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Quantification of the uncertainties produced in the construction process of a building through simulation tools: A case study

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ABSTRACT

This work considers the uncertainties in building energy performance caused by deviations introduced in the construction process. It proposes an approach based on sensitivity analysis by simulation, which allows for the quantification of the impact of these deviations isolated from other possible ones and independently from one another. This information could be useful for practitioners, helping them to identify which deviations with respect to design could be critical regarding energy savings and giving criteria to optimize the construction process. The approach is applied for a case study in which the effects of such deviations on the heating and cooling energy demand of a building located at the Solar Platform of Almeria (Spain) are quantified. The results support that possible deviation from the design specifications during the construction process can affect the building annual energy consumption and peak loads considerably in the Mediterranean area. According to the work reported in this paper, the studied parameters sorted in descending order of influence on the annual load are: infiltration rate, insulation thickness, insulation class, cement mortar thickness and frame-wall gap filled in with cement.

1. Introduction

Conventional energy consumption in buildings represents a significant percentage of the total energy consumption in many countries (around 40% in most of the EU countries [1] and 31% in Spain [2]). It has been proven that there is high potential savings in conventional energy in this sector if solar passive and active techniques are employed in construction. Therefore, an increasing interest in promoting energy efficiency in the building sector has been emerging in the last decades, and as a result, several research initiatives [3] have been undertaken and directives ([4–6]), and related standards and regulations are being generated. It must be highlighted that analysis and application of energy saving techniques require accurate knowledge of the building and the parameters that influence its energy consumption. Notice that the lower the building energy consumption is, the more important uncertainties related to energy analysis become, as far as the order or magnitude of the main energy flows could be lowered to an order of magnitude very close to the order of magnitude of usual uncertainties. Consequently accuracy is becoming more necessary as buildings are becoming lesser consumers to minimize the uncertainties produced.

The Energy Performance of Buildings Directive (EPBD) 2010/31/EU (recast) requires that from the year 2020 onwards all new buildings have to be 'nearly zero energy buildings', comply with high energy performance standards and supply a significant share of their energy requirements from local renewable sources. To achieve these objectives, an understanding of the dynamic nature of building energy flows and occupancy behavior is essential as well as a robust energy performance assessment for new and renovated buildings.

To fulfill these requirements, Spain implemented in 2006 the regulations on building construction [7], whose energy requirements have been updated in 2013 [8]. In the framework of building certification, the Spanish government has developed methodologies for Building Energy Labelling regulated by the Royal Decree 235/2013 [9]. New certification tools have been created [10] to calculate the impact of heating and cooling on the energy needs of buildings, the primary energy consumption and the carbon dioxide emissions.

Currently, most compliance checks and labelling of the energy performances of buildings considered by regulations, are done in the design phase by theoretical calculations and simulations, and are based on the building design specifications. However, studies have shown that the performance of a building may deviate significantly from this theoretical performance as discussed in several published papers ([11–15]), and considered by research collaboration in the international context of IEA EBC Annex 58 [16] Annex 71 [17] and DYNASTEE network [18]. Real building energy use is one of the high priority research and innovation themes defined in the IEA EBC Strategic Plan

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2014–2019 [3].

The construction process is one of the issues that can introduce deviations from design specifications [19]. These deviations are likely to be unavoidable and are usually acceptable if energy is not considered. However, the reliability of the results from the energy simulation depends on how closely design specifications have been followed.

Due to these undesirable design deviations that can occur during the construction, there is degree of inherent uncertainty in the final building performance. At the same time, there are controllable factors that could be prevented. For this reason, simulation tools recommend that the user verify building construction parameters.

Some of the construction factors which can cause uncertainty ([19,20] and [21]) are the unpredictability of weather, availability of labor, local worker skills and attitudes toward planning, past construction experience, etc. Depending on these factors, construction uncertainty can present varying degrees of complexity.

The knowledge of the impact of such possible uncertainties on the energy performance of the building could be useful for practitioners, helping them to identify which deviations with respect to design could be critical regarding energy savings and giving criteria to optimize the construction process.

Studies on construction management ([22] and [23]) emphasize the importance of incorporating uncertainty factors in project-cost, time forecasts and final building quality among other matters. Alencastro et al. ([24]) carried out an analysis based on a literature review, aiming to identify quality defects which undermine the thermal performance of buildings. This reference is focused on the defect characteristics and attributes; major causes and influencing factors; and their impact on the energy performance of construction projects. It postulates that understanding the generation process and effects of defects on the energy efficiency of buildings can support the implementation of appropriate quality management systems in construction projects and thus contribute to the achievement of the intended energy performance targets.

