AN INTERACTIVE WORKBENCH FOR MONITORING, IDENTIFICATION AND CALIBRATION OF BUILDING ENERGY MODELS

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ABSTRACT

This paper presents a concept and main capabilities of the Matlab-based Building Energy Modeling (BEM) Workbench developed at Ryerson University (Toronto, Canada). The workbench was designed as an interactive tool intended to facilitate and to provide common media for data processing tasks related to various building energy modeling procedures such as (i) on-site data monitoring, (ii) preparation of input data and analysis of simulation results, (iii) validation, verification and calibration of building energy models and (iv) estimation of building thermal parameters.

To illustrate the use of the BEM-Workbench several working scenarios are presented. Known inputs from literature methodologies of building thermal parameter estimation were implemented into the workbench to demonstrate one of its purposes as a hypothesis testing tool. Another scenario was introduced to show how the workbench can be used to analyze a buildings model's dynamic behavior, a critical step in the model's calibration procedure.

Programmatically, the workbench is configured as a set of Matlab GUI components and functions with capability to further expand its functionality.

INTRODUCTION

Today there exist hundreds of building energy simulation or modeling (i.e. BEM) tools. (See e.g. http://apps1.eere.energy.gov/buildings/tools_directory) Essentially, each BEM tool takes given or assumed input data, solves some mathematical algorithms, and produces required output data. There are two kinds of input data: (i) coefficients or properties, such as building envelope specifications and mechanical equipment parameters, which can be considered as static values, and (ii) non-static variables, such as weather data, various temperatures and energy flows, which are essentially time-dependant. There are two types of solvers: those that solve differential equations to model the dynamic nature of heat and energy flows in a built environment, and those that do balancing of 'averaged over time' variables. Output data are sought after variables and their derivatives are inputted or assumed. Figure 1 presents an outline of a typical BEM tool when used to evaluate how alteration of inputs' effects on outputs.

The choice of the BEM tool doesn't guarantee the similarity between simulated and real behavior. One of the challenges a modeler faces when dealing with simulation software is the limitations of both input and output interfaces of the most popular BEM tools such as EnergyPlus and eQUEST. Models, even simple ones, require hundreds of input coefficients and variables to be defined through plain text interface. Further, capabilities of BEM tools with regard to graphical presentation of the multitude of time dependant variables processed by BEM are very limited.

There exist two principally different types of BEM approaches depending on whether the modeler is dealing with a building during its design phase or with an existing building during operation. Modeling during the design phase can be categorized as a forward approach (ASHRAE 2009). A typical objective is to compare different design options in order to choose those that satisfy given design requirements (See Figure 1). Because of limitations of the interface of the most BEM tools, very often a modeler is unarmed when he or she wants to make a

quick and precise comparison of different variables What makes this problem really challenging is the fact that those variables may be of more than two different units, and they need to be displayed at such time scales as months of different length and days of the week.
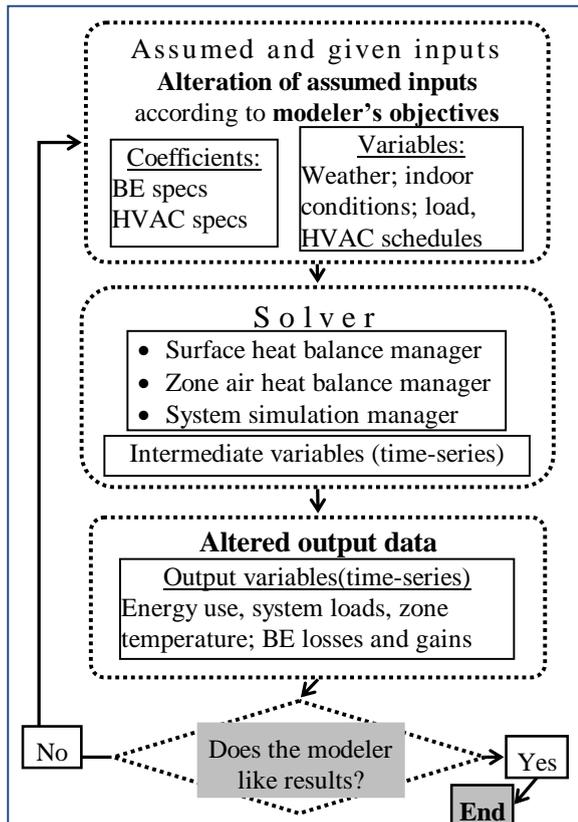

Figure 1 Simulation tool. Forward approach.

