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Seminar #29: Urban-Scale Building Energy Modeling, Part 5

Simplified Estimation of Energy Use Intensity Based on Building Façade Features

Learning Objectives

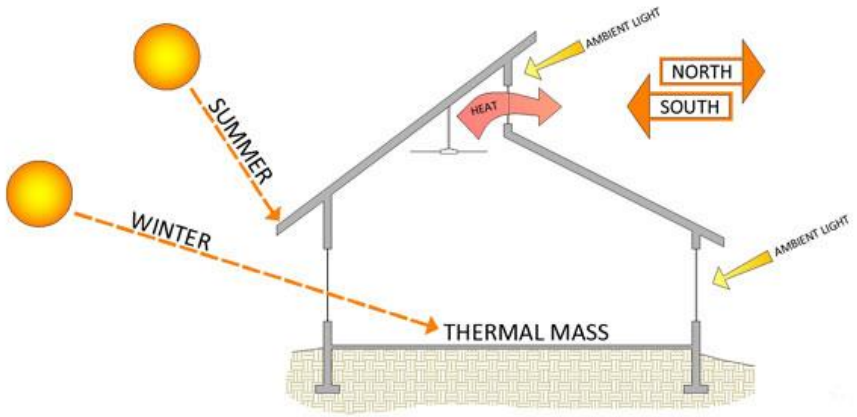
1. Provide the amount of energy consumed by buildings and cities.
2. Provide a method to develop a customized building energy use baseline estimation tool by using a data-driven approach.
3. Describe how façade features could influence certain building energy use in a specific climate condition and a particular building geometry.
4. Demonstrate how district-scale energy retrofit analysis can be performed using existing urban modeling tools.

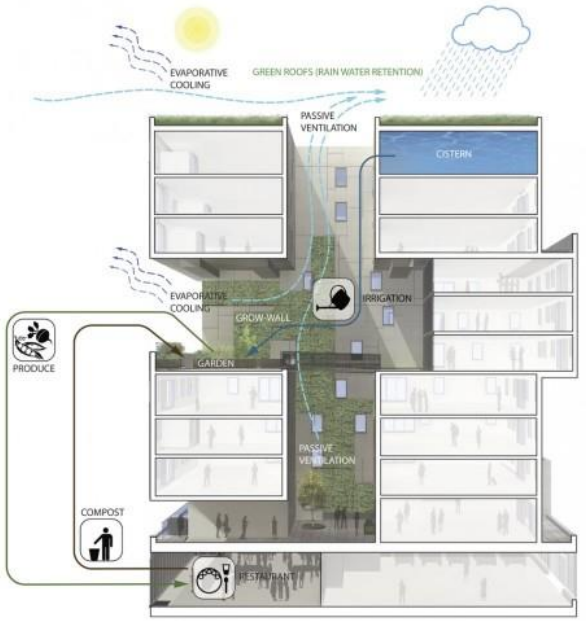
Outline/Agenda

- Introduction
- Existing Problems
- Research Results
- Discussion
- Conclusion
- References

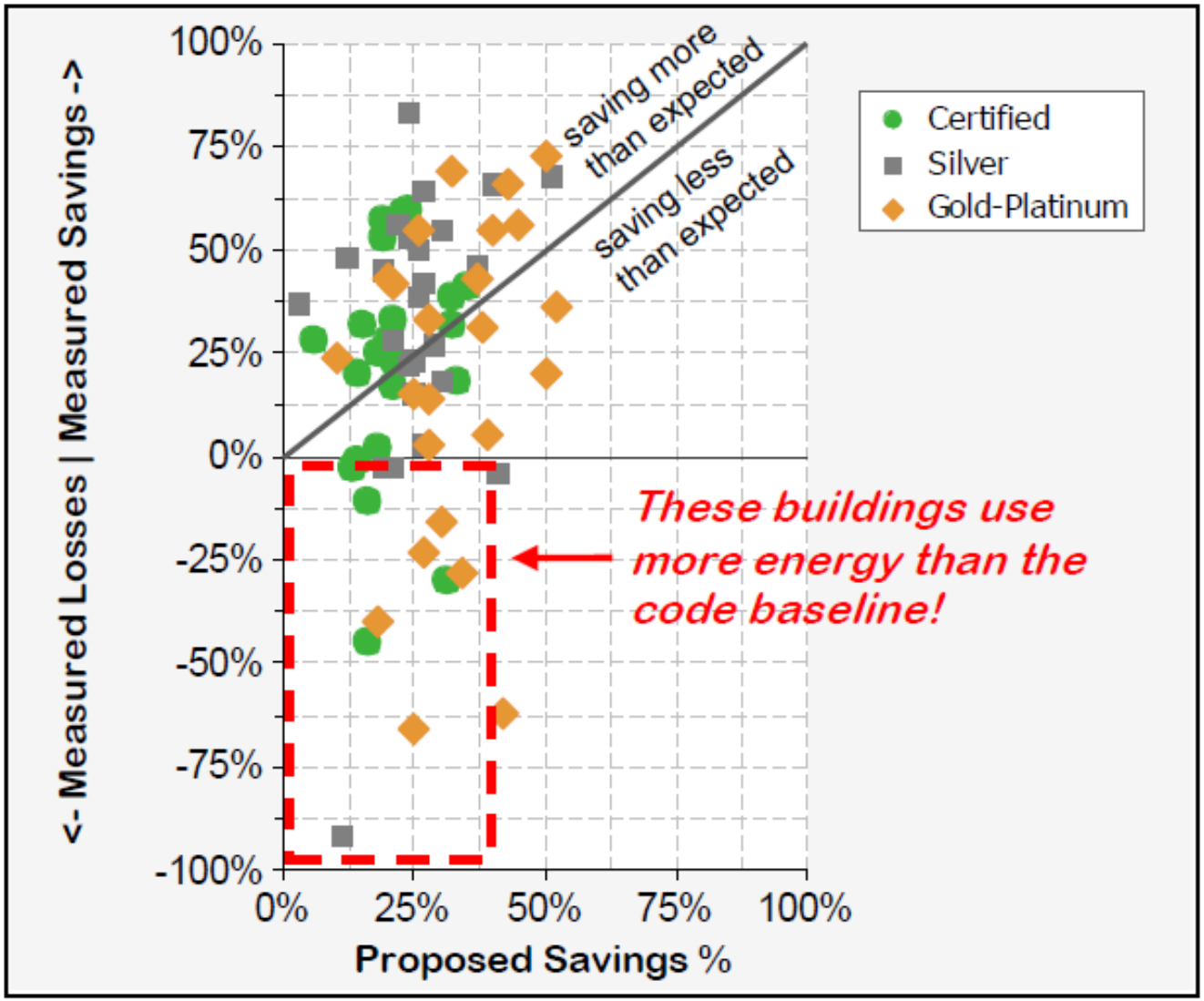
California Energy Commission

- California Net-Zero 2020
  - ZNEnergy residential by 2020
  - ZNEnergy non-residential by 2030





Measured Vs. Proposed Savings Percentages



Vision-based Building Energy Assessment

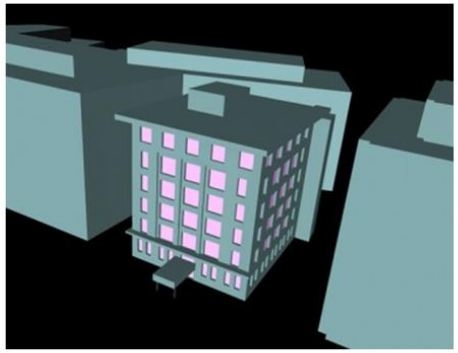
- Big-Data
  Best practice cases

Energy Star; DOE; GSA; AIA; NBI

- Database
  EUI for HVAC and lighting, climate & site conditions, adopted design & technologies

- Best design - system strategies
- Estimated building performance

- Advanced data mining algorithms
- Web-interface for Inputs
  - *Location-Climate zone*
  - *Building type*
  - *Preferred design/systems*
  - *Site / project geometry*
  - *Construction type*
  - *Target rating*



Data Collection/Model Development

Seattle Energy Benchmarking & Report

3. MINNEAPOLIS PUBLIC BUILDINGS (2012 DISCLOSURE)

2. 28 OFFICE BUILDINGS IN MANHATTAN, NYC (2011 AND 2012 DISCLOSURE)

New York City

4. BOSTON BENCHMARKING (2012 DISCLOSURE)

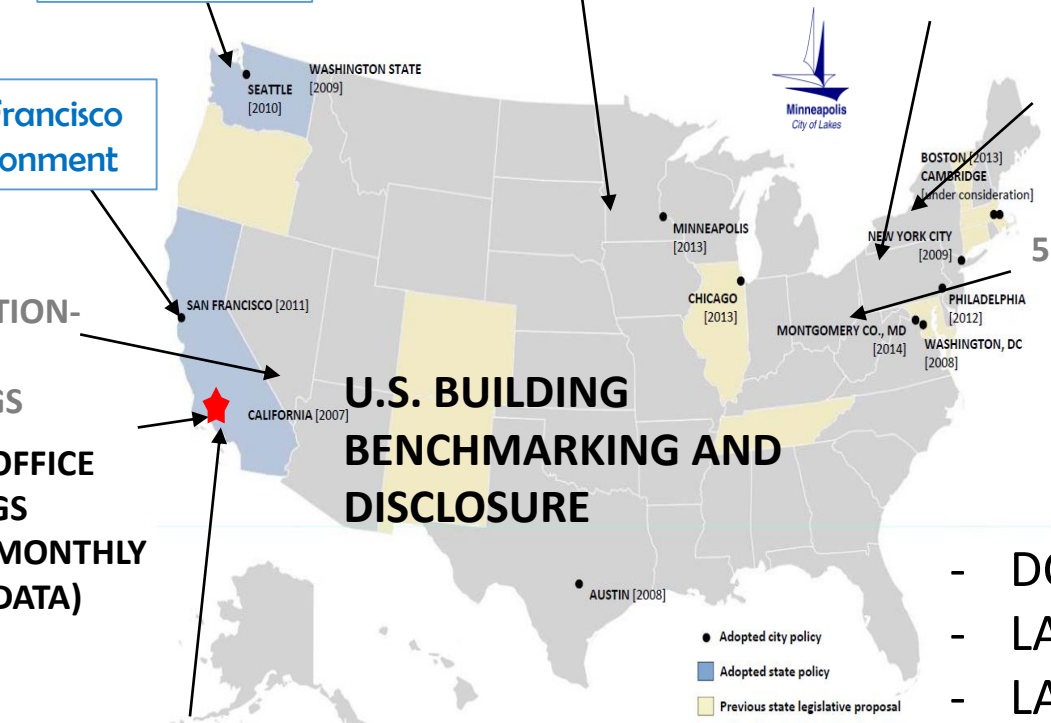
Boston

San Francisco Environment

Washington D.C.

