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A GRAPHICAL TOOL FOR CLOUD-BASED BUILDING ENERGY SIMULATION

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ABSTRACT

Building energy modeling is a field that can be computationally intensive, especially for large parametric studies that require simulating many alternate models. In the past, these types of studies have been limited to research institutions and advanced users who had the required computational resources available. In recent years, cloud computing services have come to offer a reliable platform in which relatively inexpensive computing power can be purchased and used as needed without a substantial capital investment. These services are gaining ground quickly because they are, for many companies, more cost effective than building and maintaining computing power in-house. OpenStudio has developed a workflow that allows energy modelers to create and run a customized parametric analysis using commercially available cloud computing services. This workflow will enable anyone to perform powerful parametric studies in a reasonable time for a relatively low cost. This paper demonstrates the workflow in an automated calibration application.

INTRODUCTION

Building energy modeling tools span a wide range of computational requirements. The most basic tools are spreadsheets that use very low order models of the building to simulate energy use for specific equipment or the whole building. More advanced whole-building simulation tools attempt to take in information about the entire building upon which they predict energy use. ASHRAE Standard 140 (ASHRAE 2011) provides a method for validating whole building energy modeling tools. Of these validated tools, EnergyPlus, developed by DOE, is currently one of the most advanced (Crawley et al. 2005). However, with more capability comes more computational requirements. Historically, this has meant that, in addition to assembling the complex set of necessary input data, using EnergyPlus to perform parametric studies required large computational resources not available to the average energy modeler.

One approach to this problem in the past was for research institutions, with access to large computational resources, to perform parametric studies and then publish the results in ways that average users could access (ASHRAE), (Griffith et al. 2007), (DOE 2012), (Roth et al. 2012), (NREL 2013), (DOE 2013). This approach is still valid and useful for many applications. However, a user's building, modeling assumptions, and design considerations are never exactly the same as in the pre-packaged parametric study. Also, some users want to study how the results of an analysis might change for their specific building, their modeling assumptions, and their design considerations but lack the framework and computational resources to do so. This is especially true when trying to use algorithms for automated calibration of energy models as no two buildings are operated identically. With these computational resources now available, projects such as jEPlus (Zhang & Korolija 2010) and OpenStudio have begun to address this need.

The OpenStudio workflow for parametric studies is shown in Figure 1. In this workflow, a user is able to create an OpenStudio building energy model specific to their project using a number of available frontends. The user is then able to search for and download OpenStudio measures (Hale et al. 2012) specific to their needs from the Building Component Library (BCL) (Fleming et al. 2012). OpenStudio measures are small Ruby programs that take user inputs and then modify an OpenStudio model in a specific and replicable way. If a suitable measure cannot be found, the user can write their own measure and test it using the OpenStudio Parametric Analysis Tool (PAT). The user can apply combinations of measures using their own custom assumptions about price and performance using PAT and test that these measures work correctly with their custom building model.

