



## BUILDING EFFICIENCY EVALUATION AND UNCERTAINTY ANALYSIS WITH DOE'S ASSET SCORE PREVIEW

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### ABSTRACT

Building Energy Asset Score Tool, developed by the U.S. Department of Energy (DOE), is a program to encourage energy efficiency improvement by helping building owners and managers assess a building's energy-related systems independent of operations and maintenance. Asset Score Tool uses a simplified EnergyPlus model to provide an assessment of building systems, through minimum user inputs of basic building characteristics. Asset Score Preview is a newly developed option that allows users to assess their building's systems and the potential value of a more in-depth analysis via an even more simplified approach. This methodology provides a preliminary approach to estimating a building's energy efficiency and potential for improvement. This paper provides an overview of the methodology used for the development of Asset Score Preview and the scoring methodology.

### INTRODUCTION

The Building Energy Asset Score Tool is a web based tool to help building owners, operators, and tenants understand the current and potential performance of a building asset. The building assets are defined as the building systems that are not influenced by operational changes (e.g. envelope, mechanical systems, and electrical systems). The Asset Score is based on a simple 10-point scale where the higher the score, the more efficient the building asset, relative to its population of peers. Asset Score Preview requires as few as seven user inputs and uses a regression model to calculate the possible range of the building's energy use. The seven building characteristics are used to infer

the remaining parameters to complete the building description. Preview uses a regression model to calculate the possible range of the building's energy use based on robust stock simulations and an uncertainty analysis. The estimated energy use range is mapped to the Asset Score scale to provide a user with estimated corresponding score range.

The Asset Score Tool is modular in design for clean separation of functionalities and easier development and testing. The backend simulation process of the Asset Score Tool was integrated within a framework to perform a sensitivity and energy use intensity (EUI) distribution analysis. The EUI distributions were used to create the 10-point scale used to convey the resulting scores (Long 2015, Wang 2016). The analysis framework was also used to develop the regression methodology used to calculate scores for Preview buildings. Details on the regression methodology used and parameter space evaluation are discussed in the following sections.

### ASSET SCORE TOOL ARCHITECTURE

The core components of the Asset Score Tool application (Wang et al 2015), are functionally separated into the following five subsystems, as shown in Figure 1.

- User Interface- The outward facing portion of the tool that allows the user to define the building characteristics. The user interface offers two input modes, (i) Asset Score Full and (ii) Asset Score Preview. In the full input mode a user can draw the building geometry and define building specific parameters such as construction types, mechanical systems, efficiencies, electrical

system details and more. The Preview input mode, limits user inputs to seven data points, providing defaults for the remaining inputs and a capability for the user to view and edit the default values.