5. WASHINTON, D.C. BENCHMARKING (2011 AND 2012 DISCLOSURE)

6. 188 NATION-WIDE BUILDINGS



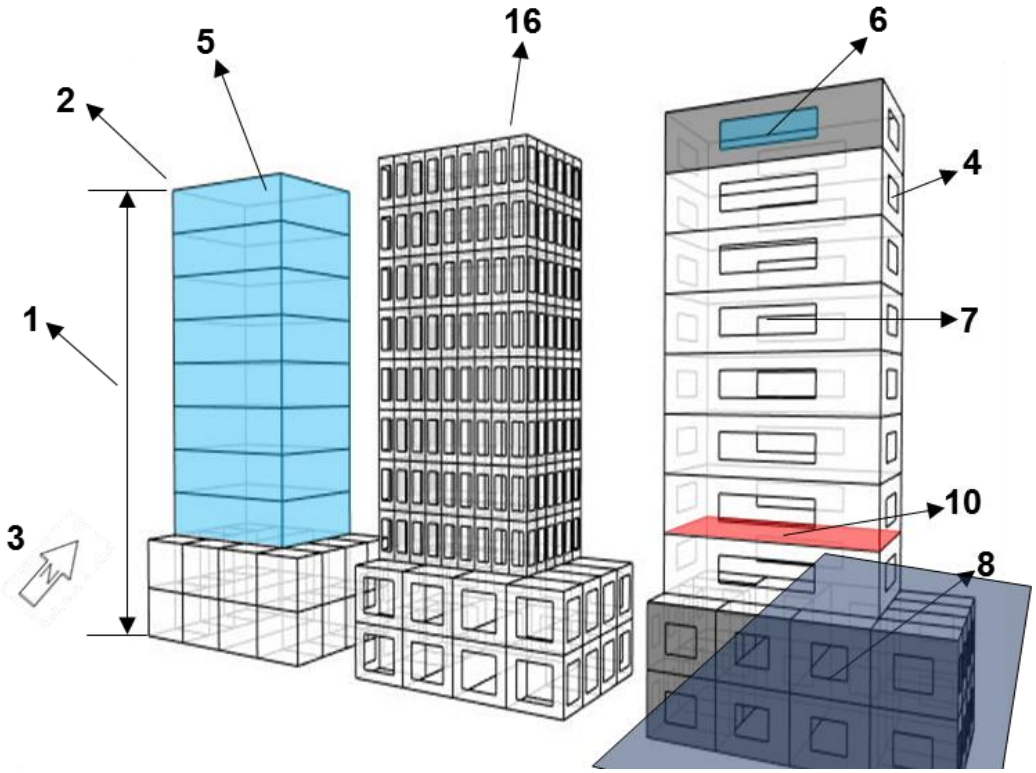
U.S. BUILDING BENCHMARKING AND DISCLOSURE

1. LA 10 OFFICE BUILDINGS (7 WITH MONTHLY ENERGY DATA)

- DC Annual EUIs
- LA Annual EUIs
- LA Monthly Cooling
- LA Monthly Heating
- NYC Annual EUIs

DATA MONITORING FOR CASE STUDY

Methodology



1. Height
2. Floors
3. Orientation
4. Operable window
5. Volume
6. WWR

7. Window area
8. Façade area
9. Site area
10. Floor area

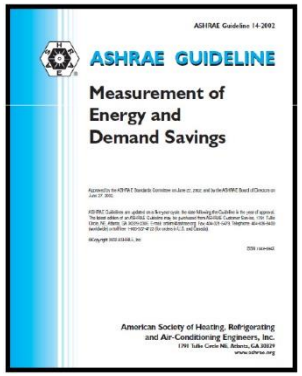
11. V/FA
12. V/SA
13. FA/SA

14. HDD
15. CDD

16. Adjacent building
17. Built year

18. Other factors

Methodology



provide guidelines for reliably measuring the energy and demand savings and examine the accuracy of simulation

Whole Building Calibrated Simulation Approach
- Uses computer simulation software to model facility energy use and demand
- Model is calibrated against actual energy use and demand data
- Calibrated model is used to predict energy use and demand of the post-retrofit period

Produce a calibration plan

IES — Software, monthly/hourly, tolerances

Collect data

Run simulation

Compare output to measure data

Refine model until an acceptable calibration is achieved

$$NMBE = \frac{\sum^{n} y_i - \hat{y}_l}{(n-p) \times \bar{y}} \times 100$$

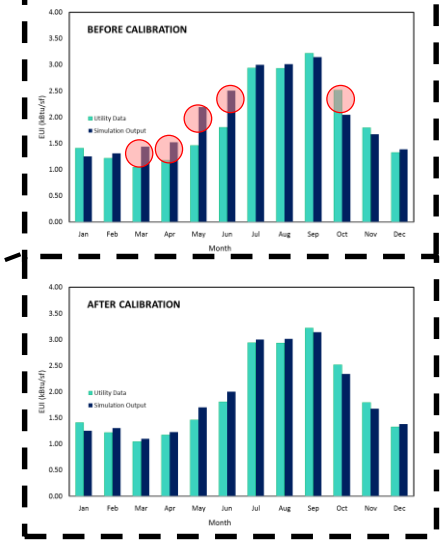
$$CVRMSE = 100 \times \left[\sum (y_i - \hat{y}_l)^2/(n-p)\right]^{1/2} / \bar{y}$$

NMBE: ±10%
CVRMSE: ±5 - 15%

Monthly EUI model

Monthly Regression Model

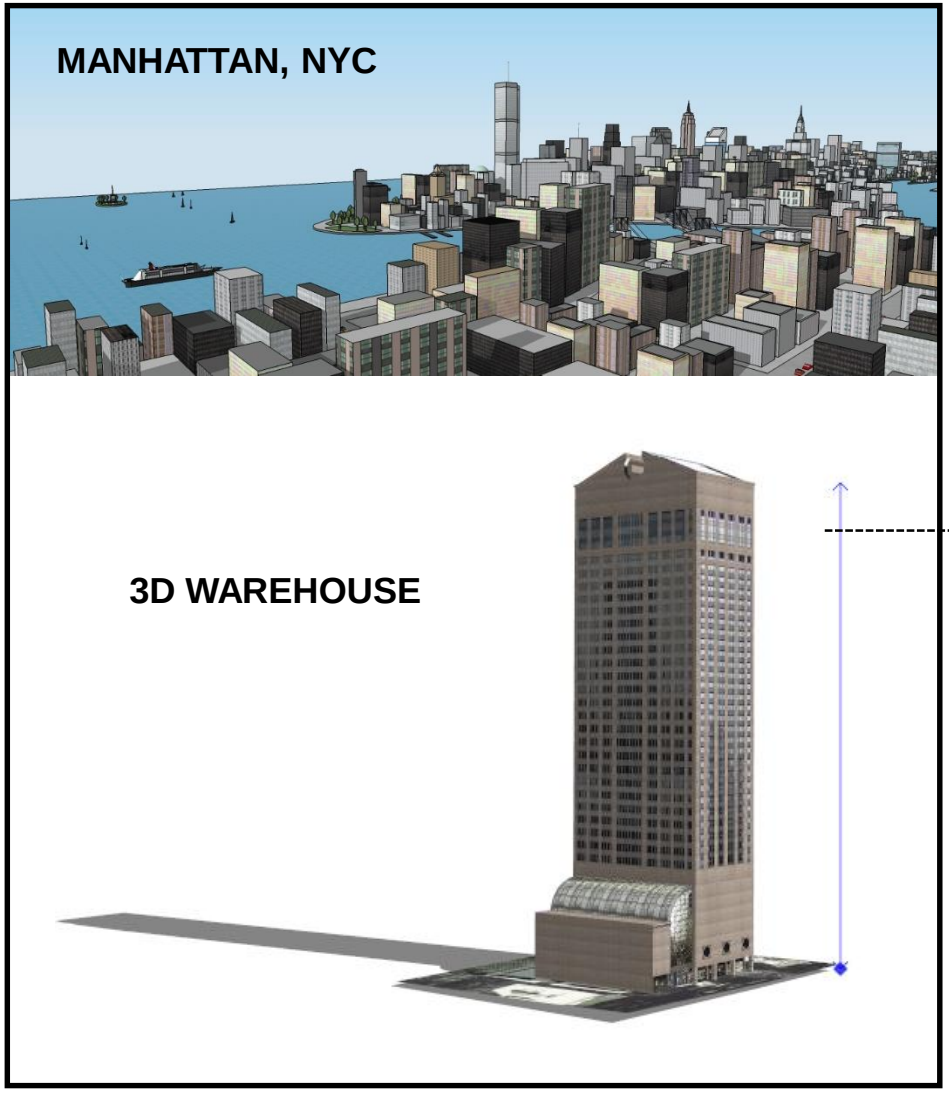
BEFORE



AFTER

*** normalized mean bias error (NMBE)**
coefficient of variation of the root mean square error (CVRMSE)
where yi is the utility data used for calibration; ŷl is the simulation predicted data; ȳ is the arithmetic mean of the sample of n observations; p=1 for calibrated simulations.