Another challenge is to ensure validity of results. ANSI/ASHRAE Standard 140-2004 addresses in part this issue providing that employed software is capable of producing accurate results. However an additional procedure and tool are needed to ensure that all relevant physical phenomena are demonstrated correctly by the model.

The test suite for analytical verification of BEM programs by Spitler et al. (2001) can serve as an example of the latter procedure. It can be applied in a broader context such that each model can be tested and evaluated with regard to the certain type of thermal behavior. This could be the model's response to the step or sinusoidal temperature change, to the solar transmission through fenestration, to the internal convective or radiative step gains, etc.

Typical objectives when modeling existing buildings are to assist in selecting proper energy saving

measures and to develop cost effective retrofit scenarios. It is a common understanding in the profession, which was conceived more than two decades ago (see for example Norford et al. 1994) and became accepted practice nowadays (ASHRAE 2002) that the computer model of existing building has to be calibrated by matching actual building energy use (See Figure 2). The caveat to this is it works only when low-resolution monthly utility data are available. The problem of tuning the model that generates high resolution (e.g. hourly) output variables (usually 8760 values per year) by matching monthly averaged data (usually 12 values per year) theoretically has an infinite number of possible solutions. General practice today is to apply the modeler's judgment, critical thinking and sensitivity analysis while tuning the model iteratively refining the building thermal properties and operational schedules (Haberl et al. 2005; Westphal and Lamberts 2005). This practical approach can be beneficial if supported by a tool that can quantitatively correlate input and output variables.
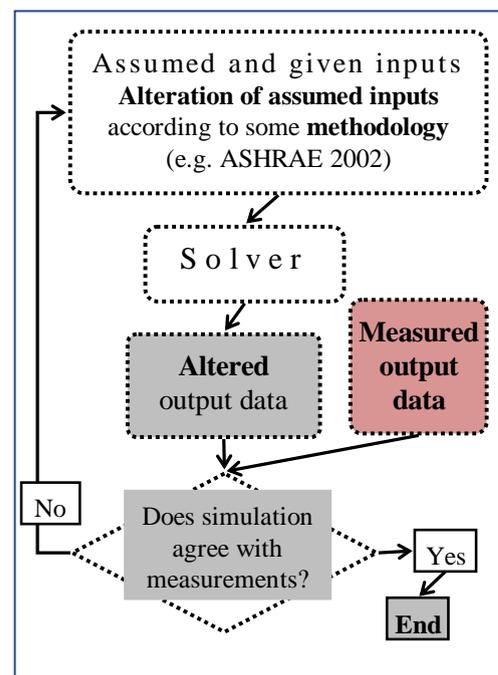

Figure 2 Calibrated simulation approach.

As high resolution (e.g. hourly) energy metering is becoming routinely available, advanced identification procedures can be employed for the purpose of evaluating parameters that control building thermal performance (Bacher & Madsen 2011; Jiménez et al. 2008; Mejri et al. 2011). This approach introduces new challenges that can be addressed by combining

existing functionality of mathematical tools such as Matlab with BEM procedures.

This paper presents a concept of the Matlab-based BEM-Workbench that was designed as an interactive tool to facilitate and to provide common media for data processing tasks related to various building energy modeling procedures including on-site data monitoring, preparation of input data and analysis of simulation results, validation, verification and calibration of building energy models, estimation of building thermal parameters.

BEM-WORKBENCH DESCRIPTION

The BEM-Workbench was created using Matlab GUI technology (http://www.mathworks.com/help/techdoc/creating_guis/bqz6qcd.html). Programmatically, the workbench is organized as a set of Matlab Figures, which can be thought of as interface windows. These Matlab Figures are the top level containers for other components including lower level containers, such as panels, and other graphical components and controls (menus, buttons, lists, tables, etc.), which are nested into containers and subcontainers. Functionality of the workbench is realized through callback functions and

utility functions.