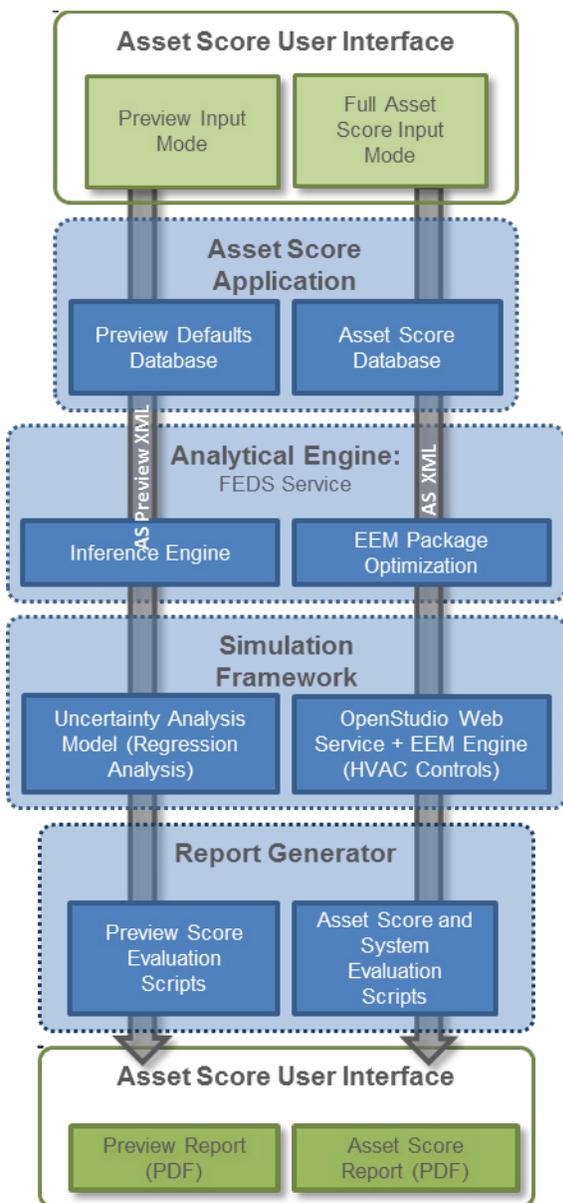


Figure 1 Asset Score Tool Architecture

- **Asset Score Application** - The Asset Score Application forms the core of the Asset Score tool. It translates all user inputs into the Asset Score schema which is then sent to the Analytical Engine. It also validates the data model and acts as the intermediary between the Analytical Engine, Simulation Framework and

Report Generator. For buildings submitted through the Preview input mode, the Asset Score Application completes the building definition through the defaults database, providing a complete Asset Score data model to the Analytical Engine.

- **Analytical Engine**- The inference capabilities of the Facility Energy Decision System (PNNL 2015), FEDS, is used to fill any missing data that needs to be inferred (e.g. Wall/Roof U-Factors as a function of building vintage). Additionally, FEDS is used to evaluate primary efficiency recommendation options, as noted below.
- **Simulation Framework**- The simulation framework is a combination of OpenStudio (NREL 2015) and EnergyPlus (DOE 2015). OpenStudio is used for model articulation and simulations are run using EnergyPlus. This framework is used for buildings submitted through the full input mode. Buildings submitted through the Preview input mode go through the uncertainty analysis framework which allows for a quick assessment of building components based on a regression model.
- **Report Generator**- the Report Generator runs a series of post-processing scripts to calculate building scores, and generate the Asset Score Report.

## ASSET SCORE PREVIEW

Asset Score Preview provides a platform for quick analysis of a building using limited user inputs. The intent of this functionality is to allow a user to assess the energy efficiency as well as energy savings potential of a building with limited investment in data collection, data entry and energy simulation. Preview requires high level input regarding a building's location, conditioned floor area, number of floors, the predominant use type and building orientation. A few additional inputs regarding year of retrofit for lighting, HVAC and service hot water systems can be provided if available. On the basis of these limited inputs, Preview's defaults database is able to populate the remaining data points required for creating a complete Asset Score model which is then analyzed for energy efficiency and energy savings.

## Process

The defaults database is built using the DOE Reference Buildings (DOE 2015b), the prototype buildings (Thornton et al) as well as the Commercial Buildings Energy Consumption survey (CBECs) database. Based on a building's location, year of construction, use-type as well as conditioned floor area, the Asset Score

Application identifies the remaining data points, including the construction types for all envelope components; basic geometry configuration such as aspect ratio and window-to-wall ratio (WWR), the most typical HVAC system type and service hot water system type. These defaults are provided to the user who can verify the value, edit the value, or mark the input as unknown. Each user action results in the default value being marked as ‘certain’ or ‘uncertain’ within the Asset Score Application. A verified or edited value, is translated to the uncertainty analysis model as a certain input and defaults marked as unknown by the user, are translated as uncertain. Some inputs are not displayed for user’s verification and are evaluated as uncertain for all scenarios. These include system controls (such as fan control, energy recovery ventilation, demand control ventilation, daylighting control, occupancy sensor control etc.) as well as geometry inputs (such as floor-to-floor height, building dimensions and aspect ratio). This allows Preview to be a quick analysis tool with additional capabilities for detailed user input being provided through the full input mode. The Analytical Engine infers the efficiency levels for all components (such as thermal properties for building envelope, system efficiency levels etc.) and the complete Asset Score data model is sent to the uncertainty analysis model for determination of its energy use intensity (EUI) range.

The uncertainty analysis model gives an estimate of the EUI range (within 95 percentile of results) as well as the mean EUI for the building with all the input values and associated uncertainties. The EUI range is post processed to give the corresponding score range. An Asset Score Preview report is generated which provides the current score range, potential score range and estimated source energy savings. The estimated savings are based on the dataset of buildings entered into the Asset Score tool and average savings seen by buildings scoring within a certain range.

