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Evaluation of Grey-Box Model Parameter Estimates Intended for Thermal Characterization of Buildings

Rasmus Elbæk Hedegaard[a],*, Steffen Petersen[a]

[a]*Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus C, Denmark*

Abstract

The ability to obtain reliable estimates the actual thermal characteristics of whole buildings through fitting dynamical resistance-capacitance grey-box models to measurement data was investigated. The actual total heat loss coefficient was identified with a maximum deviation of 4% for all the evaluated model structures. The best performing models tended to overestimate the effective thermal mass by 10-32 % compared to the Effective Thickness Method of ISO 13786. The results also indicated that identifying the distribution of the total heat loss into transmission and infiltration heat losses is unlikely to be achieved from typical building measurement data.

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Keywords: System Identification; Building thermal characterization; Model structure selection; Identifiability analysis; Estimation of heat losses.

1. Introduction

Estimation of actual thermodynamic characteristics of real buildings is relevant for many purposes, e.g. for energy labelling and verification of the desired effect of energy saving measures in new as well as renovated buildings. Several methods for this purpose already exist, which in general can be characterized as 1) local methods focusing on individual building components, and 2) methods that seek to characterize the building as a whole. Standardized local methods for characterizing the performance of building envelope walls are specified in ISO 9869-1:2014 [1]. These methods rely on measurements of the internal and external temperature conditions and heat flux, usually measured at the internal surface of the component. The ISO standard presents both a quasi-stationary method and a dynamic

* Corresponding author. Tel.: +45 61707378.
E-mail address: reh@eng.au.dk

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method; however, a recent study suggests that the dynamic method gives better estimates of the U-value when compared to theoretical values [2]. Whole-building thermal characteristics can be inferred through co-heating tests which rely on linear regression and measurement data from the building under quasi-stationary heat loss conditions to provide reliable estimates of the whole-building heat transfer coefficient [3]. A limitation of co-heating tests is the neglect of dynamic characteristics. Another more practical limitation is the need of a fairly long measurement periods; the recommended duration of co-heating experiments as specified in IEA EBC Annex 58 is 2-4 weeks [4], while a recent study concluded that newer and more insulated buildings need up to eight weeks [5]. Everett [6] list other factors that complicate the analysis such as solar gains, varying air infiltration rate, ground floor losses and shared walls. Dynamic methods have also been proposed for whole-building characterization. A common approach is to model the dynamic heat transfer in the building as resistance-capacitance (RC) networks and then fit the model parameters to experimental data. This approach is in many aspects opposite from the quasi-stationary co-heating test. A major difference is that instead of seeking stationary conditions, emphasis is put on exciting the building during the measurement campaign to reveal the transient thermodynamic behaviour in the measurement data. Studies have previously evaluated the use of different RC models for data-based whole-building characterization. Reynders et al. [7] evaluated RC models of different complexity ranging between first order and fifth order models, and came to multiple conclusions: Low-order models (third order and below) were concluded to be too simple to obtain reliable estimates while fourth and fifth order models were found to be of sufficient complexity, but came with the significant price of needing heat flux measurements in addition to temperature measurements in order to be identified. Harb et al. [8] evaluated low-order RC-models on their ability to give acceptable estimates and predictive performance without any prior knowledge of the building. Two models included in the analysis showed reasonable predictive performance, while only a second order model yielded parameter estimates considered plausible by the authors. Thus, the studies of Reynders et al. [7] and Harb et al. [8] present significantly different answers to the question of which type of reduced-order RC model structure that is suitable for data-based characterization of the thermal characteristics of buildings. The discrepancies between the two conclusions could potentially be caused by identifiability issues during the selection of model structures.

On this background, the goal of this study is to derive model structures that only rely on temperature measurements to identify the building dynamics and quantify various characteristics relating to the thermodynamic behaviour of buildings. To further improve the robustness and practical application of such models, special attention is devoted to evaluating simple models that reduce potential identifiability issues.

2. Method

The goal of this study is to identify robust model structures suitable for characterization of the thermal characteristics of real buildings. Simulations are used to ensure the availability of high-quality data. The simulation platform consists of the building performance simulation program EnergyPlus and MATLAB, coupled via the Building Controls Virtual Test Bed [9]. Two geometrically different apartments are modelled in EnergyPlus, and data collected from the thermal zones and environment is used to identify models with the MATLAB System Identification Toolbox. The two apartments are 93 m^2 and 50 m^2, respectively. Further details on the two case apartments are provided in ref. [10]. The model structures included in the analysis undergo identifiability analysis using MATLAB and DAISY [11]. The following sections provide more details on the method used.