BEM-Workbench structure is illustrated in Figure 3. The Present version of BEM-Workbench was designed to enable a modeler carrying out the following tasks:

1) Importing data of various origins (weather stations, data loggers with sensors monitoring indoor environment) as well as output data from EnergyPlus.

2) Data manipulation and visualization including data resampling and graphical presentation as time plots and X-Y correlation plots. Among functions here are mathematical operations such as mean and moving average, as well as preparation of data for further use under various parameter evaluation scenarios.

3) Providing an interface that will assist testing of methodologies for estimation of building thermal parameters. A modeler can select a pre-programmed interface, a panel with controls, text boxes and tables. They will then guide the parameter estimating procedure such as the evaluation of overall building envelope heat loss coefficient, or the solar aperture.
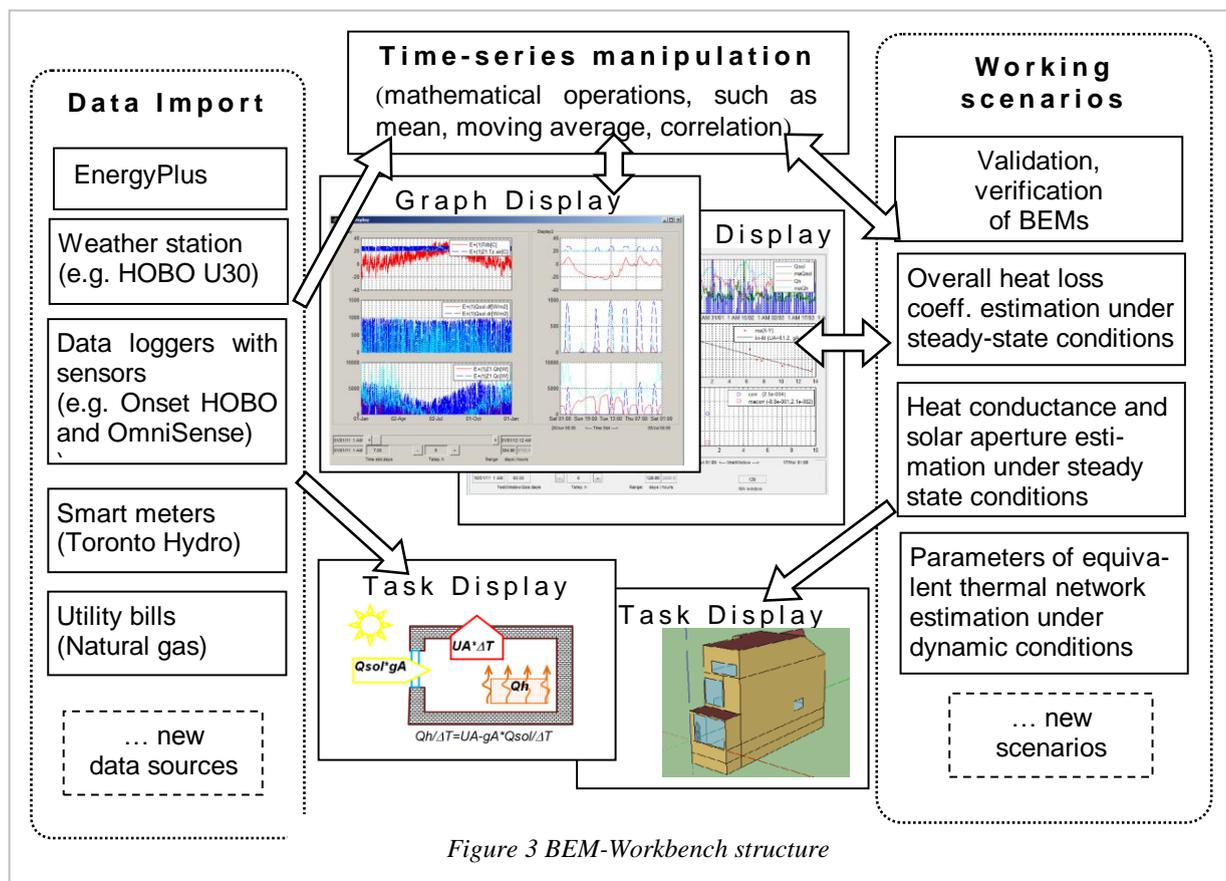

Figure 3 BEM-Workbench structure

EXAMPLES OF WORKING SCENARIOS

Evaluation of heat losses under steady state conditions based on field measurements

Objectives:

- Demonstrate use of the BEM-Workbench for estimation of the whole building heat loss coefficient based on field measurements.

