Automatic Building Energy Modeling (AutoBEM) and its Model America dataset – background, capabilities, and discussion with WIP stakeholders

For: Derek Schroeder and DOE's Weatherization and Intergovernmental Programs (WIP)

Presented by:
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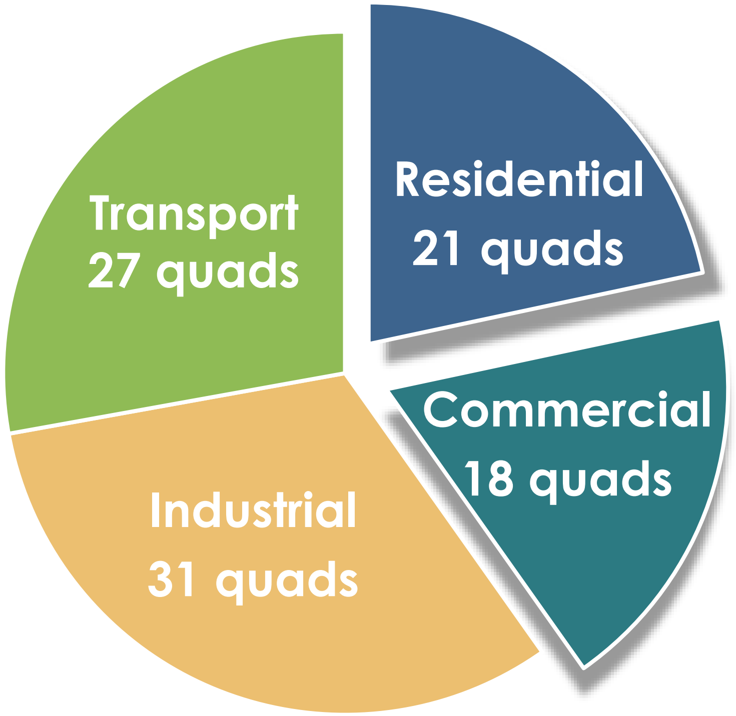
Oak Ridge National Laboratory

Date: 7/28/22

U.S. Energy and Buildings Overview



40% energy use
39% emissions

125 million buildings

~$400 billion in energy bills

73% of electricity use
80% of peak demand

Goal of DOE's Building Technologies Office:
30% EUI reduction
by 2030 compared to 2010 baseline

Building Energy Modeling
building descriptions + weather = estimated building energy consumption, demand, emissions, equity, …

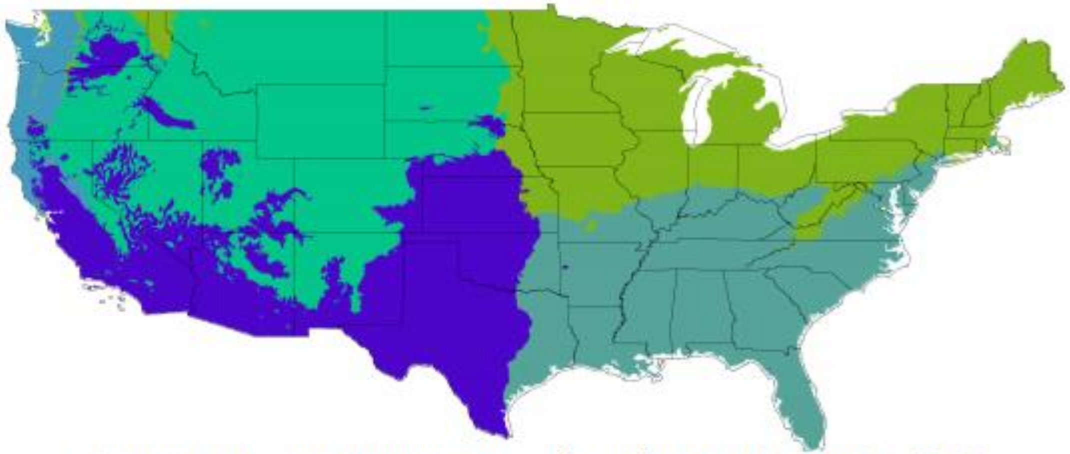
U.S. Market Sizes and Opportunities

- Utility Programs ($8B EE, $3B DRMS)
  - Pricing/tariff structures, future-proof business models, Energy as a Service (EaaS), empowering the customer; cost-effective carbon reductions
- Energy Service Companies (ESCOs, $7B)
- Investment opportunities ($71-133B)
  - New business models – automated financing
- Business relevance
  - What if we put $4 billion into the county where you live? Could we make building changes, guarantee energy performance, and make $10 billion profit in 17 years?
- So what?
  - Quantify energy (kWh), demand (kW), emissions ($CO_{2\text{-eq}}$), and cost ($) savings. What improvements to which buildings give most bang-for-the-buck of taxpayer resources?

