RAPID MODELING OF BUILDINGS WITH CALIBRATED NORMATIVE MODELS

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ABSTRACT

High-order models of building performance are the preferred tool, but their complexity and time requirements can cause difficulties when attempting to create large sets of models or when used by non-experts. Reduced-order models require fewer inputs and are simpler, but typically sacrifice accuracy for speed. This paper describes a methodology and case study for the calibration of reduced-order models using limited sets of high-order models which significantly increases the accuracy of the reduced-order model while maintaining efficiency, focusing on the examination of energy conservation measures (ECMs) applied to large portfolios of buildings.

INTRODUCTION

The development of energy consumption models can be time consuming and complex. (Clarke, 2001) The typical trade-off between accuracy and flexibility for speed and simplicity prevents any one modeling program from holding dominance over the others. (Crawley, 2008) Energy Plus is often considered to be the industry standard for building energy consumption models. (Crawley et al, 2001) Developed by the DOE and refined through use over decades, Energy Plus supplies accurate and reliable results. However, the model is relatively complex, requires experience to master, and it can be time consuming to generate results (Kalogirou. 2000, Garg, 2011). As a result, jobs requiring hundreds of models to be constructed may seem daunting, however, alternatives do exist. (Crawley, 2008)

Reduced-order models take advantage of normative equations to create rich energy consumption information quickly and with fewer inputs. (Akhtar 2012) To accomplish this reduced order models are typically not as accurate or flexible as physics based models, such as Energy Plus, but when used in the proper context they provide rapid, reasonably accurate results. (Gouda, 2000) These are advantageous qualities when a large number of models must be constructed or when the resulting tool needs to be usable by non-experts. The question posed by this paper is: Can the accuracy of reduced-order models be increased if they are calibrated against physics based models, such as Energy Plus, and is this accuracy retained as the reduced order model is varied to simulate different conditions?

There were three primary reasons envisioned for the development of a methodology for reduced-order model calibration using higher-order physics based models. Firstly, it was hoped that calibrated reduced-order models could be used to increase the speed at which the large numbers of models could be created and run. Secondly, it would serve as a quality control and quality assurance mechanism by duplicating some, or all, of the more complex higher-order, physics-based models. Finally, there was a desire to develop a standard methodology for calibrating simple, but less accurate, low-order models against complex, time consuming, high-order models in order to provide a simple reduced-order model that could be used as a close analogue to the high-order model, but one which could easily be used by non-experts to quickly obtain accurate results.

To provide the test bed in which a formal methodology for the generation of calibrated, reduced order models could be developed, an ongoing research effort was found that required a large number of models to be generated in a very limited period of time. The AER Macro-model is a tool that estimates the influence of policy and technological changes on the adoption of energy efficiency retrofits within a metropolitan region. (Hendricken, 2012; Otto, 2012) It accomplishes this by examining the existing building stock within a region and dividing it into typologies based on function, such as retail, commercial, multi-family residential, etc., and then splitting these into even more specific sub-typologies. The existing building stock within each of these sub-types is examined and baseline models are developed to describe their construction and performance. (Hendricken, 2012; Otto, 2012) The baselines are used to determine how much energy per square foot is used by buildings with similar construction.

Additional models are then constructed to determine the energy consumption of each baseline if various energy conservation measures or packages of measures were applied. By doing this for all sub typologies, the energy consumption per square foot of any type of construction may be determined, as well as the relative and absolute effectiveness of each type of ECM or combination of ECMs. This information can be used to describe the energy consumption and resulting carbon emissions of the built environment of the region, but it forms the basis for making projections of how that building stock might change over time and how the emissions would change as a result. (Otto, 2012; Hendricken, 2012)

The large number of permutations of ECMs that could be applied to the baselines makes this a perfect application for calibrated reduced order models, as they can be constructed and run quickly and simply while retaining a high level of accuracy from the calibration of the baselines against equivalent Energy Plus models. The reduced order model chosen for this study was the Building Performance Analysis Toolkit (BPAT+). (T.C. Chan Center, n.d.) BPAT+ was developed from an American adaptation and automation of NEN 2916 and was prepared for the General Service Administration (GSA) called the GSA Toolkit (now known as EPSCT). (Lee, 2012) It is a reduced-order model of energy consumption for buildings that is capable of producing accurate estimates of annual heating, cooling, electrical, and other forms of energy consumption within buildings. It was designed to use normative equations based on the average energy consumption of other buildings of similar subtypes. This allows it to avoid many of the complex, physics-based equations used by higher order models, such as Energy Plus, saving computation time and requiring fewer input variables.