2.1. Reference estimates

The thermal characteristics of the apartments are estimated through widely used methods defined in standards and compared to the estimates resulting from using different model structures. Heat losses expressed as heat transfer coefficients (equivalent to UA-values) are calculated from material properties, construction element composition and standard values for internal and external surface resistances as specified in ISO 6946 [12]. Infiltration heat loss is calculated directly from zone volume and air change rate. Heat loss through windows are calculated using the U-value for the entire window component as calculated by Window 7.4 [13], which was used to model the windows in the EnergyPlus model. The effective thermal capacity is estimated using the Effective Thickness Method of ISO 13786 Annex A [14]. Despite the fact that the heating system during the experiment period introduced smaller temperature fluctuations in the building, the period of variation defined in the standard is chosen to be 24 hours because the data spans several days and therefore include a natural day-night variation. The total thermal mass capacity is calculated as half the thickness of symmetrical internal walls separating thermal zones and all mass before the first layer of insulating material in other parts of construction parts. In addition to the abovementioned characteristics, it is interesting to evaluate whether dynamic modelling can distinguish between infiltration and transmission heat losses. If the environment surrounding the building gets colder these heat losses will naturally increase. For the opaque parts of the envelope, this increase in transmission heat loss is delayed as the envelope components with high thermal inertia cool down. Infiltration, on the other hand, is not characterized by any significant thermal inertia, and can thus be considered instantaneous. These differences in how changing weather conditions affect the measurements makes it, at least in theory, possible to distinguish between the two heat loss mechanics. Windows, however, complicate this task. On one hand, the thermal mass of the window is small compared to the rest of the envelope, which is why windows are typically modelled without mass in building energy performance simulation tools such as EnergyPlus [15]. Consequently, there is no delay as for the opaque (heavy) envelope components. The inner glass pane absorbs heat through long-wave radiation and convection. The convective part affects the room air temperature directly, and is thus often assumed to be a part of the infiltration rather than transmission heat loss. The radiative part receives a net gain of heat from other surfaces inside the zone, thereby affecting the temperature of the thermal mass. This part of the heat loss is therefore assumed to exhibit some of the same inertia as transmission losses. Following this distinction, the question is how to distribute the total heat loss through windows onto these two heat loss mechanics and thereby determine the equivalent transmission and infiltration heat loss coefficients of the system that include the contribution to heat loss from windows. In this paper, we assume this distribution corresponds to the fractions of convective and radiative heat transfer coefficients of uncoated soda lime glass as defined in EN 673 [16]. It is noted that this assumption does not affect the modelling procedure as it is only used to derive the reference measurements used for comparison. The calculated thermal characteristics of the apartments are shown in Table 1.

Table 1 White-box estimates of thermal characteristics

		Large apartment		Small apartment	
Capacities	Air capacity	2.93E+05	J/K	1.57E+05	J/K
	Total interior mass capacity	1.49E+07	J/K	7.89E+06	J/K
	Effective mass capacity (ISO 13786)	1.26E+07	J/K	6.71E+06	J/K
Heat loss coefficients	Envelope (opaque parts)	22.7	W/K	6.4	W/K
	Windows	49.9	W/K	35.8	W/K
	Infiltration	40.7	W/K	21.8	W/K
	Total heat loss	113.3	W/K	64.1	W/K
Equivalent heat loss	Transmission	49.30	W/K	25.52	W/K
	Infiltration	64.03	W/K	38.57	W/K

The dynamic characteristics such as the thermal inertia of the heavy elements in the building is also relevant to identify. From a comfort point of view, the thermal mass can reduce temperature fluctuations caused by internal or external gains throughout the day. Furthermore, the thermal inertia is also directly linked to the potential for storing energy in the building, which ties into research on the flexibility of buildings and demand response. However, since the active thermal capacity is not a static parameter in the same way as the resistance of most building components can be assumed to be, a methodology for comparing the ISO 13786 estimates with the RC-estimates is needed. One approach is to compare the capacity estimates of the model to the reference value directly. This method, however, seems impractical since the layout of resistances and capacitances in the model affects the estimates of the capacities significantly. Instead, the time constants of the models are used to calculate an effective mass using the assumptions of the lumped capacitance approach, where the estimate of the thermal mass is obtained by multiplying the time constant with the total heat loss coefficient. The capacitance estimate of the air-node is not sensitive to the specific model layout, and is thus compared directly to the reference value. In practice, this estimate will also contain the capacitance of the heating system and furniture, but this influence is outside the scope of this study. Finally, it should be noted that the estimate of the small capacity will rely on the chosen sampling time.