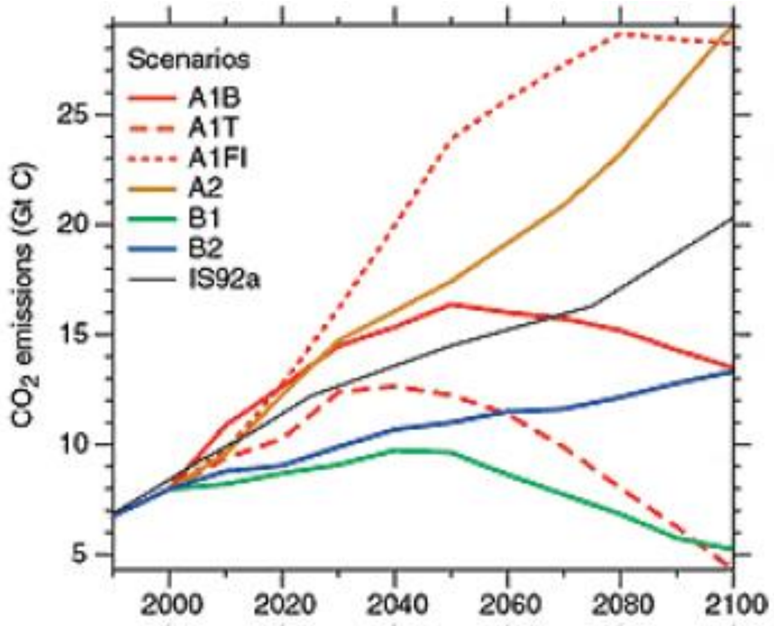
Climate Change Impacts

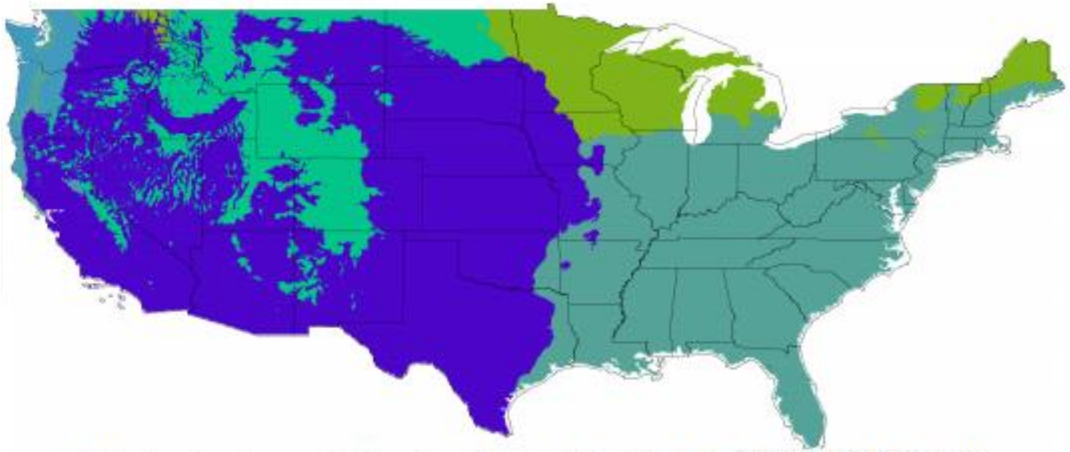
- 15% comm.
  bldg codes (90.1)
- 61% of res.
  Bldg codes (90.2)
- CCSI involvement
- IPCC scenarios
  to future Typical
  Meteorological
  Year (fTMY) files

Contemporary Period



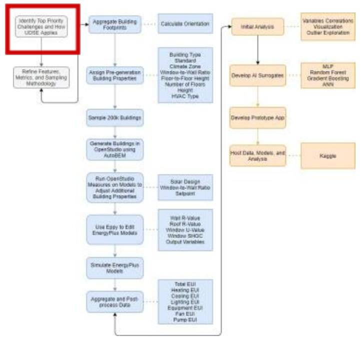
Clustering-based Climate Zones (K=5): HadGCM A1FI 2050



