Integrated heat, air, moisture and pollutant (IHAMP) modeling, Part II: Benchmarking the three main modeling methodologies FEM, BES and State-Space

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Integrated Heat, Air, Moisture and Pollutant (IHAMP) Modeling

A simulation tool for indoor air quality design and control in buildings

PART II: Benchmarking the three main modeling methodologies
FEM, BES and State-Space

Dr.ir. Jos van Schijndel
ir. R. Kramer

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1. Summary

This report is the PART II of a series of reports for the IEA EBC Annex 68. The overall objective is the development of an Integrated Heat, Air, Moisture and Pollution (IHAMP) model for the built environment in MatLab/SimuLink and Comsol.

The methodology consists of four steps:
Step 1. Benchmark existing state-of-the-art HAM models of building constructions using Comsol.
Step 2. Benchmark existing state-of-the-art HAMC models of building zones using HAMBase.
Step 3. Integrate concentration modeling in (1) i.e. HAMC for constructions
Step 4. Integrate (2) and (3) using SimuLink for building zones and constructions

PART II presents the results of benchmarking the three main modeling methodologies: FEM, BES and State-Space.
2. Appendix paper
Combining Three Main Modeling Methodologies for Building Physics

A.W.M. (Jos) van Schijndel, Assistant Professor
Eindhoven University of Technology, Netherlands

**KEYWORDS:** State-Space, FEM, BES, Building, Energy, Modeling

**SUMMARY:**
An overall objective of energy efficiency in the built environment is to improve building and systems performances in terms of durability, comfort and economics. In order to predict, improve and meet a certain set of performance requirements related to the indoor climate of buildings and the associated energy demand, numerical simulation tools are indispensable. In the paper we consider three types of numerical simulation tools: Finite Element Method (FEM), Building Energy Simulation (BES) and State-Space (SS) together. Commonly used within these tools are zonal approaches of the volumes, assuming uniform temperatures in each zone, and 1D modeling of the walls. Due to the rapid development of Finite Element Method (FEM) software and Multiphysics approaches, it is possible to build and simulate full 3D models of buildings regarding the energy demand. Another application consists of Building Energy Simulation using State space models identified from free floating data. It is concluded that the main benefits of FEM-SS-BES modeling exchange is the possibility to simulate building energy performances with high spatial resolution and low computational duration times.

1. Introduction
An overall objective of energy efficiency in the built environment is to improve building and systems performances in terms of durability, comfort and economics. In order to predict, improve and meet a certain set of performance requirements related to the indoor climate of buildings and the associated energy demand, numerical simulation tools are indispensable. In this paper we consider three types of numerical simulation tools: Finite Element Method (FEM), Building Energy Simulation (BES) and State-Space (SS). For each tool separately, there exist a vast number of references. Also on two tools combined, i.e. FEM-BES, BES-SS, FEM-SS, there is quite a lot of literature. However there is lack of research on an overall evaluation of the three tools FEM-SS-BES together. In this paper we present benefits of the FEM-SS-BES modeling exchange for building physics. The main reasons for converting models in each other are summarized in Table I.

**TABLE I. The main reasons for converting models in each other**

<table>
<thead>
<tr>
<th>From</th>
<th>FEM</th>
<th>BES</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td>*</td>
<td>Global effects</td>
<td>Computation Speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lumped results</td>
<td></td>
</tr>
<tr>
<td>BES</td>
<td>Local effects High resolution results</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>SS</td>
<td>Inverse Modeling</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>
In this work FEM is just a method of solving Partial Differential Equations (PDEs), like Finite Volume methods (FVM) or Finite Difference methods (FDM). We start with two combinations that are quite obvious and already commonly used. **BES to FEM** – BES is used to simulate the energy performance of buildings, using lumped parameter modeling. If local effects are important, FEM can be used to obtain high resolution results based on distributed parameter models and using BES simulation results as boundary values. **FEM to SS** – FEM based simulations can easily become computationally time consuming. One of the methods to improve the computing time is to reduce the mathematical model to a lower order model by using for example a State-Space (SS) approximation. One of the main benefits of SS models is, that very efficient computation algorithms exist, that are able to almost completely reduce the computation time. If such a reduced order SS model is accurate enough, this method can be used for improving computation speed. This paper comprehends an investigation of the two other combinations. Each combination is presented in a separate Section, including background information and case studies. After these Sections a discussion of the results is provided.

