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Post-Occupancy Evaluation and Partial-Calibration of 18 Design-Phase Energy Models

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POST-OCCUPANCY EVALUATION AND PARTIAL-CALIBRATION OF 18 DESIGN-PHASE ENERGY MODELS

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ABSTRACT

This paper evaluates the accuracy of 18 design-phase building energy models, used for documentation for LEED Canada certification, and analyzes the effectiveness of simple model calibration steps applied to these models. The calibration steps included inputting actual weather data, adding unregulated loads, revising process loads (often with submetered data), and updating a minimal number of other inputs. In net, the design-phase energy models under-predicted the total measured energy consumption by 36%. Following the above outlined calibration steps, this error was reduced to a net 7% under-prediction. For the monthly Energy Use Intensity (EUI) the coefficient of variation of the root mean square error improved from 45% to 24%. Revising the process loads was particularly important in these cases. This step alone increased the EUI by 32% on average (15% median) in the models. This impact far exceeded that of calibrating the weather data, even in a sensitivity test using extreme weather years. These results suggest that although compliance-type energy models can be poor predictors of actual energy use, practitioners may be able to make initial strides toward calibration with relatively little effort.

1 INTRODUCTION

Today energy codes and green building standards promote the wider spread use of building energy simulation during building design. Used primarily for relative comparison rather than absolute prediction, these models may thus be poor predictors of actual energy use in buildings (Ahmad & Culp, 2006). In fact ASHRAE 189.1 specifically alerts users that design phase energy simulations may significantly diverge from actual building energy use "due to variations such as occupancy, building operation... energy use not covered by this procedure..." etc. (ANSI, ASHRAE, USGBC, & IES, 2010). These limitations were demonstrated in a study by Turner & Frankel (2008). They collected data on LEED Version 2 (USGBC,

2001) certified buildings completed between 2001 and 2007. Using their dataset, the current authors found a 41% discrepancy on average (36% median) between predicted and measured EUI in the 92 buildings for which this data was available.

Despite these types of accuracy issues, in a recent survey of 116 energy modelers 75% believed that their design-phase models could provide value during building commissioning and operations (Samuelson, Lantz, & Reinhart, 2012). These energy modelers understood that they would need to calibrate their models, i.e. bring them into better alignment with reality, to some extent first. Despite the potential value of the calibrated models, modelers often find it difficult to convince building owners to invest in this additional service. The calibration process can be time-consuming, and calibration in general has been described as "an art form that inevitably relies on user knowledge… and an abundance of trial and error" (Reddy, 2006). Committing to an extensive calibration process at the outset might be an especially difficult sell to owners, since the process might not lead to any savings if the building already performs as it should.

Researchers have advanced the calibration process (Clarke, Strachan, & Pernot, 1993; Haberl & Bou-Saada, 1998; G. Liu & Liu, 2011). However, research focusing on code-compliance-type models and calibration within the constraints of practice has been limited to date. Meanwhile, a practitioner calibrating a design-phase energy model, built with the intent of comparing design options and demonstrating code compliance, likely faces a different starting point than a researcher calibrating an existing-building (or even a design-phase) model built with post-occupancy uses in mind. The schedule, budget, and available metered data likely differ for the practitioner too. Therefore, for this study the authors chose to study code-compliance type models built and calibrated to some extent in practice. The authors' goals were to quantify the effectiveness of this approach, understand which calibration steps had

the biggest impact, and make recommendations to others interested in using the process in practice.

2 METHODOLOGY

2.1 The Dataset

The authors analyzed a set of 18 commercial building projects located within 100 km (60 miles) of Toronto, Ontario. For each project, modelers from an energy consulting firm had originally built the energy models to support the new building design process and to document energy conservation measures for LEED Canada New Construction or Core and Shell version 1.0 certification (Canada GBC, 2007). The modelers then partially-calibrated the models, typically over the first year of occupancy, to inform the measurement and verification (M&V) and extended commissioning processes. Here the term "partial-calibration" describes the act of bringing the energy model inputs closer to as-operated conditions, as opposed to meeting a defined calibration goal.

