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Marija Trcka

United Technologies Research Center, United States of America, trckam@utrc.utc.com

Jose Miguel Pasini

United Technologies Research Center, United States of America, PasiniJM@utrc.utc.com

Stella Maris Oggianu

United Technologies Research Center, United States of America, OggianSM@utrc.utc.com

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Validation of retrofit analysis simulation tool: Lessons learned

Marija TRCKA^{1*}, Stella OGGIANU¹, José Miguel PASINI¹

¹United Technologies Research Center,
East Hartford, Connecticut, USA
{trckam,oggiansm,pasinijm}@utrc.utc.com

*Corresponding Author

ABSTRACT

It is well known that residential and commercial buildings account for about 40% of the overall energy consumed in the United States, and about the same percentage of CO₂ emissions. Retrofitting existing old buildings, which account for 99% of the building stock, represents the best opportunity of achieving challenging energy and emission reduction targets.

United Technologies Research Center (UTRC) has developed a methodology and tool that provides computational support for analysis and decision-making for building retrofits. The tool is based on simplified physics-based models and incorporates intelligent defaulting capability, automatic model calibration and package selection, as well as uncertainty quantification and sensitivity analysis (UQ/SA) on both predicted energy consumption and potential savings. UQ/SA is used to better inform decision makers on the quality of the data used for analysis and direct them in the overall process to achieve the required accuracy in the analysis.

This paper addresses the validation of the simplified physics-based models. The validation is performed using a three-tiered approach: a) validation against ASHRAE 140 BESTEST Cases; b) inter-model comparison of results obtained by other more complex tools using more detailed models than in those required by ASHRAE 140 Standard and c) comparison to real building measured utility data.

Findings and conclusions from each one of the three validation approaches are presented, as well as a discussion on model complexity vs. results accuracy based on lessons learned during the reported study.

1. INTRODUCTION

Retrofitting existing buildings represents the fastest way to reduce energy consumption for the United States building stock. The current building energy audit and retrofit assessment as defined by ASHRAE Energy Audit guideline (Deru et al. 2011) comprises three levels:

- *Level 1 energy audits* are based on walk-through data collection (surveys) and usually result in expert-based recommendations of low-cost/no-cost energy measures. The recommendations are given based on the observed state of the building assets and prior experience of the person doing the analysis. Thus, the recommendations could be limited in scope and driven by subjective evaluations of energy benefits.
- *Level 2 energy audits* are more extensive energy conservation measure analysis and involve dedicated measurements in the building. Analysis of the whole building energy measures are primarily performed using a simulation tool and is usually limited to a small set of the measures. Creating a model of a baseline and adjusting the model to account for energy performance with different energy saving measures is time consuming, because currently available tools are not specifically tailored for use in retrofit process. As a result, this stage can take up to a few weeks to complete.
- *Level 3 energy audits* (investment-grade analysis) considers in detail measures identified in the level 2 audit. It involves more specific models that facilitate comprehensive techno-economic analysis of few selected energy conservation measures and usually do not consider the whole building, but rather the part of its system that is directly impacted by the retrofit.

The current approach to the retrofit analysis requires an effort that, if fully followed, is labor intensive, focuses on a single building or small group of buildings, prioritizes equipment selection based on initial cost, and results in 10-30% energy use reduction through conventional energy conservation measures that are component- or sub-system-based, such as lighting system and central cooling/heating plant upgrades. The retrofit decision process and design tools to select and analyze energy efficiency measures are not amenable to integrated system solutions that have the potential for substantially reducing building energy use (namely, by 50% or more relative to existing levels). Furthermore, cost effective implementation of such deep retrofit solutions requires knowledge of historical energy consumption in existing buildings, from which the underlying retrofit system options and facilities, with the greatest potential benefits, can be identified. This current process requires a significant amount of data gathering via detailed audits, and time consuming modeling.