- Compare measurements and results of simulation.

Utility data for a single family house (floor area 250 m^2) representing a deep energy retrofit of an early 1900's residential building in Toronto (Canada) (Figure 4a) were used for this case study.
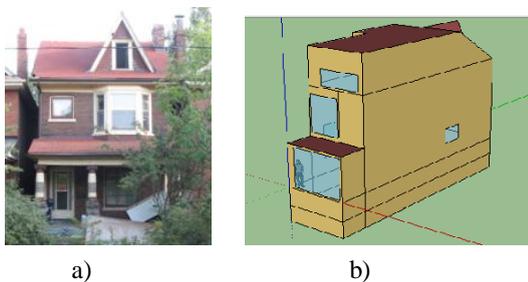

a)   b)

Figure 4 Case study building (a) and EP BEM(b)

The methodology that allows estimation of building heat loss coefficient based on monthly energy bills was originally proposed by Fels (1986). It can be expressed by the following equation:

$$f=\alpha+\beta(\tau-T_{out}) \qquad (1)$$

where $\beta = L/\eta$; L - building heat loss coefficient; η - fuel efficiency; τ - the house reference temperature. α - non-heating fuel use, e.g. DHW, appliances, etc.
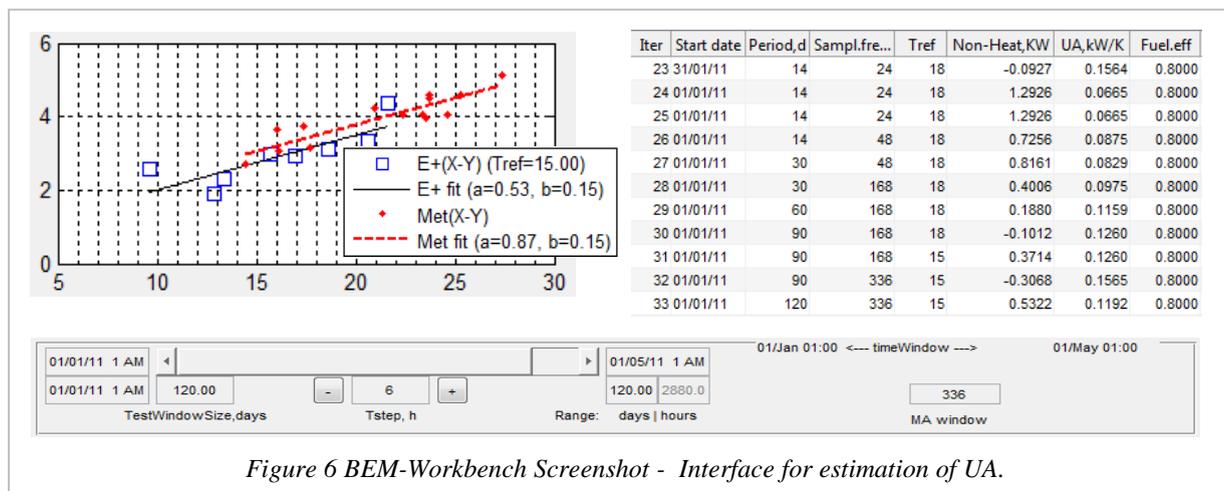
Short term daily average utility data and outdoor temperature were recorded in February 2011 (See Figure 5). Use of daily average energy consumption contradicts the original methodology that was developed for monthly averaged utility data. In order to test if this methodology can be applied when more frequent metering is available, an EnergyPlus simulation was carried out. The schematic model representation is shown in Figure 4b. Simulated temperature and energy use are shown in Figure 5.
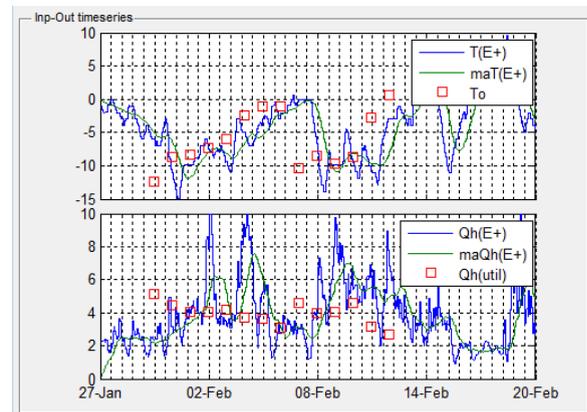