The authors started the investigation with all 34 of the firm's model/calibration projects that had at least one year of monthly measured utility data at the time. Importantly, the ten different modelers who built the original models had not documented nor archived their projects with the idea that future researchers would try to recreate their work. As such, data organization became almost prohibitively time-intensive, and nine projects needed to be eliminated due to inadequate documentation. The authors also removed another seven models, which were built in different software, in order to apply the same analysis method uniformly across all remaining 18 cases. The authors repeated each calibration step in order to validate the original calibration process.

All cases were new buildings, completed from 2008 to 2012 and then monitored for at least 12 months. The buildings ranged in size from 416–51,000m^2 (4480-550,000 ft^2) and one to 16 stories. Table 1 provides more project information.

To understand how these cases compare to other LEED-certified projects, the authors compared these cases to the previously mentioned dataset from Turner and Frankel (2008). On average, the current cases exhibited lower energy intensity than the Turner and Frankel buildings (with a mean measured EUI of 241 versus 330 kWh/m^2). However, the model accuracy was similar; here the design-phase simulation predictions deviated by 38% on average (31% median) from the measured EUI compared to 41% (36% median) in the older study.

In the current cases, the energy modelers originally followed the Performance Compliance for Buildings (National Research Council Canada, 1999) protocol, which Canadian practitioners use to demonstrate compliance with the Model National Energy Code for Buildings (MNECB) for Commercial Building Incentive Program compliance (Candian Commission on Building and Fire Codes, 1997) and LEED Canada 1.0. Importantly, this protocol encourages modelers to use default values, according to building type, for the following loads: number of occupants, receptacle power, service water heating, and outdoor air requirements, as well as occupancy, lighting, & operation schedules. Modelers can, however, add process heat gains as an additional input. The modelers used the EE4 version 1.7 software (Natural Resources Canada, 2005), which contains a library of input selections related to the loads above. These values can be over-written, but the onus then falls on the modeler to document exceptional conditions. EE4 is a simulation tool based on the DOE2.1E simulation engine[1] (Hirsch & Regents of the University of California, 1999). EE4v1.7 does not include the following modeling features: exterior lights, elevator usage, steam humidifiers, and special process equipment (Natural Resources Canada Office of Energy Efficiency & CANMET Energy Technology Centre, 2008).

The modelers performed a series of steps to improve the accuracy of the models with reasonable effort, ensuring that each revised input came from a more reliable source or estimate than the original input. In some cases the modelers made adjustments within the energy model, i.e. the EE4 software interface. In other cases, the modelers post-processed the simulation results in a spreadsheet, for example they replaced model-predicted plug-loads with data from building sub-metering. They also used spreadsheet post-processing to add loads from building features that the software interface could not support, as described above.

2.2 Analysis Procedure

2.2.1 Overview

The original modelers performed the calibrations in an ad hoc fashion, for example inputting three-months of actual weather data while simultaneously changing the

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[1] The authors have made available the custom Python scripts created for this research to batch process DOE (.sim) results files and extract key monthly and annual results. These scripts may be helpful to EE4, eQuest, and other .sim file users. available here: https://gist.github.com/hollywas/4757770 https://gist.github.com/alexstorer/4219834.

occupancy schedules. This process hampered anyone from ascertaining which calibration tasks substantially affected the simulations. The authors therefore reran all simulations and systematically isolated each step.

The starting point for each case study was the "design-phase model", i.e. the energy model that the team submitted to demonstrate compliance with the LEED energy credits. After an initial analysis of the cases, the authors divided the original calibration procedure into the following updates: weather, process loads, occupancy, lighting, HVAC equipment, HVAC schedules, infiltration, and unregulated loads. The authors changed one category of inputs at a time and, after each step, identified the net change from the previous model's results.