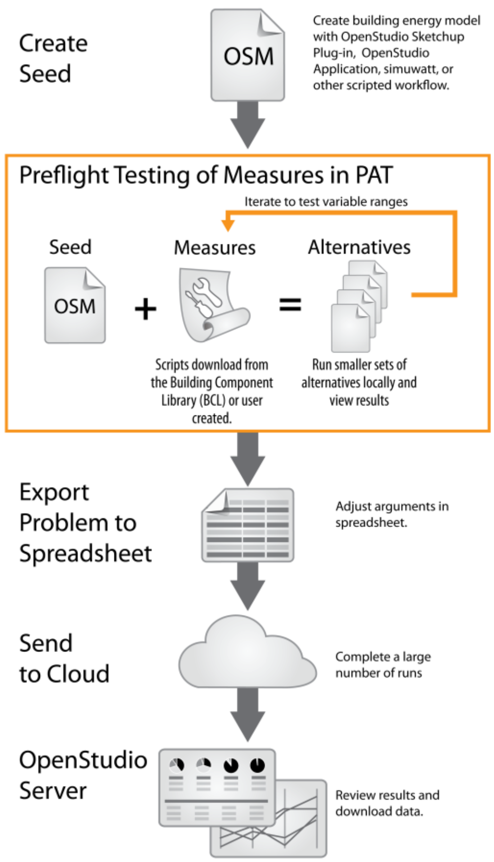

Figure 1 OpenStudio Parametric Workflow

After the user is satisfied that the measures are working correctly in PAT, they may choose to run additional design alternatives on the cloud directly through the PAT interface (Hale et al. 2014). However, in this case the user must construct all of the design alternatives to be run **by hand**, which is tedious, time consuming, and error-prone. As an alternative, the user may choose to export the project to a spreadsheet format for a more automated, large-scale, cloud-based analysis. This path is the focus of this paper. The spreadsheet allows the user to specify detailed information about the analysis that is not available in the PAT interface. Once this spreadsheet is completed, the user is able to run a script that parses the spreadsheet, starts cloud resources, uploads information, and begins the analysis. While the analysis is running in the cloud, the user may monitor progress and interact with results via a web interface that is embedded in the OpenStudio Server. The web interface also allows the user to download individual models and results in various formats for further analysis. The OpenStudio SDKs with which the spreadsheet interacts are all available as open source projects. This allows software developers to perform all of these steps programatically to create custom parametric building energy modeling applications.

The remainder of this paper describes using this workflow to set up and run an automated energy model calibration to monthly measured utility data. In this example, the seed model was developed using the simuwatt Energy Auditor® software (Macumber et al. 2014). This software allows an energy auditor to perform an energy audit of a commercial building using a tablet based workflow. The tool generates an initial OpenStudio model based on the audit data which is then calibrated to actual monthly utility data. However, any OpenStudio model could be used as the input. In this example, the measures will be selected for their ability to tune uncertain parameters of the model. However, measures used to model improved energy performance could be chosen for an optimization study.

The model used in this work was the same one used for a case study of a manual calibration process in (Hale et al. 2014). Ideally, the automated process should yield calibration parameters similiar to the carefully considered manual process, but at a lower cost. However, certain parameters were tuned by hand using graphical user interfaces instead of measures during the manual calibration. As reported in (Hale et al. 2014) the parameters that were manually changed were to adjust lighting and equipment schedules, hard size fans, and implement supply air temperature reset. Measures could have been written to achieve these same model changes. However, five parameters could already be manipulated by measures and only 12 monthly electric data points. To avoid overfitting, we used only the measures that were already available and did not consider parameters that were previously manipulated by hand, resulting in a more automated process.

SEED MODEL

The building considered in this study is a 7,560-m^2 (81,400-ft^2) office building at Tyndall Air Force Base in Panama City, FL. The building is all electric and uses a chilled water variable air volume system with electric reheat for space conditioning. The occupancy is primarily office space with small areas that include a courtroom, restrooms, conference rooms, a health clinic, and mechanical space. The building was constructed in 1988, and since has had many space use changes, as well as several wall demolition/construction projects that did not include HVAC redesign. The building has not been commissioned recently, and occupants complained of hot and cold spots.

An initial OpenStudio model was developed using the simuwatt Energy Auditor software tool (Macumber 2014). This model is shown rendered in the OpenStudio SketchUp plug-in in Figure 2. As described in (Guglielmetti et al. 2011), the OpenStudio SketchUp plug-in can be used to visualize and develop geometry for building energy modeling.

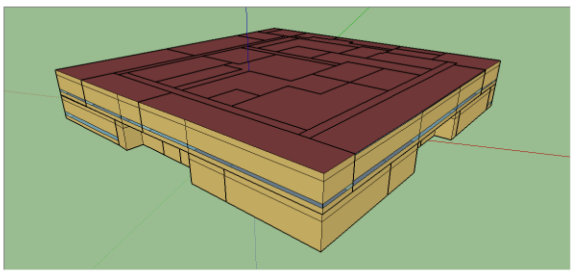

Figure 2 Initial Building Model Geometry

As described in (Weaver et al. 2012) details about schedules, constructions, HVAC, and other energy modeling content can be modified using the OpenStudio application. An HVAC system belonging to the initial OpenStudio model is shown as rendered by the OpenStudio application in Figure 3.

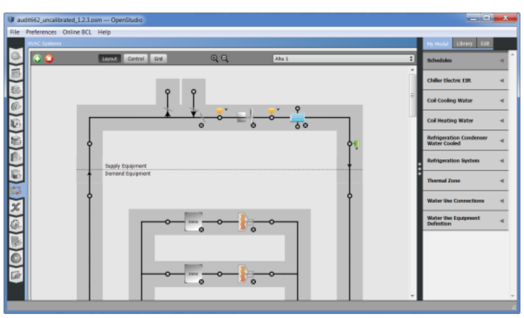

Figure 3 Initial Building Model HVAC

The simuwatt Energy Auditor tool allows for entry of actual monthly energy use. This information is automatically added to the initial OpenStudio energy model. When the energy model is simulated using EnergyPlus in the OpenStudio application, a calibration report comparing the modeled energy use with actual energy use is automatically created, shown in Figure 4.