For deep retrofit projects, “investment-grade” level 3 ASHRAE audits may be required when pursuing significant system upgrades since those upgrades would require significant investment of capital, personnel, and other limited resources. Such audits involve sub-metering of electricity and other utilities such as natural gas and steam over the course of weeks or months. Building energy simulations are then calibrated against the actual energy consumption measurements at the building level. Accurate estimation of the building energy performance improvements due to major HVAC retrofits or architectural modifications to walls, windows, and roof is then performed. Consequently, the current approach is cost-prohibitive for analysis of big building portfolios and also limited in the number of system configurations that can be considered.

In order to facilitate analysis of building energy retrofit solutions, an easy to use, reliable and accurate computational support is required. DoD ESTCP program funded the research project within UTRC that resulted in DeepRetro, the tool that is introduced in this paper. Section 2 describes the tool’s capabilities, Section 3 focuses on three approaches used to validate the tool, and Section 4 discusses the balance between available data and expected accuracy for predicting the energy use of a specific building.

2. DEEPRETRO TOOL DESCRIPTION AND CAPABILITIES

The Deep Energy Efficiency Retrofit Analysis Tool (DeepRetro) developed at UTRC aims at providing the capability to perform energy audits within one building and also to rapidly evaluate energy retrofit opportunities for portfolios of buildings.

In particular, DeepRetro provides deep analysis of individual buildings (when data is available) by:

1. achieving 10× time reduction in creating and calibrating building models, compared with state of the art tools: from weeks to perform level I and level II energy audits to about a calendar day to provide level I and an intermediate level II audit (Deru *et al.*, 2011); and
2. providing an accuracy within 15% of measured or reported annual building energy consumption, broken down by major energy sources.

With the state of the art methodologies incorporated, validated models and clear analysis process, DeepRetro enables much faster evaluation of the retrofit solutions for:

- Detailed single building analysis (very few parameters filled in by default values);
- Small portfolios (some defaulting capability exercised);
- Large portfolios (full use of the intelligent defaulting capability).
- To accommodate the above, the tool interface includes a hierarchy of required inputs Fully defaulted (for large portfolio analyses);
- Qualitative description of the building and its systems;
- Quantitative specification of all (or most relevant) building parameters.

The methodology and software tool developed to support the energy efficiency retrofit analysis is based on building and systems models and tools supporting parameter calibration, uncertainty analysis, and ECM package selection. Oggianu (2013) presents a full description of DeepRetro’s capabilities.

In this paper we focus our discussion on building modeling resolution with respect to its applicability to energy retrofit analysis tools. Broad energy retrofit analysis represents a particular application for the building modeling that comes with specific requirements among which we list the following:

- Model generation based on small number of easily obtainable inputs (the project aimed at analyzing 250,000 buildings);
- Easy model calibration to the metered/utility data, if available;
- Quick model-based evaluation or wide range of retrofit options;
- High accuracy for specified key performance indicators (KPIs). The requested KPI is identified to be annual building energy consumption. The accuracy is required to be within 15% by energy type and 10% for total annual site energy, compared to metered data.

In the following section we explain the modeling assumptions in DeepRetro that are meant to address the above listed requirements.

2.1 Building Demand Modeling

The model is easily created and rapidly executed, with building and system attribute inputs that are easily accessible, and is capable of providing accurate and quick building energy performance estimates. The characteristics of the current model are:

- The building is represented by a single, well mixed zone (i.e., single inside-air temperature node). Besides, the single-zone modeling assumption was extended with to a multi-zone modelsto allow for better differentiation of core and envelope loads.
- The tool now supports two methods for well-known heat transfer calculation:
 - ASHRAE Radiant Time Series (RTS) method: The sol-air temperature method allows wall and roof conduction processes to be modeled using the ASHRAE Radiant Time Series (RTS) method, which accounts for the thermal resistance and capacitance effects of exterior surfaces. Different RTS are assigned for relevant radiant heat gains (i.e. solar, lighting, equipment).
 - Conduction transfer function (CTF): This algorithm relies on more detailed description of the construction and can only be used in cases where such details are available. The calculation is based on (Seem, 1987). The dynamics of each wall construction is explicitly taken into account (based on exact thermo-physical properties of the walls) and does not rely on availability of additional data as done in RTS method.
- The thermal capacitance of building structure and furnishings can be represented by:
 - a single lumped mass;
 - explicit definition of floor and internal wall constructions using the CTF method.
- Wall surface temperatures are assumed to be uniform, and therefore heat transfer processes are 1-D. The building heating/cooling load can be calculated from a quasi-steady energy balance on the zone air node.

2.2 HVAC and Central Plant Model

HVAC system and central plant performance are calculated using hourly load data to drive the system response. The building load is passed to the system module. The coupling is sequential, without feedback from the system back to the load calculation. This assumes that the capacity of the system is always sufficient to meet the building load and that desired temperature set points will always be maintained. The air loop system component models are defined based on heat and mass balance equations, while the primary system components are defined based on the performance curves and/or constant COPs/efficiencies.

For single zone representation, the air side of the primary HVAC system was modeled as a single loop serving the single building thermal zone.

The robustness and range of validity of the single-loop model were verified and refined as appropriate in combination with the building load model described in the previous paragraph. The list of systems supported by the tool was primarily based on that by Griffith *et al.* (2008).

2.3 Energy Conservation Measures, Models and Packages

A list of various low-energy design principles, or energy conservation measures (ECMs) are modeled in DeepRetro. These measures are categorized based on how they affect the building: Lighting and equipment, envelope, HVAC terminal side and HVAC supply side. . One unique aspect of our approach is that, while modeling each ECM, the interaction of that ECM with the others is captured to the level of detail which is consistent with the fidelity of energy performance and HVAC model described in the previous sections. Models for each ECM are described by Oggianu (2013).

2.4 Greenhouse Gas Estimation

Currently, the percent energy savings is provided based on site energy. The tool includes the capability to convert site energy into source energy. Thus, savings based on source energy provides insights on which ECMs are more appropriate per building type and climatic zone to provide energy savings and reduction in greenhouse gas emissions.

Furthermore, the tool provides additional calculation of reduction of greenhouse gases (CO₂ in particular). The calculation is based on the assumptions on the emission of greenhouse gases outlines from <http://www.eia.gov>.

2.5 Analysis Capabilities in DeepRetro

The analysis capabilities within DeepRetro include:

- uncertainty quantification (UQ) and sensitivity analysis (SA);
- model calibration, and
- package selection optimization (PSO).

These analysis capabilities have been developed around the design principles of simplicity and speed on which DeepRetro is predicated. Specifically the methods for UQ/SA/Calibration/PSO have been chosen to tradeoff computational speed with solution accuracy, and so that they are simple to use (without requiring specialized training) with appropriate user knobs (to provide user transparency).

UQ is based on engineering assumptions on how much parameters can change. More details on PSO are described by Ahuja and Peles, (2013) and Oggianu (2013).

2.6 Tool User Interface

A graphical user interface (GUI) and a relational database provide an ease-of-use tool, enabling part of the building energy-audit speedup, and ensuring the robust management and reuse of large volumes of building-audit and energy- and cost-analysis data. The GUI was developed using a data-driven approach, so that the tool functionality can be extended simply by modifying data in the database, with the GUI reflecting these modifications without any change to the GUI code itself.

2.7 Portfolio Analysis

The core engine of DeepRetro was utilized to analyze and study a large portfolio building database, such as the DOD Real Property Database (RPAD). We use the RPAD as the test case to demonstrate the efficiency and accuracy of the tool, as well as its ability to provide insight for making recommendations and deriving policies.

The task objective is a statistical analysis of the technical suitability and potential of DOD RPAD buildings for deep energy efficiency retrofits.