### **Application**

The score range estimated through Preview is intended to be indicative of energy efficiency of a building. Preview provides a batch-analysis workflow through which a user can upload data for Preview buildings through a spreadsheet template and generate a score range for all buildings through a simple three step process of spreadsheet upload, batch simulation for the uploaded buildings and a CSV download with score ranges of all buildings. The intent is to provide a capability to organizations looking to conduct analysis on a large number of buildings in order to identify buildings for more detailed review.

## **UNCERTAINTY ANALYSIS**

The Uncertainty Analysis was conducted to aid in the development of Asset Score Preview’s scoring process. This analysis required running many thousands of whole building simulations which were then used in the development of the regression models.

The OpenStudio Analysis Framework (Long 2014) was used to run the analyses, and is defined in the sections below. This section describes the framework in more detail the methodology used for the analysis and some high level results from each.

### **Seed Models**

A seed model is the initial model from which all the model perturbations stem. Seed models were created for 22 archetype buildings and were closely aligned to the PNNL prototype buildings (Thornton, et al., 2011). These prototypes were originally developed for DOE to assess the relative improvement of sequential versions of ASHRAE Standard 90.1. They represent 80% of the commercial building floor area in the United States for new construction, including both commercial buildings and mid- to high-rise residential buildings. The main difference between the prototype buildings and the seed models is the file format (XML vs IDF) and building geometry (rectangular for all buildings). The seed models were also more homogeneous than the prototype buildings, such that the loads were more evenly distributed throughout the buildings. The seed model defaults were of importance since seed model inputs (e.g. total floor area, U-Factors, system efficiencies) was assumed to be the mean for that building type. For example, the square footage of the medium office was 53,638 square feet, which is equivalent to stating that medium office buildings on average are 53,638 square feet. Multiple versions of each seed model were developed, to represent the typical HVAC system types found for a particular use type. For instance, a medium office building was analyzed using a seed model with a packaged VAV with electric reheat system as well as a packaged single zone air conditioning system.

### **Input Variables**

38 most impactful input variables for commercial buildings (including location) were identified by subject-matter experts. Each variable was assigned a minimum, maximum, mean, standard deviation, and distribution (e.g. uniform, triangle) representative of typical efficiency ranges based on the vintage of existing building stock as well as current technologies. Current technology limits defined the minimum and maximum values. The mean value was defined as ASHRAE Standard 90.1-2004 code

requirements. Distributions that best represent the variable across the commercial building stock in the United States were then developed using these identified efficiency values. These inputs ranges, along with their respective distributions, were peer-reviewed by architects, mechanical engineers, and building scientists (Wang 2016). The majority of the variables were implemented as multipliers from the value in the seed model. This allows for the same analysis configuration to be used for all of the seed models. Table 1 below lists the input variables analyzed and Table 2 shows the efficiency ranges sampled for a few envelope parameters. The distribution for these parameters was considered to be triangular.

Table 1 Variables Analyzed for Seed Models

NO.	VARIABLES	NO.	VARIABLES
1	Air Handler Fan Efficiency	20	Heating Fuel Type
2	Aspect Ratio	21	Interior Lighting Power Density
3	Chilled Water Reset	22	Location
4	Chiller Pump Control	23	Minimum Airflow Fraction
5	Condenser Pump Control	24	Orientation
6	Cooling Efficiency	25	Perimeter Zone Depth
7	Cooling Tower Control	26	Roof Construction Type
8	Daylighting Control	27	Roof U-Value
9	Demand Control Ventilation	28	Shading Height above Window
10	Economizer	29	Shading Projection Factor
11	Energy Recovery Ventilation	30	Supply Air Temperature Reset
12	Fan Control	31	Wall Construction Type
13	Fan Static Pressure Reset	32	Wall U-Value
14	Floor Plate Area	33	Water Heater Efficiency
15	Floor R-Value	34	Window Sill Height
16	Floor-To-Ceiling Height	35	Window Solar Heat Gain Coefficient
17	Floor-To-Floor Height	36	Window U-Value
18	Gross Floor Area	37	Window Visible Light Transmittance
19	Heating Efficiency	38	Window-To-Wall Ratio