Figure 5 Energy and outdoor temperature from field measurements (Qh(util)[kW]; To[C]) and from EP BEM (Qh, To and moving averages maQh and maT)

The corresponding BEM-Workbench scenario for evaluation of heat losses produces linear regression of daily energy use versus degree-day (See Figure 6). Results of parametric study are shown in the table for different value of parameters such as house reference temperatures (τ=15C and 18C), period of observation (from 14 to 120 days), sampling frequency (from 1 day to 2 weeks), fuel efficiency (η =0.8).

Iter	Start date	Period,d	Sampl.fre...	Tref	Non-Heat,KW	UA,kW/K	Fuel.eff
23	31/01/11	14	24	18	-0.0927	0.1564	0.8000
24	01/01/11	14	24	18	1.2926	0.0665	0.8000
25	01/01/11	14	24	18	1.2926	0.0665	0.8000
26	01/01/11	14	48	18	0.7256	0.0875	0.8000
27	01/01/11	30	48	18	0.8161	0.0829	0.8000
28	01/01/11	30	168	18	0.4006	0.0975	0.8000
29	01/01/11	60	168	18	0.1880	0.1159	0.8000
30	01/01/11	90	168	18	-0.1012	0.1260	0.8000
31	01/01/11	90	168	15	0.3714	0.1260	0.8000
32	01/01/11	90	336	15	-0.3068	0.1565	0.8000
33	01/01/11	120	336	15	0.5322	0.1192	0.8000

Figure 6 BEM-Workbench Screenshot - Interface for estimation of UA.

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Based on field measurements the building heat loss coefficient is evaluated as 120 *W/K*. Results of express simulation on the given trial set of parameters give a spread of values from 66 to 156 W/K. Comparison clearly indicates that further revision of building energy model is required in order to justify use of measurements for BEM calibration.

Visual analysis capabilities with simulation models

This section illustrates the concept of why a modeler needs a specific tool to aid an analysis of input/output relations of energy simulation and the features this tool should have.

The EnergyPlus model of a single family house representing a deep energy retrofit of a double brick high thermal mass building (Fig.4b) was used. The typical high frequency time series outputs of a building energy simulator are shown in Figure 7. This seemingly 'dynamic' picture, indeed, reflects an influence of outdoor weather variation. Under such conditions it is difficult to evaluate, for example, specific overall parameters of temperature step response of thermal zone such as settling time or time constant. These parameters can serve as measurable characteristics - unique single number tags if you wish - of heat transfer dynamics of given thermal zone.

Extending some ideas presented by Spitler et al. (2001) a capability was implemented in the BEM-Workbench that aids the user to defining a time series as an arbitrary sequence of steps. This time series, when incorporated with a weather file as an environmental temperature, allows for demonstrating
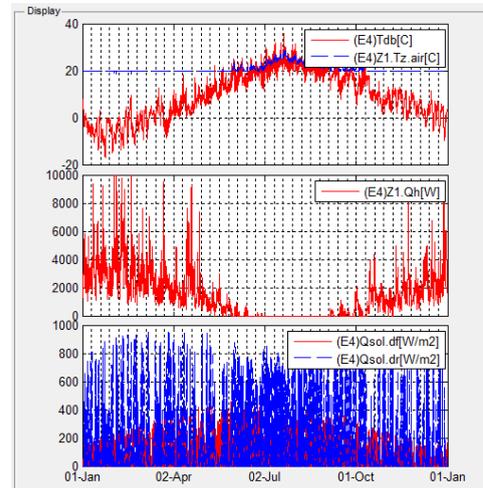

Figure 7 An example of simulated inputs (outdoor temperatures, solar radiation) and outputs (indoor temperatures, heating energy)

and studying of dynamic behavior of the simulated building envelope (See Figure 8).