3. BUILDING RETROFIT ANALYSIS MODEL VALIDATION

Quality assurance of building simulation models is an important part of model development, and has the main purpose to build credibility of the model and understanding of its applicability range. This section presents three different approaches we used to validate modeling assumption relative to identified KPIs for energy retrofit analysis: standard envelope and system model validation, comparisons with calibrated eQuest models, and field tests.

3.1 Standard quality assurance for building envelope

Buildings consist of numerous dynamically interacting components that exhibit nonlinear and transient behavior and dynamically interact with other building components. So far, many mathematical methods exist to capture this complexity (Clarke, 2001; ASHRAE, 2009). The most popular models are:

1. numerical methods for approximate solution of differential equations in time domain, such as finite difference (as implemented in ESP-r);
2. solutions of time differential equations in frequency domain, such as conduction transfer function (CTF) (as one of the options in EnergyPlus), and
3. a simplified method, based on pre-computed time series that are applied to the radiant portion of the building load, thus delaying its impact in time. This method is known as the radiant time series (RTS)

procedure (Spitler *et al.*, 1997). Radiant time series for specific constructions are available in the literature (ASHRAE, 2009).

Even though they are most straightforward, numerical methods in the time domain can be more computationally expensive than CTF. The CTF method requires time to compute transfer function coefficients at the beginning of the simulation, but does not require extensive numerical computations throughout the simulation period. However, both numerical methods and CTF require thermo-physical properties of every layer in the building construction. For existing buildings, this can be very difficult to obtain.

The most efficient method is RTS, with time series inherited from the known sources (ASHRAE, 2009). Since the series are given for a specific construction, far fewer inputs are required than in other two approaches. However, the variety of construction materials for which RTS are available is limited, and might not be able to capture vast range of existing building constructions present in the buildings. We will look at three levels of validation for the models used in the tool and later discuss required level of modeling complexity based on the presented cases.

Based on ASHRAE Standard 140 (IEA BESTEST procedure), inter-model comparison has been performed to validate procedures for thermal transfer through envelope simulation. The results are shown in Figure 1.

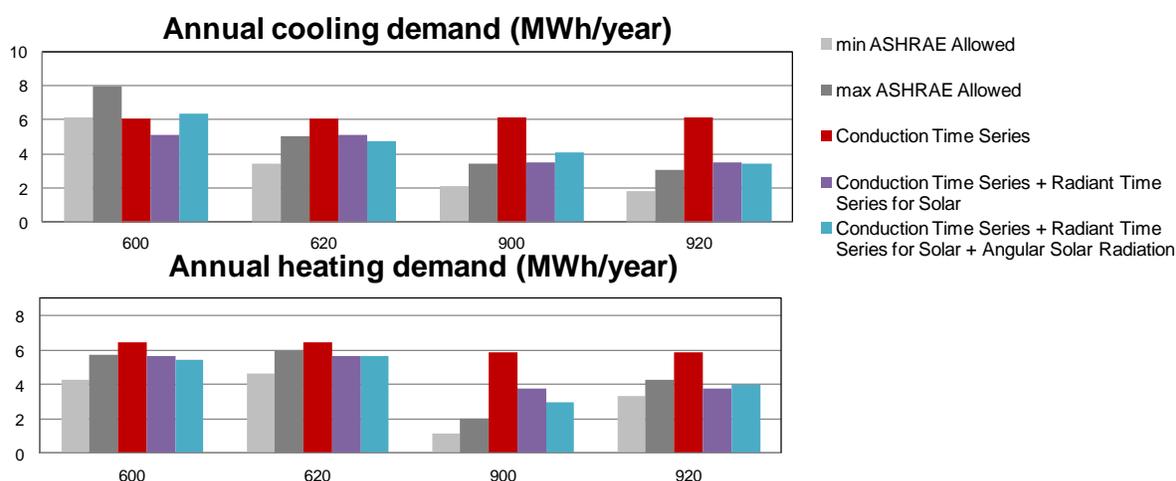


Figure 1: Results obtained by using alternative envelop algorithms compared to ASHRAE Standard 140, cases 600, 620, 900, 920.

