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Evaluation of the physical interpretability of calibrated building model parameters

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ABSTRACT

Identifying building envelope thermal properties from the calibration of a lumped model raises identifiability issues. Not only needs the simplified model to be structurally identifiable, i.e. deliver unique estimates after calibration, but also the data used might not be informative enough to result in either or both accurate estimates and physically interpretable values. This could particularly be the case when data is extracted from non intrusive in situ measurements, in the sense not disturbing potential occupancy. In this frame, this paper develops a method to investigate the physical interpretation of the parameters of lumped models through a numerical tests procedure. Each test runs a simulation of a comprehensive thermal model of a building, with variations in thermal resistance properties of the envelope. Each simulation delivers data used to calibrate a lumped model. The parameters of the lumped model are then physically interpretable if their value vary according to the variations of the comprehensive model. The overall test procedure is applied to the study of a 2R2C model. Results show that the calibration of this model delivers robust calibration results for all parameters but one and also shows satisfactory robustness of the estimation of the overall thermal resistance. This paper concludes that the numerical test procedure does allow to evaluate practical identifiability of lumped models, and will in future work be used to examine more complex lumped models.

KEYWORDS

Practical identifiability, Parameter estimation, Model calibration, Lumped models

INTRODUCTION

A major lever for decreasing energy consumption in both newly built and existing buildings would be to accurately estimate, in situ, the building envelope thermal performance. Delivering valuable information on that performance relies then on an accurate, detailed and robust analysis of the building's envelope. Methods such as the coheating test, QUB or ISABELE methods (Sonderegger 1978; Mangematin et al 2012; Schetelat and Bouchié 2014) deliver a satisfyingly accurate Heat Loss Coefficient of the envelope, but cannot identify weaker parts of the building's envelope on which concentrate retrofit efforts. Furthermore, these methods are hardly applicable for in-use buildings as they rely on a lot of measurement equipment and require inoccupancy for a period from a few days to a few weeks. Recent literature (Reynders, Diriken, and Saelens 2014; Deconinck and Roels 2017; Menberg, Heo, and Choudhary 2017) has focused on calibrating dynamic simplified thermal models in the hope of physically interpreting calibrated parameters. It showed that the overall Heat Loss Coefficients may be robustly estimated, but that in the particular settings studied, thermal properties of each layer of the envelope could not. This paper presents a method that assesses how each parameter of a lumped model truly represents the building envelope. The method is first described and then applied to a 2R2C lumped model.

METHODS

Overview of the numerical test procedure

To test different envelope settings, the method is based on an entirely numerical study. Given known weather boundary conditions, a comprehensive model defined in EnergyPlus (Figure 1 : I) is written in N versions representing as many envelope settings to test. Each setting generates a thermal dynamic simulation. Each simulation returns an indoor temperature profile (Figure 1 : II) from which 5 days data in January are extracted. Noise from a normal distribution N(0,0.2) is then added to the data. The third step is to calibrate the selected lumped model , i.e. fit it to the noisy data (Figure 1 : III). The objective of the overall procedure is then to study the variability of the calibrated parameters (Figure 1 : IV) : do the estimations of the parameters vary according to the changes made in the original complete thermal model? In other words, to what extent are the parameters of an RC model representative of the physical thermal properties of the original comprehensive model?

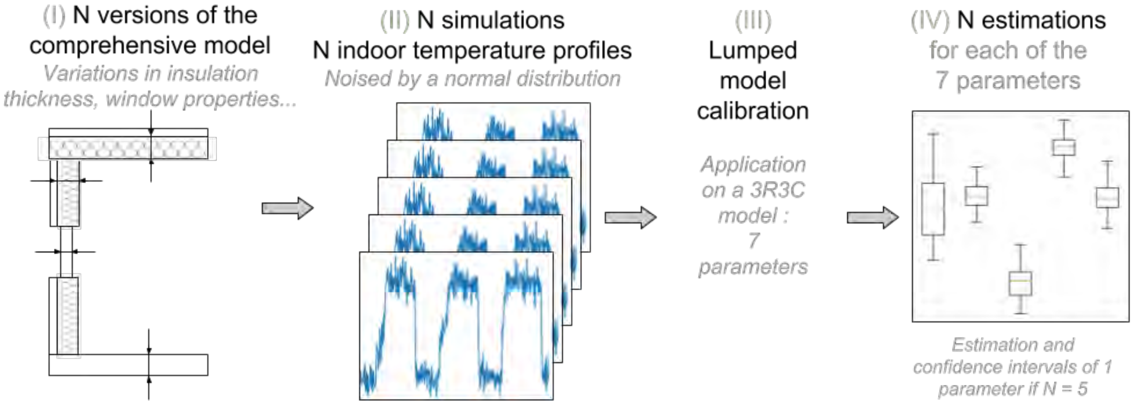

Figure 1: Numerical test procedure

Specific settings of this case study

The comprehensive model used in this work is based on a Bestest 600 case (Judkoff and Neymark 1995) equipped with a convective electric heater and no air infiltration nor ventilation. Window area is 3 m^2 to avoid the overheating from the original Bestest scenario. Indoor temperature setpoint schedules are set to reach 17°C at night and 20°C during the day.