2.2.2 Weather

The authors compared simulation results using typical versus historical weather data corresponding to the utility measurement periods. The modelers/authors used typical weather data included in the EE4 library, which originated from the Canadian Weather for Energy Calculations (CWEC) database, an amalgamation of 1960-1991 weather data. They obtained the historical weather data from the National Climate Data and Information Archive and formatted it for use in DOE2.1E using the DOEWTH.exe converter (Hirsch & Regents of the University of California, 1999). Since this historical data did not include solar radiation information, a common problem for modelers in many locations, the modelers used solar radiation data from the CWEC typical weather file, a known modeling inconsistency that will be addressed below. The weather converter script uses the monthly average clearness, which the modelers estimated from the hourly CWEC horizontal irradiance and monthly average extraterrestrial radiation for the latitude, per Duffie and Beckman (1991). The authors then used this custom weather data throughout the partial-calibration process.

The authors also performed a sensitivity analysis to investigate the effect of weather on the energy simulation results in extreme weather years. In his research, Crawley (2008) investigated the impact of historical weather data from 1961 to 1999 on the annual simulation results of multiple test-case buildings, in various cities including Toronto. He found that 1998 and 1972 resulted in the lowest and highest simulated energy consumption respectively in his Toronto cases. Therefore the authors used weather data (Environment Canada, 2001) from these two years in their sensitivity analysis.

Due to the known modeling inconsistency with the solar radiation data in the original calibration procedure (solar radiation values in the model may not correlate realistically with temperature and other weather values), the authors then performed a second sensitivity analysis to understand the potential impact of the solar inputs on resulting simulated energy consumption. The 1998 and 1972 weather files (Environment Canada, 2001) did include solar radiation data. The authors performed simulations first using the unadulterated 1998 and 1972 weather data then exchanging the solar radiation inputs for values taken from the CWEC typical weather file.

2.2.3 Other Calibration Categories

The modelers also added unregulated loads to the design-phase models and revised the original process load assumptions. Here, the authors defined "unregulated loads" to include loads, such as elevators and exterior lights that the modelers *totally excluded* from the design-phase models due to code protocol and limitations of the software. In contrast, the authors defined the "process loads" category to include *revisions* to receptacle loads, or other energy consumption not used to light or condition the building. In many cases the modelers originally used the MNECB default values for process load densities and operating schedules as described in Section 2.1, which they later revised.

The authors divided the other model changes into the following categories: HVAC equipment, HVAC operation schedule, occupant density/schedule, lighting, and infiltration. The authors made minor revisions to the modelers' original approaches if they suspected an error or if expanded sub-metered data became available.

3 RESULTS

3.1 Overview

The "goodness-of-fit" between measured and predicted results improved substantially with the partial-calibration, as illustrated in Figure 1. In net, the design-phase energy models under-predicted the cumulative measured energy consumption for all 18 buildings by 36%. Following calibration, this error decreased to a net 7% under-prediction. To avoid the situation of under-predictions and over-predictions partially cancelling each other, the authors used the absolute value of the discrepancy in each building to calculate the following statistics. In this case, the mean annual percent error improved from 38% in the design-phase models to 16% in the partially-calibrated models. The accuracy also improved in terms of monthly normalized mean bias error and coefficient of variation of the root mean square error, improving from 41% to 18% and 45% to

