ENERGY PERFORMANCE CHARACTERISATION OF THE TEST CASE “TWIN HOUSE” IN HOLZKIRCHEN, BASED ON TRNSYS SIMULATION AND GREY BOX MODEL

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ABSTRACT
In the frame of the IEA Annex 58 project, this paper presents an exercise of building energy performance characterization based on full scale dynamic measurements. First focus of the exercise is the verification and validation of the numerical TRNSYS BES-model of the case study test house in Holzkirchen. Second focus is on the modelling of the house through a second order inverse “grey box” model in order to determine reliable performance indicators which include UA-value, total heat capacity, and solar aperture. Final issue is the comparison of predicted indoor temperatures of free floating period, results of TRNSYS and “grey box” models simulation.

INTRODUCTION
Different models and known methodologies for energy performance characterization can be summarised in three categories of models: white-box, grey-box and black-box models (Bohlin, 1995) (Madsen et al., 1995) (Kristensen et al., 2004). TRNSYS model is typically a white box model based on a complete description of the physical properties of the building. Grey-box model is used when the knowledge of these properties is not comprehensive enough. It is based on a partial dataset and partially on empiricism (Kramer and al., 2012). Black box model is used when parameters have no direct physical meaning. No physical properties knowledge is required for this model (De Coninck et al., 2014).

This paper presents an exercise of verification and validation of a test case house using white box and grey-box models. First section describes the test case house, experimental set up and data sets. Second section concerns TRNSYS modelling, according to the "modelling specification report" provided in the exercise.(Strachan et al., 2014).

EXPERIMENT SET UP
Description of the test case house
The experiment was undertaken on a test case house named “House 05” situated at Holzkirchen, Germany (near Munich). The latitude and longitude are respectively 47.874 N, 11.728 E. The elevation above mean sea level (MSL) is 680m. Figure 1 shows an East view the house. Figure 2 shows a vertical section and the internal layout. For the experiment, the layout was divided into north and south areas. South side includes: the living room, the children’s bedroom, the corridor and the bathroom. North side includes: the parent’s bedroom, the lobby and the kitchen.

A full specification of the house, including: constructions, windows and roller blinds description, systems of ventilation, heating and cooling, air leakage, ground reflectivity and weather data, was provided in the "modelling specification report" of the exercise.(Strachan et al., 2014).

Figure 1 East view of the test case “house 05”
Data and experiment device

Measurements were undertaken on the house in cooler conditions on April and May 2014. The Schematic of proposed test schedule is shown in figure 4. The schedule used is shown in Table 1.

TRNSYS SIMULATION MODELLING

TRNSYS model

TRNSYS is a package for energy simulation of solar processes, building analysis, thermal energy, and more (Klein, 2000). The reported work was done with TRNSYS version 17.

Figure 5 shows the developed TRNSYS simulation model. "Type 56" represents the multizone model of the building. It includes descriptions of: zones, walls, windows, infiltration, internal gains and schedule, ventilation, heating and cooling systems as described in the "modelling specification report".
Simulation results and comparison with in situ measurements

Simulation results are presented in figures 6, 7, 8 and 9. Each zone’s result is presented with the corresponding indoor measured temperatures. The gap between simulated and measured values is directly readable and allows to measure the reliability of the achieved TRNSYS model.

However, results of measured temperatures of: parent’s bedroom, lobby and kitchen, include data logging failure period as shown in corresponding curves.

Temperatures of: living, children’s bedroom, bathroom and corridor, are not measured during the free floating period as shown also in corresponding curves.

Results show that simulated and measured values are close. This level of reliability was possible following a large number of simulations performed and improved each time by adjusting the various parameters of the TRNSYS model.

THERMAL MODEL DEVELOPMENT AND PARAMETERS ESTIMATION

Grey box model

Grey box model consist of a set of continuous stochastic differential equations formulated in a state space form that are derived from the physical laws which define the dynamics of the building (Madsen, 2008). The model structure is formulated by equations 1 and 2.

\[
\dot{X}(t) = A(\theta)X(t) + B(\theta)U(t)
\]

(1)

\[
Y(t) = C(\theta)X(t) + D(\theta)U(t)
\]

(2)
Equations (1) and (2) are respectively: the state equation and the output equation, where: X(t) is the state vector, Xdot(t) is the change of the state vector, U(t) is a vector containing the measured inputs of the system, A is the state matrix, B the input matrix, C the output matrix and D the direct transition matrix.