Since it is prohibitively expensive to install a full range of sub-meters on every building on a large campus (Lewis, 2011), the BPAT+ models have served as an alternative to estimate both the current energy usage of buildings on a subsystem level, as well as to estimate how those subsystem energy consumption levels might change under different conditions. It has also been used to identify problem areas within individual buildings, such as when more energy is being consumed by a building than the model predicts. BPAT+ is well suited to this task as it allows quick snapshots of a buildings expected energy usage to be taken without significant input of time or resources. BPAT+ was first extensively utilized outside of the University of Pennsylvania campus when it was applied to the Philadelphia Navy Yard as a part of the research being conducted by the DOE funded Energy Efficient Building (EEB) Hub.

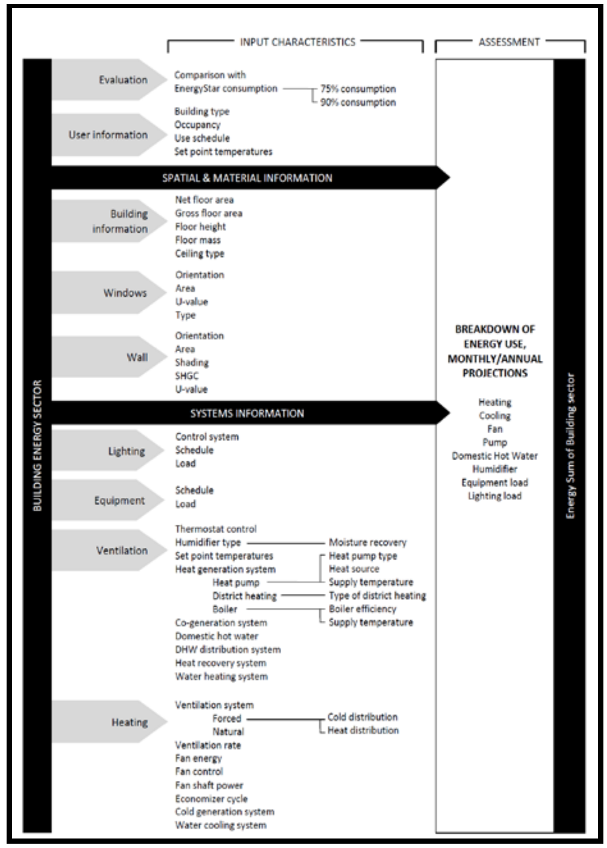

Figure 1: Description of BPAT+ Inputs and Outputs

For this study, models of six row-home baseline constructions were created using both Energy Plus and BPAT+. The BPAT+ models were then calibrated against the Energy Plus models and were used to predict the effects of several hundred energy conservation measures that could potentially be applied to the baselines. These results were compared to the results provided by the Energy Plus models when the same ECMs were applied to those baseline models. A comparison of the results showed that the calibration of reduced order models against physics based models does improve the accuracy of the reduced order model and that the effects of this increase in accuracy remain even when the models are altered to reflect potential changes to the building.

METHODOLOGY

The Building Performance Analysis Toolkit (BPAT+) is a normative model of energy consumption used to create energy consumption models providing rich information with simple information. While Energy Plus is a complex, high-order physics based model of energy consumption, which produces very accurate models but which take a long time to construct and run, BPAT+ models are less accurate but may be completed with less information, in less time, and are less prone to errors due to a less complex construction process. The baseline models of the row-home sub-typology created in BPAT+ were created in parallel with models created in Energy Plus.

The Energy Plus models were constructed using the same input parameters so that similar, pre-calibration outputs were expected. The outputs from the two models were then compared and the BPAT+ model was calibrated against the Energy Plus model to increase its accuracy. The calibration took place by making slight adjustments to the operating schedules for lighting and plug loads, as well as minor adjustments to the thermostat set points, in the BPAT+ models. Through this calibration it was hoped that BPAT+ would become a fast and accurate reduced-order model, with the simpler BPAT+ gaining much of the accuracy seen in the more complex Energy Plus models. BPAT+ could then be used to create large sets of models which rely on many variations to a limited set of baselines.

