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Empirical validation and local sensitivity analysis of a lumped-parameter thermal model of an outdoor test cell

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ABSTRACT

This paper presents the experimental validation of a thermal model describing the ZEB Test Cells Laboratory, located at the Gløshaugen campus of NTNU and SINTEF in Trondheim, Norway. Besides, a local sensitivity analysis identifies the parameters and inputs that are most influential on the thermal behaviour of the test cell, in terms of temperature profiles of the internal air and internal surfaces. The analysis shows that, in free-running conditions, the most important parameters and inputs, out of the 49 tested ones, are: the air temperature in the guard zone, the initial temperature(s) of the test cell envelope, the linear dimension of the square window, the solar irradiance on the vertical plane of the window, the depth of the test cell, the thermal conductivity and the thickness of the polyurethane layer in the envelope, the solar direct transmittance of the window, the internal height and width of the test cell, the external air temperature and the electrical power input to the mixing fan. Based on the outcome of the local sensitivity analysis and on in-field observations, some practical measures to improve the quality of the input data provided to a dynamic energy simulation tool, and thus the accuracy of prediction of the temperature evolution of the test cell. Based on the outcome of the local sensitivity analysis and on in-field observations, we propose some practical measures to improve the quality of the input data provided to a dynamic energy simulation tool, and thus the accuracy of prediction of the temperature evolution of the test cell. For example, we suggest monitoring accurately the environmental conditions in the guard zone, which are particularly influential under free-running conditions, and installing a global irradiance pyranometer next to the window in order to reduce the uncertainty related to the entering solar load.

1. Introduction

The goal of the present study is to identify actions that can improve the measurement techniques adopted in outdoor test cell experiments. This has been achieved by (i) modelling the thermal behaviour of an existing test cell adopting a lumped-parameter approach, (ii) comparing the obtained simulation results with measurements, (iii) performing a local sensitivity analysis in order to highlight the most relevant model inputs and parameters.

The influence of a model parameter depends also on the specific experimental conditions and on the algorithms used by the thermal model. Thermal simulations and sensitivity analyses applied to a range of expected operating conditions can guide the design process of new test cell facilities and the operational procedures in new and existing ones. Highlighting the most critical parameters can support the research team in the choice of the features of the envelope, of the conditioning system and of the measurement set-up and in the choice and control of conditions under which specific experiments are performed.

1.1. Lumped-parameter thermal models for building energy simulation

In general terms, the lumped-parameter approach (also called thermal-network approach) consists of discretizing the temperature field of a thermodynamic system, by identifying a certain number of representative nodes where an energy balance is computed. Each node is connected to the adjacent nodes by means of thermal resistances, and thermal capacities are assigned to all elements that are capable of storing internal energy, such as walls, transparent elements (whose

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thermal capacity is in some cases assumed negligible), water tanks, and relevant volumes of air (e.g., the whole air volume inside a room or a whole building, while usually the thermal capacity of the air volume in the gap of double-glazing unit is considered negligible). Thermal bridges are usually treated in a simplified way, for example by decreasing the thermal resistance of adjacent elements by an estimated quantity. Common underpinning hypotheses when adopting a lumped-parameter thermal model are that (i) each node represents a sufficiently small finite volume (i.e., a portion of a solid body or a liquid/gas volume) to be considered at uniform temperature; (ii) air is perfectly transparent to electro-magnetic radiation, hence not involved in radiative heat exchanges, (iii) thermal capacities and thermal conductivities are time-invariant and independent from temperature and moisture content; (iv) convective and radiative heat transfer coefficients are constant within the calculation time step. The hypotheses at points (iii) and (iv) are necessary to consider the thermal system as linear, hence permitting the superimposition of effects. Additional hypotheses that are specific to each model (and whose validity has to be evaluated for each individual model) concern the interactions between the elements: only main heat exchanges are considered, neglecting minor heat flows. Examples of often neglected heat flows are those due to local non-homogeneities in the construction elements.

Lumped-parameter models are also closely correlated to physical characteristics of the thermal system (hence being classifiable as *white box* models) and they allow for an intuitive graphical representation in the form of resistor–capacitor (RC) circuits. In the following paragraphs, we propose a selection of previous studies dealing with specific aspects of linear lumped-parameter thermal models. For a theoretical background, the reader can also refer to Athienitis and Santamouris [1], Davies [2] and Underwood and Yik [3].