The original algorithm implemented in the model was partial Radiant Time Series (RTS): RTS excluding RTS for radiant solar gains. The results obtained by applying RTS w/o RTS solar gains are not valid for all types of buildings. For example, for heavyweight buildings the accumulation of heat received by radiation onto internal surfaces by transmitted solar radiation becomes relevant. Thus, the case with higher amount of transmitted solar radiation (building with windows oriented South) and heavyweight walls show significant discrepancies with reference data. The accuracy has been improved by developing additional algorithms:

1. RTS for solar radiant gains,
2. Incident angle dependent solar radiation upon windows, and
3. Conduction Transfer Function (CTF).

The improved results are also shown in Figure 1.

3.2 Standard quality assurance for system simulation

Both Volume 1 and Volume 2 HVAC BESTEST set of tests were exercised. Due to the simplicity of the tool, only a subset of the tests could be modeled.

Volume 1 set of test cases contains tests with constant boundary conditions: all transient phenomena are ignored. For example, the corresponding weather file is artificial, with all weather variables kept constant throughout the year. These tests are used to verify system models in steady state settings.

The building envelope model contains no windows and has near-adiabatic envelope. The internal gains are controlled. Here, we report on the results from four tested cases from Volume 1. The test cases are summarized in table in Figure 2.

The simulation results for these cases are shown in Figure 2. DeepRetro produced results comparable to the other tools used to define the accepted accuracy range in the procedure.

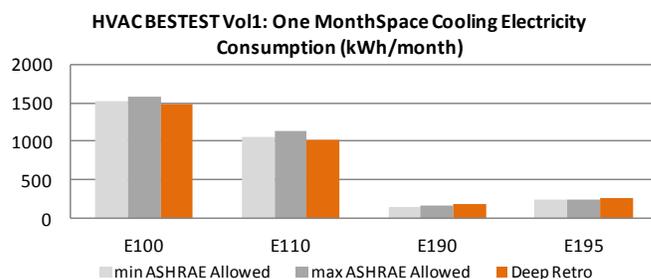


Figure 2: Simulation results for HVAC BESTEST Volume 1 test cases.

Case	Coil condition	Indoor temp.	Outdoor temp.
E100	dry	low	high
E110	dry	low	low
E190	wet loSHR	low	low
E195	wet loSHR	low	high

The difference in Volume 2 is that the transient phenomena are included in the model. This is extension of the previous tests and is used to test system response to transient boundary conditions. The test cases for Volume 2 are summarized in table in Figure 3.

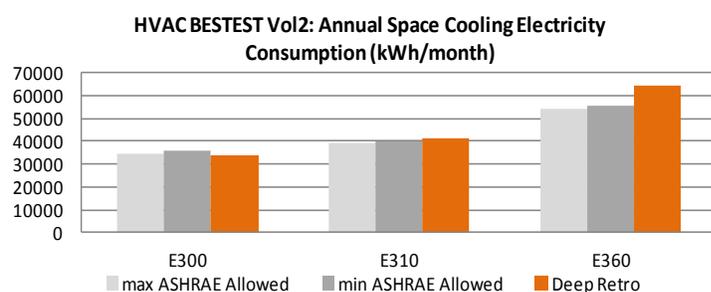


Figure 3: Simulation results for HVAC BESTEST Volume 2 test cases.

Case	Load
E300	Dynamics included low latent load
E310	Dynamics included high latent load
E360	Dynamics included undersized system

Note that the case E360 tests the system response to loads which are higher than the installed system capacity. Originally, DeepRetro was not designed to deal with undersized systems. The results for the case E360 illustrate the results when the tool is used outside of its applicability range. For all other tested cases, the tool produces results comparable to the other tools used to define the accepted accuracy range in the procedure.