Table 2 Evaluation Ranges for Select Envelope Parameters

DISPLAY NAME	UNITS	MIN	MEAN	MAX
Floor R-Value (Slab-On-Grade)	K·m <sup>2</sup> /W (ft <sup>2</sup> ·°F·hr/Btu)	RSI-0 (R-0)	RSI-0 (R-0)	RSI-5 (R-27)
Wall (Wood Siding U-Value)	W/K·m <sup>2</sup> (Btu/hr·ft <sup>2</sup> ·°F)	USI-1.31 (U-0.23)	USI-0.5 (U-0.089)	USI-0.182 (U-0.032)
Roof (Built-up Wood Deck U-Value)	W/K·m <sup>2</sup> (Btu/hr·ft <sup>2</sup> ·°F)	USI-5.68 (U-1)	USI-0.35 (U-0.063)	USI-0.091 (U-0.016)
Window U-Value	W/K·m <sup>2</sup> (Btu/hr·ft <sup>2</sup> ·°F)	USI-6.93 (U-1.22)	USI-3.23 (U-0.57)	USI-0.681 (U-0.12)

Each of the input variables required an OpenStudio measure in order to be perturbed in the eXtensible Markup Language (XML), OpenStudio Model (OSM), or EnergyPlus Input Data Files (IDF) file. In some cases, multiple variables are impacted in a single measure. For example, the Aspect Ratio, Floor Plate Area, and Square Footage variables were all perturbed by a single measure. The three variables are all interconnected and the measure reports out changes to the number of floors. Other measure constraints were implemented, for example, if the Heating Fuel Type is changed to electricity, then efficiency would be set to 100% always.

### Analysis Framework

The OpenStudio Analysis Framework allows for an efficient setup of analyses (e.g. sampling, optimization, etc.) by using an Excel-based spreadsheet to select the seed model, algorithm details, variables, and outputs. The OpenStudio Analysis Framework uses a combination of Ruby, R, OpenStudio, and MongoDB to create a cluster of machines in Amazon's Elastic Compute Cloud (EC2) to run the simulations in parallel. The result of the analysis is a CSV or R data frame with each row representing a single simulation. The columns of the data are defined as outputs during the initial setup. The OpenStudio Analysis Framework has the ability to run several algorithms including sampling (i.e. Latin Hypercube Sampling), batch runs, optimization, or calibration.

Typically, the OpenStudio Analysis Framework requires OpenStudio models (OSM files) to run the simulations; however, because the analysis made use of the already existing Simulation Framework to create the models from XML files, the analysis framework was extended to operate on XML files as well as OSM files and EnergyPlus IDF files. Figure 2 shows the workflow for running simulations with the Simulation Framework and XML file injected.

The OpenStudio Analysis Framework relies heavily on the use of OpenStudio measures (NREL 2015b). In the most simplistic terms, a measure is a small Ruby script that is executed against the input file to make a controlled change. These changes can be simple perturbations (e.g. change the Chiller COP to 5.0) or can be quite complex (e.g. add 2 stories to my building while maintaining the same square footage). For the Asset Score analysis, the concept of measures was extended to enable the perturbation of the Simulation Framework's XMLs. The Asset Score used a combination of XML measures (which manipulated the Simulation Framework's XML file), OpenStudio measures, and EnergyPlus measures.

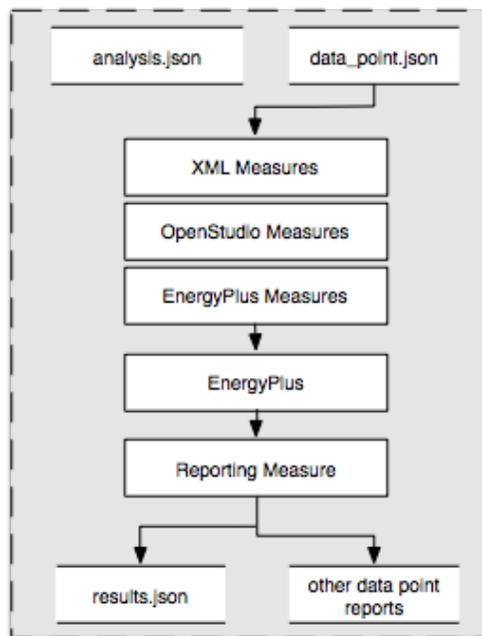


Figure 2 Workflow for Running XML-Based Measures

## REGRESSION METHODOLOGY

Multiple regression techniques were initially investigated to determine the best technique for use in meta-modeling. It was clear from initial experimentation that the non-linear regression models performed better on the data set. Further exploration

found that Support Vector Machines did not regress accurately across differing climate zones, leading to the implementation of a Random Forest algorithm as the regression engine. All methods were tested in R, using the packages random Forest, e1071, and gam. The details of this machine learning procedure are described in mathematical detail (Breiman 2001) and algorithmic detail (Breiman 2002), however the authors found Breiman's presentation to ENAR (Breiman 2015) to be an excellent introduction to the topic.