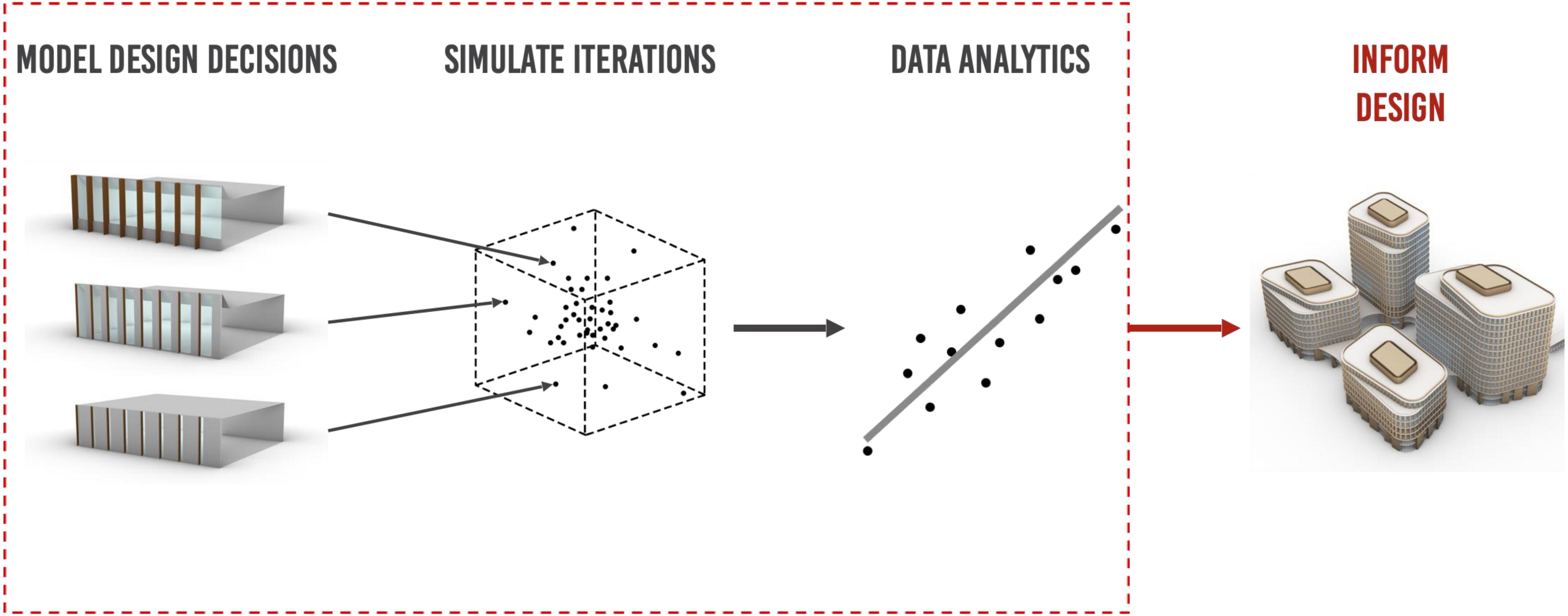


Clustering-based Climate Zones (K=5): HadGCM A1FI 2100

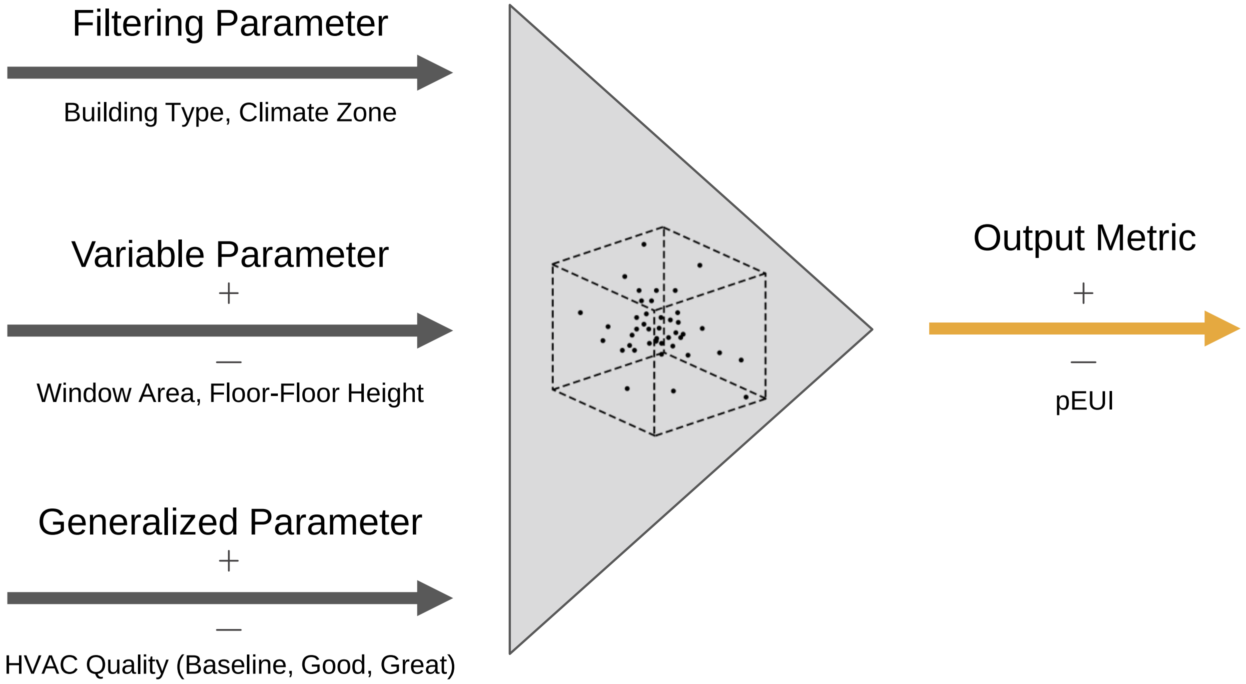
