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Quantifying uncertainty in thermophysical properties of walls by means of Bayesian inversion

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ABSTRACT

We introduce a computational framework to statistically infer thermophysical properties of any given wall from in-situ measurements of air temperature and surface heat fluxes. The proposed framework uses these measurements, within a Bayesian calibration approach, to sequentially infer input parameters of a one-dimensional heat diffusion model that describes the thermal performance of the wall. These inputs include spatially-variable functions that characterise the thermal conductivity and the volumetric heat capacity of the wall. We encode our computational framework in an algorithm that sequentially updates our probabilistic knowledge of the thermophysical properties as new measurements become available, and thus enables an on-the-fly uncertainty quantification of these properties. In addition, the proposed algorithm enables us to investigate the effect of the discretisation of the underlying heat diffusion model on the accuracy of estimates of thermophysical properties and the corresponding predictive distributions of heat flux. By means of virtual/synthetic and real experiments we show the capabilities of the proposed approach to (i) characterise heterogenous thermophysical properties associated with, for example, unknown cavities and insulators; (ii) obtain rapid and accurate uncertainty estimates of effective thermal properties (e.g. thermal transmittance); and (iii) accurately compute an statistical description of the thermal performance of the wall which is, in turn, crucial in evaluating possible retrofit measures.

1. Introduction

There is continuous global evidence of a discrepancy between the predicted energy performance of buildings and the measured performance [1,2]. This, often called *energy performance gap*, has been attributed to occupancy, poor construction quality [3–6] and uncertainties in the thermophysical composition of the building fabric [5,7–10]. In the context of the existing housing stock, the performance gap hinders predictive capabilities which are essential to inform optimal retrofitting strategies, cost-effective energy-saving measures and ultimately, to produce sound and robust carbon saving policies towards international decarbonisation targets [11].

Using measured data to calibrate simulations of the energy performance of a building is perhaps the most obvious pathway to minimise discrepancies between measured and predicted performance [1,12]. However extensive reviews of current approaches for the calibration of Building Energy Performance Simulation (BEPS) tools/software reveal that there is no generic framework suitable for a wide class of dwellings (see [13] and references therein). One substantial challenge faced by existing calibration workflows is that thousands of BEPS input variables/parameters need to be optimised/inferred given only very limited amount of displayed measurements. A particularly relevant subset of inputs are those that characterise the thermophysical properties of the building fabric. It has been shown that incorrect assumptions on the these properties, for example, based on tabulated values and/or visual inspections, may lead to inaccurate predictions of energy performance [7,8] and hence, unreliable estimates of carbon reductions from retrofit interventions [14]. More accurate and robust characterisations of the building fabric can be achieved by inferring thermophysical properties from in-situ monitored data of the thermal behaviour of individual fabric elements [15–17]. These inferred estimates can be used to better inform inputs of BEPS tools prior to calibration workflows.

Since the thermal transmission through external walls accounts for the largest share of heat losses in a typical dwelling, using in-situ measurement to infer the thermal transmittance (or U-value [W/m^{2}K]) of external walls is a primary goal when assessing the thermal performance of an existing building. Although theoretical estimates of the U-value can be obtained from (steady-state)

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calculations, these assume that a wall comprises a number of clearly defined layers with known geometry and homogeneous thermophysical properties, such as conductivity and heat capacity [18]. In practice, the number and properties of layers may be unknown and heterogenous due to the presence of thermal bridges including those arising from material defects, moisture penetration and residual cavities. Consequently, theoretical computations of U-values based on visual inspections and the use of tabulated values often provide an inaccurate characterisation of a walls thermal performance. In contrast, inferred U-values from in-situ measurements can better capture the thermal properties of walls thereby providing a more accurate description of their thermal performance [7,16,17].

The current practice to infer U-value from in-situ measurement is defined by the ISO9869:2014 [19] as the average method, Eq. (1), where the U-value is derived from M measurements of the internal surface heat flux, $q_{I,\,m}$ ($m = 1, \dots M$), and internal and external air temperature measurements, $T_{I,\,m}$ and $T_{E,\,m}$:

$$\mathcal{U}_{AV} = \frac{\sum_{m}^{M} q_{I,m}}{\sum_{m=1}^{M} (T_{I,m} - T_{E,m})} \tag{1}$$

The monitoring time (i.e. number of measurements M) necessary to obtain a reliable measurement indicated by the ISO:9869:2014 [19] is at least 72 h but, in practice, monitoring periods of above 10 days are common [20]. These lengthy testing periods lead to the practice of in-situ measurements being seen as a rare exception rather than the norm. Additionally, the uncertainty associated to this practice can be as high as 25% as indicated by the ISO:9869:2014 [19]. This uncertainty in the U-value follows through into energy saving predictions, which in turn, affects estimated pay back periods and makes investment decisions challenging [21].