Methodology



BENCHMARKING DATA — 14112

MANHATTAN OFFICE — 40

SketchUp MODEL — 5

FAÇADE FEATURES READING × 2011/2012 SITE EUI

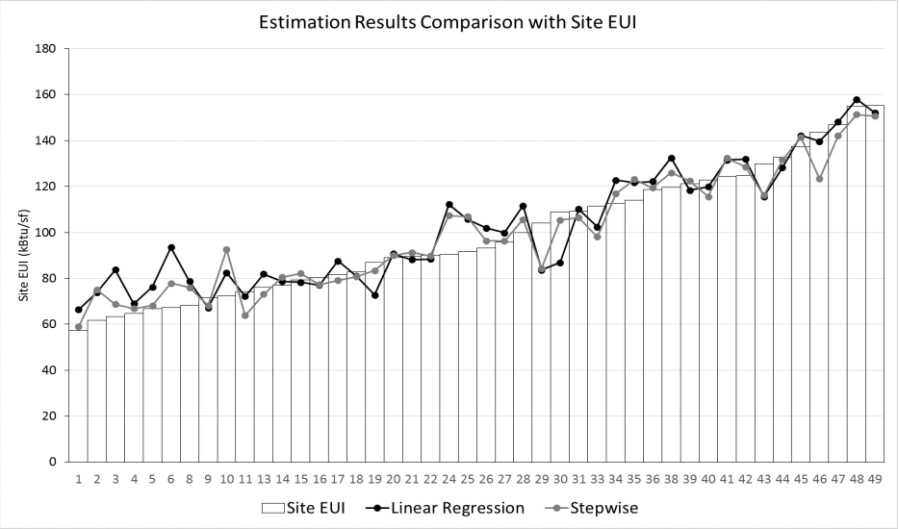
Datamining Tool

REGRESSION

Site EUI = -75.3 + 0.1553 Height (ft) + 0.719 WWR (%) + 18.77 Orientation - 19.65 Operable Window (Y/N) - 0.000054 Floor Area (SF) + 0.1352 V/SA - 9.47 FA/SA + 0.0324 HDD + 0.001340 S Facade - 0.000634 W Facade

Results

Determination	Linear Regression			Stepwise Regression		
R^2/ R^2 (Adj)/ R^2 (pre)	77.64%	56.18%	-	88.15%	84.66%	77.72%
D-W	2.022			1.989		
Predictors	Coef	P-value	VIF	Coef	P-value	VIF
Constant	27302	0.174		-75.3	0.047	
Height	0.087	0.593	83.84	0.1553	0.000	3.85
Floors	0.06	0.979	78.14			
Built year	-0.339	0.586	17.67			
WWR	0.542	0.507	25.16	0.719	0.000	2.03
Orientation	26	0.033	25.61	18.77	0.000	4.53
Operable Window	-29.9	0.15	12.2	-19.65	0.000	2.11
Volume	0	0.995	605.78			
Window Area	0.000149	0.55	100.77			
Site Area	0.00035	0.729	54.2			
Floor Area	-0.00007	0.031	29.78	-0.000054	0.000	8.55
V/FA	-0.84	0.809	127.38			
V/SA	0.185	0.515	132.69	0.1352	0.001	4.52
FA/SA	-10.29	0.11	77.31	-9.47	0.000	8.61
Adjacency	-1.85	0.502	12.44			
HDD	5.86	0.178	53879.79	0.0324	0.006	1.02
CDD	-22.7	0.181	53885.9			
N Façade Area	-0.01101	0.201	6298.99			
S Façade Area	0.125	0.23	1023528.62	0.001340	0.000	11.46
W Façade Area	-0.00249	0.2	598.28	-0.000634	0.009	13.83
E Façade Area	-0.0889	0.243	862326.34			
NW Façade Area	-0.000146	0.806	49.89			
NE Façade Area	-0.00017	0.892	553.6			
SW Façade Area	-0.000118	0.849	148.17			
SE Façade Area	0.000571	0.471	101.53			



KEY INDICATORS:

R^2 : explain 88% of variance in the annual EUI value.

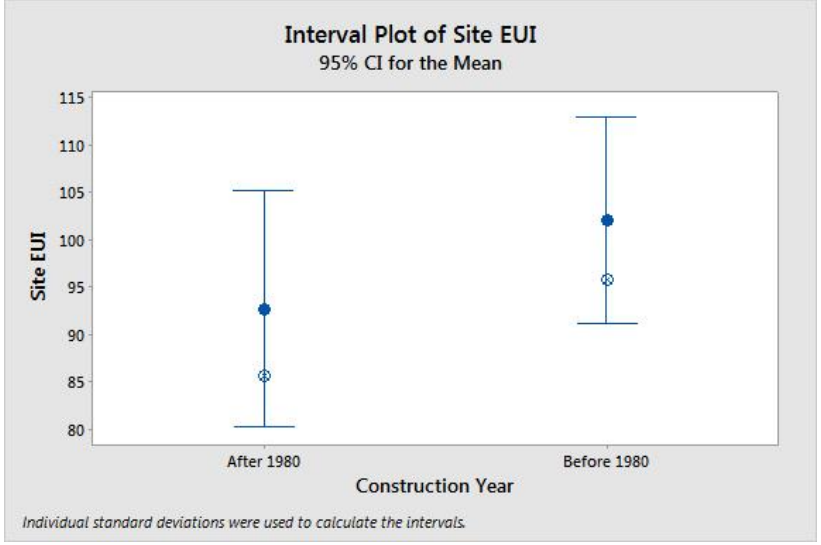
R^2(adj): how well the model fits the model well.

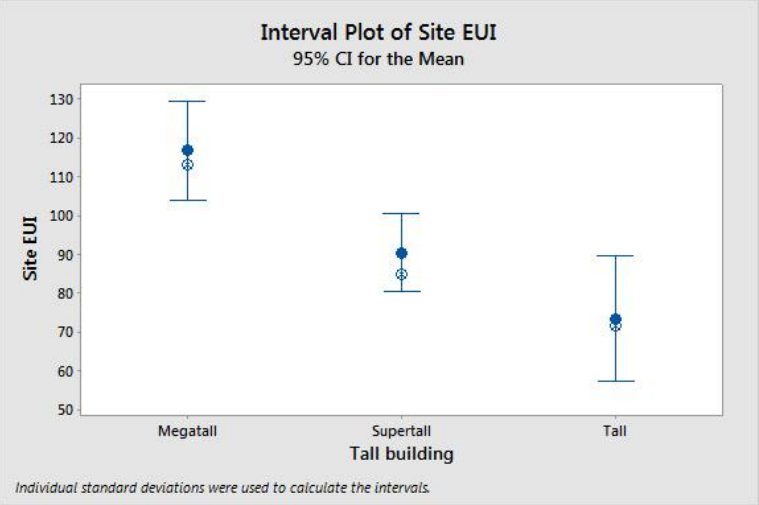
Durbin-Watson statistic: 2 means no autocorrelation

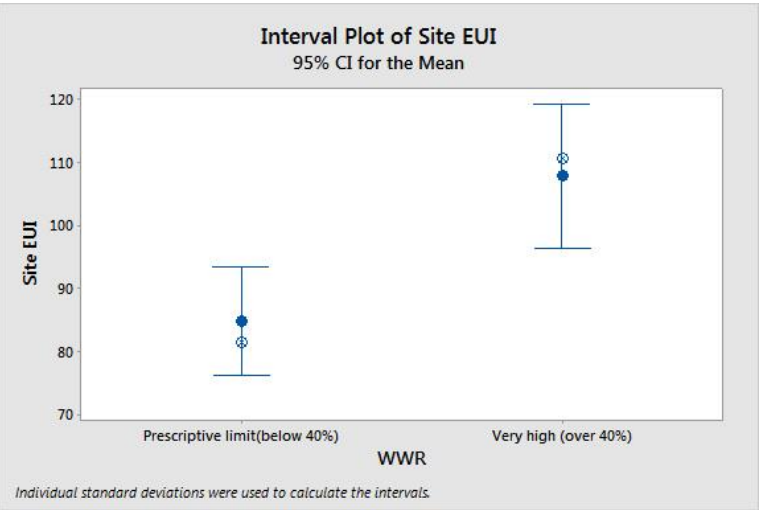
P-value: significantly related to annual EUI at a α-level of 0.05