24% respectively. These numbers suggest that the partial-calibration process helped rectify the discrepancy, but some noteworthy building energy use remained unexplained by the models. Trends such as the pervasive design-phase under-predictions may indicate that the modelers need to adjust their future design-phase assumptions.
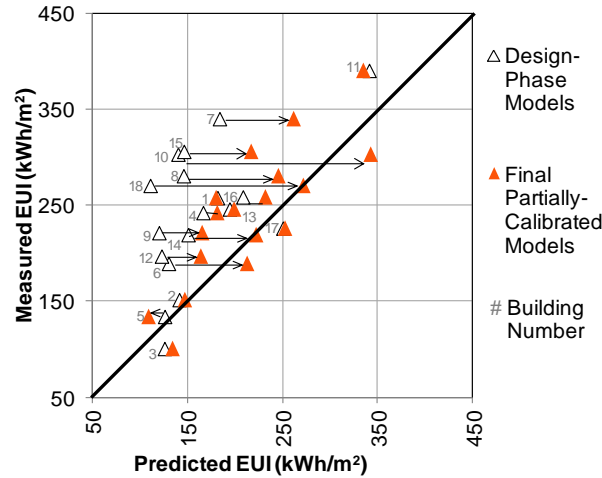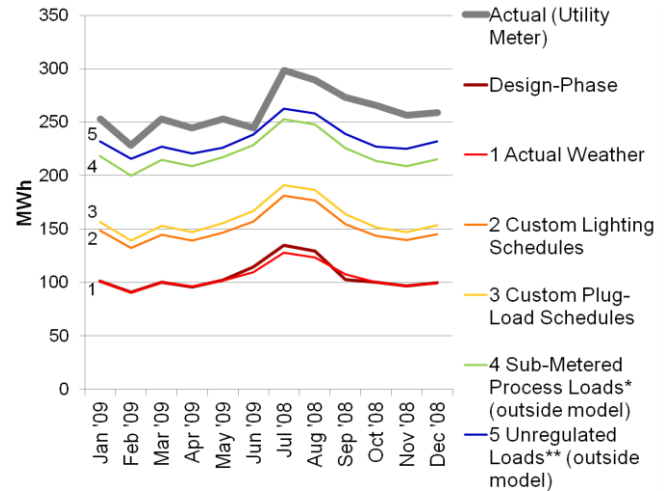

Figure 1: Goodness-of-fit: Design-Phase Models vs. Final Partially-Calibrated Models

Figures 2 & 3 show examples of the step-by-step calibration process for Building 8, a warehouse-type or "big box" store. The authors included this case here because it most clearly delineates the process from one step to another. In contrast, Figure 4 shows the same data for Building 3, an ecology center, which had the highest error statistics and least improvement with calibration, which illustrates that the process did not always improve the model's goodness-of-fit.

Table 2 lists each calibration step and indicates in how many cases the modelers implemented that step. The authors also calculated the mean impact of the step, where implemented, and evaluated the relative effort involved (in the calibration effort itself, not the gathering of input data). The modelers adjusted model inputs when they had more informed values to input, based either on measured data or more refined estimations. Therefore, they implemented three calibration steps in most of the cases --namely, updating process loads, missing unregulated loads, and weather data, since revised values for these inputs were readily obtainable. Therefore, for the group as a whole, those three relatively easy steps accounted for the majority of the model improvement.

Figure 2: Building 8 Calibration-Monthly Electricity
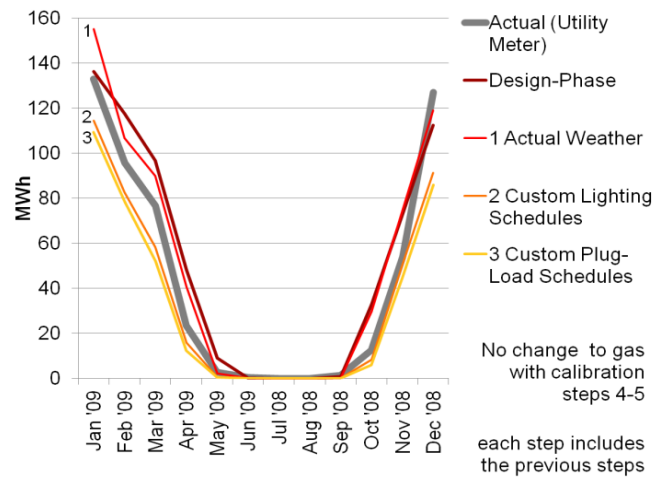

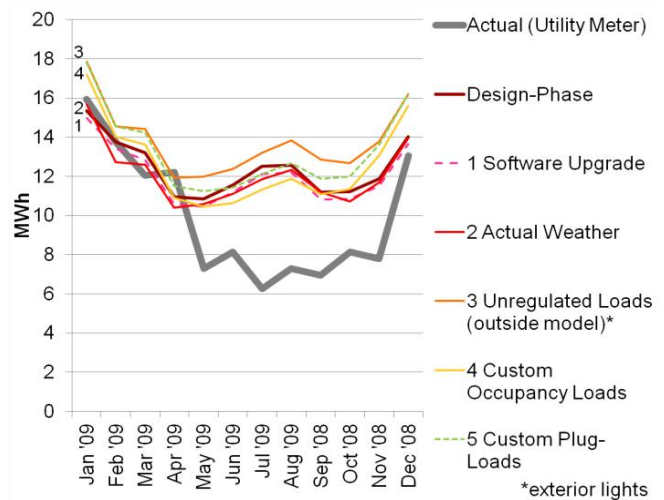*Figure 3: Building 8 Calibration-Monthly Natural Gas*