As seen in Figure 8, a response of indoor air temperature (Tdb) to the step raise of outdoor temperature (Tz air) can be characterize by settling time which for the given model is of the order of 10 days. The heating system is also characterized by some step response time constant. Numerical values of these time constants can be used as integral signatures of dynamic behavior of the simulated building envelope and mechanical system. Further development of the BEM-Workbench is required to implement such evaluation capability. This work is currently being
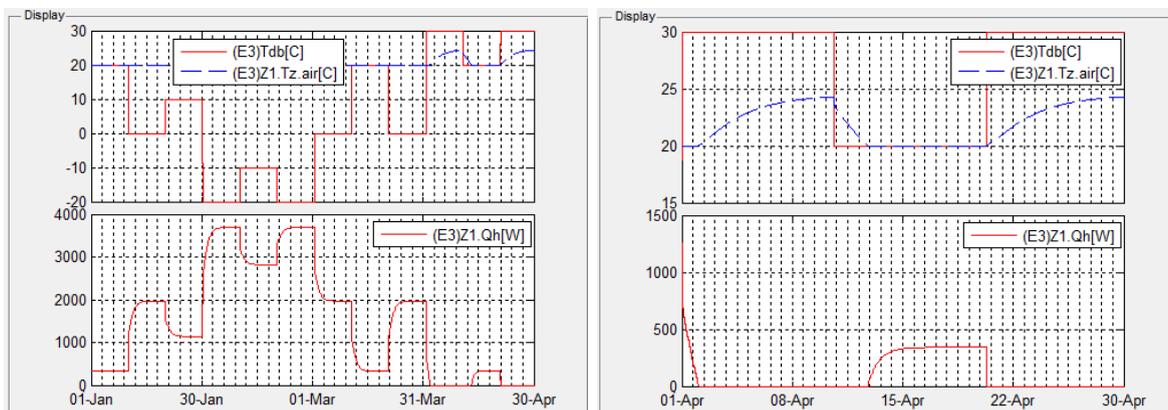

Figure 8 BEM-Workbench Screenshot – Time step responses caused by stepped dry-bulb temperature.

completed with preliminary capability expected by September 2012. This example indicates the importance of dynamic similarity between simulated and real behavior of building for the purposes of model validation, verification and calibration.

Evaluation of whole-building heat loss *UA* and solar aperture *gA* of the building envelope

Objective:

- To test known methodology, which is explained in (Baker & van Dijk, 2008).

The model driving this methodology is outlined in Figure 9. Originally it was applied for outdoor testing of building components. This section shows how this approach was implemented into Workbench to be applied for entire building envelope.
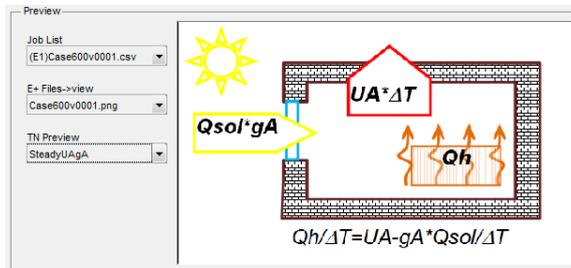

Figure 9 Task panel showing the model's idea

The balance of main heat losses and gains can be expressed by the following equation:

$$Qh = UA_{BE} \times \Delta T - gA \times Qsol \qquad (2)$$

where $Qh[W]$ is heat produced inside thermal zone; $UA_{BE}[W/K]$ is heat loss of overall building envelope; $\Delta T[K]$ is the average temperature difference across the building envelope; $gA[m^2]$ is a coefficient that characterize the size of glazing portion of the building envelope and together with incident solar radiation $Qsol[W/m^2]$ they define total solar heat gain.