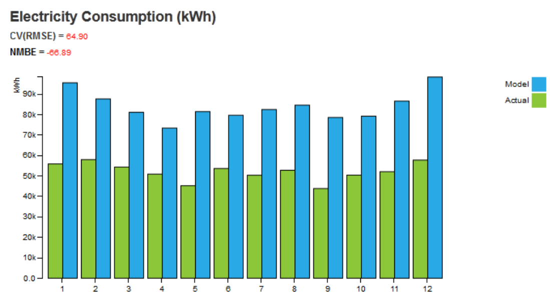

Figure 4 Initial Model Calibration Report

This calibration report computes the normalized mean bias error (NMBE) and the coefficient of variation of the root mean squared error CV(RMSE) between the model and actual energy use. These metrics are compared to the ASHRAE Guideline 14 (ASHRAE 2002) requirements that NMBE must be ± 5% and the CV(RSME) must be ≤ 15%. As shown in Figure 4, NMBE of the initial model was -66.89% and CV(RMSE) was 64.90%. As these metrics are outside the acceptable limits in ASHRAE Guideline 14, uncertain model parameters must be tuned until the modeled energy use better matches actual data.

USING MEASURES WITH PAT

After importing the initial OpenStudio model into PAT, the first step in the calibration process is to identify uncertain parameters of the initial model. Because an on-site audit of the building was conducted, lighting and equipment counts, HVAC system types, and constructions are well known. However, other parameters such as infiltration, operational schedules, and actual system efficiencies are not known with certainty. As shown in Figure 5, PAT allows the user to search for measures on the BCL, which vary these uncertain parameters to improve model predictions. As noted in (Hale et al. 2014), good engineering judgement must be used when selecting the measures and calibration parameters to use for any given building.

In this example, suitable measures for varying uncertain parameters were already available from the previous manual calibration work (Hale et al. 2014). Although other calibration parameters of interest, such as infiltration rates, are available as measures on the BCL, this work was restricted to the measures from the previous manual calibration in order to compare the manual to the automated calibration process. The existing measures were added to the measure library in PAT and then dragged into the simulation workflow, shown in Figure 6.

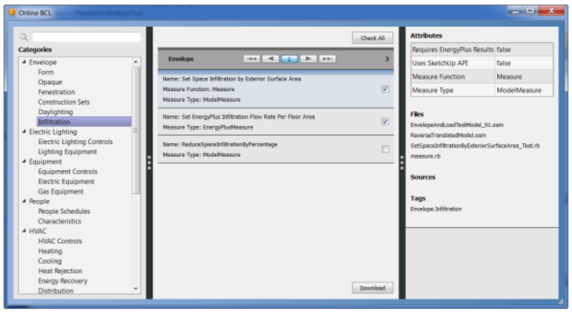

Figure 5 Online BCL Interface

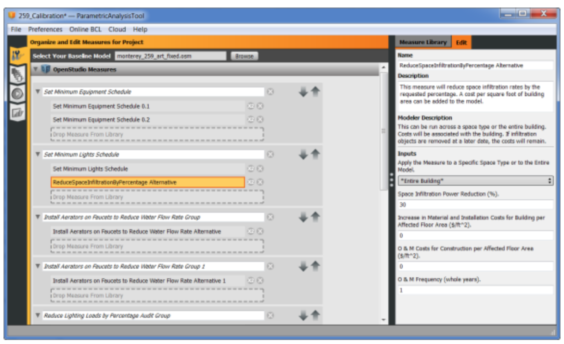

Figure 6 Configuring Measure Parameters in PAT

Clicking on a measure allows the user to enter custom values for the measure's arguments. Multiple instances of the same measure may be configured with different input values for testing the measure across a range of inputs. It is important to test each measure at the nominal and extreme values of the variable space. If each measure is found to work correctly for these values, the user may assume that simulations will run cleanly on a high percentage of the interior of the variable space.