VIF: multicollinearity

Results



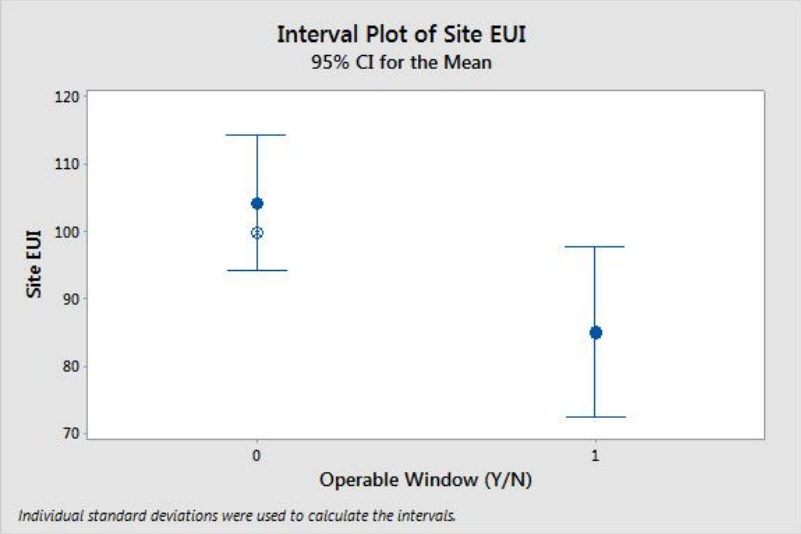


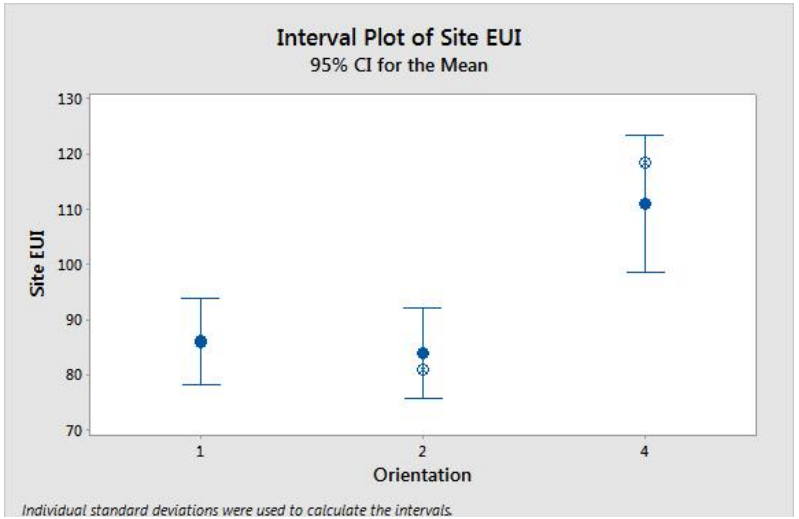


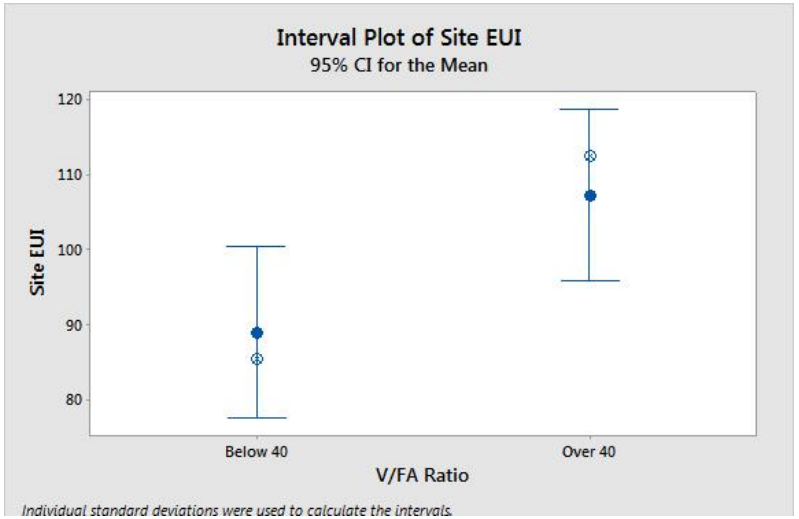
ANALYSIS

1. 1979 NYC 1st state energy code
2. Tall (165-300 ft), Supertall (300-600), Megatall (600+)
3. WWR ≤ 40%, NYCECC prescriptive requirement

Results







ANALYSIS

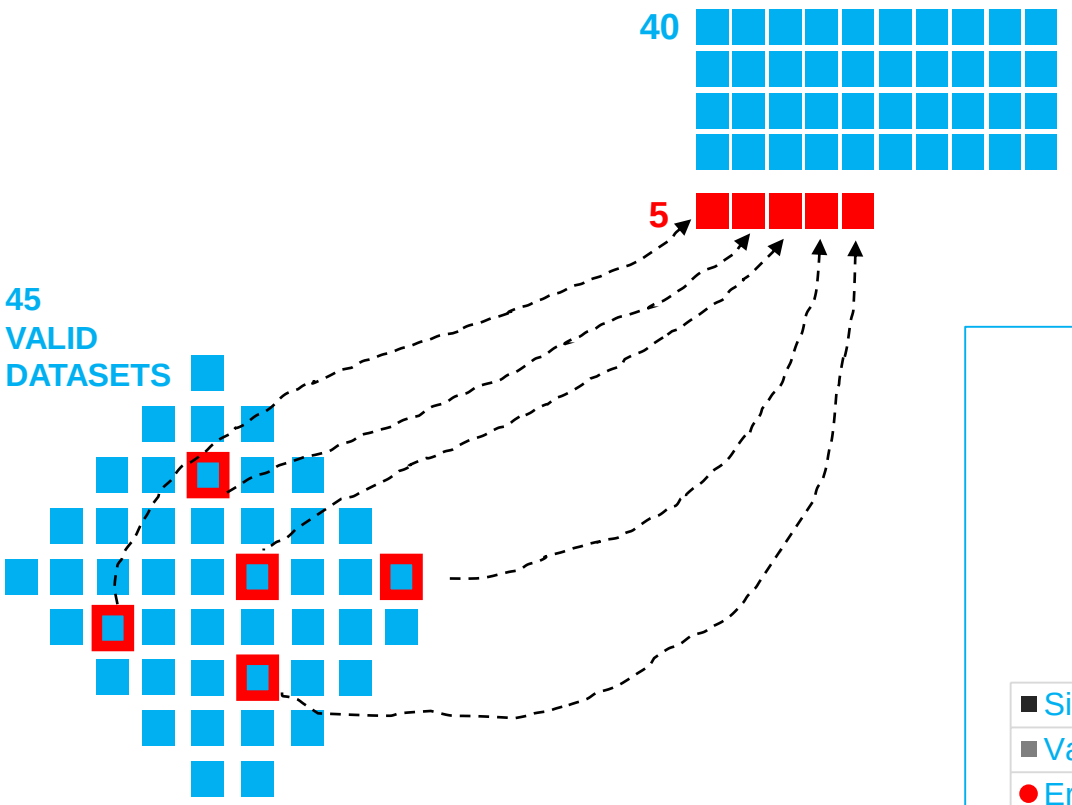
1. Operable window
2. Orientation (N-S/NE-SW/NW-SE)
3. Volume/Façade Area ratio