Different experimental approaches can be applied to deal with the problem of uncertainty in energy performance of buildings and building components that arise due to deviations from the design during construction. Research based on full-scale dynamic measurements can help to bridge the gap between the theoretically predicted and real life energy performance of buildings considering outdoors test of building components ([25] and [26]), full scale test of buildings ([27], and [29]), or in-situ measurements [31]. In-use experimental campaigns can provide support to build data based models. Such models could be used along the lifecycle of the building for energy performance assessment or control application. Different modelling techniques, based on experimental data, can be applied to assess the actual performance of buildings and building components and can help to assess the performance gap: identification techniques and time series analysis tools [32], and validation and calibration of simulation models [28,29].

This paper proposes and reports the application of an approach based on sensitivity analysis by simulation tools in a Mediterranean area ([33] and [34]), which allows the quantification of the effects of these deviations separately from other possible ones. It also allows the analysis of the relative influence of different potential deviations on the building energy performance.

The building considered for the case study is located in Tabernas (Almería) in the south-east of Spain. This is relevant taking into account that most reported works dealing with the performance gap consider case studies in northern European countries. However very few case studies are reported from Mediterranean countries where warm and moderate weather, high level of solar radiation and different building typologies can introduce relevant differences regarding the analysis and its results.

A theoretical model has been developed using the TRNSYS dynamic simulation code, and theoretical results have been compared with experimental data for summer and wintertime. Design parameters susceptible of variation during construction and their feasible deviations have been identified. Afterwards, annual loads have been obtained by simulation batteries and sensitivity analysis methods have been used to quantify the impact of the given parameters' variations on the annual heating and cooling energy consumption, load profiles and peak loads.

Such simple single zone building allows identifying significant deviations that highlight the relevance of the studied deviations that would become even higher in buildings with increased complexity. There are a wide variety of methods to quantify those deviations: local and global ([35–38]). Local methods vary only one parameter at a time while global methods are employed to study the impact of parameters throughout the input space. One local method has been used in this document due to its implementation and low computational cost but it should be taken into account that these procedures have some limitations in the selection of their sensitivity analysis algorithms and in the outputs obtained. However, even a local sensitivity analysis reveals the influence of different design parameters. Other environmental parameters could also vary, such as ground reflectance [39]. This effect has been shown to be of a lower order of magnitude with respect to construction-related parameters [27]. This work evidences the relevance of improving construction process looking for better accordance between design specifications and as built buildings. It also evidences the need of advanced procedures to validate and calibrate simulations models applicable to building with higher level of complexity, as reported in [28,29]. This is particularly relevant if these models are aimed to be used along the lifecycle of the building (for example in Model Predictive Control applications [30]).

2. Case study

2.1. Building and location description

The building studied is a single-zone building constructed at *"Plataforma Solar de Almería (PSA)"*, located in Tabernas, Almeria, South Spain (a semiarid region with latitude 37°03, longitude –2°23 and altitude 404 m). The building is facing south and is free of nearby obstacles. It has an area of 31.9 m^2 and a height of 3.6 m. The shading devices are designed to minimize solar gains in summer and maximize them in winter. Fig. 1 shows schemes and views of the exterior and interior of this building. More detailed information of this building is reported in [40,41].

All the wall surfaces of the envelope are painted white, except for the pebbled roof. North and south aluminum-frame 4/6/4 double-glazed windows are 2.25 m^2. The eastern 1.94 m^2 aluminum door has a 0.56 m^2 4/6/4 double-glazed window. The building walls, floor and ceiling composition are shown in Table 1.

2.2. Experimental campaigns

In order to quantify the thermal response of the building to external and internal fluctuations, two experimental campaigns have been developed: from December 20th, 2003 to January 5th, 2004 and from July 16th to August 16th, 2004. In both, the following outdoor and indoor variables have been measured: global and diffuse horizontal radiation (W/m^2), ambient temperature (°C), relative humidity of air (%), wind speed (m/s) and indoor air temperature (°C) at 1.5 m height on the west side near the north and south walls. The measuring instruments used are: PT100 (solar radiation shield and naturally ventilated) for air temperature, thermoelectric pyranometer for solar radiation, capacitive sensor (solar radiation shield and naturally ventilated) for relative humidity and optoelectronic transducer for wind speed measurements. The accuracy of the corresponding measurement devices is summarized in Table 2.

During the monitored period, the building was unoccupied, the door and windows were closed and indoor air was not stirred. The lighting, heating and cooling systems were turned off. A data logger, a router and a computer were located on the south-west side of the room.