3.3 Dedicated inter-model comparison tests based on real building models in eQuest

A retrocommissioning project ongoing at Ft. Bragg was leveraged. In that project, eQuest models had been developed and calibrated based on a short metering period for eight buildings representative of the scope of that project. The eQuest models for those buildings were provided to UTRC for inter-model validation, in which the output from eQuest is used as virtual metered data.

Table 1 shows eight buildings included in the inter-model validation, comparing DeepRetro results with well eQuest results. eQuest models were provided for each building. These models were run and checked against the Ft. Bragg retrocommissioning report. In the case of the dining facility (A3556), the model output did not match the report. However, we used the model output as effective metered data. Note also that for buildings in which one form of energy dominates, like building A4148, the calibration procedure focused on the dominant form for matching total annual consumption. This means that, in such cases, it is not easy to control the relative error by energy type for the *non*-dominant energy type.

In Figure 4, we demonstrate the accuracy achieved for this set of buildings after using DeepRetro's automatic calibration procedure. The model in DeepRetro is based on RTS procedure and single zone model assumption is used. The accuracy, resulting to 15% by energy type and 10% for total annual site energy, is highlighted. As noted

earlier, the natural gas consumption of building A4148 is more than twenty times less than electric consumption, and therefore any relative error is exaggerated even though the building total energy consumption is very well modeled.

Table 1: List of Ft. Bragg buildings for which eQuest models were provided and annual electric and gas consumption from the models.

Building	Sq. ft.	Floors	Type/Purpose	Energy Sources	Annual electricity [kWh]	Annual Natural Gas [kWh]
A2356	11,664	1	In-processing facility	Electricity, Natural Gas	157,150	86,292
A2444	20,096	2	COF		174,430	112,510
A2547	45,600	1	COF		555,040	380,523
A2649	37,904	4	Barracks		216,880	370,106
A3162	24,768	4	Barracks		217,410	304,120
A3351	52,624	4	Barracks		783,520	416,307
A3556*	29,247	1	Dining facility		1,189,400	545,604
A4148	17,128	2	COF		773,210	28,828
Total	239,031					

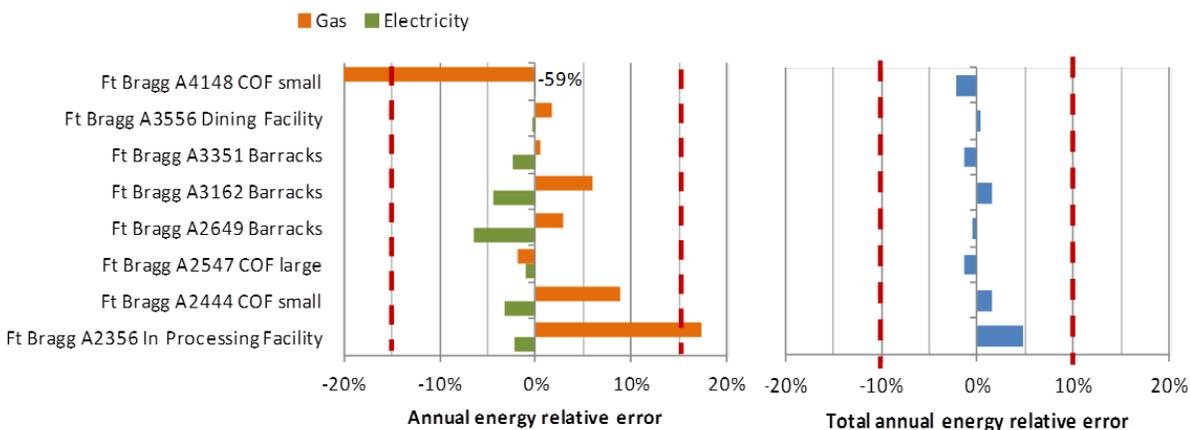


Figure 4: Relative error in annual site energy by energy type (left) and in total (right) for Ft. Bragg buildings. The lines mark the $\pm 15\%$ (resp. $\pm 10\%$) relative error limits for energy use by energy type (resp. total energy).