HDD/CDD Impact

2011: 3272/2018

2012: 2988/1945

10 – Cross Validation



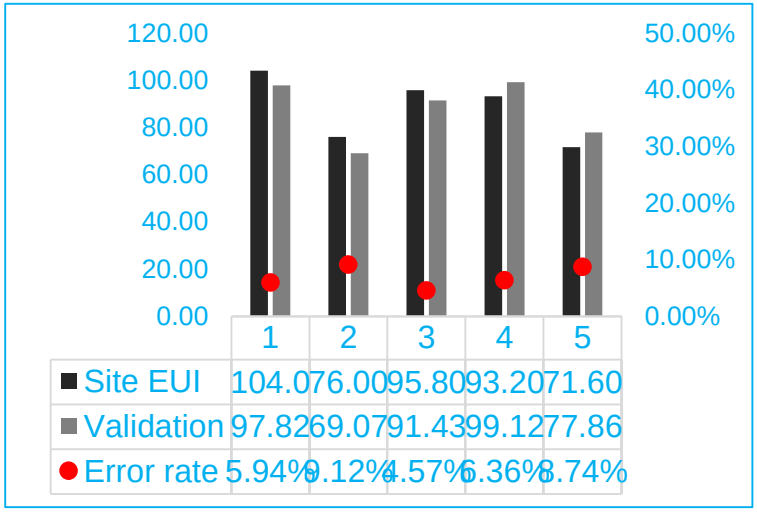
90% TRAINING SAMPLES

Test EUI Regression Model

R^2/ R^2 (Adj) = 91.02%/85.98%

D-W = 2.04

10% RANDOMLY SELECTED VALIDATION SAMPLES



Results

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WWR	0.542	0.507		0.719	0.000	
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Volume	0	0.995		-	-	
Window Area	0.000149	0.55		-	-	
Site Area	0.00035	0.729		-	-	
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V/SA	0.185	0.515		0.1352	0.001	
FA/SA	-10.29	0.11		-9.47	0.000	
Adjacency	-1.85	0.502		-	-	
HDD	5.86	0.178		0.0324	0.006	
CDD	-22.7	0.181		-	-	
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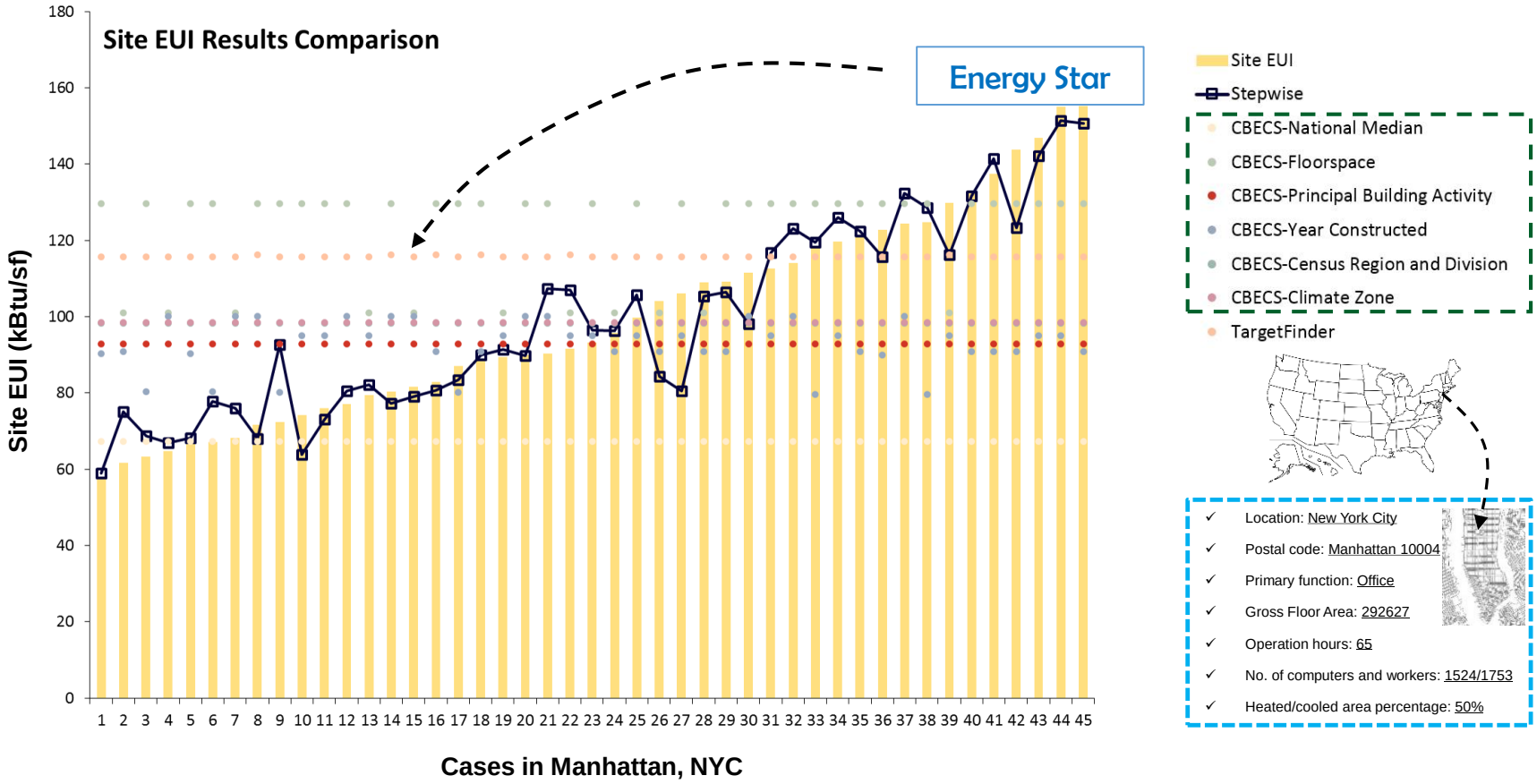
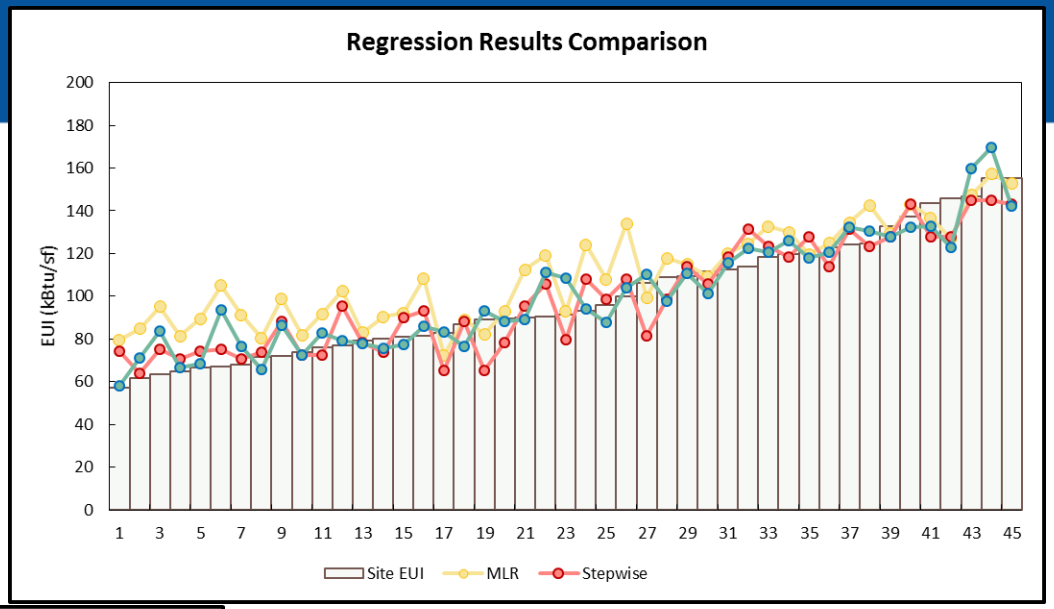
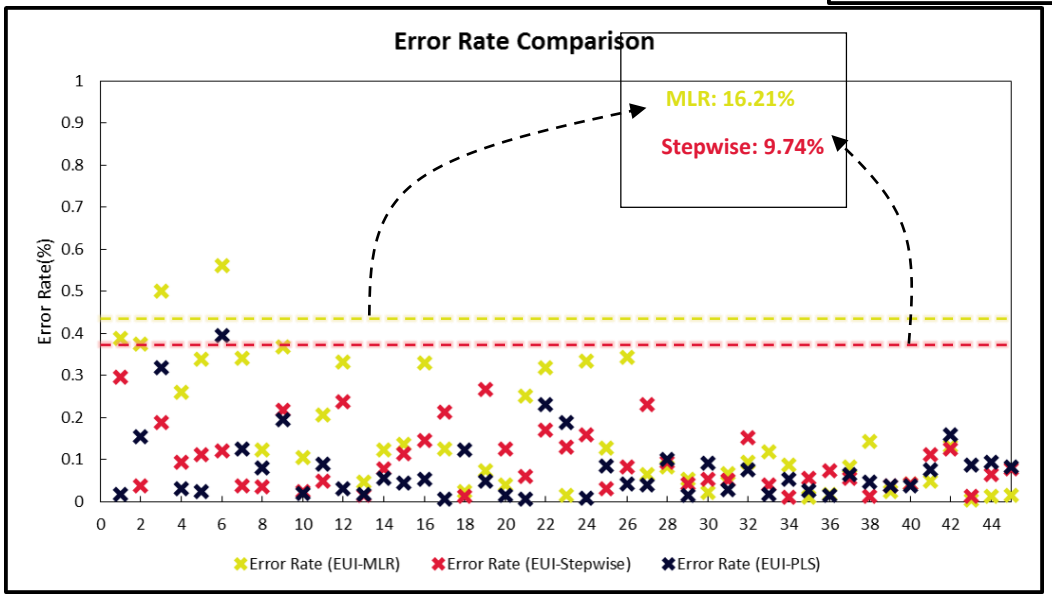
S Façade Area	0.125	0.23		0.001340	0.000	
W Façade Area	-0.00249	0.2		-0.000634	0.009	
E Façade Area	-0.0889	0.243		-	-	-
NW Façade Area	-0.000146	0.806		-	-	-
NE Façade Area	-0.00017	0.892		-	-	-
SW Façade Area	-0.000118	0.849		-	-	-
SE Façade Area	0.000571	0.471		-	-	-


Site EUI Results Comparison
Energy Star
Site EUI (kBtu/sf)
Cases in Manhattan, NYC
Site EUI
Stepwise
CBECS-National Median
CBECS-Floorspace
CBECS-Principal Building Activity
CBECS-Year Constructed
CBECS-Census Region and Division
CBECS-Climate Zone
TargetFinder
Location: New York City
Postal code: Manhattan 10004
Primary function: Office
Gross Floor Area: 292627
Operation hours: 65
No. of computers and workers: 1524/1753
Heated/cooled area percentage: 50%