Equation 2 is written for values, which are averaged over certain period of time. Baker & van Dijk (2008) use 10 days averaging. Finally, parameters *UA* and *gA* can be derived from the following equation:

$$Qh/\Delta T = UA_{BE} - gA \times Qsol/\Delta T \qquad (3)$$

as parameters of regression line of the set of points $(Qsol/\Delta T, Qh/\Delta T)$ presenting field measurements in the *X-Y* plane.

For the purpose of hypothesis testing the results of simulation for the model #600 (with 0.001 instead of 0.018 m3/sec infiltration flow rate) (refer to Figure 10)

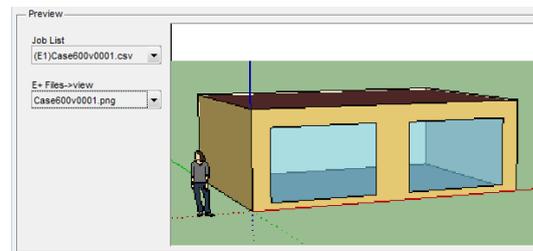from the ASHRAE Standard 140 were used as a substitution of measurements.

Figure 10 Simulation model #600

BEM-Workbench functionality was extended to allow for flexible control of time line parameters such as start/end time and interval of averaging, as well as sampling frequency. Looping algorithms were introduced to automate parametric study and data collection.

Figures 11 shows the hourly sampled time series for *Qh, ΔT, Qsol* and the moving averages over 120 time steps, which in this case corresponds to the averaging over 5 days intervals.

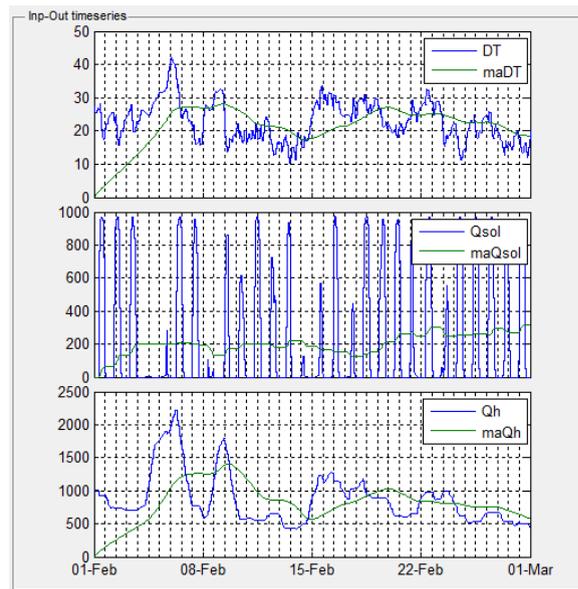*Figure 11 BEM-Workbench Screenshot – Qh, ΔT, Qsol time series and their moving averages over 120 time steps for the model #600*

Figure 12 illustrates elements of the BEM-Workbench interface that supports regression analysis for the problem discussed above. The graph in Figure 15 shows X-Y scatter and the best fit line denoting y-intersect, which is a *UA* estimate, and slope of the line, which is a *gA* estimate. The Table in Figure 15 accumulates results of parametric study. It contains the
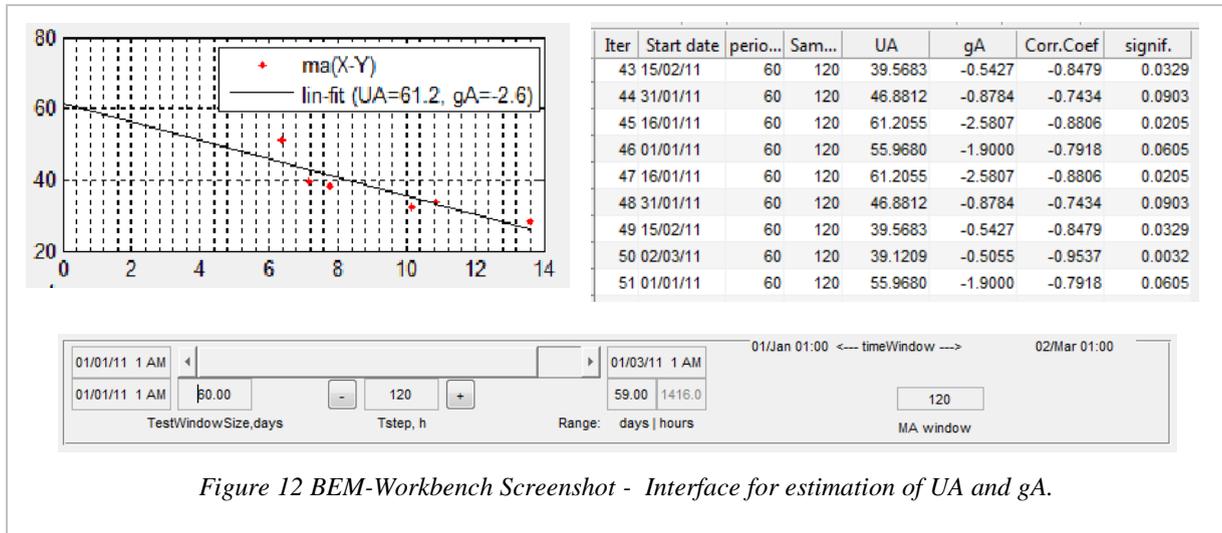
Figure 12 BEM-Workbench Screenshot - Interface for estimation of UA and gA.