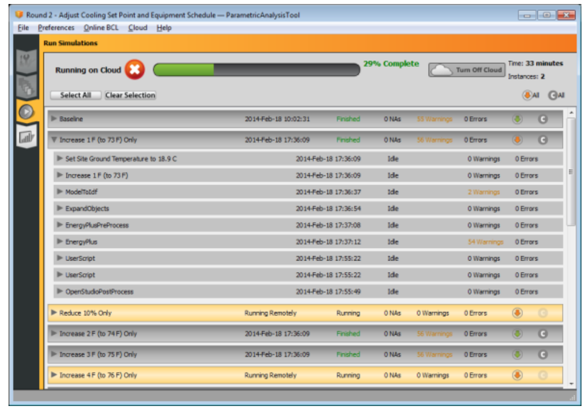

Figure 7 Simulation Details in PAT

After individual measures are configured, design alternatives can be constructed by applying different combinations of measures to the input model. Each design alternative is then simulated. Each measure may issue errors, warnings, and informational messages which are shown directly in the PAT user interface as shown in Figure 7. Each resulting OpenStudio model and detailed results may also be inspected using the OpenStudio graphical user interfaces to ensure that the measures were applied correctly. The following parameters, with initial model value, were investigated over the ranges shown in Table 1.

Table 1 Parameter Ranges

PARAMETER	INITIAL	MIN	MAX
Ground temperature (°C)	18	17	20
Cooling set point (°C)	22.2	22.2	26.2
Reduce lighting power (%)	0.0	0.0	40.0
Reduce equipment power (%)	0.0	0.0	40.0
Fan static pressure (in. H_2O)	2.0	2.0	4.0

Testing measures with PAT in this manner is important before initiating large cloud analyses to avoid spending money on cloud resources, only to find bad simulation results because of erroneous measures or measure arguments. Once all the measures are tested with an expected range of input arguments locally, the user can be more confident that cloud-based simulations will provide high-value results. Once PAT has been used in this manner, the user can quickly export the project to a spreadsheet format better suited to describe a range of large-scale simulations to be performed in the cloud.

PROBLEM DEFINITION

The analysis capabilities of the OpenStudio platform are far more extensive than what can be quickly exposed in a polished user interface. One expedient method for exposing the full functionality is to use a spreadsheet input format in conjunction with scripts that leverage the OpenStudio Ruby bindings. The spreadsheet interface allows the user to enter the required information using familiar tools while allowing the interface to be updated easily as new features are added or refined. At the time of writing, an example spreadsheet, installation, and configuration instructions are available at https://github.com/NREL/OpenStudio-analysis-spreadsheet, although future releases of OpenStudio will make installation more seamless.

Exporting a project from PAT creates a default spreadsheet with the baseline model and measures used in the PAT analysis. The user may then add information to the spreadsheet to define measure arguments as variables with associated distributions and ranges.

Sampling and optimization algorithms with associated objective functions are specified in the spreadsheet. Several algorithms are currently available for optimization including the evolutionary multi-objective optimization algorithms NSGA2 (Nondominated Sorting Genetic Algorithm 2) (Deb et al. 2002) and SPEA2 (Strength Pareto Evolutionary Algorithm 2) (Zitzler et al. 2001), the single-objective optimization algorithms GENOUD (GENetic Optimized Using Derivatives) (Mebane & Sekhon 2011), DEoptim (Mullen et al. 2011), and the gradient based L-BFGS-B (Byrd et al. 1995). The workflow also supports several sampling algorithms for continuous and discrete variables including, LHS (Latin Hypercube Sampling) (Stein 1987), pure random sampling and sampling based on Sobol sequences (Burhenne et al. 2011). In this example, we want to minimize the difference between actual and model energy use. Therefore, we selected the GENOUD optimization algorithm and an objective function that corresponds to CV(RMSE).

Objective functions may be specified flexibly using combinations of model values, simulation outputs, and additional data. PAT exports a list of machine-readable attributes that are generated by reporting measures in the simulation workflow. Any of these outputs may be chosen as an objective function for the algorithm. In addition, any L^p norm may be applied to output variables when defining objective functions for optimization problems (Rudin 1991). Standard reporting measures are available, but users may also create customized measures to report specific values of interest.

LAUNCH CLOUD

After the parametric problem has been defined in the spreadsheet the user is ready to launch cloud instances. Amazon's Elastic Compute Cloud (EC2) service is the first cloud service to be supported by OpenStudio. To use this service, the user must register for an EC2 account on Amazon and provide a payment method. The user then copies credentials for their EC2 account onto their computer to authorize it to launch cloud resources. The number and type of cloud resources may be set in the spreadsheet based on analysis requirements. Once configured per the instructions provided in the above github link, the user types a single rake command to parse the spreadsheet, stand up the EC2 cluster, and upload the problem for analysis. The script also returns a URL that the user can enter into a web browser to monitor progress and interact with results as they become available, Figure 8.