Figure 4: Building 3 Calibration- Monthly Electricity (all electric building)

The modelers implemented other calibration steps only on a limited portion of the cases, presumably the specific cases where more accurate inputs were available and the modelers believed that their impact would warrant the calibration effort. For example, the modelers had no additional information regarding infiltration rates. Therefore, they resisted adjusting the modeled infiltration rates except in two special cases where they had valid reason to suspect significant problems with the default assumptions, such as the case described in Section 3.5.

3.2 Updating Process Loads

The modelers produced the biggest overall calibration impact, by far, by revising the process loads. As shown in Figure 5, they implemented this step in 14 cases which increased the predicted EUI by 32% on average (15% median). Revised process loads included the following: receptacle loads (in 13 cases), computer servers (in two cases), laboratory equipment, retail displays, battery charging stations, café equipment, and communal laundry (in one case each), using monthly sub-metered data unless otherwise noted. As can be seen in Figure 5, the process loads decreased slightly (2% and 7%) in only two (warehouse-type) buildings and increased considerably in four notable cases.
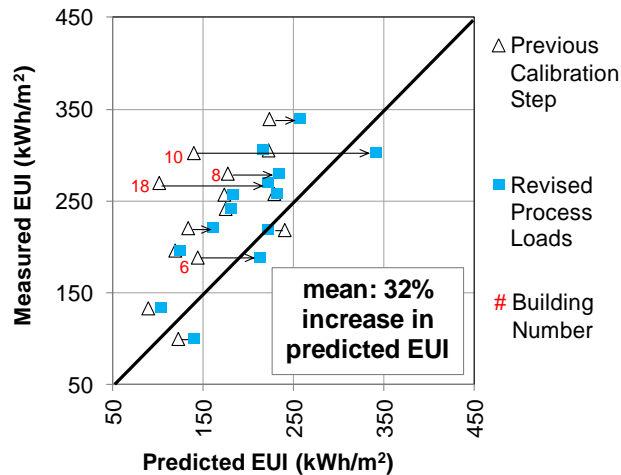

Figure 5: Effect of Revising Process Loads

In Buildings 10 and 18, both large core-and-shell office buildings, the modeler assumed typical office functions using MNECB default loads and schedules. After construction, Buildings 10 and 18 housed more energy-intensive functions including a call center and broadcast equipment respectively. Both cases resulted in much higher sub-metered than predicted process loads. In Building 6, police offices, the sub-metered forensic laboratory loads proved to be much higher than modeled. In Building 8, a warehouse store, the modeler ultimately added missing loads from retail displays

(estimated from short-term measurement) and sub-metered loads from battery charging stations for equipment such as forklifts. Revising the process loads in these four buildings increased the EUI by 145%, 142%, 48%, and 32% respectively.

3.3 Adding Unregulated Loads

The modelers added unregulated loads in all but three cases. Considering the group as a whole, this calibration step made the second largest impact on the predicted EUI. The modelers added missing loads from exterior or parking lighting (calculated via installed lighting power and predicted hours of operation) in 15 cases, resulting in a mean EUI increase of 5% (4% median). The modelers similarly added missing elevator loads (estimated based on measurements from a benchmark building) in eight cases, resulting in a mean EUI increase of 1% (1% median). They also added estimated or metered loads from security equipment, emergency equipment, pool heating, motorized doors, and a snow-melt system (1 case each). In total, the modelers added unregulated loads in 15 cases, which increased the EUI by a mean of 7% (median 5%). The largest impact (32% increase in EUI) from this step occurred in Building 12, a multi-unit residential building, when the modeler added metered loads from a large parking facility.