This would be applicable to the task of creating the hundreds of models which apply various ECM packages to the row-home baselines to determine their effect on energy consumption as it would require far less time than would be required to create and run the same models and permutations in Energy Plus. Once calibrated baselines were created in BPAT+, sets of energy conservation mechanisms (ECMs) were applied to the baseline models to determine the effects that different HVAC, envelope conditions, equipment usage, and operational changes might have on energy consumption. The large number of ECM combinations that needed to be modeled meant that the faster BPAT+ would have a significant advantage over Energy Plus in terms of completing the task within the timeline identified. The information from the baseline and ECM models would then be fed into the macro-model structure.

While a formal methodology and comprehensive results for the calibration of reduced-order models against physics based models was not able to be developed through this work, the results were promising for the concept. Calibration proved to be possible and the initial results suggest that the accuracy gained through the calibration is maintained even as the reduced order model is altered to represent potential renovations to the building. The use of calibrated-reduced order models still holds significant promise for non-expert users, particularly the owners and operators of large portfolios of buildings. If calibrated reduced-order models, which could be quickly and easily maintained and operated by the people managing the buildings, could be left in their hands then the expense and time associated with energy simulations could be greatly reduced allowing for a more complex and nuanced consideration of energy efficiency retrofit options by decision makers.

Two factors interfered with the development of a formal methodology for creating calibrated-reduced order BPAT+ models. First, there were significant delays encountered when attempting to calibrate the BPAT+ baseline models against the Energy Plus models for the row-home baseline models. This was primarily due to repeated errors in the creation of the Energy Plus models which returned results that could not be matched to BPAT+ results. While this lead to the discovery and correction of these errors, it also delayed progress significantly and so full calibration was never achieved.

The delays encountered led to the decision to use the Energy Plus add-on module, jEPlus, which automated much of the process of making multiple series of model runs under varying conditions. This add-on program enables hundreds of simulations to be performed overnight with little manual interaction beyond setting up the database of inputs and a file to receive the results. This allowed the high-order Energy Plus models to be created and run even faster than could be accomplished with BPAT+, which relies on manual changes to be made for each model between runs. While this did not undermine the premise for the utility of using calibrated, reduced-order models in lieu of a large set of high-order physics based models, this development made the practice less efficient given the time constraints of this particular application. While jEPlus was used to produce many of the results used in this experiment, this was only possible through the time and efforts of a simulation expert and would not have been as effective in other circumstances.

Due to these two factors, the use of BPAT+ was altered to emphasize the quality control aspects of its application. Rather than simply running parallel baseline models with Energy Plus for the purpose of calibration, parallel models were also created for single ECMs being applied to those baselines as well as for select packages of ECMs. These results were compared and used to refine the input parameters being used to develop these models in Energy Plus, as well as to look for potential errors in the results and in the construction of the model. This alteration had the added benefit of generating additional points of comparison between the models in BPAT+ and in Energy Plus once they had deviated from the baseline, providing a better test of the accuracy and flexibility of the calibrated, reduced order models.

Basic Parameters of Baselines (2 of each age with different HVAC systems were made)	Volume	Wall Area	Roof Area	Window Area	Wall Ins R-Value	Total Wall R-Value	Roof Ins R-Value	Total Roof R-Value	Window U-Value	Window SHGC	Infiltration Rate	Lighting Density	Equipment Density
	(ft^3)	(ft^2)	(ft^2)	(ft^2)	((h-ft^2-°F) /Btu)	((h-ft^2-°F) /Btu)	((h-ft^2-°F) /Btu)	((h-ft^2-°F) /Btu)	(Btu/ (h-ft^2-°F))		(h^{-1})	(W/ft^2)	(W/ft^2)
Baseline 1 (old, Pre-1950)	12,015	673	1,088	125	0	16.20	5	8.14	1.04	0.86	1.25	1.80	16.36
Baseline 2 (newer, 1950-1980)	12,015	673	1,088	125	5	8.39	11	13.24	1.04	0.86	0.63	1.80	16.36
Baseline 3 (newest, Post-1980)	12,015	673	1,088	125	13	15.19	19	20.04	0.48	0.76	0.31	1.80	16.36