Hudson and Underwood [4] propose a simple building model coupled to the model of a convective heat emitter for the purpose of investigating control system design. The lumped-parameter model proposed by the authors worked well for short-term dynamics, but began to diverge from experimental data on the long-term (> 45 h). The study compares the results obtained with first-order and second-order models of the external walls and the ceiling (in the latter case two thermal capacitances were assigned to those building components). The authors conclude that, on a short-term horizon, no appreciable advantages can be observed with the higher-order model when predicting the internal air temperature. However, the study does not investigate the temperature evolution across the envelope; in fact, physical considerations suggest that only a fraction of the thermal capacity of the building is activated by phenomena such as solar radiation or internal gains. Depending on the thermal characteristics of the building envelope and the fluctuations of the boundary conditions, a variable fraction of the *apparent thermal capacitance* (which results by adding the distributed thermal capacities of all building elements into a lumped capacitance, as stated in Antonopoulos and Koronaki [5]) may be activated. This means that only a portion of the envelope may show temperature changes within the investigated time span and hence vary its internal energy. Antonopoulos and Koronaki [5] state that «The real or effective thermal capacitance of buildings, which quantifies the ability of a building to store thermal energy and is useful in dynamic thermal performance calculations, differs considerably from the apparent thermal capacitance, as the ability of structural elements and furnishings to store heat is different when these are distributed in the building or considered together forming a unified volume».

The determination of this effective thermal capacitance is however a complex task, which shall take into account both the characteristics of the building envelope and the variation of the boundary conditions. In a study investigating strategies for minimizing the peak cooling demand by thermally activating the building structures, Lee and Braun [6] conclude that the effective thermal capacitance «would probably be somewhere between the internal and total building capacitance values, but closer to the internal capacitance», meaning the capacitance of the internal air, the furnishing and the internal walls.

The works by Gouda et al. [7] and by Fraisse et al. [8] investigate more in depth the impact of the model order on the accuracy of the results, where the model order reflects the number of thermal capacities assigned to each building element.

A more recent work by Underwood [9] proposes an improved method for the extraction of simplified model parameters based on a multiple-objective-function search algorithm and the use of a reference model based on a rigorous finite-difference method. In particular, Underwood develops an optimization procedure to adjust the resistance and capacity distributions of a second-order model in order to enable a correct prediction of the surface temperatures.

In summary, despite the abundant presence of more complex models, the lumped-parameter thermal models are still currently used (i) in fit-for-purpose manner (e.g. when it is necessary to develop a simple white box model of a physical phenomenon) (ii) because, if properly constructed, they can describe a physical phenomenon with a good accuracy, and (iii) since they are very effective computationally-wise.

1.2. Empirical validation of building energy models

The US Department of Energy's Advanced Simulation and Computing (ASC) program defines *validation*, as «the process of confirming that the predictions of a code adequately represent measured physical phenomena». As highlighted by Trucano et al. [10], validation differs considerably from *verification* and *calibration*, where the former aims at assessing the mathematical accuracy of the numerical solutions; while the latter is a process in which a certain set of parameter values are fine tuned to improve the agreement between the numerical predictions and the chosen benchmarks. In particular, the authors underline that the calibration should not be used to increase the credibility of a certain calculation code.

In the present work, the main objective is to improve the quality of the match (in other terms, the range and appearance of residuals) only by physical considerations; the model parameters are kept at their *nominal values* (e.g., the values provided by the technical sheets of the building materials). Therefore, we here adopt the conclusions by Trucano et al. [10] and we exclude the calibration phase from the present validation process. For a deeper discussion on the topic of validation of building energy simulation models the reader can refer to the works by Judkoff et al. [11], Judkoff et al. [12] and Cattarin et al. [13]. In addition, the literature review by Cattarin et al. [14] presents an overview of experimental studies that used outdoor test cell facilities to validate airflow and daylight models and to characterize the performance of single building components or control systems. The review reports and discusses also the potential sources of discrepancy between measurements and numerical predictions.

1.3. Brief introduction to sensitivity analysis

Sensitivity analysis has been defined as «the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input» [15]. An intuitive definition is given by Lam & Hui [16]: «In the simplest terms, the aim of sensitivity analysis is to compare quantitatively the changes in output with the changes in input». The final goal is to guide research priorities towards factors that are responsible of the greatest output variability, with the design aim of achieving energy savings, improvement of comfort conditions and others ([16], [17]). Sensitivity analysis is strictly related to uncertainty analysis: while the former determines and ranks the most important set of parameters affecting a given model output, the latter quantifies the variation of the model output given the uncertainty ranges of the model inputs [18]. For example, Pagliano et al. [19] report an uncertainty analysis applied to the measurement of the solar factor under dynamic conditions, for