2.2. Model structures

EN ISO 13790 suggests a single-capacity RC-model in the simple hourly method for calculating the heating and cooling needs of buildings [17]. However, this study does not include single-state models for several reasons. While the assumptions of the ISO 13790 model related to the temperature of the zone air may be sufficiently accurate when estimating energy performance under fairly constant temperature conditions, it is not sufficient in the case of changing set points and fluctuating heating output. A sudden step in heating power from fast-response systems such as radiators and convectors will result in an initial fast temperature increase as the air heats up followed by a slower response as the capacity of the construction is activated. A single state model is unable to predict or simulate the combined response from these very different capacities. Finally, first-order models have been shown to have too low predictive performance [7]. For these reasons, this study investigated a simple second-order model which was expanded upon using a forward modelling approach. The resulting model structures are depicted in Figure 1.

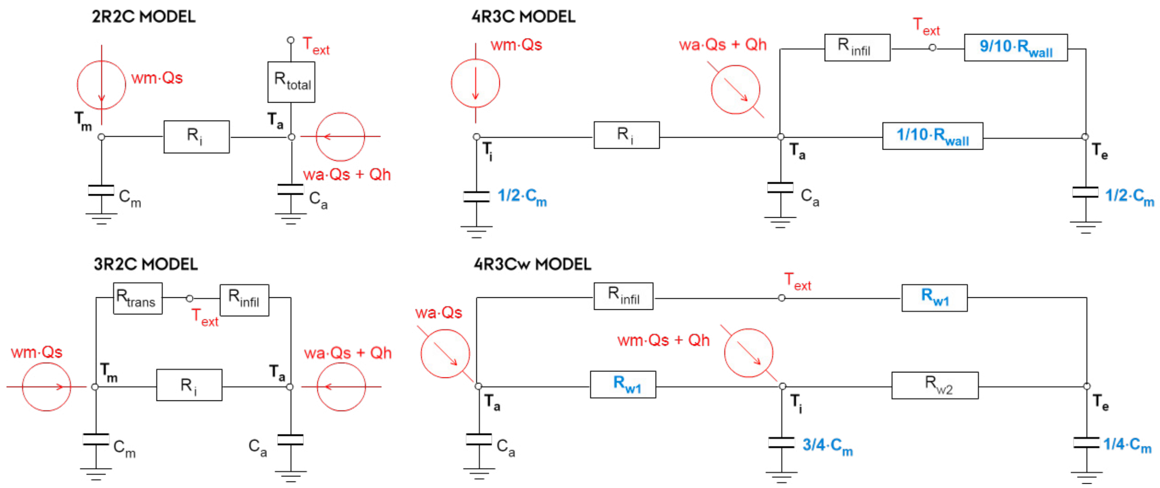

Figure 1 Model structures depicted as RC-networks. Red text denotes inputs, blue highlights the assumptions made for third order models.

The initial model (2R2C in Figure 1) is a modified version of the model presented in ref. [18], which was initially intended for white-box simulation. The modification was to replace an algebraic equation describing the surface temperature in the original model with a single resistance to reduce the number of parameters and thereby improve the identifiability of the model. The proposed 3R2C model extends the modified 2R2C model by adding a transmission heat loss directly from the thermal mass to the exterior. The 3R2C model was finally expanded into two third-order models: The 4R3C model contains an interior capacity representing internal elements that only interact with the zone air. In the 4R3Cw model the third thermal mass node is placed in the envelope in an attempt to better model the distribution of capacity in the envelope. The heating system was assumed to be fully convective in all models, which matches the heating system modelled in EnergyPlus. However, the two third order models required further assumptions to be introduced in order to reduce identifiability issues: In the 4R3C model, where the mass capacity is separated in internal capacity and envelope capacity, two dependencies between parameters were introduced to ensure identifiability. These dependencies were 1) an equal distribution of the thermal mass between the interior and envelope nodes, and 2) that 90 % of the envelope resistance is placed on the cold side of the envelope capacity node. Assumption 2 draws on the assumption that only the capacity on the warm side of the insulation layer will significantly add to the efficient thermal capacity. In the 4R3Cw model, where the envelope contains two states, assumptions were again made both with respect to the distribution of resistance and thermal mass: 1) The internal mass node contains the majority (75%) of total thermal mass, as it represents all mass on the warm side of the insulation layer and 2) the resistance is assumed to be symmetrically distributed around the insulation layer, corresponding to a ‘sandwich-type’ envelope. This assumption is considered likely in apartment blocks and less likely in buildings where the envelope also contains ground floor and roof constructions.

3. Results

The four model structures were used to estimate the thermal characteristics of the two apartments using two weeks' worth of measurements with a 1-minute sample rate. To investigate the consistency of the estimates across different weather conditions, data from four of the coldest months were used (Nov-Feb). The estimates were normalized against the reference values from Table 1 to ease the model comparison. Figure 2 depicts the estimates of all model structures using data from each of the four months. The red line denotes the reference values.