Figure 2: Input Parameters for Baseline Models

APPLICATION OF METHODOLOGY AND RESULTS

The first task was to develop the theory and methodology by which the BPAT+ simulations would be compared and calibrated against the Energy Plus models that were being created in parallel. Six baseline buildings were modeled in both Energy Plus and in BPAT+. The baselines were based on common typologies of homes found within the row-home sub-type and they primarily differed in terms of their envelope composition and the HVAC systems used to condition their spaces. The characteristics of the baselines were derived primarily from the CBECs building database and other regional databases for building characteristics. Assuming that the baseline results were similar for both the Energy Plus and BPAT+ runs, the BPAT+ models were then calibrated against the Energy Plus models, which were believed to be more accurate, so that the results would be made to match as closely as possible.

The layout of each of the baselines was identical. Each building had 1,100ft^2 of gross floor area and consisted of two floors. Each was assumed to be a middle unit, rather than an end unit, and as such only presented narrow north and south orientations to the external environment, while the two larger east and west walls were considered to be adiabatic. The southern orientation had a window to wall ratio of 0.32 and the northern orientation had a window to wall ratio of 0.16. Each was assumed to be occupied by 4 individuals and the temperature set points for winter and summer were initially assumed to be 68 and 72 degrees Fahrenheit. Most other parameters did not remain constant between the baselines. The primary differences between the baselines were in the thermal resistive properties of the envelope or in the efficiencies of the heating or cooling systems used.

Once the baseline models were parameterized and the basic methodology for calibrating the BPAT+ models had been developed the six single-family attached baselines were created in both Energy Plus and BPAT+. Many issues arose at this point that were ultimately mostly attributed to errors in the creation of the Energy Plus models. The initial results from the two models were far enough from each other that the BPAT+ model could not be calibrated to match the Energy Plus results without introducing parameters that were ludicrous or physically impossible. When this first occurred there was substantial debate as to which model was correct and which contained errors. Eventually a significant error was discovered in the Energy Plus models where the walls that were attached to other buildings were being modeled as though they were exposed to the outside air, resulting in unusually high energy consumption predictions. This error was corrected but the models still could not be successfully matched. This process repeated several times, and each time the discrepancy was discovered to be due to an error in the construction or operation of the Energy Plus models, which lends significant support to the idea of utilizing a simpler reduced-order model, as a quality control step if nothing else, that would present fewer opportunities for improper parameter inputs or simple construction errors.

When the baselines constructed in BPAT+ were successfully calibrated against the baselines created in Energy Plus and all of the errors in the construction of the models had been eliminated, the outputs of the two models were quite close to one another. Figure 3 summarizes the annual consumption estimated from a variety of sectors of building operation predicted by each set of models and calculates the percentage deviation in the consumption predicted by BPAT+ compared to Energy Plus. 62% of the two models' outputs were within 1% of each other after calibration and 82% were within 3%. None of the outputs deviated by more than 7.5% and only 7% of the BPAT+ baseline outputs deviated from the Energy Plus results by more than 5%. This high level of congruity was expected at this stage due to fact that the calibration against the Energy Plus models had just occurred with no changes made afterwards.

This stage served as an initial check point to confirm that the reduced-order BPAT+ models could, in fact, be reasonably calibrated against the Energy Plus models. Failure to achieve parity through calibration was assumed to indicate an error in the construction of either the BPAT+ or the Energy Plus models. This was demonstrated several times when discrepancies between the two sets of results successfully identified construction errors in the Energy Plus models that lead to inaccurate results. Once the BPAT+ models had been calibrated it was hypothesized that they would then behave similarly to the models created in Energy Plus when changes were introduced to the input parameters. This would allow the hundreds of permutations of ECM packages that could be applied to each baseline to be modeled quickly in BPAT+ while maintaining the accuracy of Energy Plus.