3.4 Updating Weather Inputs

The modelers replaced the CWEC weather data with historical data in all 18 cases, which changed the EUI by an average magnitude of 2% (2% median). The years 2008-2012 were all warmer than average in Toronto (Environment Canada, 2001), and in this heating-dominate climate, in all but two cases, using the historical weather data resulted in lower simulated energy use. Contrary to expectations, calibrating the weather data generally *increased* the discrepancy between measured and simulated energy use, due to the fact that the less-accurate weather data partially counteracted other inaccuracies in the model at that point in the calibration.

Figure 6 shows the results of these weather calibrations as well as the sensitivity analysis using Toronto extreme weather years, as described in Section 2.2.2. Compared to the CWEC data, the extreme cool year had -18% cooling degree days (CDD) and +23% heating degree days (HDD), whereas the extreme warm year had +20% CDD and -25% HDD. Despite this wide variability, the cool and warm extreme years resulted in only a 4% increase and 8% decrease respectively in simulated EUI, averaged across the 18 cases, compared to the typical-weather year (also 4% and 8% median). In the sensitivity analysis of the impact of solar radiation data

described in Section 2.2.2, the change in solar radiation data produced an average of 1% (1% median) change in EUI over the 18 cases.
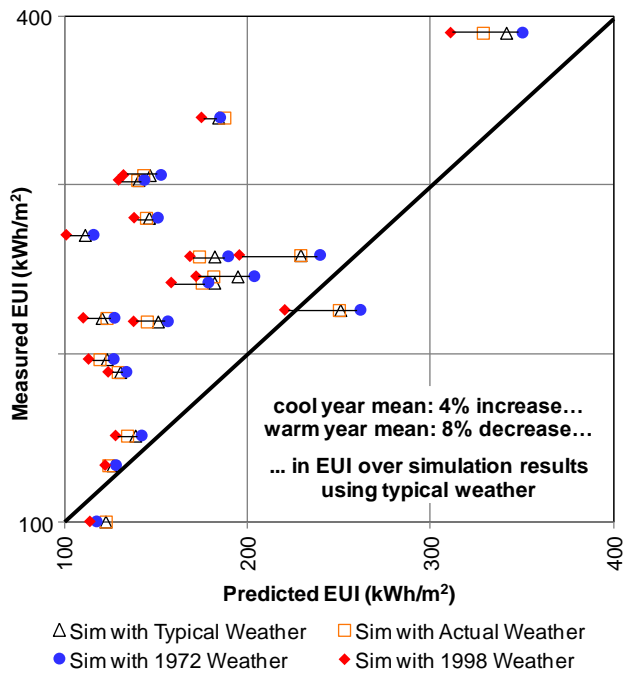

Figure 6: Weather Sensitivity Analysis

3.5 Other Calibration Steps

This section includes the highest-impact cases for each of the remaining calibration categories. In Building 14, a mail sorting warehouse, revising the infiltration rate to consider the often-open loading dock doors made a substantial impact, increasing the simulated EUI by 75%. The new infiltration rate came from the modeler's hand calculations based on opening size, i.e. still estimation, but the modeler believed it to be more accurate than the default assumptions. In Building 18, an office/call center described above, revising the HVAC operation schedules, based on operator interview, increased the EUI by 20%. The installed HVAC equipment differed from the design-phase assumptions in Building 7, a police office. This change increased the predicted EUI by 19%. In Building 8, a warehouse store, the modelers revised the lighting schedules, based on short-term measurements, resulting in a 19% increase in EUI. Conversely in Building 3, an ecology center, their revised occupancy schedules, based on building owner interview, decreased the EUI by 9%.

4 DISCUSSION AND OUTLOOK

4.1 Partial Model Calibration

The previous section revealed that the uncomplicated partial-calibration process described above reduced the annual and monthly mean bias errors between measured and simulated energy use in 18 building by more than 50% compared to using the original design-phase models. This finding is both important and encouraging and the authors recommend that design teams and owners adopt a version of this procedure to improve their compliance-type models. While the revised inputs still may include inaccuracies, the project followed the spirit, if not the details, of an "evidence-based" calibration approach (Raftery, Keane, & O'Donnell, 2011). It is important to note that the 18 case study projects did not receive any additional research funding to support the calibration process described above. This demonstrates that partial model calibration can, in fact, be conducted in a for-profit context.