To create each regression model the ~6000 data-points associated with each seed model were randomly divided into two sets: a training set comprising 80% of the data points and a test set comprising the remaining 20% which was used to measure the accuracy of the regression model. The training set of ~4800 data points was then passed to the random forest generating algorithm, contained in the R package random forest. A random forest is a large aggregation of binary decision trees, each of which is independently trained. Each tree is given at random 80% of the data provided to the forest which it then regresses on. The remaining 20% of the data-points are used by the random forest to measure the accuracy of the tree and to simultaneously ensure the independent nature of each tree.

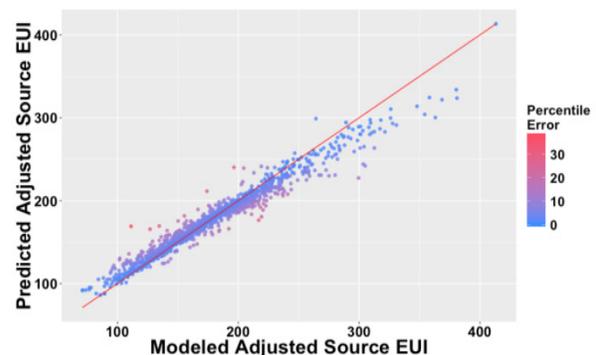


Figure 3 Results of Regression Model Testing

Although each random forest keeps robust internal accuracy statistics, the test set comprising of ~1200 data points is used to gauge the overall efficacy of the regression. As such each data point in the test dataset is entered into the regression model, which returns the average exit values across all the trees in the forest. The returned predictions are compared with the known values and the resulting graph, commonly called a parity plot, is saved to file every time the regression engines are rebuilt. An example parity plot can be seen in Figure 3 for the medium office (packaged rooftop VAV with electric reheat) seed model. It is worth noting that building the regression models can be relatively time consuming, on the order of 2-10 minutes per regression engine, however the prediction process is exceptionally fast.

## Prediction Methodology

To capture the uncertain nature of the inputs to Asset Score Preview the meta-model utilizes the information provided by the user as a basis for creating and sampling 10,000 data points using the regression model. Depending on the user's certainty in the information they provided on different variable categories (HVAC, lighting, hot water, walls, roof, windows, and floor) the respective sets of variables are either fixed for all data points, sampled over a triangle distribution centered at the user's input, or sampled uniformly. The user's input variable groups and their certainty in these values are passed to the meta-model through an Asset Score XML created by the Asset Score Application. This XML contains user inputs, inferences added through the tools analytical engine's as well as the certainty associated with each input. These values are used to populate the regression engine. Given the limited input of the Asset Score Preview tool, the geometry variable groups of the xml, as well as all control strategies are always set to uncertain.

The Asset Score XML certainty inputs are parsed in one of three ways. If the user indicates they are certain regarding a variable group then the values for that group are fixed for all 10,000 data points. In the case that the user indicates they are uncertain about a variable group (excluding HVAC) the values inferred by the analytical engine are used as the modes of a set of triangle distributions spanning the entire range of each variable in the variable group. See Figure 4 and Figure 5 for an example (non-HVAC) unspecified variable. If the user does not specify the HVAC system there is a significantly greater amount of uncertainty associated with the model. Multiple solutions were evaluated for addressing uncertainty with HVAC system selection, including running the uncertainty analysis on multiple system types. However, this approach was ultimately not selected as it would in many cases saturate the score range, thus providing no useful information. Instead, in the case of an unspecified HVAC system the default value defined by the Asset Score Application is used and all HVAC related values are considered to be uniformly uncertain across their entire range. Due to the sensitivity of several of these variables, this produces a sufficiently wide EUI range, while still providing valuable information to the user. Figure 6 gives an example of the distribution of an uncertain HVAC system variable. In the case of a categorical variable, i.e. wall construction type, if the input is not certain all possible values are uniformly sampled. Finally, Figure 7 shows a flowchart of this process. Here the HVAC system variables are first designated either certain or uncertain depending on the system certainty. The remaining

variables are subsequently parsed into certain and uncertain sets based off the Asset Score XML. In the case of certain variables the values are fixed according to the XML file, while in the case of uncertain variables either a triangle or uniform distribution is assigned to the variable, depending on whether it's a numeric or categorical variable respectively.