It is the limitations associated with the average method calculation, both in terms of test duration and the need for a better understanding of the associated uncertainty within the result, that have led to novel approaches for estimating thermophysical properties within statistical frameworks that enable uncertainty quantification. In particular, [16,17] has recently proposed to infer thermal properties (U-value and thermal mass) of solid walls given in-situ measurements via the Bayesian calibration of *lumped thermal mass models*. By means of an electrical network analogy, lumped thermal mass models provide a simplified description of the heat transfer process through the wall. The input parameters of these models include the nominal values of a prescribed number of resistances and capacitances which, in turn, characterise the thermophysical properties of the wall under investigation. The approach proposed in [16,17] infers these parameters given air temperature and heat flux measurements.

The small number of input parameters of lumped thermal mass models constitute their main advantage over fully descriptive heat transfer models. The calibration of those parameters from in-situ measured data is often computationally tractable either via standard optimisation [22] or statistical approaches such as those used in [16,17]. The Bayesian approach, in particular, provides the tools necessary to characterise uncertainties in the thermophysical composition of a wall via the probability distributions of inferred model parameters. The variance arising from these distributions can be used, in turn, to quantify the uncertainty on the predictions of thermal performance of the building element under investigation and thus inform decision-making workflows during retrofit interventions. However, the simplicity of the underlying simplified lumped thermal mass models calibrated with existing approaches [16,17] can reduce both their accuracy and their portability, as the model topology (number of resistances/capacitors) requires to be adjusted for different wall types. For example, the single thermal mass model successfully calibrated to fit the experimental data reported in [16], was unsuitable to characterise the thermal performance of the walls investigated in [17] and which was, in turn, properly characterised via the Bayesian calibration of a more complex lumped thermal mass model with two capacitors. Some further limitations of lumped thermal mass models for walls that are thick, well insulated, or have large indoor convection coefficients have been discussed in [23,24].

1.1. Contribution of this work

With the development of recent Bayesian methodologies that enable the calibration of large sets of parameters [25] and the wide availability of more computer power, it is timely to consider more physically realistic models of the building fabric in order to understand their applicability to larger class of dwellings and to provide a more accurate quantification of the uncertainties that arise from inhomogeneities within the fabric. In this paper we propose to use in-situ measured data to calibrate, within a sequential Bayesian approach, a high-dimensional heat transfer model capable of describing the thermal performance of an arbitrary wall regardless of its (possibly heterogenous) thermophysical composition. In contrast to existing Bayesian approaches [16,17] where simple lumped thermal mass models have been used for the inference of effective properties, our heat transfer model of the wall is based on the 1D heat equation. Within this model, the wall's thermophysical properties are unknown/unobservable input parameters characterised by the internal and external surface resistance, R_I and R_E, as well as two heterogenous spatially-varying functions of the thickness of the wall: thermal conductivity of the wall $\kappa(x)$ and the volumetric heat capacity $c(x)$. For a given wall under investigation, the proposed sequential Bayesian methodology approximates the posterior probability distribution of R_I, R_E, $\kappa(x)$ and $c(x)$ conditioned to in-situ measurements of near-air and surface heat fluxes. Upon discretisation, the estimates of $\kappa(x)$ and $c(x)$ provide a statistical characterisation of the wall's thermophysical properties (e.g. number of multiple layers and thermophysical properties on each layer). Moreover, our computational approach enables us to convert Bayesian posteriors of these thermal properties into probability distributions of (i) (averaged) thermal properties such as the wall's U-value and C-value (heat capacitance per unit of area) and (ii) predictions of observable quantities (e.g. surface heat fluxes) which are essential to compute risks of retrofit options and thus to inform optimal energy saving measures.

The proposed Bayesian approach is embedded in a computational algorithm that uses an ensemble Kalman methodology [26] to merge in-situ measurements with computer simulations of heat fluxes, and generate an ensemble of realisations of the thermal properties that approximate the posterior distribution in a sequential fashion. The Kalman-based methodology at the core of the proposed algorithm is derived from a Sequential Monte Carlo (SMC) approach which, in contrast to the standard all-at-once existing Bayesian approaches [16,17], enables us to update our probabilistic knowledge of the thermal properties as new in-situ measurements are collected. The capabilities of the proposed approach are demonstrated by means of numerical experiments with both synthetic and real data. We show that by incorporating a high-dimensional characterisation of the spatial variability in thermal properties (via the inference of $\kappa(x)$ and $c(x)$), the proposed computational framework can reveal internal inhomogeneities of the wall (e.g. residual cavities) that are unknown a priori. We further demonstrate that the proposed framework can provide more accurate uncertainty estimates of the effective thermophysical properties (e.g. U-value) and higher degree of confidence in the predictions of the wall's surface heat fluxes, compared to those obtained via low-dimensional (coarse-grid) heat transfer models which are the basis for lumped thermal mass models used