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Characterization of the thermal structure of different building constructions using in-situ measurements and Bayesian analysis

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Abstract

A dynamic method, comprising a two lumped-thermal-mass model and Markov Chain Monte Carlo sampler, was used to analyze in-situ-monitored data and estimate the thermophysical properties of two walls of different construction. This method, unlike maximum a posteriori approaches, estimates the parameters' probability distributions, providing insight into the wall's thermal structure.
Total R-values were well defined for both walls, whilst constituent estimated R-values for a solid wall having layers of materials with similar thermal properties were anticorrelated (thermal mass locations weakly constrained), but were not correlated for an insulated cavity wall with thermally distinct layers (thermal mass locations strongly thermally constrained).

Keywords: Heat transfer; In-situ measurements; U-value; R-value; Thermal mass; External wall; Bayesian statistics; MCMC; Grey-box model

1. Introduction

Evaluating the energy performance of buildings is key to reduce energy demand and carbon emissions of the built environment [1] and to achieve climate change mitigation targets [2-5]. Understanding the thermophysical structure and behavior of the building envelope is fundamental to inform targeted policy-making strategies; to ensure quality assurance of new constructions; and to inform the decision-making process prior to retrofitting interventions to deliver tailored and cost-effective solutions that aim to reduce energy consumption while maximizing the thermal comfort [6].

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In principle, the thermal properties (*e.g.*, R-value and thermal mass) of a building element can be easily estimated knowing the thickness and the tabulated thermal properties (*e.g.*, thermal conductivity, density and specific heat capacity) of the materials it is made of [7]. However, several studies [8-10] have shown discrepancies between the performance expected from lookup tables and that estimated from in-situ measurements – a phenomenon known as performance gap [8].

Thermophysical properties evaluated from tabulated values often present a number of uncertainties as only visual inspection or quick surveys of the element under study is common [11]. Literature values for a given material may present quite broad ranges, and materials with similar appearance may have quite different thermophysical behavior [7]. Environmental conditions, structural and situational inhomogeneities (*e.g.*, cracks, gaps, moisture accumulation) [11] – which are not accounted for in tabulated values – may also influence the as-built performance of building elements and contribute towards the performance gap. The use of monitored data (*i.e.* heat flux and temperatures) overcomes these limitations as they account for the local environmental conditions the element is exposed to and its state of conservation [12], and do not require any knowledge of the stratigraphy under study.

This paper uses the dynamic grey-box method presented by Gori et al. [6,13] to estimate the thermophysical properties of two walls of different construction. The method consists of a combination of a two lumped-thermal-mass model (used to describe the heat transfer across the element) and Bayesian-based optimization techniques with a Markov Chain Monte Carlo (MCMC) sampler (used to estimate the best set of parameters and the associated errors). Unlike the maximum a posteriori (MAP) approach, the MCMC framework also allows the full estimation of the probability distributions of the parameters of the model instead of just their most probable value. Additionally, the statistical framework enables the characterization of the errors on the estimates and the potential correlation among them.

Practical advantages of the use of monitored data and the statistical framework include its suitability for any type of building (including historical ones) as it is non-destructive and does not require any knowledge of the stratigraphy of the element investigated. This enables the identification of retrofitting strategies that maximize thermal comfort and minimize energy use through customized insulation, heating and cooling strategies. This paper explores the potential applicability of this method to complement in-situ surveys and provide additional insight into the thermal structure of building elements using relatively cheap and non-destructive techniques (*e.g.*, to identify whether the element is likely to have been already insulated).

Nomenclature

R_n	n-th lumped thermal resistance (starting from the internal side) [m^2KW^{-1}]
C_n	n-th lumped thermal mass (starting from the internal side) [$Jm^{-2}K^{-1}$]
$T^0_{C_n}$	Initial temperature of the n-th lumped thermal mass (starting from the internal side) [°C]
$Q_{\mathrm{m,in}}$	Measured heat flux entering the internal surface of the wall [Wm^{-2}]
$Q_{\mathrm{m,out}}$	Measured heat flux leaving the external surface of the wall [Wm^{-2}]
T_{int}	Measured temperature on the internal surface of the wall [°C]
T_{ext}	Measured temperature on the external surface of the wall [°C]
$\boldsymbol{\theta}$	Vector of parameters of the model
$\boldsymbol{\theta}_{\mathrm{2TM}}$	Vector of the best-fit parameters of the model
D	Measured data
H	Model
$P(\boldsymbol{\theta}\|D,H)$	Posterior distribution
$P(D\|\boldsymbol{\theta},H)$	Likelihood
$P(\boldsymbol{\theta}\|H)$	Prior distribution
$P(D\|H)$	Evidence