The initial work plan called for a select number of ECM permutations were to be run in Energy Plus to confirm that the results remained close after changes were made to the inputs, while the majority of the models would be constructed in BPAT+ alone due to the greater speed with which they may be developed and run using the reduced-order model. The results of BPAT+ would have then been used to supply the macro-model with the information needed regarding the energy consumption of each baseline under all possible ECM combinations. This would be used to both determine the carbon footprint of the existing stock but also to inform economic factors which are used to determine how that stock might change in composition over time based on the decision making process building owners go through when contemplating a renovation.

As noted earlier, two factors caused this initial plan to be changed: the length of time needed to correct the errors in the Energy Plus baselines during the calibration process and the discovery of an Energy Plus add-on which would allow this particular task to be performed more quickly than normal. jEPlus allows large batches of ECM permutations to be run automatically with minimal time or interference from a researcher. This allowed Energy Plus to effectively run the simulations faster than they could be

Energy+ (kWh)	Heating	Cooling	Vent.	Refrig.	Lighting	Cooking	DHW	Lg Plug	Sm Plug
Baseline 1a	14,486	1,639	29	1,577	2,738	2,132	6,873	1,934	1,563
Baseline 1b	14,486	5,590	435	1,577	2,738	2,132	6,873	1,934	1,563
Baseline 2a	6,877	1,639	82	1,577	2,738	2,132	6,873	1,934	1,563
Baseline 2b	6,877	5,143	357	1,577	2,738	2,132	6,873	1,934	1,563
Baseline 3a	1,483	3,873	218	1,577	2,738	2,132	6,873	1,934	1,563
Baseline 3b	970	3,873	209	1,577	2,738	2,132	6,873	1,934	1,563

Energy+ (kWh)	Heating	Cooling	Vent.	Refrig.	Lighting	Cooking	DHW	Lg Plug	Sm Plug
Baseline 1a	14,486	1,639	29	**Added to Lg Plug to match BPAT+ outputs**	2,738	2,132	6,873	5,074	**Added to Lg Plug to match BPAT+ outputs**
Baseline 1b	14,486	5,590	435		2,738	2,132	6,873	5,074	
Baseline 2a	6,877	1,639	82		2,738	2,132	6,873	5,074	
Baseline 2b	6,877	5,143	357		2,738	2,132	6,873	5,074	
Baseline 3a	1,483	3,873	218		2,738	2,132	6,873	5,074	
Baseline 3b	970	3,873	209		2,738	2,132	6,873	5,074	

BPAT+ (kWh)	Heating	Cooling	Vent.	Refrig.	Lighting	Cooking	DHW	Lg Plug	Sm Plug
Baseline 1a	15,137	1,639	29	n/a	2,749	2,130	6,869	5,084	n/a
Baseline 1b	14,263	5,328	435		2,749	2,130	6,869	5,084	
Baseline 2a	6,630	1,639	88		2,749	2,130	6,869	4,781	
Baseline 2b	7,134	5,253	345		2,749	2,130	6,869	4,780	
Baseline 3a	1,490	3,803	214		2,749	2,130	6,869	5,110	
Baseline 3b	1,010	3,954	214		2,749	2,130	6,869	5,072	

% Difference	Heating	Cooling	Vent.	Refrig.	Lighting	Cooking	DHW	Lg Plug	Sm Plug
Baseline 1a	**4.5%**	**0.0%**	**-2.0%**	n/a	**0.4%**	**-0.1%**	**-0.1%**	**0.2%**	n/a
Baseline 1b	**-1.5%**	**-4.7%**	**-0.1%**		**0.4%**	**-0.1%**	**-0.1%**	**0.2%**	
Baseline 2a	**-3.6%**	**0.0%**	**7.4%**		**0.4%**	**-0.1%**	**-0.1%**	**-5.8%**	
Baseline 2b	**3.7%**	**2.1%**	**-3.5%**		**0.4%**	**-0.1%**	**-0.1%**	**-5.8%**	
Baseline 3a	**0.5%**	**-1.8%**	**-1.6%**		**0.4%**	**-0.1%**	**-0.1%**	**0.7%**	
Baseline 3b	**4.2%**	**2.1%**	**2.7%**		**0.4%**	**-0.1%**	**-0.1%**	**0.0%**	

Figure 3: Comparison of BPAT+ and Energy+ Baseline Energy Consumption

performed in BPAT+ and thus removed some of the benefits of performing the majority of the ECM permutations in BPAT+ at all. Since BPAT+ had been very effective at spotting errors in the Energy Plus baselines as they were being created it was decided that, while the majority of the modeling would be shifted to Energy Plus, BPAT+ would still be used to confirm the results of the every ECM that was applied on its own as well as for several packages of ECMs.