Table 1: Design of experiments used in this study. From left to right, the envelope is poorly to highly insulated

Experiment number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wall insulation (cm)	5	5	5	5	5	5	5	5	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**
Roof insulation (cm)	5	5	5	5	**20**	**20**	**20**	**20**	5	5	5	5	**20**	**20**	**20**	**20**
Window air gap (mm)	4	4	**20**	**20**	4	4	**20**	**20**	4	4	**20**	**20**	4	4	**20**	**20**
Floor insulation (K/W)	10	**25**	10	**25**	10	**25**	10	**25**	10	**25**	10	**25**	10	**25**	10	**25**

We choose for a design of experiments, as suggested in (Iooss 2011). The thermal comprehensive model therefore undergoes four different changes in insulation thicknesses, ground floor thermal resistance and double pane glazing air gap thickness. This design of experiment is therefore intended to only assess the influence of thermal resistance properties. Each parameter takes two possible values as shown in Table 1 and a full factorial design is run, i.e. 16 different configurations.

In the present paper, we apply the method to the calibration and study of a 2R2C model (Figure 2). As for any model calibration, the structural identifiability of the 2R2C model has to be checked and it has been found structurally identifiable (Bellu et al. 2007). This means that, in theory, there exists only one set of parameter values towards which the calibration algorithm will converge.

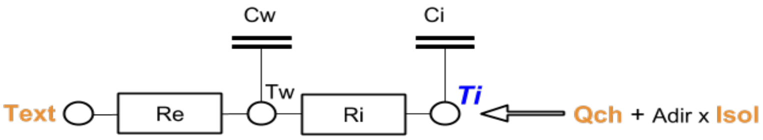

Figure 2: Model 2R2C. In blue the model output, in orange the model inputs, in black the unknown parameters and state variables

Each model is calibrated by bayesian inference (Figure 1 III), where the parameters and the unknowns are considered to be probability distributions. Calibrating the model then means determining the parameters probability distributions given the available data, also known as posterior distributions. The literal expressions of the posterior distributions cannot be known and are therefore sampled by an adaptive Metropolis algorithm (Haario, Saksman, and Tamminen 2001). Each parameter distributions can then be plotted with a boxplot as in Figure 1 IV, showing the most probable value, its standard deviation and its 95% confidence intervals.

RESULTS

Contribution of envelope properties to the calibrated parameters

Estimations of all five parameters of the 2R2C model for each experiment setting are shown in Figure 3.

Resistance parameters R_{ext} and R_{int} in Figure 3 (a) vary differently. R_{ext} shows a significant correlation with the thermal properties variations in the experiment, whereas R_{int} is quite steady and takes values between 4.10^{-4} and 9.10^{-4} K/W. From this experiment could be inferred that R_{ext} actually represents the thermal resistance of the envelope itself. R_{int} might rather represent the resistive air layer at the indoor surface, which is theoretically in the range [8.10^{-4} K/W , 13.10^{-4} K/W].

The solar coefficient A_{sol} estimation in Figure 3 (b) is also significantly correlated to the thermal resistance properties of the building envelope. The better the insulation, the lower the parameter estimation. Ground floor insulation or window air gap show however no significant influence on the value taken by the solar coefficient A_{sol}. This result is not coherent with the expectation that this parameter should not vary with thermal properties. We indeed expect it to be physically related to window orientation and size, that are not changed in this design of experiments. We explain this unexpected result first by the fact that the 2R2C lumped model is quite simplistic and might not be entirely interpretable when fitted to data. Also, the solar irradiation and the indoor-outdoor temperature differences are probably partially correlated to begin with. A different indoor temperature setpoint schedule and/or adding a shading schedule might give better interpretability of the A_{sol} parameter.

Figure 3 (c) shows that the thermal capacity parameter C_{ext} is not significantly varying with the different experiment settings, which is the expected result. Indeed, the comprehensive model is one of the Bestest low thermal inertia scenarii and has indoor insulation. As the experiments only varied thermal resistance properties, the thermal capacity is expected to remain steady. Compared to the values taken by the thermal capacity C_{int} in Figure 3 (d), C_{ext} seems to represent the thermal capacity of the envelope itself. Noteworthy is that C_{int} takes values indicating that it could represent the indoor air thermal capacity, but with extremely large confidence intervals. This shows that this parameter is poorly identifiable, meaning that its exact value cannot be inferred from these results. Data with more frequent measurements, every 1 to 5 min instead of 10 min, might enhance its identifiability though.