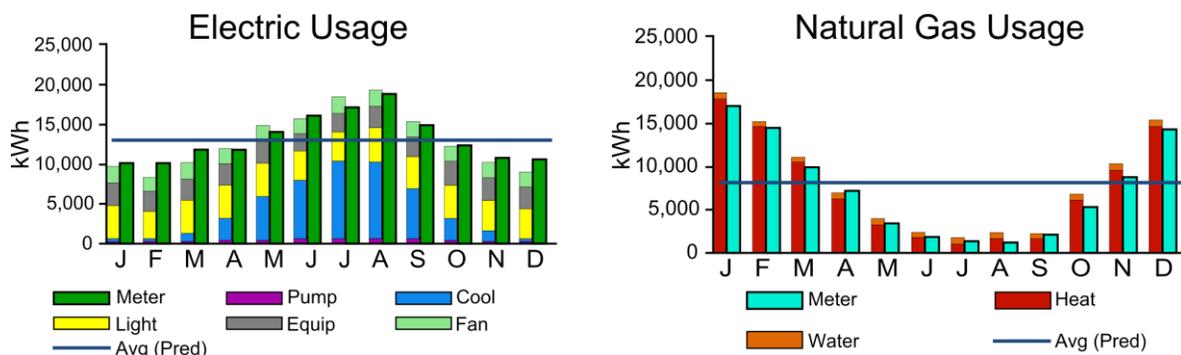


Figure 5: Comparison of monthly electricity and gas predictions from DeepRetro and provided eQuest model for building A2356 (In-processing facility).

Figure 5 shows a sample comparison of monthly predictions from DeepRetro and from the provided eQuest model for building A2356, after using DeepRetro's automatic calibration procedure. This example demonstrates how not only the annual values, but also the monthly trend is matched.

3.4 Field Tests

DeepRetro was field-tested on 25 buildings at Joint Base San Antonio (JBSA), comprised of Ft. Sam Houston, Randolph Air Force Base, and Lackland Air Force Base. The models were built based on building walk-throughs by Building Intelligence Group (BIG) and UTRC. Also used, where available, were utility data, and additional details were supplemented with as-built drawings and mechanical schedules.

Even though 25 buildings were assessed in the field test (Oggianu, 2013), we focus here on the seven buildings where the most reliable metered data was available, and where buildings were isolated, so the metered data referred to each modeled building alone. An exception is a pair of large buildings that share a central plant (2840 and 2841 in Ft. Sam Houston): these two were modeled as a single, larger building in DeepRetro. In all cases we used the RTS method and single-zone model. Note that most buildings at JBSA have relatively low fenestration, indicating that separating peripheral and core zones would not be necessary.

For each model with good quality metered data, we deployed DeepRetro's automatic calibration capabilities. Figure 6 shows the resulting relative error for these six buildings after calibration. For most of them, the annual consumption results are within 15% per energy type, and within 10% in total.