Universal Design Space Exploration



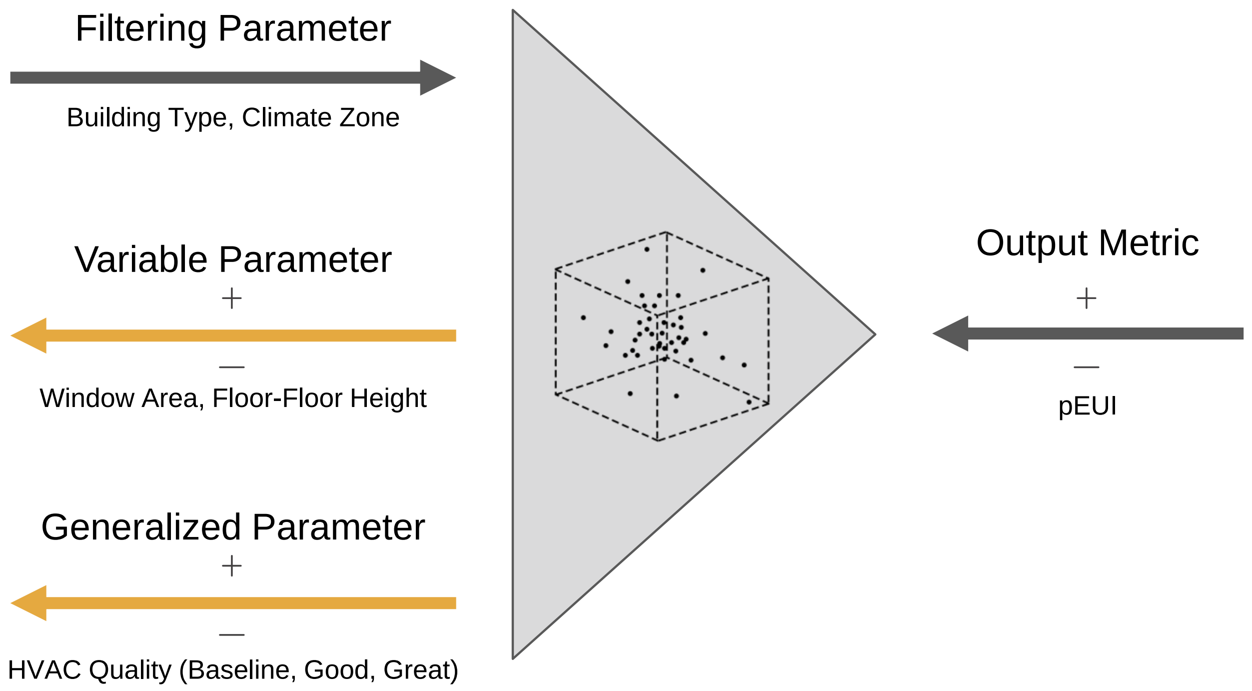
Pre-simulated analysis that encapsulates a common problem