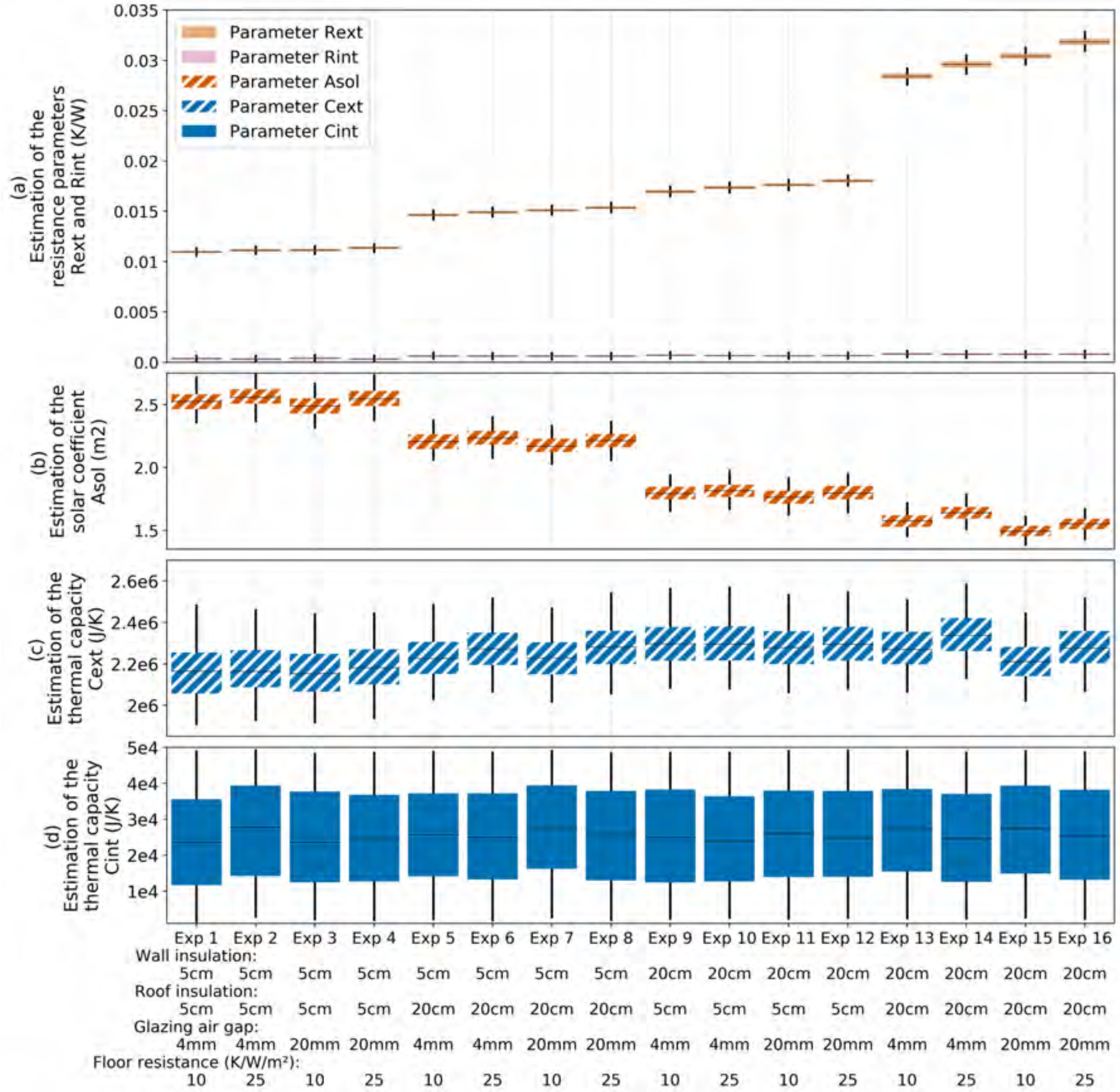

Figure 3: Variation of all 5 parameters of the lumped model with the experiments settings

Robustness of overall thermal resistance of the envelope

An equivalent resistance R_{eq} can be calculated from the estimation of both resistances of the 2R2C model : $R_{eq} = R_{ext} + R_{int}$. The equivalent resistance Req may then be compared to a theoretical overall thermal resistance R_{th} of the comprehensive model envelope.