	Projected Data	Heating	Cooling	Ventil.	Lighting	Cooking	DHW	Plug Loads
ECM #	Scenario Name (Baseline + ECM Package)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)
0	MFH_A_1a	14,464	716	150	2,748	2,130	6,867	5,086
1	MFH_A_1a+Home Weatherization	8,717	716	150	2,748	2,130	6,867	5,086
2	MFH_A_1a+Professional Weatherization	6,124	716	150	2,748	2,130	6,867	5,086
3	MFH_A_1a+Double Pane w/ Low-e	10,871	716	150	2,748	2,130	6,867	5,086
4	MFH_A_1a+Double Pane w/ Low-e and Argon/Krypton	10,591	716	150	2,748	2,130	6,867	5,086
5	MFH_A_1a+Triple Pane	10,513	716	150	2,748	2,130	6,867	5,086
6	MFH_A_1a+Triple Pane w/ Low-e	10,416	716	150	2,748	2,130	6,867	5,086
7	MFH_A_1a+Triple Pane w/ Low-e and Argon/Krypton	10,259	716	150	2,748	2,130	6,867	5,086
8	MFH_A_1a+R-13 Batt Wall	7,139	716	150	2,748	2,130	6,867	5,086
9	MFH_A_1a+R-21 Spray Wall	6,458	716	150	2,748	2,130	6,867	5,086
10	MFH_A_1a+R-20 Batt Roof	12,542	716	150	2,748	2,130	6,867	5,086
11	MFH_A_1a+R-40 Batt Roof	11,973	716	150	2,748	2,130	6,867	5,086
12	MFH_A_1a+R-60 Spray Roof	11,736	716	150	2,748	2,130	6,867	5,086
16	MFH_A_1a+Setback Thermostats	12,429	716	150	2,748	2,130	6,867	5,086
19	MFH_A_1a+Permanent Overhangs	16,254	716	150	2,748	2,130	6,867	5,086
20	MFH_A_1a+CFL	14,600	716	150	687	2,130	6,867	5,086
21	MFH_A_1a+LED	14,623	716	150	343	2,130	6,867	5,086
22	MFH_A_1a+Occupancy Sensors	14,510	716	150	2,061	2,130	6,867	5,086
24	MFH_A_1a+Low Flow Fixtures	14,510	716	150	2,748	2,130	4,806	5,086
25	MFH_A_1a+Energy Star Appliances	15,387	716	150	2,748	2,130	4,806	4,075
26	MFH_A_1a+Smart Power Strips	14,787	716	150	2,748	2,130	6,867	4,725
27	MFH_A_1a+HVAC 2	12,656	716	150	2,748	2,130	6,867	4,725
28	MFH_A_1a+HVAC 3	11,250	716	150	2,748	2,130	6,867	4,725

Figure 4: Raw Results of BPAT+ Single ECM Runs for Baseline 1a

Since BPAT+ was not applied to the full set of ECM packages it was not able to be determined if the calibrated reduced order model would retain its accuracy as the model parameters shifted further from the initial baseline conditions. However, the data gathered from the examination of the application of single ECMs to the baselines indicates that a high level of parity remains between Energy Plus models and the BPAT+ models that were calibrated using them, even after changes are made to the parameters that were utilized during the calibration process. However, these results were not perfect, as substantial deviation can be seen in some ECM sets in Figure 5. It can be seen that substantial deviation occurred in those ECMs relating to changes to the envelope's thermal resistive properties so that the BPAT+ models benefits substantially more than the Energy Plus models when insulation is improved.

This is most likely indicative of a lingering problem in the initial calibration whereby the close results were generated by the calibration but where differences in the underlying models remained which caused the two to perform differently. However, significant time constraints had arisen by the end of the study. While the original goal was to completely model the multi-family residential sector, only a single sub-type had been significantly examined up until this point. As a result it was not possible to return to the baselines to discover the underlying error and to recalibrate and the results gathered from the examination of row-homes were forced to serve as the only available data.