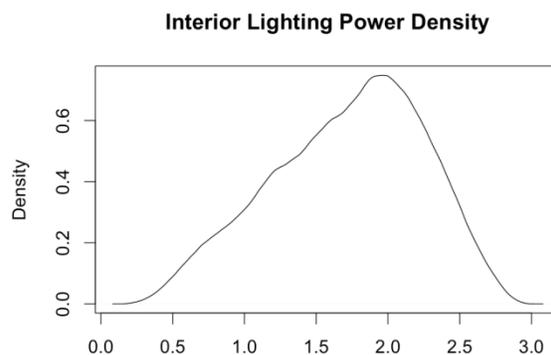


Figure 4 Input Distribution for Interior Lighting Power Density

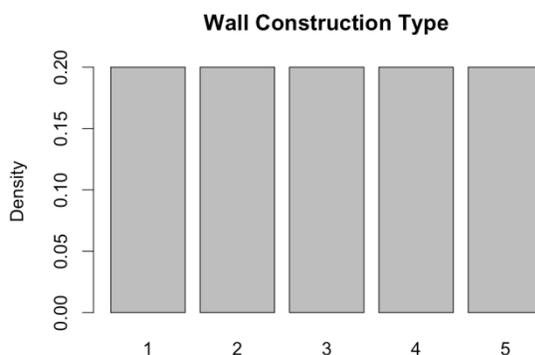


Figure 5 Input Distribution for Wall Construction Types

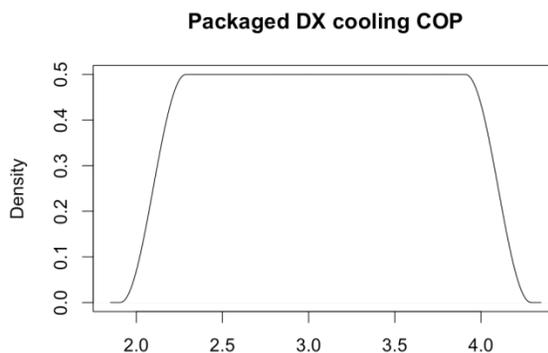


Figure 6 Input Distribution for an Uncertain HVAC Variable Group

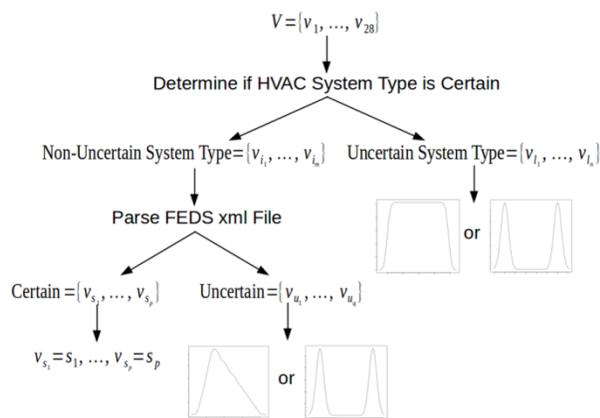


Figure 7 Workflow for Mapping Variables to Distributions

The results of the regression engine are highly dependent on the user’s certainty of input, as expected. Figure 8 shows the EUI distributions returned from a medium office Asset Score Preview XML that sampled against the medium office (packaged rooftop VAV with electric reheat) seed model. The XML defined the building as a medium office and the HVAC system as ASHRAE system type 5. Four different sets of certainties were used to generate the distributions. In the first case all variable groups (except building geometry and system controls which are always uncertain) were set to certain. In the second case only the HVAC variable group was set as certain, in the third case only lighting was set as certain. In the last case all variable groups were set to uncertain. As can be seen in the figure, the regression engine is highly sensitive to the certainty inputs. The EUI range narrows as the number of certain inputs is increased. Particularly desirable is that the mean, mode, and range of the distributions are highly articulated, allowing simple statistical measures to provide a high degree of information to the user. The source EUI as modeled by EnergyPlus was 185 kBtu/ft<sup>2</sup>/yr, which falls in the middle of and is approximately the maximum likelihood estimation of the all certain distribution.