Revising the process loads generally created the largest impact followed by adding unregulated loads. Both steps required relatively little effort. In some cases, the modelers implemented a spreadsheet shortcut for updating these loads. In those cases, they minimized the calibration effort but excluded the interrelated effects of the revised load on other systems in the model. Even so, this spreadsheet approach could be a cost-effective initial calibration step that the modeler could replace with a more exacting approach later if desired.

Revising the infiltration rate produced a large impact on the two cases where this step was implemented (including estimations based on frequently open loading dock doors). One cannot discern from this experiment whether the infiltration rates in the other buildings warranted more attention in the calibration process.

Where installed, building sub-metering provided valuable data for calibration. Nevertheless, in this research, sub-metering seldom supplied data in the desired level of detail for input into the model. Therefore, translating this coarse-grained data into more granular end-uses and building zones still required effort and judgment. In the future, software developers will likely help address this difficulty. In addition, the practice of building sub-metering is growing with the increasing affordability of equipment (Claridge, 2011) and the influence of codes and standards (ANSI et al., 2010, USGBC, 2009). For these reasons, going forward the effort required for model calibration will likely fall even further.

4.2 Accuracy of Compliance Models

Another, more sobering takeaway from these findings is that the difference between simulated and measured energy use in certified green buildings is actually quite large, averaging 32% (31% median) for the whole

group and reaching as high as 59% in the worst case. This study shows that routinely-voiced claims and/or expectations that future energy use can be predicted to within 10% to 20% during design should be upwardly adjusted. Notably, the bulk of these discrepancies was not caused by the simulation algorithms, the availability of good weather data, or the modelers' ability to reliably model building envelope properties. The main discrepancies were rather a result of the compliance modeling software & protocols (some process loads were not required or even possible to be modeled during design) as well as how buildings are used and operated. For example, in Building 1, a small ecology center and the building most impacted by weather variation, switching from the 1998 (extreme warm year) to 1972 (extreme cool year) weather increased the annual EUI by 23%. This is a large effect, but it nevertheless pales compared to the impact of revising the process loads in Buildings 10 & 18, which increased the EUI by over 140% in each case.

Policy-makers have begun requiring modelers to include more accurate predictions of process loads in an effort to bring compliance model predictions closer to reality (ASHRAE & IESNA, 2010). More research is needed to determine whether modelers are actually capable of predicting these loads accurately in the design-phase. Also, the particulars of the baseline versus design-case modeling protocol generally penalize teams for high loads that are outside of their design control, meaning that modeling protocols may nevertheless incentivize the under-estimating of process loads in the models.

4.3 Calibration Triage

In these cases, the remaining predicted/measured discrepancies helped guide the search for operational problems in the buildings. For example, according to the commissioning agent for Building 8, shown in Figures 2 & 3, the simulation helped uncover a problem with the building automation system, a fault in the energy recovery ventilation equipment, and unintentional off-hours lighting. Higher quality models and calibrations could help the teams uncover more operational problems like these, but at an increased cost.

Building owners may hesitate to invest in an extensive model calibration process to start the investigation, since the process might not lead to remunerable savings if the building already performs generally as it should. A coarse first-pass approach can provide a cost-effective means to identify projects that warrant further calibration effort, just as triage helps to prioritize care

in a hospital emergency room.