	Projected Data	Heating	Cooling	Ventil.	Lighting	Cooking	DHW	Plug Loads
ECM #	Scenario Name (Baseline + ECM Package)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)	(kWhr)
0	MFH_A_1a	-0.4%	-0.6%	-1.1%	0.4%	-0.1%	-0.1%	0.2%
1	MFH_A_1a+Home Weatherization	-0.2%	-0.6%	57.9%	0.4%	-0.1%	-0.1%	0.2%
2	MFH_A_1a+Professional Weatherization	2.7%	-0.6%	120.9%	0.4%	-0.1%	-0.1%	0.2%
3	MFH_A_1a+Double Pane w/ Low-e	-19.7%	-0.6%	6.3%	0.4%	-0.1%	-0.1%	0.2%
4	MFH_A_1a+Double Pane w/ Low-e and Argon/Krypton	-20.4%	-0.6%	7.7%	0.4%	-0.1%	-0.1%	0.2%
5	MFH_A_1a+Triple Pane	-21.6%	-0.6%	7.0%	0.4%	-0.1%	-0.1%	0.2%
6	MFH_A_1a+Triple Pane w/ Low-e	-22.5%	-0.6%	7.2%	0.4%	-0.1%	-0.1%	0.2%
7	MFH_A_1a+Triple Pane w/ Low-e and Argon/Krypton	-22.6%	-0.6%	8.4%	0.4%	-0.1%	-0.1%	0.2%
8	MFH_A_1a+R-13 Batt Wall	-39.8%	-0.6%	33.7%	0.4%	-0.1%	-0.1%	0.2%
9	MFH_A_1a+R-21 Spray Wall	-44.2%	-0.6%	38.3%	0.4%	-0.1%	-0.1%	0.2%
10	MFH_A_1a+R-20 Batt Roof	1.2%	-0.6%	14.0%	0.4%	-0.1%	-0.1%	0.2%
11	MFH_A_1a+R-40 Batt Roof	2.0%	-0.6%	19.1%	0.4%	-0.1%	-0.1%	0.2%
12	MFH_A_1a+R-60 Spray Roof	2.3%	-0.6%	21.3%	0.4%	-0.1%	-0.1%	0.2%
16	MFH_A_1a+Setback Thermostats	-1.1%	-0.6%	11.6%	0.4%	-0.1%	-0.1%	0.2%
19	MFH_A_1a+Permanent Overhangs	10.7%	-0.6%	-1.7%	0.4%	-0.1%	-0.1%	0.2%
20	MFH_A_1a+CFL	-2.7%	-0.6%	-3.1%	-9.4%	-0.1%	-0.1%	0.2%
21	MFH_A_1a+LED	-3.2%	-0.6%	-3.4%	-4.8%	-0.1%	-0.1%	0.2%
22	MFH_A_1a+Occupancy Sensors	-1.2%	-0.6%	-1.8%	-9.0%	-0.1%	-0.1%	0.2%
24	MFH_A_1a+Low Flow Fixtures	-6.5%	-0.6%	-5.6%	0.4%	-0.1%	-0.1%	0.2%
25	MFH_A_1a+Energy Star Appliances	-3.1%	-0.6%	-7.6%	0.4%	-0.1%	-0.1%	-4.1%
26	MFH_A_1a+Smart Power Strips	1.6%	-0.6%	-1.3%	0.4%	-0.1%	-0.1%	-5.4%
27	MFH_A_1a+HVAC 2	-12.8%	-0.6%	-1.1%	0.4%	-0.1%	-0.1%	-6.9%
28	MFH_A_1a+HVAC 3	-22.5%	-0.6%	-1.1%	0.4%	-0.1%	-0.1%	-6.9%

Figure 5: % Difference between the BPAT+ and Energy Plus Single ECMs for Baseline 1a

CONCLUSIONS

The results of utilizing BPAT+ to generate the energy consumption data needed to populate the AER macro-model were mixed. Of the stated goals, several were unable to be completed due to time constraints or due to the discovery of a more efficient method part way through the study. The primary purpose that BPAT+ was to be utilized was to increase the speed with which the many different combinations of ECMs that might be applied to the baselines in this specific case study. Two factors rendered this task first difficult and then pointless. The theory was that the accuracy of the reduced order model, BPAT+, could be increased if it were calibrated against the higher order model, but this calibration proved to be difficult and time consuming.