These inputs can be controllable, such as the heat delivered by the heating system or the airflow rate of the ventilation system, or not controllable, such as the outdoor temperature, solar and internal gains.

The model structures can be described as resistance-capacitance (RC) networks analogue to electric circuits to describe the dynamics of the systems. Thereby the distributed thermal mass of the dwelling is lumped to a discrete number of capacitances, depending on the model order.

The unknown parameters \( \theta \) in these equations are calculated using estimation techniques. For current case study, the used technique was the Prediction Error Method (PEM). The goal is to find the parameter set that minimizes the error between the simulation result and the measurements. PEM estimator criteria is given according to equation 3.

\[
\hat{\theta} = \arg \min_{\theta} \{ S(\theta) = \sum_{i=1}^{N} e_i^2(\theta) \} \quad (3)
\]

\( \hat{\theta} \) are the estimated parameters based on the data set called “estimation data”. \( e_i(\theta) \) is the simulation error depending on the parameter and time value.

Following estimation of parameters \( \theta \), validation process will ensure that the model is useful not only for the estimation data, but also for other data sets of interest. Data sets for this purpose are called validation data.

To quantify the model’s accuracy, the goodness of fit (fit) performance criteria were used as per equation 4.

\[
\text{fit} = 100.(1 - \frac{\text{norm}(y' - y)}{\text{norm}(\bar{y}' - \bar{y}')} ) \quad (4)
\]

Where \( y' \) is the measured signal, \( \bar{y}' \) is the average measured signal; \( y \) is the simulated signal \( \text{norm}(y) \) is the Euclidean length of the vector \( y \), also known as the magnitude.

Accordingly, equation 4 calculates in the numerator, the magnitude of the simulation error, and in the denominator, how much the measured signal fluctuates around its mean. Consequently, the goodness of fit criterion is robust with respect to the fluctuation level of the signal.

**Data set measurements of the test case house**

Data set used for the model completion and validation were measured in situ, except the heat supplied by ventilation system \( P_v[W] \) estimated according to equation 5 (Delff, 2013).

\[
c_v P_v = c_v c_{air} \rho_{air} (\dot{V}_{v,in} T_{v,in} - \dot{V}_{v,out} T_{v,out}) \quad (5)
\]

The period of measurements was from 09.04.2014 to 20.05.2014 as detailed in Table 1. Measurements from 09.04 to 14.05.2014 were used for the "estimation of thermal model parameters" stage. Remind measurements from 14.05 to 20.05.2014 were used for the "validation of the model".

Figure 10 and figure 11 represent respectively: data measurements of the “estimation” and “validation” stages. In both figures data are represented as following : indoor temperatures (the output) noted Tint[°C]; Outdoor temperatures Te[°C], attic temperatures Ta[°C], weighted temperatures of north zone (kitchen, lobby and parent’s bedroom) Tn[°C], heat power P[W], solar radiation on horizontal [W/m²] and heat supplied by ventilation system \( P_v[W] \).
RC model of the test case house

Thermal model concerns solely the south side of the house (living, corridor, bathroom, children’s bedroom). It aims at estimating the heat loss coefficients to the outside, to the adjacent north spaces (kitchen, lobby and parent’s bedroom), to the attic and basement, the effective heat capacity and the solar aperture. Figure 12.

Identified models will be used to predict the output based on input data recorded in the free float period.

The model is made of 6 resistances and 2 capacitances (R6C2 following the electrical analogy) where: \( C_i \) and \( C_m \) represent the structure and the interior air capacities. \( R_n \) (i=1:6) are the thermal resistances between states or inputs. The model has been built to have a small number of parameters, simple enough to be identifiable but complex enough to represent all physical phenomena. Hazyuk in (Hazyuk et al., 2011) has demonstrated that a two order model is enough accurate for building energy parameters estimation. The representation of solar gains can be improved by separating the solar flux arriving on the external wall from the solar flux entering through windows. The model can handle changes in mechanical ventilation thanks to the \( C_v \) parameter that represents the scaling of ventilation heating signal.
The state space matrices of the RC model are:

\[
A = \begin{bmatrix}
\frac{1}{R_1C_1} & \frac{1}{R_1C_2} & \frac{1}{R_1C_3} & \frac{1}{R_1C_4} & \frac{1}{R_1C_5} & \frac{1}{R_1C_6} \\
\frac{1}{R_2C_1} & \frac{1}{R_2C_2} & \frac{1}{R_2C_3} & \frac{1}{R_2C_4} & \frac{1}{R_2C_5} & \frac{1}{R_2C_6} \\
\frac{1}{R_3C_1} & \frac{1}{R_3C_2} & \frac{1}{R_3C_3} & \frac{1}{R_3C_4} & \frac{1}{R_3C_5} & \frac{1}{R_3C_6} \\
\frac{1}{R_4C_1} & \frac{1}{R_4C_2} & \frac{1}{R_4C_3} & \frac{1}{R_4C_4} & \frac{1}{R_4C_5} & \frac{1}{R_4C_6} \\
\frac{1}{R_5C_1} & \frac{1}{R_5C_2} & \frac{1}{R_5C_3} & \frac{1}{R_5C_4} & \frac{1}{R_5C_5} & \frac{1}{R_5C_6} \\
\frac{1}{R_6C_1} & \frac{1}{R_6C_2} & \frac{1}{R_6C_3} & \frac{1}{R_6C_4} & \frac{1}{R_6C_5} & \frac{1}{R_6C_6}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
\frac{1}{R_1C_1} & \frac{1}{R_1C_2} & \frac{1}{R_1C_3} & \frac{1}{R_2C_2} & \frac{1}{R_2C_3} & \frac{1}{R_2C_4} \\
\frac{1}{R_1C_5} & \frac{1}{R_1C_6} & \frac{1}{R_2C_5} & \frac{1}{R_2C_6} & \frac{1}{R_3C_5} & \frac{1}{R_3C_6} \\
\frac{1}{R_1C_6} & \frac{1}{R_2C_6} & \frac{1}{R_3C_6} & \frac{1}{R_4C_6} & \frac{1}{R_5C_6} & \frac{1}{R_6C_6}
\end{bmatrix}
\]

\[
C = [1 \ 0] \quad D = [0 \ 0 \ 0 \ 0 \ 0 \ 0]
\]

With: input matrix: \( \tilde{U} = [T_m \ T_r \ T_i \ G \ P \ \tilde{P}] \)

State matrix: \( \tilde{X} = [T_{in} \ T_{in}] \)

And output Y: \( Y = T_{in} \)

**Results and discussion**

The grey-box model Identification was done using MATLAB. It consists on founding the parameter set that maximize the fit between the simulation and measurement results. The parameters set was identified under a fit of 85.46% as per figure 14.

Validation stage consists on using the identified parameters set to simulate the indoor temperature and compare it to the measurements of the “validation period”. The resulted fit given by MATLAB was equal to 70.60%.

Insipie of good values of fit criteria, it is important to make an analysis of residuals to ensure an adequate model.

The part of the measured signal that is unexplained by the model, results in simulation errors, called residuals. Hence, \( \varepsilon = y' - y \) where \( \varepsilon \) is the residuals, \( y' \) is the measured signal and \( y \) the simulated signal. There are many possible reasons for the remaining residuals: measurement errors, missing inputs, over simplified model, incorrect model structure and computational errors (Kramer et al., 2013).

The residual analysis consists of two tests: The whiteness test and the independence test. The whiteness test was used to analyze the autocorrelation between the residuals. Ideally, the residuals only consist of measurement errors as white noise and the autocorrelation is within acceptable limits. If the model fails on the whiteness test, there is a strong indication that inputs are missing and the model is over simplified (Kramer et al., 2013).

The independence test was used to analyze the cross correlation between residuals and inputs. A significant cross correlation indicates that the influence of input \( x \) on output \( y \) is not correctly described by the model. This denotes an incorrect model structure.

Figure 16 shows the autocorrelation and cross correlation for the thermal model. The yellow area represents the tolerated bandwidth. The model’s autocorrelation exceed the tolerated bandwidth in some points. This is an indication of missing inputs. However, Ljung in (Ljung, 1999) states that less attention should be paid to the autocorrelation function if no error model is included. The cross correlation of all inputs is within the tolerated bandwidth; this shows that the models’ structure is correct and that it describes the influence from inputs to outputs correctly. Accordingly, table 2 summarizes the parameters values with the related uncertainty, where \( H_i \), \( (i=1:6) \) is the inverses of \( R_i \), \( (i=1:6) \).