### 2. Application 1: Building Energy Simulation using 3D FEM with lumped parameter modeling for air.

BES using 1D FEM with lumped parameter modeling for air already exist. For example Wufi+ (2013) and HAMBase (de Wit 2006 & HAMLab 2013) are such tools. Commonly used within these tools are zonal approaches of the volumes, assuming uniform temperatures in each zone, and 1D modeling of the walls. Due to the rapid development of Finite Element Method (FEM) software and Multiphysics approaches, it should possible to build and simulate full 3D models of buildings regarding the energy demand. Moreover, the 3D models would also provide detailed (i.e. high resolution) results of the indoor climate and the constructions. The main problem regarding the use of FEM for BES is how to compare a distributed parameter model (FEM) with a lumped parameter model (BES)? Because BES and FEM have quite different approaches, we used the following method: Step 1, start with a simple reference case where both BES and FEM tools provide identical results. Step 2, add complexity and simulate the effects with both tools. Step 3, compare and evaluate the results. For step 1, a suitable reference case was found at the current International Energy Agency Annex 58. It concerns a test box with overall dimension 120x120x120 cm³. Comsol was used to build a 3D model of the test box. In order to compare the Comsol 3D FEM model with the BES lumped model (using HAMBase(de Wit 2006 & HAMLab 2013)), an equivalent heat conduction of the air is used in the FEM model. This provides identical FEM versus BES results.

For step 1, a suitable reference case was found at the current International Energy Agency Annex 58 (2013). It concerns a test box with overall dimension 120x120x120 cm³. Floor, roof and three of the four walls are opaque, one wall contains a window with opening frame. Details of the overall geometry with the exact dimensions can be found in figure 1.

*Figure 1. The reference case.*
We started to build a 3D model of the opaque test box, heavy weight, air change rate: ACH=0 using Comsol (2013). In order to compare the Comsol 3D FEM model with the HAMBase (de Wit 2006 & HAMLab 2013) lumped model, an equivalent heat conduction of the air is used in Comsol instead of CFD. Equation (1) shows the PDE:

$$\rho c \frac{dT}{dt} = \nabla \cdot k \nabla T$$  \hspace{1cm} (1)

where $T$ is temperature (K), $t$ is time (s), $\rho$ is density (kg/m$^3$); $c$ is specific heat (J/kgK) and $k$ is heat conduction coefficient (W/mK). Equation (2) shows the boundary values:

$$q_{boundary} = h(T - T_e) + q_{irrad}$$  \hspace{1cm} (2)

where $q_{boundary}$ is the heat flux at a specific boundary (W/m$^2$), $h$ is the heat transfer coefficient (W/m$^2$K), $T_e$ is the external air temperature (K) and $q_{irrad}$ is the net radiation from the sun and sky to the surface (W/m$^2$). The temperature distribution in the test box is simulated using Dutch weather data. As mentioned above the model was implemented and solved using Comsol. The default second-order Lagrange element type was used. The mesh contained 4414 tetrahedral elements and with average element quality of 0.7512. The number of degrees of freedom solved for was 6679 using the PARADISO algorithm with absolute and relative tolerances of 0.001. The temporal convergence error was less than $10^{-5}$ for each time step. After the solution was obtained with these settings, the grid dependency was evaluated by a grid refinement study. The latter showed no significant changes in the solution. Figure 2 shows the 3D snapshots of the isosurfaces in simulated by the FEM software.

Figure 2. 3D snapshots of the temperature isosurfaces.
The main challenge now is how to match the high resolution distributed temperature results of Comsol with the lumped temperature results of the BES model. For this reference case (opaque test box, heavy weight, \( \text{ACH}=0 \)) we were able to get a very good match by using a so-called equivalent heat conduction coefficient for the air inside the box in Comsol.

\[
\frac{k_{eq}}{d} = \frac{1}{0.34} = 2.9
\]

(3)

Figure 3 shows the comparison of the simulated mean indoor air temperature using Comsol (thin line) and HAMBase (bold line) during the first month. The verification result is satisfactory.

From figure 3, two important facts can be concluded: Firstly, these results can be used as an additional verification benchmark for both Comsol as well as HAMBase. And secondly, it is seems to be possible to accurately reproduce a BES simulation using a relative simple heat conduction based FEM model with a equivalent heat conduction coefficient for the indoor air, but so far without CFD and internal radiation. The latter is left over for future research.

3. Application 2: State-Space models identified from measured data.

At the IEA Annex (2013) a test box was built to investigate it’s thermal characteristics.

![Figure 4. The test box from the IEA Annex 58 (2013), Left: design, Right: as built](image)
The test box was tested at the premises of BBRI in Limelette, Belgium (Lat. 50°41’ N, Long. 4°31’ E). In general, the weather conditions here are temperate, consisting of mild winters and rather cool summers. The experiments extended over a period of one month. Testing was done under real outdoor weather conditions. The following outdoor climate sensors installed near the test box are included in the supplied data: air temperature (with a solar radiation shield and ventilated), vertical global solar radiation (parallel and next to the glazing) and horizontal long wave radiation from the sky. Additional meteorological sensors installed at the test site (200 m from the test box) are also included in the data sets: horizontal global solar radiation, horizontal diffuse solar radiation, vertical long wave radiation from the South direction, wind velocity, wind direction (North 0°, East 90°) and relative humidity. The following experiments have been carried out: Test A: free-floating temperature (with no heating power during 2 weeks) and Test B: co-heating test with constant indoor temperature of 25°C during 2 weeks.

### 3.1 Free floating experiment

Figure 5 shows the measured indoor and outdoor temperatures of the test box:

![Graph showing indoor and outdoor temperatures](image)

*Figure 5: The measured indoor and outdoor temperature are shown. Both temperatures are averages of the two available measurement positions for respectively indoor and outdoor temperature.*

A model structure that is suitable for a thermal zone is provided by Kramer et al. (2013) and is shown in Figure 6.