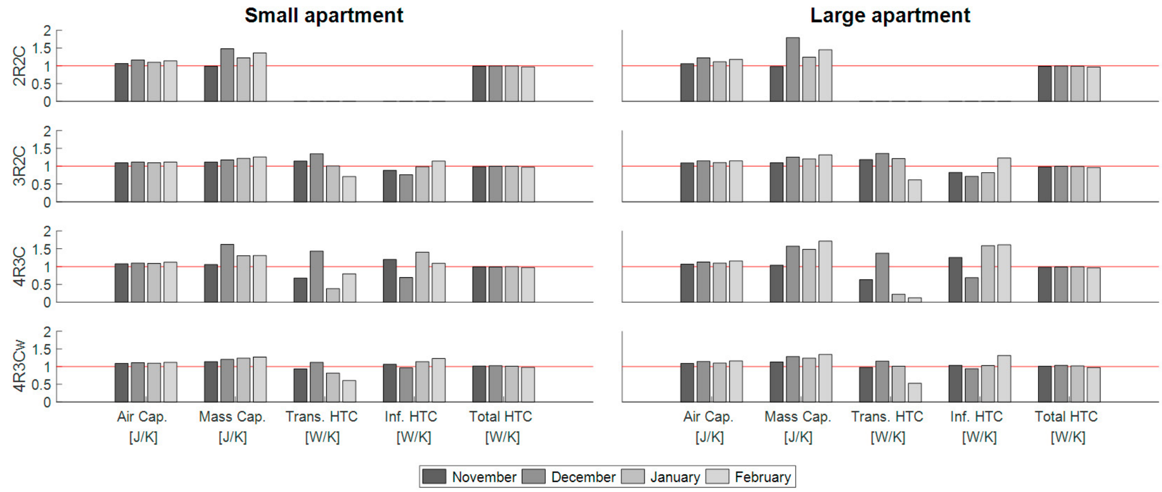

Figure 2 Comparison of normalized parameter estimates. Red line denotes the reference value of the characteristics.

The results show that all model structures yielded accurate and consistent estimates of the short time constant (air cap.) and the overall heat loss coefficient (total HTC). The 2R2C model is not capable of providing estimates of the individual heat loss coefficients due to its structure. It is also clear that this simple model together with the 4R3C model lack the consistency and accuracy of the other two models, and are therefore not suitable for thermodynamic characterization purposes. The 3R2C and the 4R3Cw models showed very similar estimates of all characteristics, with decent accuracy and consistency across all datasets. Both models tended to slightly overestimate the effective thermal mass by 10-32 %. Upon closer inspection of the results, the 4R3Cw model outperformed the 3R2C model in terms of the average deviation seen over all parameters and all data sets. The third-order model deviated on average 8% and 7% on the small and large apartment, respectively. With the second order model the deviations were 13% and 17%, respectively. Despite decent accuracy on average, the estimates of the individual heat loss components exhibit the by far highest inconsistency across all models, thus suggesting that these are difficult to reliably estimate.

4. Discussion

The 4R3Cw model showed slightly better performance than the second order model 3R2C. This performance was gained through the added complexity of the model, which came at the price of introducing interdependency assumptions between some of the parameters of the model. The question is then whether these assumptions hold for other types of building models and, more importantly, for real buildings. The assumption concerning the distribution of capacities in the 4R3Cw model is considered to some extent to be case-specific. Future work could therefore be to carry out a sensitivity analysis of the assumptions, e.g. for several different building compositions, before such assumptions can be assumed reasonable for a wider range of buildings. The models estimated the thermal capacitance higher than the reference value calculated with a simplified (yet impractical) method described in ISO 13786. It remains to be concluded which of the two approaches – data-based identification or calculation – yields the most accurate or useful result. Finally, Gaspar et al. [2] concluded that dynamic local characterization methods outperformed the static ones. An in-depth comparison of the co-heating test and the dynamic RC-model approach should therefore be conducted to determine whether the same applies to whole-building characterization methods.

5. Conclusion

This paper presented an evaluation of four different RC-model structures intended for data-based estimation of the thermal characteristics of buildings. The four model structures were evaluated in a comparative analysis, where estimates from each model were compared to estimates from calculation methods described in relevant standards. The results indicated that both second order and third order models, depending on their RC-network structure, are capable of yielding consistent estimates of the short time constant (zone air, furniture), the effective thermal mass and the total heat loss coefficient. Individual estimates of infiltration and transmission heat losses were found to be highly inconsistent across all models, with deviations as high as 47% even for the better performing models.

The 3R2C model is considered to be the most practically viable model structure for characterization purposes over the third order models because of 1) the additional assumptions needed to make consistent estimates with the investigated third order models, and 2) the relatively low performance increase gained by introducing the extra state.

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