From Figure 4 can be seen that fitting the 2R2C model gives a satisfactory estimation of R_{eq} (mean error up to 6,5 %). In the case of a highly insulated envelope (experiments 9 to 16), the error to the theoretical value is higher than with poorly insulated envelopes (experiments 1 to 8), especially when the ground floor is poorly insulated, for example in the experiments 13 or

15. The 2R2C model does not include any term representing the losses to the ground to differentiate them from the losses to the ambient air. So as soon as losses to the ground become significant compared to losses to the ambient air, the resistances of the model take the losses to the ground into account. This needs to be considered when comparing the estimated equivalent resistance of the building to a target value from a norm or a regulation, as in theory losses to the ground are not taken into account in the theoretical calculations.

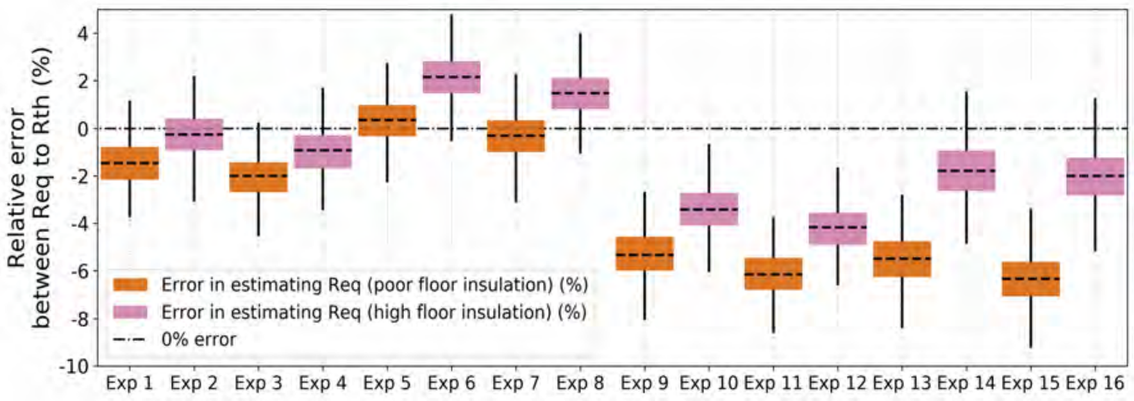

Figure 4: Estimation of the overall thermal resistance : agreement to the theoretical value

DISCUSSION

First of all, the methodology applied to a 2R2C model showed that the parameter estimation converged towards unique estimates, except for parameter C_{int}. This stresses out that theoretical identifiability is necessary but not sufficient. The data here is not informative enough for the parameter C_{int}. It is however sufficient to uniquely estimate values for the other parameters, which is promising for future work where data from occupied buildings are used. Indeed, this shows that major temperature differences, as seen in Schetelat and Bouchié (2014) or in Mangematin et al (2012) are not necessary to identify thermal properties of a building envelope. Additionnaly, it would be interesting to study the robustness of the results with fewer days data. In particular, one could study the influence of outdoor conditions which might particularly affect the results when the model is fitted on fewer days. We refer here to (Juricic et al. 2018).

Secondly, the study showed that the estimates could be, to a certain extent, identified with true thermal properties of the envelope. R_{ext} and C_{ext} have been found representing the envelope thermal properties itself, whereas R_{int} and C_{int} were found rather related to properties of the indoor air. It seems though that this model cannot identify thermal properties of layers inside the envelope. It would be interesting to study how parameters of more complex models can be identified to different envelope layers, starting with 3R3C models. At the same time, estimating the overall thermal resistance in these conditions shows satisfactory robustness, unless ground floor insulation is much poorer than envelope insulation, which would rarely happen in existing buildings though. This result is promising when considering testing existing buildings for regulatory purposes. Compared to Deconinck and Roels (2017) who found poor identifiability in all of the tested RC models for a cavity wall in winter, this case study studies the whole envelope has quite different boundary conditions which is probably why the parameters here were found to be identifiable even in winter. The work of Deconinck & Roels however suggests, by extrapolation, that estimations from the 3R3C model should be more trustworthy.

Finally, if a design of experiments approach was coherent with the goal of this study, further work should focus on variations of many more envelope properties of the reference building. A preferable approach will be to use sensitivity analysis tools, namely the RBD-FAST variance decomposition approach, allowing at the same time an efficient parameter space exploration and a more detailed study of the parameters interactions.

CONCLUSIONS

This paper shows how the numerical tests procedure allows to evaluate practical identifiability, i.e. interpretability of model parameters. Future work will focus on different comprehensive models, starting with scenarii with heavier thermal mass, on more complex lumped models in the hope of distinguishing contributions of separate parts of the envelope and finally on combining this methodology with a study of the influence of boundary conditions on identifiability.

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