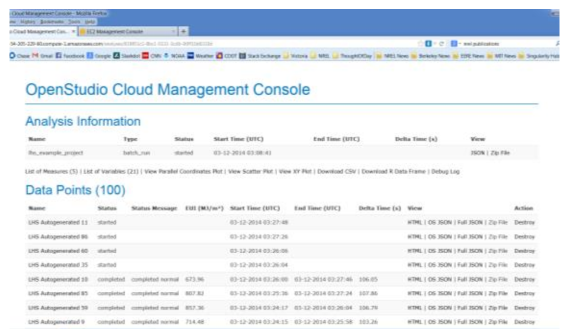

Figure 8 OpenStudio Cloud Management Console

The user may monitor and terminate all their EC2 resources through Amazon's EC2 interface as well. Monitoring the cluster is important to prevent unwanted charges for unnecessary cloud resources, and a number of web and mobile interfaces are available to facilitate this task. All cluster nodes remain available for analysis (and billing) until they are explicitly halted. Halting the server also removes the cloud management console and all data that has not been downloaded or pushed to longer term, low cost storage. Although OpenStudio is easily configured to use EC2, advanced users may set up distributed analyses on other cloud services or local virtual machines and clusters.

OPENSTUDIO SERVER

Each cluster includes one server and multiple workers depending upon the spreadsheet configuration, Figure 9. Each node is automatically provisioned with Amazon Machine Images containing the resources required to perform a distributed analysis.

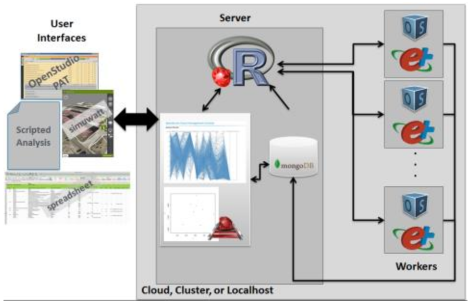

Figure 9 OpenStudio Distributed Analysis Architecture

The OpenStudio server cloud management console provides a significant amount of built-in functionality. It enables the user to browse multiple analyses that may have been performed by the cluster as well as individual points within an analysis. Point reports include the standard EnergyPlus reports along with OpenStudio logs describing outcomes from the application of individual measures and other useful diagnostic information. The server also provides summaries of input variable distributes for sampling problems including distribution histograms associated with measure inputs. A number of visualizations are also available to assist in review of large-scale analysis results. One useful visualization is the parallel coordinate plot shown in Figure 10.

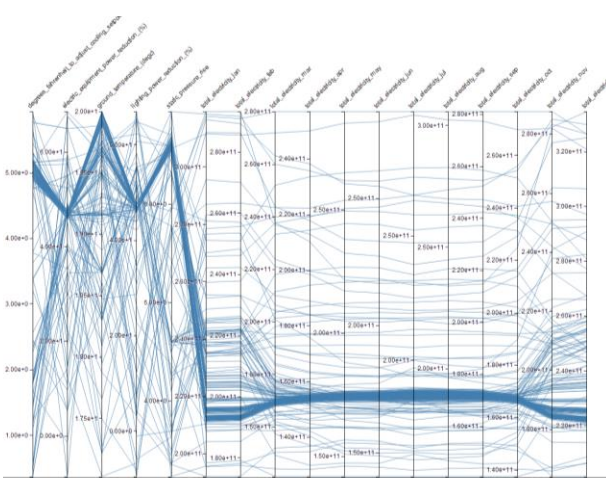

Figure 10 Parallel Coordinate Plot Used to Explore an OpenStudio Analysis

This interactive plot shows the connections between multiple measure variables and key outcomes such as energy use intensity or life cycle cost. The columns can be dynamically reordered, and the user can graphically apply filters to the data to focus on, for example, only those solutions that produce ranges of EUI and cost. Parallel coordinate plots can provide rapid insight into the myriad interactions taking place in a complex analysis and are valuable for identifying the most sensitive parameters in a model.

The calibration problem described earlier in the paper provides an illustrative example of using the distributed optimization framework and visualizations.