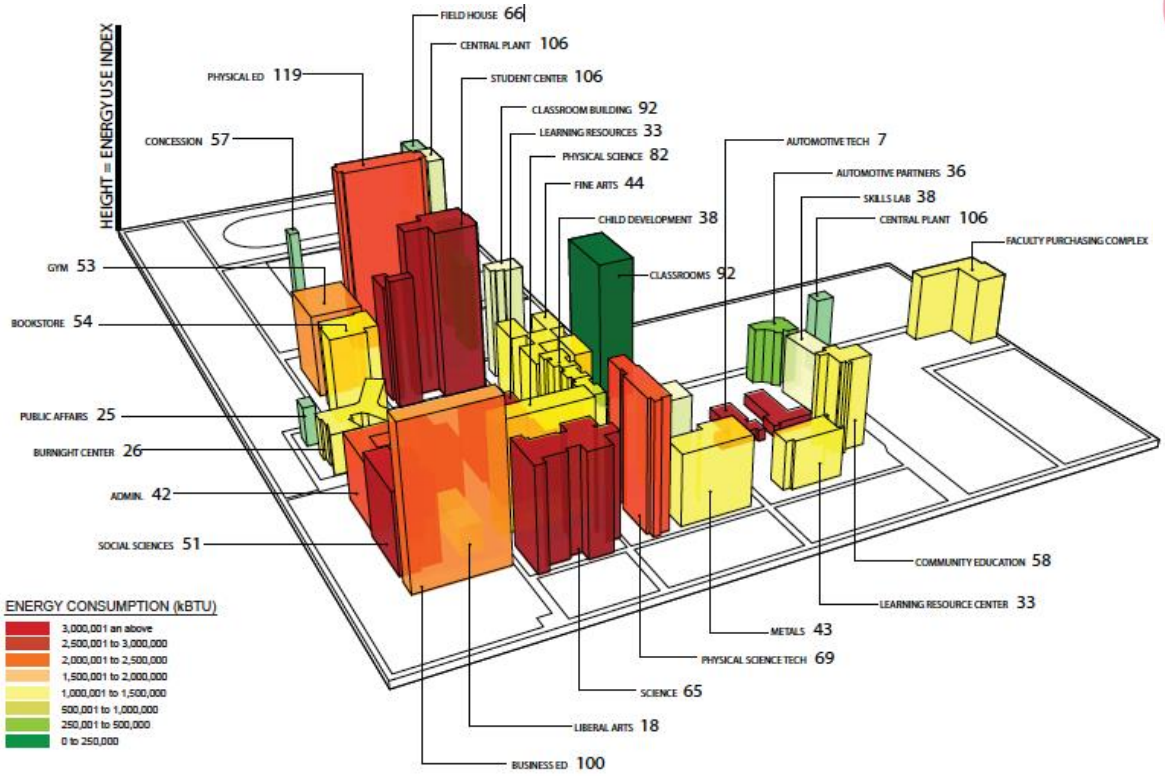
Results

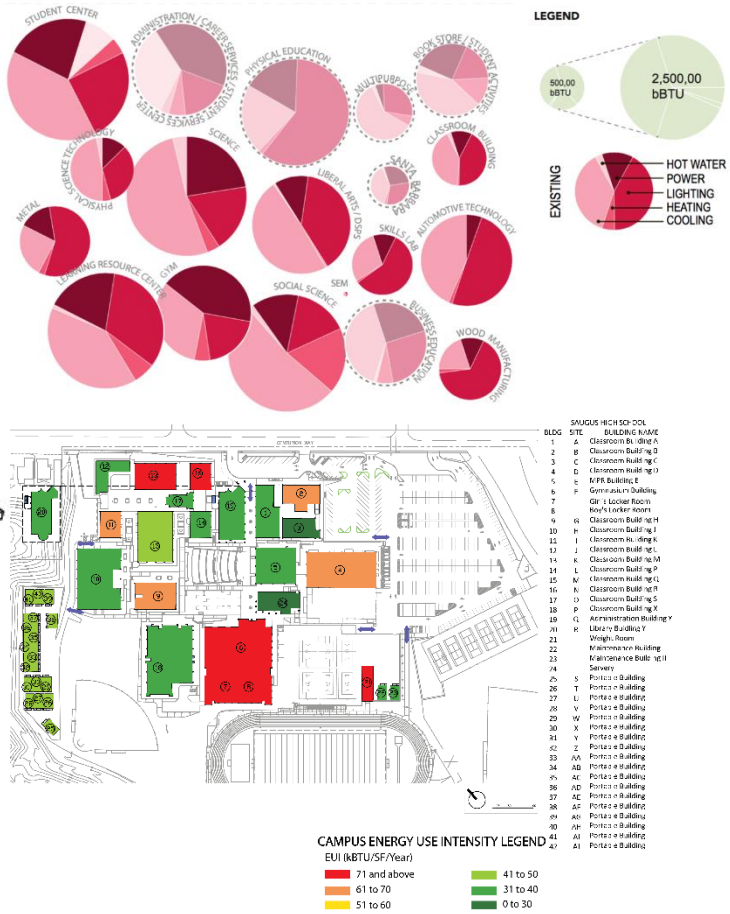

Regression Results Comparison
EUI (kBtu/sf)
200
180
160
140
120
100
80
60
40
20
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45
Site EUI
MLR
Stepwise


Error Rate Comparison
MLR: 16.21%
Stepwise: 9.74%
Error Rate(%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44
Error Rate (EUI-MLR)
Error Rate (EUI-Stepwise)
Error Rate (EUI-PLS)

Discussion - Case Study

Local College School District – 100 buildings





Source: Harley Ellis Devereaux

Discussion - Case Study

No.	Façade & Climate	Definition
1	Function	Building occupant pricipal activities
2	Vintage	Year of construction complete
3	Height	From open air pedestrian entrance to highest occupied floor
4	Floorspace	Total floor area inside the building envelope
5	Orientation	Positing of a building with respect to the North
6	WWR	Window-to-wall ratio (total window area/total exterior wall area)
7	Volume	Inner space volume enclosed by external envelope
8	Window Area	Total glazing area
9	Façade Area	Total area of all parts of the structure's façade
10	Aspect Ratio	proportional relationship between the width and height
11	Shape Coefficient	Ratio of volume to façade area
12	Shading	any external shading device
13	Number of Floors	Total occupied stories or levels
14	FAR	Floor to Area Ratio
15	Operable Window	Window could be open or close based ventilation need4
16	South WWR	Window-to-wall ratio of south facing façade
17	West WWR	Window-to-wall ratio of west facing façade
18	North WWR	Window-to-wall ratio of north facing façade
19	East WWR	Window-to-wall ratio of east facing façade
20	Monthly CDD	Cooling degree day (the demand for energy to cool a building)
21	Monthly HDD	Heating degree day (the demand for energy to heat a building)
22	Dry-Bulb Temperature	Monthly average outdoor air temperature
23	Diurnal Temperature	Monthly average daily temperature swing range
24	Monthly Average RH	average of relative humidity

Title 24 Building Energy Efficiency Standard

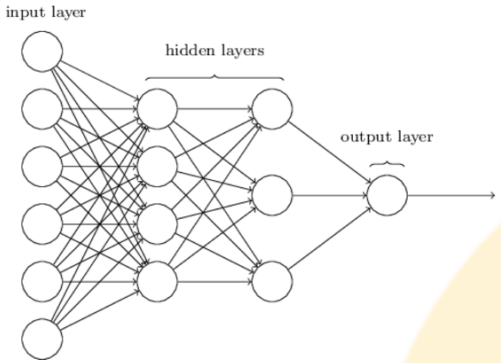
Btu/(hr.ft.°F)

Version	Wall	Roof	Floor	Window
1980	0.44 ow	0.1 ow	N/A	N/A
1982	0.44 ow	0.1 ow	0.29	N/A
1984	0.44 ow	0.1 ow	0.29	N/A
1986	0.44 ow	0.1 ow	0.29	N/A
1987	0.44 ow	0.1 ow	0.29	N/A
1988	0.44 ow	0.1 ow	0.29	N/A
1992	0.43	0.078	0.158	1.23
1995	0.43	0.078	0.158	1.23
1998	0.43	0.078	0.158	1.23
2001	0.43	0.078	0.158	1.23
2005	0.43	0.078	0.158	1.23
2008	0.44	0.039	0.269	0.77
2013	0.44	0.039	0.269	0.36
2016	0.44	0.034	0.269	0.36

Sample Data Organization

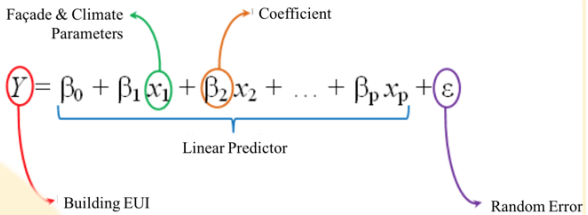
	Month	EUI (kBtu/sf)	HDD	CDD	Dry-Bulb Temperature	Diurnal Temperature	RH	Vintage	Floorspace (sf)	WWR (%)	Height (ft)	Façade Area	Orientation	Volume	Window Area	Aspect Ratio
BLDG 1	Jan	3.163	275	21	58.8	16.9	68.6									
	Feb	2.857	150	131	60.1	19.9	70.8									
	Mar	3.226	147	62	61.2	18.7	71									
	Apr	3.324	93	111	63.8	18.2	67.7									
	May	3.730	70	71	64.3	15.7	71.1									
	Jun	3.824	23	225	77.7	16.7	72.7									
	Jul	4.131	4	339	82.3	18.1	72.2	1963	45568	20	16	65765.6	1	729088	4008	1.540
	Aug	4.094	1	313	83.1	16.7	70.8									
	Sep	3.666	12	264	80	17.1	71									
	Oct	4.026	34	169	73	23.7	69.7									
	Nov	3.101	197	79	64.9	14.3	65.8									
	Dec	3.025	324	33	60.5	12.9	67.3									
	Total	42.165	1330	1818	69.1	17.4	70.1									