length of time series used for analysis (60 days), the averaging interval (120 hours), estimates *UA* and *gA*. Statistics of estimation is characterized by a correlation coefficient and by value of significance. An absolute value of a correlation coefficient more than 0.95 signifies strong correlation between X and Y variables. Value of significance should be less than 0.05 to consider observed correlation as a significant event rather than mere random coincidence.

Results of this analysis show that the balance Equation 2 suggested by the given methodology does not provide good confidence using single value estimation of parameters for the given EP simulation model. The model #600, on the other hand, has, by definition, the *UA* value of 51 *W/K* for the building envelope without windows and 87 *W/K* for building envelope with windows. As the first *UA* value falls within the scatter of the former estimate, it may give an incentive for further study, given the attractive simplicity of Equation 2.

CONCLUSION

Reliability and the computing power of Matlab made it possible to complete development of the first BEM-Workbench prototype from first concept to working tool in very short period of time (3 months) by a single individual. The following is outlining the BEM-Workbench main features.

In the area of data import, export, processing and visualization the following functions have been implemented:

- Importing of EnergyPlus outputs. Modification of EnergyPlus input and weather files to test and validate basic heat transfer phenomena demonstrated by building envelope.

- Importing of monitored data from HOBO weather station, onset HOBO data loggers with temperature and moisture content sensors, OMNI sense loggers with temperature and RH sensors, electricity smart meters of Toronto hydro, and natural gas utility bills.

- Mathematical computation of statistics and characteristics of time series data, their resampling and correlation between each other.

- Graphical presentation of data into two different time scales simultaneously to allow detailed and precise targeting of any time interval from one hour in length to one year or longer. Here, the powerful capabilities of Matlab in formatting date and time variables were especially helpful.

Using the workbench for the analysis of BEMs assists the modeler in testing qualitatively that the appropriate physical effects are demonstrated by the given model and that that these effects are modeled quantitatively right.

For example, the capabilities for visual analysis implemented into BEM Workbench has already allowed for estimation of indoor temperature settling time (refer to Figure 8). And according to the Workbench concept this simulation based estimation could be compared against results of field measurements right in the same common workspace. This example shows how the dynamic similarity between simulated and real behavior of building can be used for the purposes of model validation, verification and calibration.

As was demonstrated by two other examples the workbench allows for the fast and comprehensive testing of hypothesis development related to various parameter estimation scenarios.

The workbench along with its usefulness as an analysis tool can assist in an educational process when studying building energy modeling with EnergyPlus simulation software.

New ideas that were identified during the development of BEM-Workbench indicate that the entire concept of this project and its implementation demand further research.

Future work on the workbench can be seen in the following directions:

- Improvements of BEM-Workbench software both in the part related to the user interface and to the mathematical core and data structure.

- Collection of more field measurements for further development of model validation, verification and calibration methodologies.

- Adding scenarios to carry on more sophisticated methodologies in estimating dynamic behavior of built environment.

ACKNOWLEDGEMENTS

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