RESULTS

The automated calibration was run on a cluster of 24 CPUs. A total of 241 simulations were run over 6 generations taking a total of 13 hours. The solution was found after 4 generations; however, 2 extra generations were run to ensure convergence. In addition, gradient calculations were done after the 2nd generation. Turning off these features of the algorithm would have reduced simulation time by approximately 50%. In addition, simulation time could have been reduced by purchasing additional computing power (at an additional cost). The average simulation runtime was around 26 minutes for this complicated model. It is estimated that the manual tasks of setting up the problem, testing measures, and analyzing the results took about one day in total. The GENOUD algorithm was selected with parameters:

Table 2 Algorithm Parameters

PARAMETER	VALUE
Population Size	24
Generations	6
solutionTolerance	0.01
waitGenerations	2
pPower	2
Bfgsburnin	2

The algorithm found a family of model parameters that satisfied the ASHRAE Guideline 14 recommendations. Those parameters are shown in Figure 11.

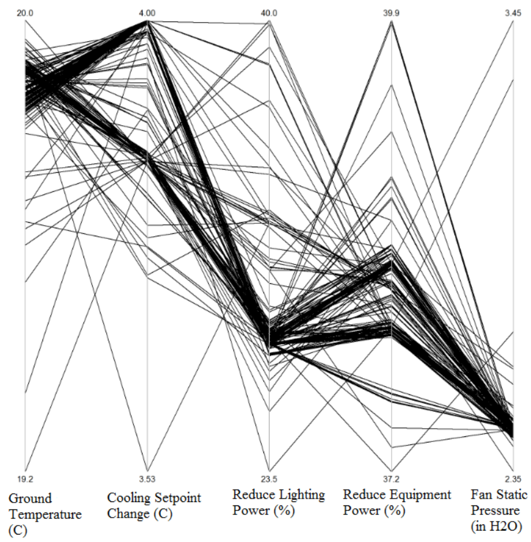

Figure 11 Parameters Satisfying ASHRAE Guideline 14

The final parameter values found by the optimization algorithm are reported along with those found during the manual calibration in Table 3.

Table 3 Final Parameter Values

PARAMETER	MANUAL CALIBRATION	AUTOMATED CALIBRATION
Ground temperature (°C)	19.9	19.83
Cooling set point (°C)	24.4	26.19
Reduce lighting power (%)	0[1]	28.25
Reduce equipment power (%)	40	37.98
Fan static pressure (in. H_2O)	3.5	2.43
NMBE	-1.35%	0.09%
CV(RMSE)	7.61%	8.43%

As shown in Table 33, NMBE of the final model was 0.09% and CV(RMSE) was 8.43%. In order to compare with the metrics from (Hale et al. 2014) the five degrees of freedom of the calibration problem were not included in calculation of these metrics. However, considering the five degrees of freedom when calibrating against 12 data points gives NMBE of the final model as 0.17% and CV(RMSE) was 11.92%. These metrics are still within the ASHRAE Guideline 14 recommendations.

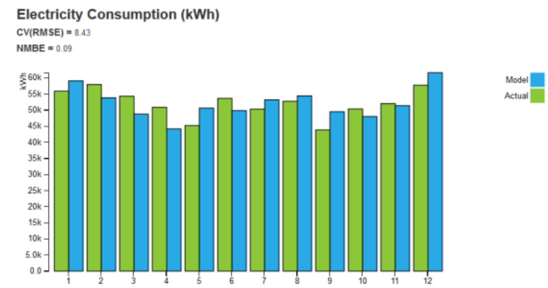

Figure 12 Final Model Calibration Report

CONCLUSION

The advent of commercial cloud computing services gives users access to previously unavailable computing resources for building energy modeling. These resources allow average users to perform large parametric studies customized to their specific buildings, performance and cost assumptions, and design considerations. The OpenStudio parametric workflow described in this paper provides a convenient means for users to perform these types of studies. The workflow was successfully demonstrated for an automated calibration application. However, it can be used for design optimization or sensitivity analysis applications as well.

FUTURE WORK

The OpenStudio parametric workflow described in this paper is functional and useful for a large number of applications, including automated calibration. However, there are many improvements that could increase the usability and utility for the user:

- Improve the PAT to spreadsheet export
- Support more options for cloud resources
- Add support for additional algorithms
- Add more measures for calibration, including hard sizing measures
- Add degrees of freedom as an input to the calibration reporting measure for calculating NMBE and CV(RMSE)
- Add additional calculations and visualizations on the server (e.g., sensitivity heat maps)
- Automate cloud launch from spreadsheet

[1] Lighting schedules were manually modified using the OpenStudio Application.

- Use metrics, such as Akaike Information Criterion (AIC), for comparing calibrations using different parameter sets

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