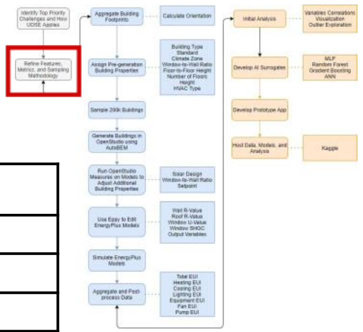
UDSE: Assign Inputs => Explore Outputs



UDSE: Assign Outputs => Explore Input Ranges



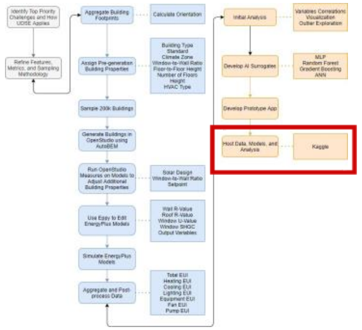
Parametric Sampling

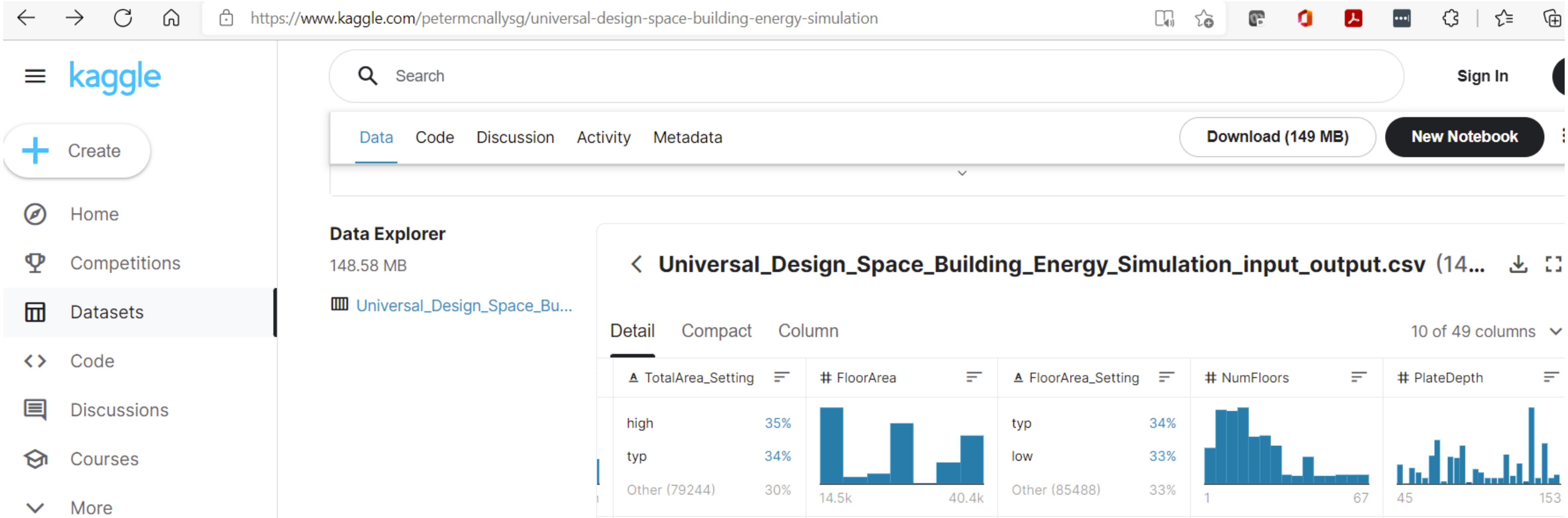


Sampling parameter	Inputs	Sampling parameter	Inputs
Program type	Higher education	Plate depth	Low
	Lab - high intensity		Typical
	Office		High
	Hospital	Floor-to-floor height	Low
	Healthcare - outpatient		Typical
	Residential (Apartments)		High
Climate zone	1A	Solar design	Bad
	1B		Typical
	2A		Good
	2B	Average window-to-wall ratio	0.25
	3A		0.4
	3B		0.7
	3C	Envelope quality	Baseline
	4A		High
	4B		Ultra
	4C	Construction type	Common
	5A		Less Common
	5B	Lighting power density	Baseline
	5C		Better
	6A		Best
	6B	HVAC system	Baseline
	7A		Good
	7B		Great
Total square footage	Low		Ultra
	Typical	Set points	Baseline
	High		Expanded
Target floor area	Low		
	Typical		
	High		

Data Hosting

[UDSE Kaggle]





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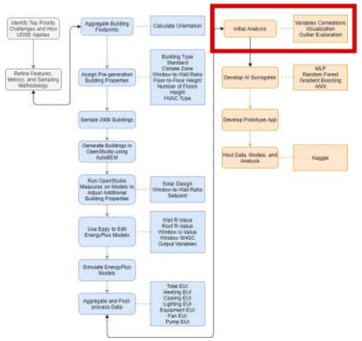
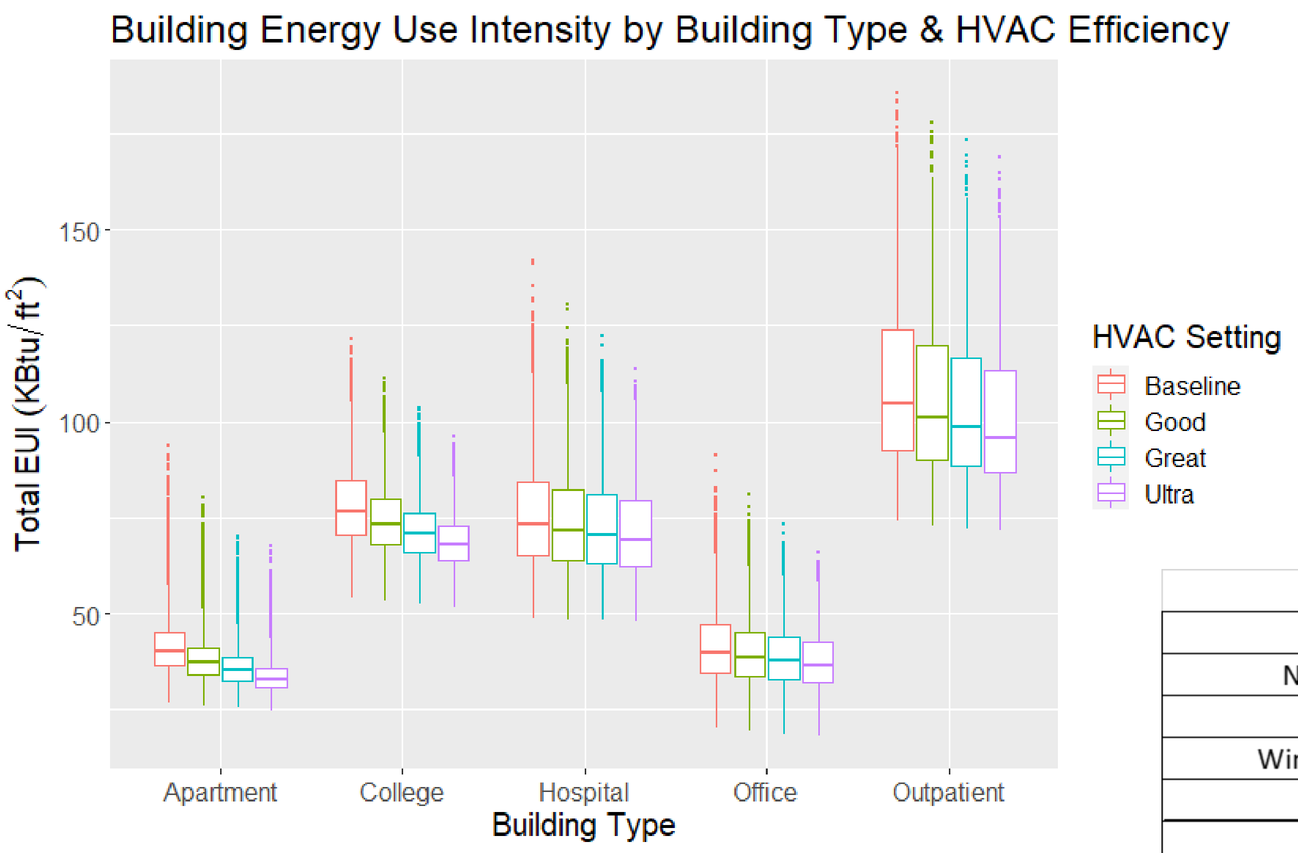
Data Exploration