**Table 2**

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>ESTIMATED VALUE</th>
<th>UNCERTAINTY (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H6 (W/K)</td>
<td>37.46</td>
<td>0.0059</td>
</tr>
<tr>
<td>C1 (KJ/K)</td>
<td>170.3</td>
<td>0.0142</td>
</tr>
<tr>
<td>H2 (W/K)</td>
<td>4.5</td>
<td>0.0154</td>
</tr>
<tr>
<td>H4 (W/K)</td>
<td>11.75</td>
<td>0.0137</td>
</tr>
<tr>
<td>H3 (W/K)</td>
<td>28.86</td>
<td>0.0158</td>
</tr>
<tr>
<td>H5 (W/K)</td>
<td>15.29</td>
<td>0.0152</td>
</tr>
<tr>
<td>H1 (W/K)</td>
<td>5</td>
<td>0.0008</td>
</tr>
<tr>
<td>C_m (KJ/K)</td>
<td>6303.6</td>
<td>0.0005</td>
</tr>
<tr>
<td>GA (m²)</td>
<td>2.9</td>
<td>0.0176</td>
</tr>
<tr>
<td>c_v (-)</td>
<td>0.8</td>
<td>0.0047</td>
</tr>
<tr>
<td>Am (m²)</td>
<td>20</td>
<td>0.0032</td>
</tr>
</tbody>
</table>
INDOOR TEMPERATURES PREDICTION FOR THE FREE FLOATING PERIOD

The grey-box model was simulated using MATLAB software during the period of free floating. This is to permit the prediction of indoor temperature. In addition, the TRNSYS model was simulated during the same free float period.

In order to allow the comparison between results the two models, the TRNSYS resulted temperatures of south side of TRNSYS were weighted to a single indoor temperature \( \frac{\sum \text{room temperature} \times \text{volume}}{\sum \text{volume}} \). Figure 17 shows the results of simulation in free float period, both for TRNSYS and grey-box models. Blue curve is representative of the prediction results of MATLAB and black curve is representative of the prediction results of TRNSYS.

Comparison shows that both models gave fairly the same results. This could be explained by the fact that TRNSYS model was performed following several simulations and the grey-box model was validated by fit criteria and residual analysis. It reminds nevertheless a small difference of behaviour between the two curves due to the different mode of construction of the models.

CONCLUSION

A double verification and validation of the energy performance of a test case house was presented based on two types of energy building models: white-box and grey-box models.

Both experiments are based on full-scale in situ measurements. The protocol of measurement and configuration of experiment were well documented and introduced. The quality and quantity of measurements have a direct impact on the reliability of obtained models.

First verification and validation with white-box model was performed with TRNSYS 17 software. The experiment demonstrates that it is possible, with a good knowledge of physical proprieties, to realise a reliable TRNSYS model. Results of simulation show that the TRNSYS model is capable of reproducing indoor climate temperature accurately.
Second verification and validation with grey-box model was performed with MATLAB. The building model in state space form was presented with an inverse modelling approach to identify parameters. Identification and validation were analysed according to fit criteria. Additionally, validation took into account an analysis of residuals. Obtained model shows that it is capable to simulate as good an analysis of residuals. Obtained model can be considered enough reliable to perform other identification of parameters of similar construction to the test case house.

**NOMENCLATURE**

- $A_{s}$: area with which the global horizontal solar radiation is scaled (m$^2$)
- $C_{i}$: Heat capacity of the indoor air (J/K)
- $C_{m}$: Heat capacity of heavy walls of the envelope of the chamber (J/K)
- $c_{v}$: scaling of ventilation heating signal
- $gA$: solar aperture (m$^2$)
- $R_{i}$: inverse $R_{i}$ represent the thermal conductances $i=1:6$
- $P$: Heating power injected into the chamber (W)
- $P_{n}$: estimated ventilation heating (W)
- $R_{1}$: External convection resistance + ½ of the wall conduction resistance (K/W)
- $R_{2}$: Internal convection resistance + ½ of the wall conduction resistance (K/W)
- $R_{3}$: Equivalent resistance of adjacent walls in north side (K/W)
- $R_{4}$: Equivalent resistance of ceiling (K/W)
- $R_{5}$: Equivalent resistance of floor. (K/W)
- $R_{6}$: Equivalent strength light walls and infiltration (K/W)
- $T_{a}$: attic indoor air temperature (°C)
- $T_{c}$: cellar indoor air temperature (°C)
- $T_{ext}$: Outside temperature (°C)
- $T_{in}$: Indoor temperature (°C)
- $T_{n}$: Node temperature corresponds to the walls of the south side (°C)
- $U_{A}$: common UA-value for the building envelope (W/K)

**REFERENCES**


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Kramer R. van Schijndel J., Schellen H. 2013. Inverse modeling of simplified hygrothermal building models to predict and characterize indoor climates, Building and Environment journal. Reference?