![Thermal model diagram](image)

*Figure 6: The used lumped thermal model with inputs outdoor temperature (Te) and solar irradiation (Irrad).*
The thermal model is a 3rd order model with 7 parameters: Cw represents the capacitance of the envelope part, Ci represents the capacitance of the indoor air and Cint represents the capacitance of the interior parts which are not directly connected to the outdoor air. Gfast represents the heat loss due to ventilation and windows. The solar irradiation is placed on the interior node. This model structure proved to be the most suitable amongst several other assessed model structures. For more information see Kramer et al. (2013). The thermal model inputs are: Temperature outdoor and solar irradiation on vertical plane oriented on south. For this experiment, the solar input is limited to the global irradiation on the vertical south plane because this has the most influence. The objective is to identify the parameter values of the model by repeatedly trying different parameter values and comparing the simulated output with the measured output (Kramer et al., 2013). The result of the optimization procedure is shown in Figure 7. The measured indoor temperature is reproduced fairly accurately at first sight.

Figure 7: measured and simulated indoor temperature for the free floating situation using the thermal model from Figure 6 with inputs Te and global solar irradiation on vertical South plane (Gv).

3.2 Co-heating experiment

The state-space (SS) thermal model of the previous section was coupled with a PI controller (see Figure 8) in order to simulate the co-heating experiment.

Figure 8: the identified thermal model is coupled to a PI-controller maintaining the indoor temperature at 25°C.

The simulation results compared with the experiments are shown in figures 9 and 10.
Figure 9: Simulated and measured indoor temperature for co-heating test. The first 10h (left) and 10 – 320h (right).

Figure 10: The simulated power is scaled by a factor 3.11e5 (Ci) and plotted with the measured power.

The results show a good agreement between simulation and measurement. Moreover, now that the indoor air capacitance Ci has been identified, the other parameters can be isolated. E.g., the individual parameters like Gi can be isolated, see Table 2:

TABLE 2. The identified parameters are split up by using the identified Ci.

<table>
<thead>
<tr>
<th>#</th>
<th>Par.</th>
<th>identified</th>
<th>expected</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>G_m</td>
<td>0.86</td>
<td>2.3</td>
<td>W/K</td>
</tr>
<tr>
<td>2</td>
<td>C_in</td>
<td>1.2e-1</td>
<td>41</td>
<td>J/K</td>
</tr>
<tr>
<td>3</td>
<td>G_i</td>
<td>3.11e4</td>
<td>43</td>
<td>W/K</td>
</tr>
<tr>
<td>4</td>
<td>C_i</td>
<td>3.11e5</td>
<td>1.1</td>
<td>J/K</td>
</tr>
<tr>
<td>5</td>
<td>G_{fast}</td>
<td>3.11</td>
<td>0.3</td>
<td>W/K</td>
</tr>
<tr>
<td>6</td>
<td>G_{int}</td>
<td>0.31</td>
<td>-</td>
<td>W/K</td>
</tr>
<tr>
<td>7</td>
<td>C_{int}</td>
<td>2.63e-4</td>
<td>-</td>
<td>J/K</td>
</tr>
<tr>
<td>8</td>
<td>fl-S</td>
<td>0.13</td>
<td>0.27</td>
<td>m^3</td>
</tr>
</tbody>
</table>

From Table 2 there it is noted that there is still a discrepancy between identified and expected values. The latter are estimated by hand calculations based on information provided by the IEA Annex 58. This is discussed in the next Section.
4. Discussion and Conclusions

The inverse modeling procedure presented at the previous Section provides a state-space model that is capable of accurately simulating the experiment. The identified parameters should be interpreted as effective parameters. For example the air inside the box has a heat capacity of 1.1 J/K. However, in this experiment it is impossible to heat up the air alone because it immediately affects the construction also. Therefore it could be very difficult if not impossible to get the expected parameters from the inverse modeling method. Nevertheless, the model is a very accurate representation of the dynamics.

It is concluded that one of the main benefits of FEM-SS-BES modeling exchange is the possibility to simulate building energy performances with high spatial resolution and low computational duration times. Regarding FEM to BES – Firstly, these results can be used as an additional verification benchmark for both Comsol as well as HAMBase. Secondly, it is seems to be possible to accurately reproduce a BES simulation using a relative simple heat conduction based FEM model with an equivalent heat conduction coefficient for the indoor air, but so far without CFD and internal radiation. The latter is left over for future research. Regarding BES to SS - The paper presents case studies where SS models are successfully used for reducing computational times for BES models. Regarding SS to BES – Using this so-called inverse modeling approach, it is possible to obtain building energy performances from SS models. The FEM-SS-BES modeling exchange provides two alternative modeling approaches for each other. This may be beneficial if some specific limitations are encountered within one of the single FEM, BES, SS modeling methods.

References

Comsol (2013), www.comcol.com
Wufi+ (2013), http://www.wufi.de/