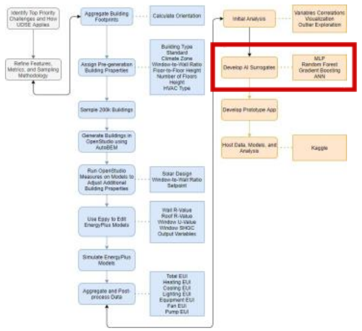


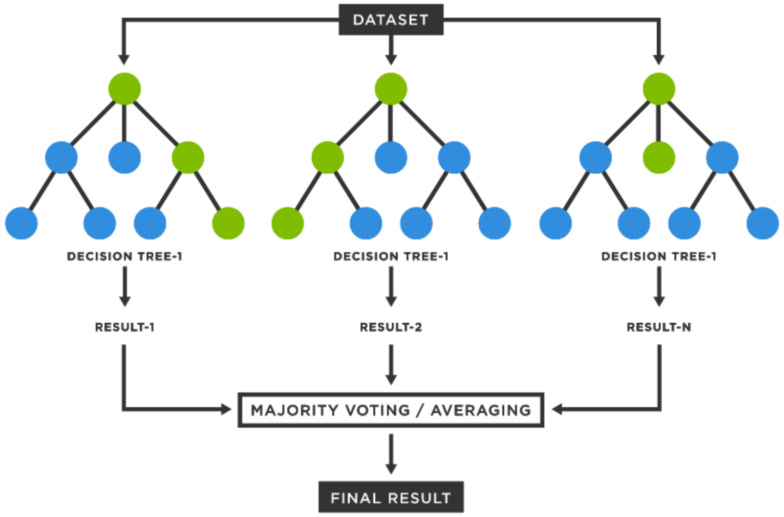


	Outpatient_1A	Outpatient_2A	Outpatient_3A	Outpatient_4A
Height	-0.50	-0.57	-0.55	-0.42
NumberFloors	-0.50	-0.56	-0.57	-0.45
TotalArea	-0.77	-0.79	-0.78	-0.67
WindowWallRatio	-0.02	-0.06	0.11	0.00
FloorHeight	0.06	0.00	-0.04	0.19
PlateDepth	0.05	0.14	-0.13	0.08
PlateLength	-0.13	-0.22	-0.09	-0.16
SkinArea	-0.47	-0.52	-0.51	-0.39
SkinFloorRatio	0.28	0.25	0.17	0.26
GlassArea	-0.43	-0.50	-0.46	-0.36
EnvelopeFloorAreaRatio	0.30	0.27	0.19	0.28
EnvelopeQuality	0.04	-0.04	0.01	0.13
LightingPowerDensity	-0.18	-0.47	-0.37	-0.17
SetpointSetting	-0.14	-0.14	-0.12	-0.18
HVACSetting	0.36	0.27	0.19	0.15