The minimum, mean, and maximum of the distribution of values from the regression engine is written as a csv and returned as the output of the meta-model. This file is used by the Asset Score application and report generator to map to a score range that can be displayed to the user. The testing process revealed an average score range of four points for all seed models analyzed when all inputs were specified as uncertain and an average score range of 2.5 points when all of the inputs were specified as certain. The score range is developed considering the EUI range identified by the uncertainty analysis model, so that the calculated score represents the median and mean. This method ensures that tails

and skewness are well represented in the Preview Asset Score presented to the user.

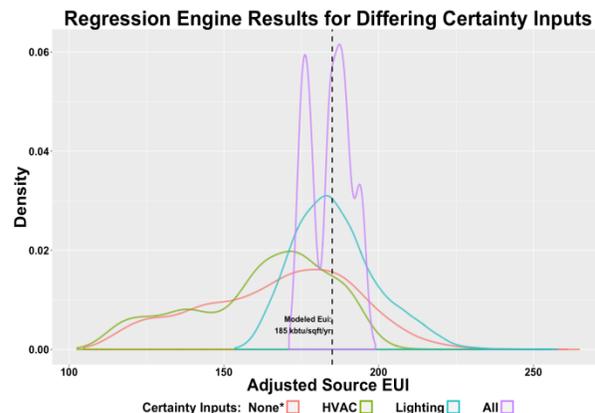


Figure 8 Regression Engine Results for Varying Uncertainties

## TESTING THE UNCERTAINTY ANALYSIS MODEL

Testing of the process was carried out using the seed models developed for the regression model as well as using the buildings entered by users into the Asset Score tool during pilots conducted in 2012 and 2013 (Wang 2013). The intent of this testing process was to determine if the uncertainty analysis model could accurately reflect the efficiency of a building considering the limited data provided.

Seed models were run through the regression model to generate the score range and were also run, with all inputs defined, through the Asset Score tool to generate the current score using whole building energy simulation. The acceptance criteria for each seed model was a required correspondence between the score generated through full Asset Score as well as the score range generated through the uncertainty analysis model. All the buildings analyzed passed the test as the actual scores lay within the score range determined through Preview. Table 3 below shows results for a few of the seed models analyzed. HVAC system controls and building geometry are always considered uncertain, which influences how the full building scores in reference to the Preview score range. The fact that some seed models score closer to the Preview high score or the low score depends on the sensitivity of the applicable HVAC system controls.

The pilot buildings were tested with two configurations, the minimal seven inputs as well as the seven inputs with all other default Preview inputs edited or verified. The first set, submitted with seven inputs and none of the default inputs verified did not consistently display

the score within the uncertainty range. The alignment was dependent on how closely the preview defaults coincided with the actual values as well as the sensitivity of the parameters that did not coincide. Hence, the criteria was met in some cases and not all. The second configuration created the Preview test cases for the same pilot buildings using the seven minimal inputs and modified the default value to coincide with the user entered values. A high degree of correlation was seen in this case where the actual score of the building mapped to the score range calculated through the uncertainty analysis model.

Table 3 Test Results for Select Seed Models

Seed Model	Preview Low Score	Preview High Score	Full Input Mode Score
Retail Stand Alone	6.5	9.5	6.5
Warehouse	5.5	8.5	8
Small Office	2.5	5.5	5
Medium Office	1.5	4.5	4
City Hall	3.5	6.5	4.5
Library	6	9	7
Small Hotel	5.5	8.5	8
Large Hotel	7	10	8.5

## CONCLUSION

Asset Score Preview has proven to be a viable framework for analyzing building efficiency where limited effort from the user can provide helpful information about a building's assets and can be used in the decision making process for identifying buildings for additional analysis. The use of random forest models to ascertain the range of uncertainty in adjusted source EUI allows limited input from the user to generate results which are meaningful and based in first-principle modeling, without the significant computation time and power required for real-time modeling. In addition, the validation of this framework allows for a high degree of confidence in the credibility of results that will be generated by this approach when fully deployed.

The spreadsheet upload and batch analysis capability reduces the amount of manual work required to generate Preview scores and can be used to analyze large portfolios of buildings with relatively minimal effort and can serve as less daunting entry to the full capabilities of the Asset Score

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