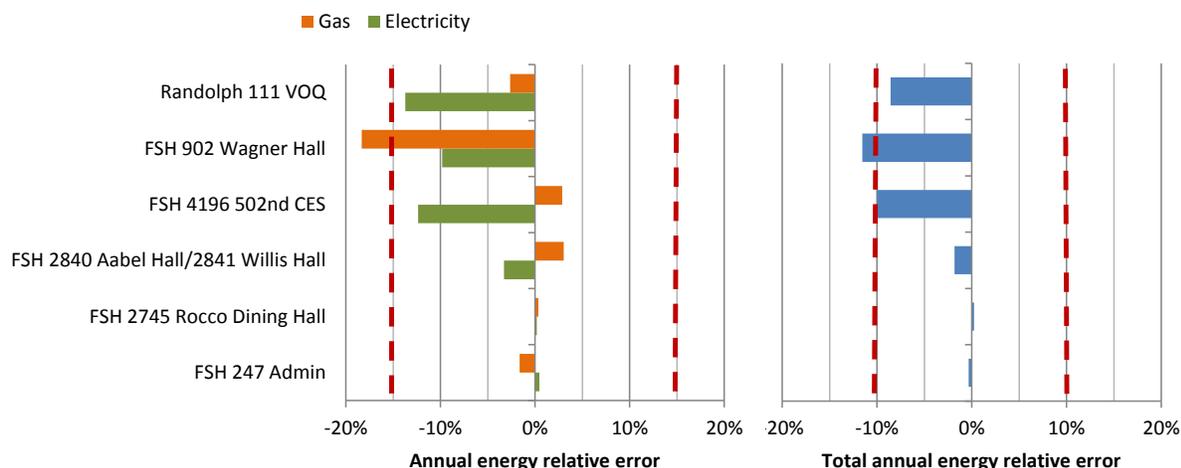


Figure 6: Relative error in annual site energy by energy type (left) and in total site energy (right) for JBSA buildings. The lines mark the $\pm 15\%$ (resp. $\pm 10\%$) relative error limits for energy use by energy type (resp. total energy).

4. DISCUSSION OF THE REQUIRED MODELING COMPLEXITY

Even though the standardized diagnostic procedure for quality assurance for algorithms used in building heat transfer models required high modeling resolution based on CTF and all inputs associated with it, RTS procedure used for inter-model comparison with full-size building model and field tests met required accuracy of identified KPIs for energy analysis.

In general, heat transfer through the envelope in the building reported in this paper constitutes only a portion of the overall building load, and thus the investigated KPIs are not sensitive to small inaccuracies introduced by the simplified (but efficient) heat transfer calculation procedure.

For the reported cases, single-zone modeling assumption seems to provide required prediction accuracy for KPIs. However, even though the buildings reported in this paper are all in warmer parts of the United States, higher accuracy with multi-zone model has been observed for buildings in colder climates with lower levels of insolation and higher percentages of window area.

Here we illustrate findings from an office building (the building was not part of the project presented in this paper) where multi-zone approach significantly improved accuracy of the building. Comparison is shown in Figure 7. The implementation of multi-zone model significantly improved accuracy in prediction of natural gas consumption.

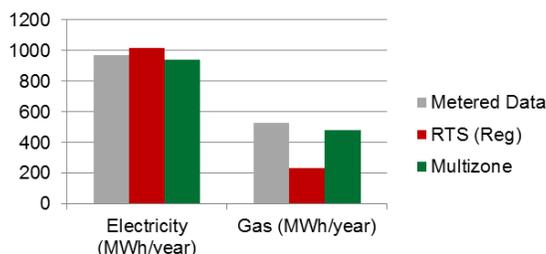


Figure 7: Comparison of results between single-zone and multi-zone model for an office building

5. CONCLUSIONS

The paper presented a modeling approach used for quick and accurate energy retrofit analysis in DeepRetro. We presented results from an extensive validation procedure. Even though the standard set of tests required a more detailed heat transfer model, field tests were less sensitive to these phenomena, and a simpler modeling approach was successfully applied. The simplified modeling approach also speeds-up the time required for automatic calibration, because of the fewer number of parameters involved.

Overall, the approach has so far been applied to facilitate energy retrofit analysis in more than 50 individual buildings, as well as a portfolio analysis of 250,000 buildings from the DoD domestic building stock. The evaluation of the baseline energy performance of an individual building can be achieved in less than one minute and a complete retrofit analysis can be achieved in about half hour of computational time (on individual PC, performance can be significantly improved if super computers are used) with minimum human intervention. While the tool only requires eleven basic input building characteristics, results significantly improve when building parameters, systems, and schedules are well known. An accuracy of 10% was achieved when comparing tool results against known and reliable annual energy consumption in a building.

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