Data Mining Techniques adopted



Artificial Neural Network

Multivariable Regression

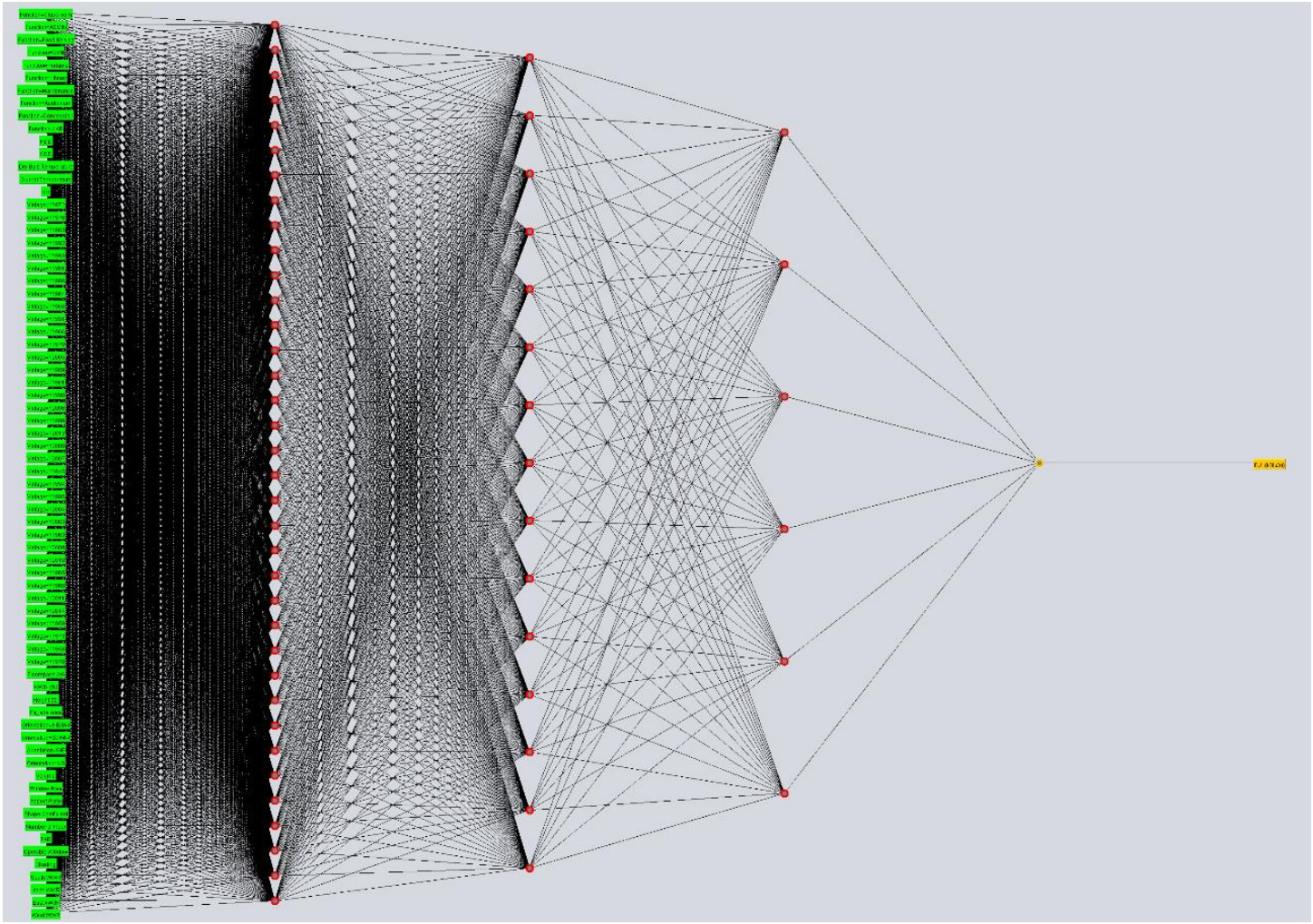


Stepwise Regression Output

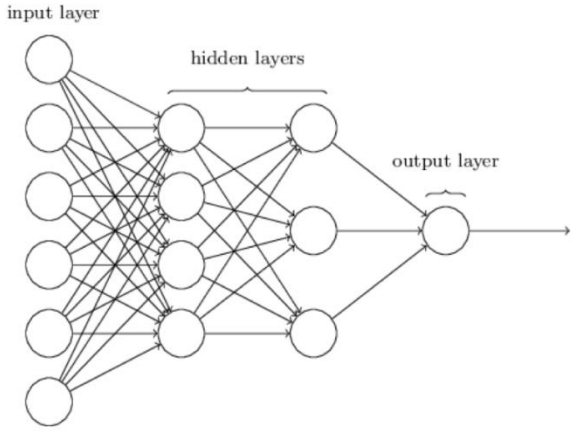
	Step 1		Step 2		Step 3		Step 4		Step 5	
	Coef	P	Coef	P	Coef	P	Coef	P	Coef	P
Constant	0.897		-26.21		-28.49		-39.51		-43.68	
HDD	0.025429	0.000	0.027461	0.000	0.027622	0.000	0.027856	0.000	0.027869	0.000
Dry-Bulb Temperature			0.3873	0.000	0.3839	0.000	0.3537	0.000	0.3422	0.000
South WWR					0.138	0.000	0.1009	0.000	0.0932	0.000
RH							0.2159	0.000	0.3124	0.000
Façade Area									-0.000039	0.000
s	6.78355		6.10505		5.70983		5.57225		5.48038	
R-sq	68.27%		74.36%		77.63%		78.75%		79.49%	
R-sq(adj)	68.19%		74.24%		77.47%		78.54%		79.24%	
R-sq(pred)	67.14%		73.16%		76.06%		77.14%		77.84%	
Mallows' Cp	232.84		111.03		46.65		25.96		12.81	

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-43.68	3.58	-12.20	0.000	
HDD	0.027869	0.000715	39.00	0.000	1.08
Dry-Bulb Temperature	0.3422	0.0358	9.56	0.000	1.12
South WWR	0.3124	0.0521	6.00	0.000	1.64
RH	-0.000039	0.00001	-3.86	0.000	1.32
Façade Area	0.0932	0.0189	4.93	0.000	1.23

Artificial Neural Network (EUI value prediction)



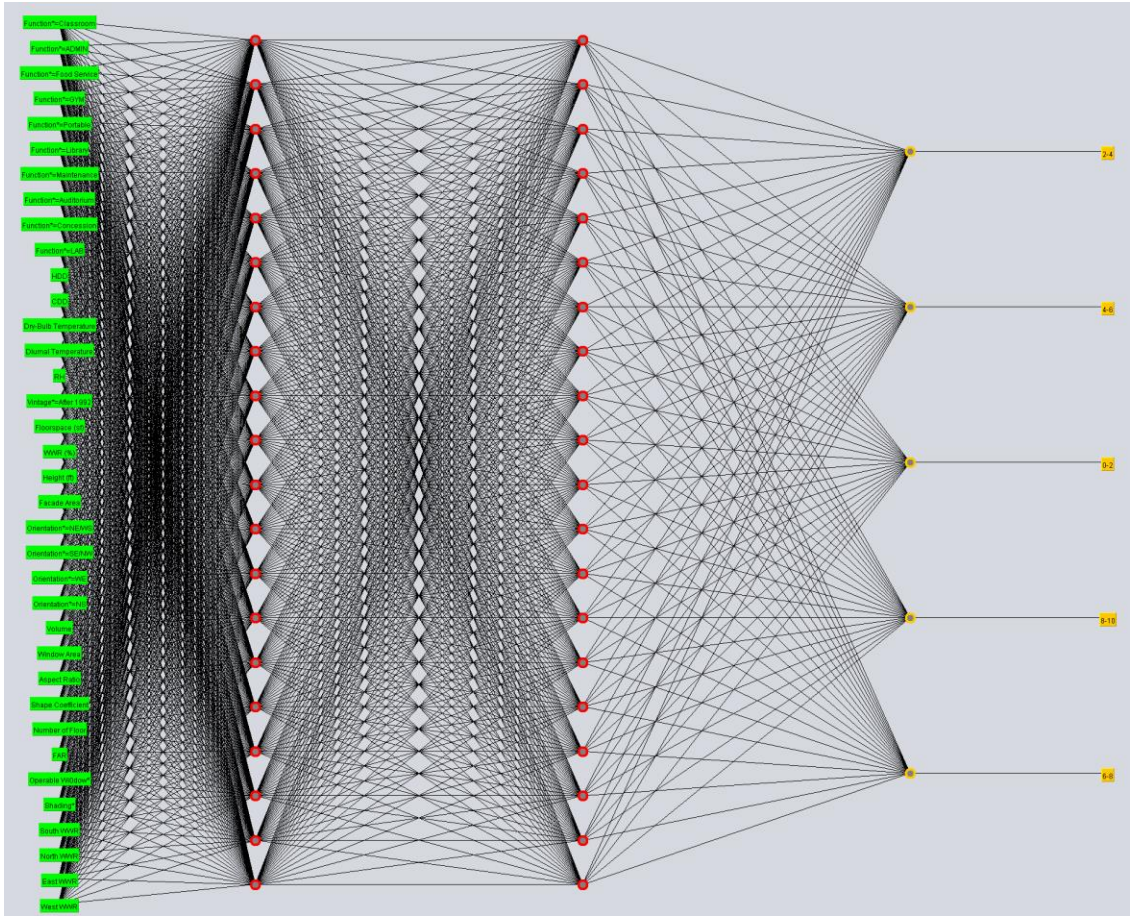
Artificial Neural Network (EUI value-prediction)



Correlation coefficient	0.9939
Mean absolute error	0.7325
Root mean squared error	1.4335
Relative absolute error	12.1756%
Root relative squared error	11.9319%
Total Number of Instances	416

- Correlation coefficient
  - Annual EUI: 99.39%
  - Monthly EUI: 99.5%
- Relative absolute error
  - Annual EUI: 12.13%
  - Monthly EUI: 11.87%

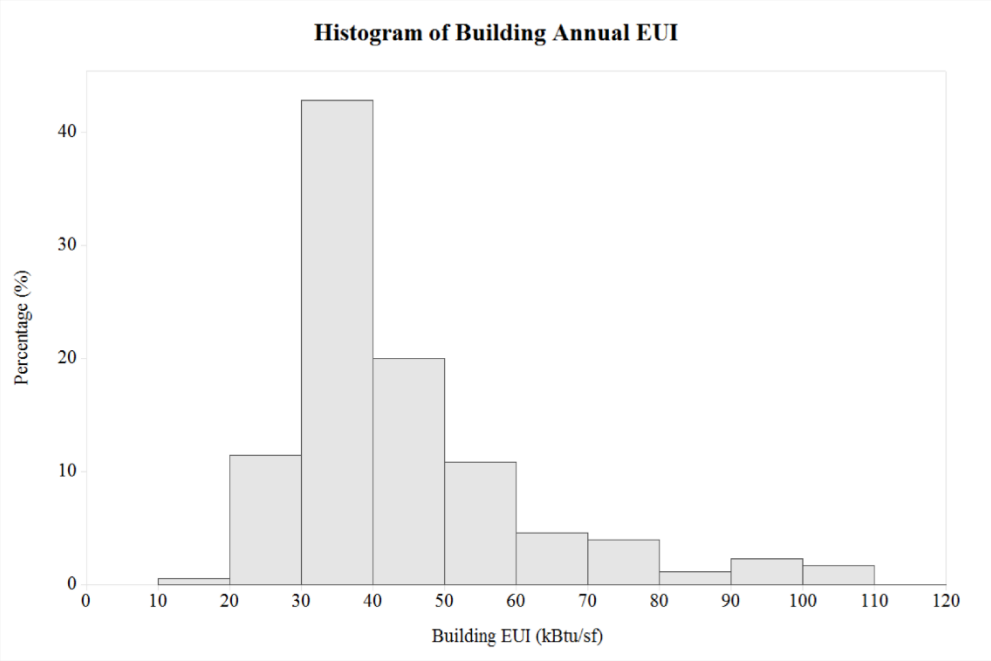
Artificial Neural Network (EUI value range prediction)



Annual EUI estimation

Artificial Neural Network (Classification)

