall) and is associated with a high risk of moisture condensation [11].

2.2. Optimization of the insulation thickness

The appropriate design and selection of a building envelope and its components are efficient means to reduce the space heating/cooling loads. Therefore, determining both the type and thickness of insulation materials used in the building envelope is an important topic for many research and engineering investigations.

It is well known that the heat transmission load decreases without any limit when increasing the insulation thickness. However, the decrease rate drops quite fast as the thickness increases. From a purely conservative point of view, the designer should select an insulation material with the lowest possible thermal conductivity and with the highest thickness that the owner can afford. However, the cost of insulation increases linearly with its thickness, and there is a thickness for each type of material, beyond which the saving in energy consumption will not compensate the additional cost of insulation. In other words, there is an optimum insulation thickness for which the total cost of the insulation material, added to the present worth of the energy consumption over the lifetime of the building, is minimum [2].

In the literature, the studies on the determination of the optimum thickness of insulated walls of buildings consider mainly the sequence of the layers and the chosen materials. In most studies, the optimum insulation thickness computations are mainly based on the heating and cooling loads, the costs of the insulation material and energy, the efficiency of heating and cooling systems, the product lifetime, and the current inflation and discount rates. Usually, the estimation of the heating and cooling energy requirements uses the *degree-day* (DD) concept which is one of the simplest methods that are applied under static conditions [1]. In fact, instead of calculating the heat flow for each second of the day using the internal and the external temperatures, the DD-value simplifies the calculations and gives the sum of all the difference of temperatures obtained during all the heating days of the year.

Early studies on optimum sequence of insulation and concrete layers in building elements are due to Sodha et al. in the late 1970s [12], that studied the optimum distribution of a given total thickness of insulation inside and outside the roof achieving the maximum leveling in the heat flux entering through the roof. They finally concluded that the outside and inside thicknesses should be equal. Many other studies such as those of Eben Saleh [13] and Bojic and Loveday [14], evaluated the thermal performance of different arrangements, types, and thicknesses of insulation materials in buildings, but all of them used deterministic input variables.

Regarding the prediction of the optimum thickness of insulation, works such as those of Bolatturk [15] and Kaynakli [3,16] used the degree-hours method and long term meteorological data. Another interesting work done by Comakli and Yüksel [17] used the same method to determine the annual heat losses, which have been related to the annual heating energy. The cost of insulation was then added to the cost of heating energy to form the Life Cycle Cost for a given thickness of insulation. Finally, the optimum insulation thickness was given by the minimum cost [18]. Although these works show the importance of the choice of the optimum insulation thickness and structural materials, they are mainly based on deterministic assumptions and data used from surveys and experimental measurements. However, all these data are often uncertain due to intrinsic variation of properties, unavoidable measurement errors, random errors, non-representativeness of sample data, etc. [19].

2.3. Uncertainty analysis

In recent years, the use of uncertainty and sensitivity techniques has been largely popularized in different engineering fields [19] (such as structural design [20], climate changes [21], . . .). As models represent a simplification of reality, it is necessary to quantify to what extent they are imperfect before employing them in design, prediction and decision-making process [7]. The aim of the uncertainty analysis is to support the design process by providing additional information on the chosen parameters. In general, physical uncertainties are widely considered and they are mostly identified as the standard input parameters in energy or thermal comfort simulation. Physical uncertainties refer to the physical properties of materials such as density, thermal conductivity, etc., and as a matter of fact, they are always unavoidable [9].

In the literature, some studies focused on assessing uncertainty in building simulations while others focused on the investigation of uncertainties and/or sensitivities of input parameters for building design support and prediction of energy consumption [19].

Concerning uncertainties related to design parameters, Spitz et al. [6] and Hopfe and Hensen [9] used the uncertainty analysis during the design process to determine uncertainties in physical properties and considered them in BPS to improve the design decision support. whereas, Heiselberg et al. [22] used the sensitivity analysis to identify the important design parameters to be changed in order to reduce the primary energy consumption and concluded that lighting control and the amount of ventilation during winter are the most important parameters. In another study, Domínguez-Muñoz et al. [23] worked on the quantification of the uncertainties linked to the thermal conductivity of insulation materials, which is mainly due to the lack of specific experimental measurements. They showed the effect of these uncertainties on the simulated peak cooling loads and how a stochastic simulation can improve a design decision [8].

Concerning the numerical simulation models, Lu et al. [19] quantified the uncertainties in building energy consumption data on the basis of Monte Carlo simulations. They proposed a procedure for uncertainty analysis (Fig. 1) in which the first step is the compilation of energy consumption inventory data, including the identification of the parameters that might influence the final results. In the second step, the model is established using