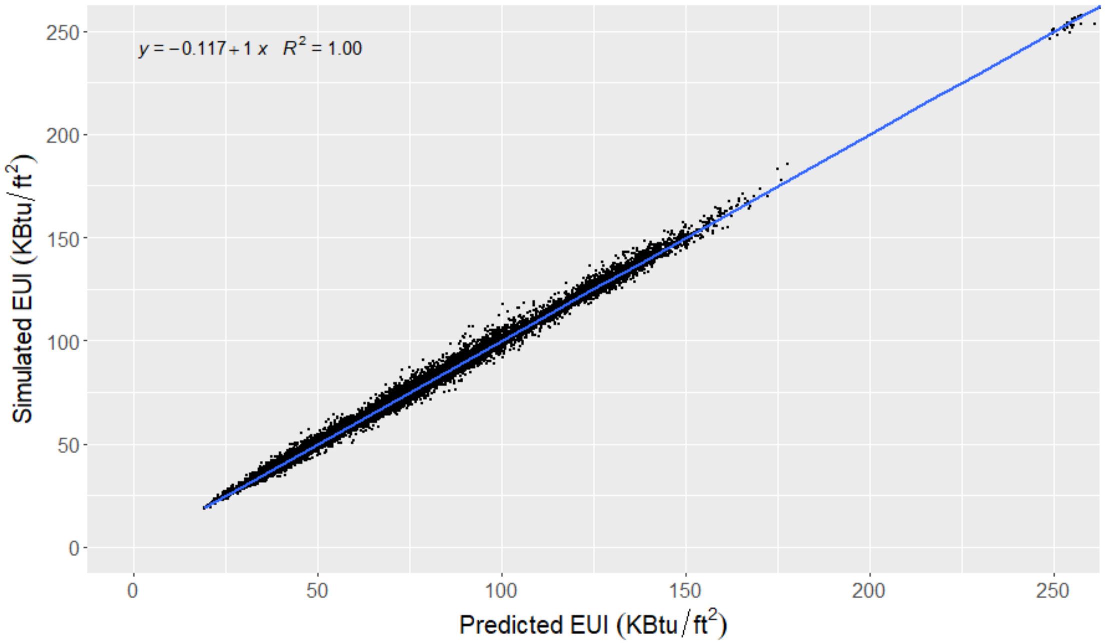
Artificial Intelligence

- AI can be used as surrogate for EnergyPlus simulations
  - Don't need every point of design space
- Use input variables (building type, area, height, etc.) to predict building energy usage
- Several algorithms evaluated
  - Linear Regression
  - Neural Network
  - **Random Forest**

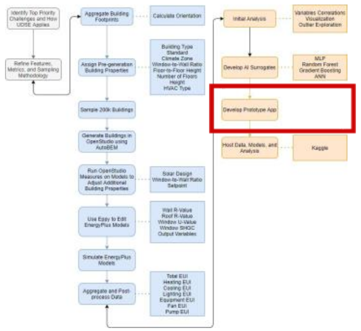




Random Forest



Prototype App: Real-time Analytics



5-year vision

Digital Twin of every U.S. Building by 2020

Methodology: Scalable compute, data, simulation, and empirical validation

1. Quantitatively rank most important building inputs

	Small Office	Outpatient	Large Office	Medium Office	Hospital	Warehouse	Small Hotel	Large hotel
Inputs	458	3483	1072	760	1955	333	1823	887
	Strip Mall	Retail	Quick Service Restaurant	Full Service Restaurant	Mid Rise Apt	High Rise Apt	Secondary School	Primary School
Inputs	800	438	281	286	1464	4617	1621	1051

Sensitivity Analysis

2. Time on world's #1 fastest high-performance machines

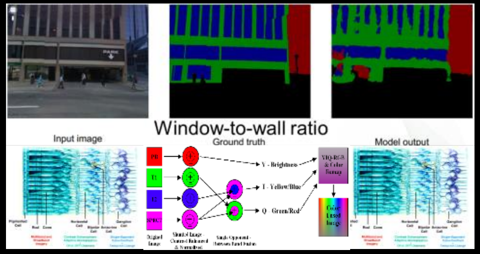
3. Identify and compare data sources for important inputs

	Short Title
Summary	Satellite imagery, including panchromatic and multispectral images
Data type	Image
Company	
Website	
Temporal resolution	Cities - 3-11 times per week
Spatial resolution	0.3 m
Measure accuracy	
Cost	$11 per sq. km
Format	GeoTiff
Mapping to building input variables	Building footprints
Mapping to area properties	Vegetated areas, road surface, buildings, parking lots
Mapping to material properties	Road pavement materials (e.g., concrete, asphalt), parking lots (e.g., gravel, soil)
Coverage of US	Over 10 million km^2 of coverage of the contiguous US
Orientation	Aerial
Existing internal software	N/A
Existing expertise	Remote sensing data analysis tool
Restrictions	N/A
Comments	

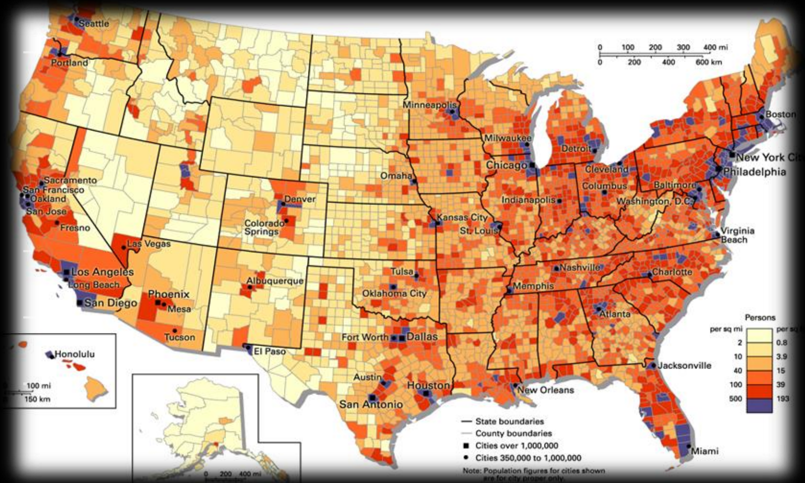
Comparison Matrix

4. Establish partnerships and APIs for scalable data retrieval

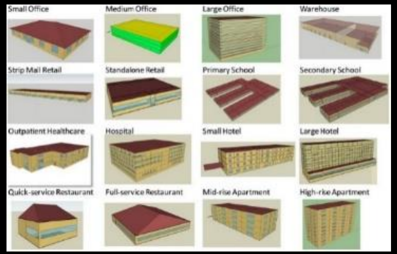
5. Algorithms to extract building properties