Annual EUI Range Prediction Model

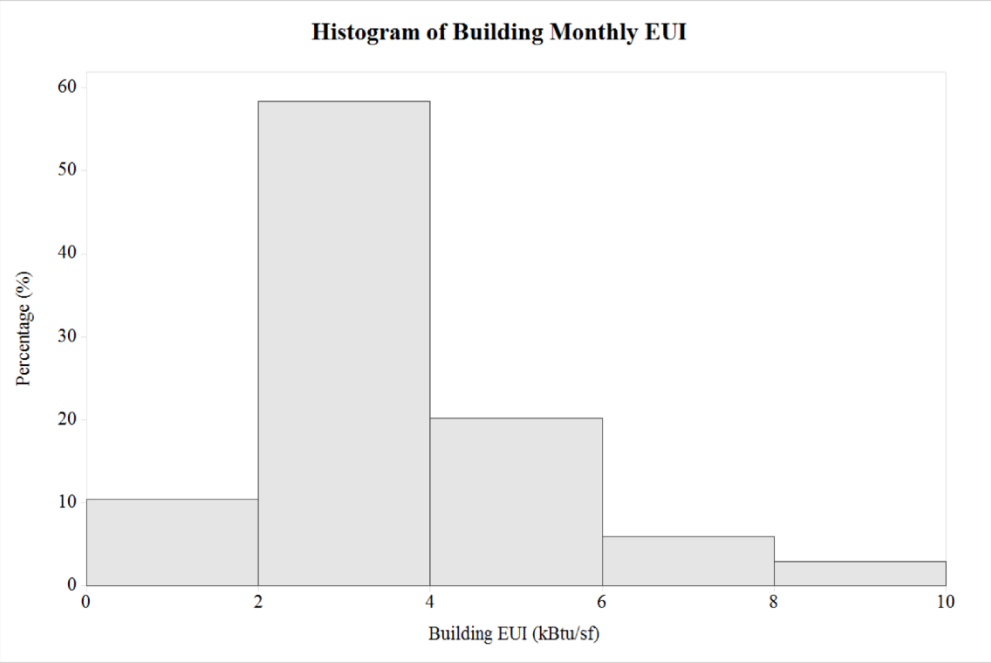


Correctly classified instances	90.3%
Incorrectly classified instances	9.7 %
Kappa statistics	0.8941
Mean absolute error	0.0314
Root mean squared error	0.201
Relative absolute error	15.3%
Root relative squared error	42.2%
Total number of stances	100

Monthly EUI estimation

Artificial Neural Network (Classification)

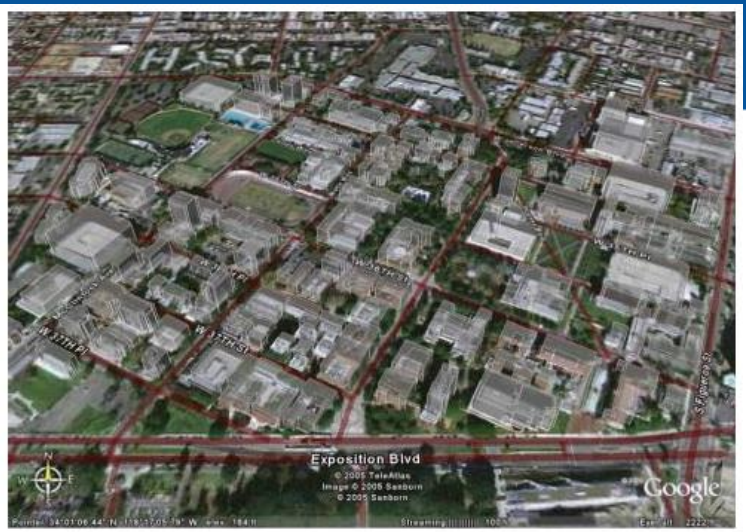
Monthly EUI Range Prediction Model

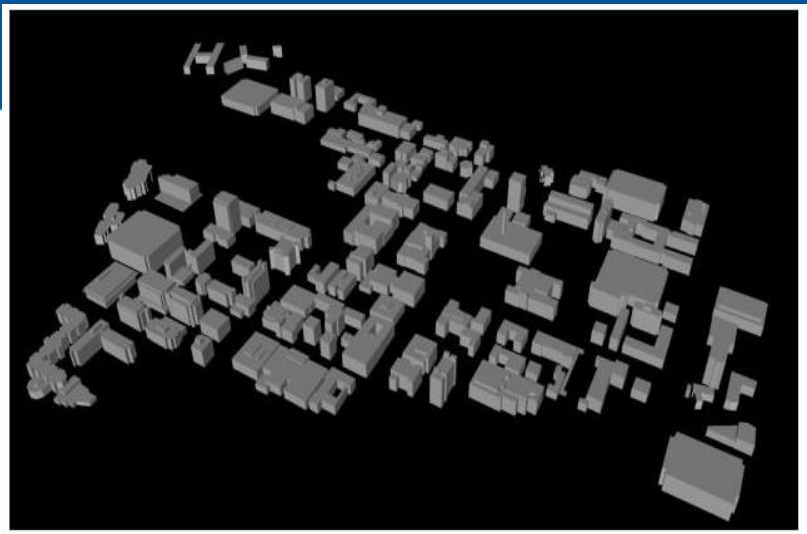


Correctly classified instances	93.5%
Incorrectly classified instances	6.5 %
Kappa statistics	0.981
Mean absolute error	0.0258
Root mean squared error	0.012
Relative absolute error	9.6%
Root relative squared error	28.2%
Total number of stances	1200

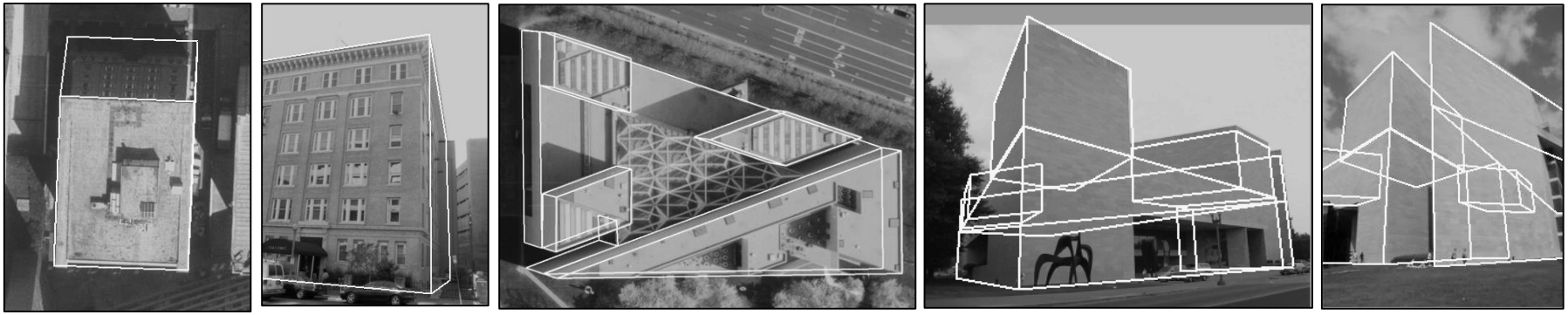
Bird’s eye view images in Internet

Street view images



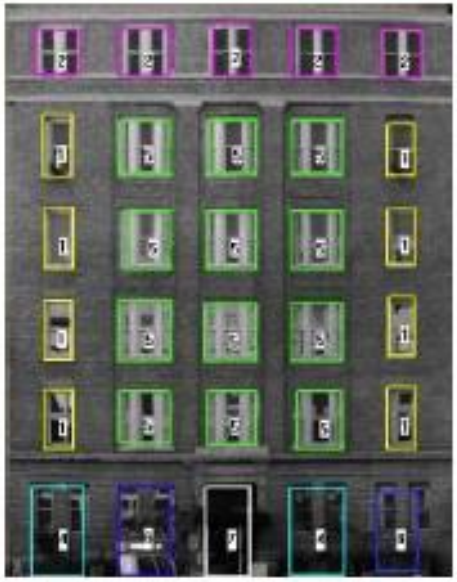


3D building models generated by the campus semi-automatic building systems and the obtained 3D building models



Examples of pose estimation of 3D building models in ground view images; wireframe of 3D model is overlaid from aerial image (left) and ground view images (right) per example





Example of extracting windows from a facade

Conclusions

- The research outcome revealed that the building façade features and the relevant information can be used as significant building EUI performance indicator.
- Multiple linear regression including stepwise regression and multivariable regression based on selected principal components were capable of investigating the relationship among numerous façade attributes and the building EUIs, but a limited accuracy issued was raised.
- The advantages of using artificial neural network and decision tree were presented with the high predictive ability of the EUI performance model.
- The studied data-driven approach has a high potential to be applicable to urban-scale energy modeling applications.

Bibliography

- Hong, Tianzhen, Yixing Chen, Sang Hoon Lee, and Mary Ann Piette. “CityBES: A Web-based Platform to Support City-Scale Building Energy Efficiency”. (2016).
- Andrews, Clinton J., and Uta Krogmann. 2009. “Technology Diffusion and Energy Intensity in US Commercial Buildings.” *Energy Policy* 37 (2) (February): 541–553.
- Asadi, Somayeh, Shideh Shams, and Mohammad Mottahedi. 2014. “On the Development of Multi-Linear Regression Analysis to Assess Energy Consumption in the Early Stages of Building Design.” *Energy & Buildings* 85: 246–255.
- CBECS. 2007. “Total Energy Consumption by Major Fuel for Non-Mall Buildings , 2003” (October 2006): 1–269.
- Crawley, Drury B., Jon W. Hand, Michaël Kummert, and Brent T. Griffith. 2008. “Contrasting the Capabilities of Building Energy Performance Simulation Programs.” *Building and Environment* 43 (4) (April): 661–673.
- Ekici, Betul Bektas, and U. Teoman Aksoy. 2009. “Prediction of Building Energy Consumption by Using Artificial Neural Networks.” *Advances in Engineering Software* 40 (5) (May): 356–362.

QUESTIONS?

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