The simulated/measured discrepancy can shed light on the potential magnitude of the problem, as illustrated in Figure 7. This graph highlights the unexplained energy expenditures for Building 13, the worst case, in which the building consumed an extra $188,000 per year in electricity and natural gas compared to the partially-calibrated model. For building owners, who must weigh the cost of the investigation and remediation against the potential operational savings, this type of estimate can help owners decide if and how to proceed.
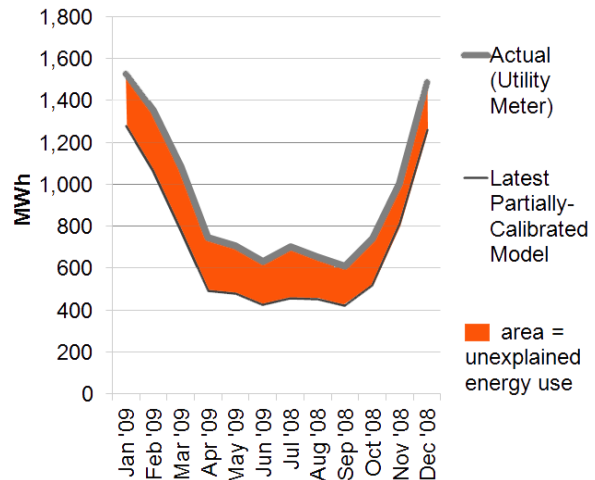

Figure 7: Building 13 Theoretical Potential for Improvement

CONCLUSION

In this research the authors analyzed the partial-calibration process of design-phase energy models, performed within the context of for-profit projects. Practitioners originally built the 18 models to demonstrate compliance with the LEED Canada version 1.0 rating system in buildings constructed between 2008 and 2012. The partial-calibration effort focused on adding value to the design-phase models within limited calibration budgets and schedules. The modelers performed the original calibration steps in an ad-hoc fashion, and the authors recreated the process systematically in order to discover the calibration tasks that provided the highest impact for the least effort. In aggregate, the partial-calibration process improved the annual and monthly mean bias errors of the design-phase models by more than 50%. In these cases the bulk of this improvement came from revising the plug-loads and adding unregulated loads. In general, the impact of each of these calibration steps far exceeded that of the change from CWEC to historic weather data, and each of these calibration steps required relatively little effort.

ACKNOWLEDGEMENTS

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Table 1: Characteristics of Building Cases

Building #	Area (m²)	Building Type	Stories	LEED Canada 1.0 version
1	416	Ecology Center	2	New Construction
2	1,037	Ecology Center	2	New Construction
3	1,185	Ecology Center	1	New Construction
4	5,575	Office	3	New Construction
5	7,934	Office	4	Core & Shell
6	4,148	Police Office with Laboratory	2	New Construction
7	10,879	Police Office	2	New Construction
8	13,000	Warehouse-Type Retail, non-food	1	New Construction
9	10,590	Warehouse-Type Retail, non-food	1	New Construction
10	51,000	Office	8	Core & Shell
11	12,600	Higher Education (labs, classrooms, office, assembly)	5	New Construction
12	16,568	Social Multi-Unit Residential Building (MURB)	15	New Const. (MURBs)
13	45,700	MURB (two buildings)	14 & 16	New Const. (MURBs)
14	1,730	Mail Sorting/Warehouse	1	New Construction
15	1,147	Mail Sorting/Warehouse	1	New Construction
16	4,130	Higher Education (classrooms)	2	New Construction
17	18,013	Luxury MURB (two buildings)	10 & 8	New Const. (MURBs)
18	27,000	Office/Call Center	10	Core & Shell

Table 2: The Calibration Steps Implemented, their Impact, and the Effort Involved

Calibration Step	Number of Cases Including this Step	Mean [median] Change in EUI, where implemented	Effort Involved
Replacing Typical with Actual Weather	**18**	-2% [-2%]	Easy to moderate
Revising Process Loads	**14**	**32%** [15%]	Via spreadsheet = easy* In model = moderate*
Adding Unregulated Loads	**15**	7% [5%]	Via spreadsheet. easy
Revising Occupant Density/Schedules	4	-4% [-6%]	Moderate*
Revising Lighting Density/Schedules	3	11% [11%]	Moderate*
HVAC Updates (not including schedules)	3	9% [7%]	Depends
Infiltration	2	**58%** [58%]	Easy
HVAC Schedules	1	**20%** [20%]	Moderate
Revising Domestic Hot Water	1	-6% [-6%]	Via spreadsheet. easy

* if information is available. More zones in model = more effort.