The length of time was partially due to BPAT+ completing its second task, to serve as a quality control mechanism. In this capacity it repeatedly enabled the detection of errors in the construction of the Energy Plus models, which would have provided wildly inaccurate results had these errors not been detected. However, each time an error was detected, the Energy Plus baseline models would need to be corrected and rerun, a process which often took a week or two. Several months were lost trying to find and correct errors in the Energy Plus models.

It was during this time it was decided to use jEPlus to complete the simulations of the ECM packages. While running individual models in Energy Plus takes longer than an individual model in BPAT+, since this particular project involved only 6 baselines and then many small changes to these, jEPlus was able to complete the batch of several hundred runs in significantly less time than BPAT+ would have been capable. So while BPAT+ proved to be very effective at its second task, quality control, it ended up being the slower of the two options for running large batches of permutations of a small number of models. Because of this, and because of the time constraints introduced through the long error checking process, there was no opportunity to refine and perfect a methodology for calibrating reduced-order models against high-order models, which was the third task we had hoped to accomplish.

Of the three tasks, only the third remains incomplete. The first task, to provide speedy results to the AER macro-model, was abandoned as a more effective method was discovered and the second task, to serve as an error check for the development of the more complex Energy Plus models, was very successful. While this work did not provide the opportunity to refine and develop a methodology for calibrating reduced-order models against high-order models, which would have been based on the abandoned work in the first task, the potential use of such a methodology remains and the results of the show promise for the technique.

While Energy Plus was able to be used more quickly in this circumstance, the difficulties experienced this year showed that the complexity of higher order models, such as Energy Plus presents an ongoing obstacle to the construction and use of energy consumption models by non-experts. Accurate reduced-order models could be created by energy experts, properly calibrated, and then handed to building owners, portfolio managers, or tenants as a simple tools that could provide them with information on the performance of their building as it currently is, but more importantly giving them an energy analysis tool that they could utilize on their own to help with energy retrofit or operational decisions without having to hire a consultant.

Such a tool could increase the speed at which organizations make decisions and reduce costs for determining the impacts of changes to their buildings. However, since BPAT+ was not used as a reduced-order model to generate data for the AER macro-model and too much time was expended trying to fix the Energy Plus models, there was simply insufficient time to formally develop the methodology that would allow this technique to be widely applied. Making this third task the primary goal of a future study would create a valuable tool that would allow lay people to analyze the energy consumption of their own buildings, thus increasing the availability of accurate information when they need to make decisions regarding building operations or retrofit.

While there were several reasons for incorporating BPAT+ into the framework for the development of the AER Macro-model, most of these disappeared when the add-on was discovered that allowed Energy Plus to complete the ECM permutation models more quickly than would have been possible using BPAT+. While BPAT+ was still very useful as a quality control mechanism, acting as a check for the initial results provided by the Energy Plus models, this was always a secondary purpose. While the reason for using BPAT+ in this particular study was negated, the concept of using BPAT+ as a calibrated reduced-order model still holds potential as a tool that could be used individuals and organizations who make decisions regarding the construction, retrofitting, and operation of their facilities, but who do not have the technical capabilities of generating or maintaining a higher order energy model for themselves.

BPAT+ performed as expected throughout the course of the study and it was not the direct cause for the failure to complete two of the three intended tasks. Instead, the length of time needed to correct the Energy Plus models greatly reduced the amount of time during which BPAT+ could be applied to a large set of data which made it impossible to develop a formal methodology for calibration. This is not a flaw in the theory or the proposed methodology, but was a user error caused by the user of the Energy Plus model. As such further study is warranted into the use of reduced-order models calibrated using high-order models such as Energy Plus. This study has shown the proof of the concept, but additional work is needed to refine the calibration process, both to increase the long term accuracy of the calibrated reduced-order models, but also to reduce the time needed to achieve parity between the two sets.

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DISCLAIMER

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