Computer Vision



6. Create OpenStudio & EnergyPlus models



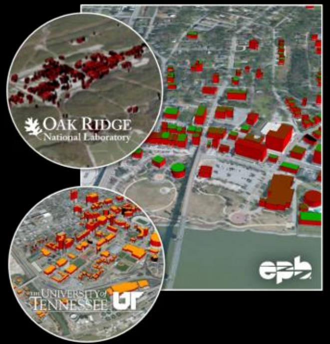
DOE Prototype Buildings

7. Make models freely available online

Download BEM for your building(s)

HPC Tools for Modeling and Simulation

Capturing building energy consumption



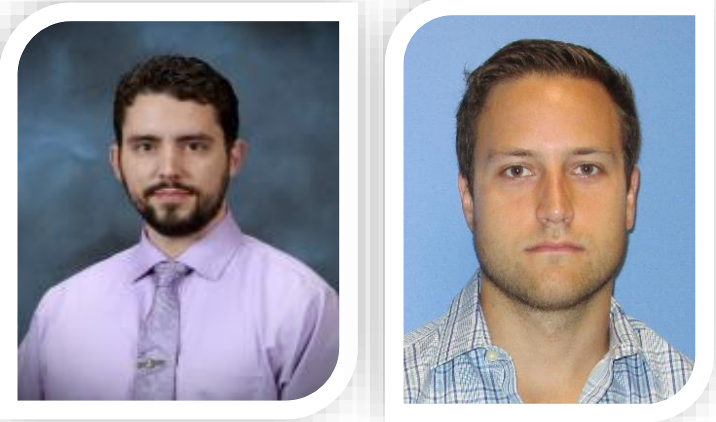
Demonstrate and stimulate opportunities toward a sustainable built environment

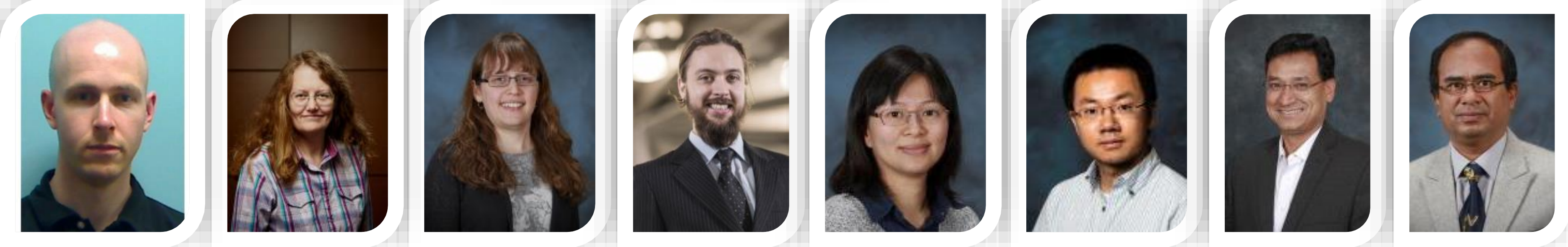
Use cases:

- Simulation-informed analysis
- Utility program formulation (utility)
- Business model evaluation (ESCO)
- City-scale emissions (cities)
- Sales/marketing leads (local jobs)
- New building design (AEC firms)
- Resilience (government, insurance)
- Automated financing (PACE, banks)

Acknowledgements

- EPB/ORNL partnership
- U.S. Department of Energy
  - EERE/Building Technologies Office
  - Office of Electricity
  - National Nuclear Security Administration
- Oak Ridge National Laboratory



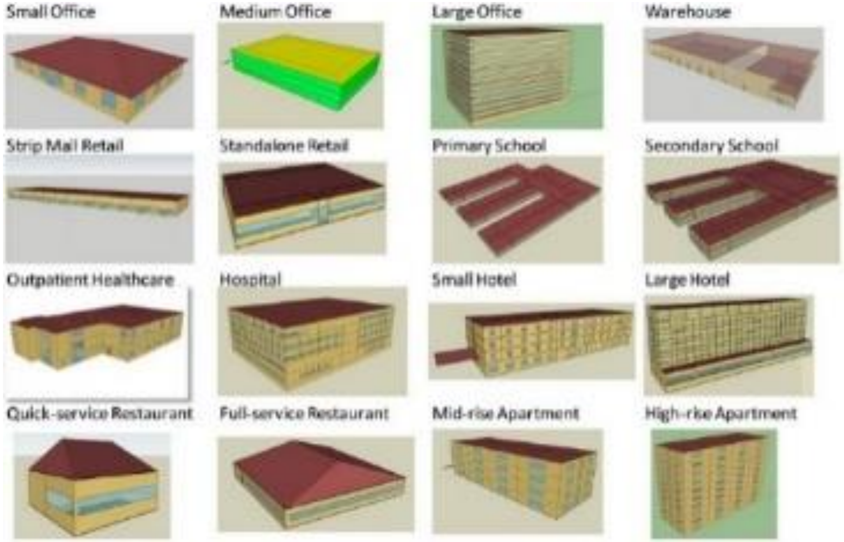


AutoBEM

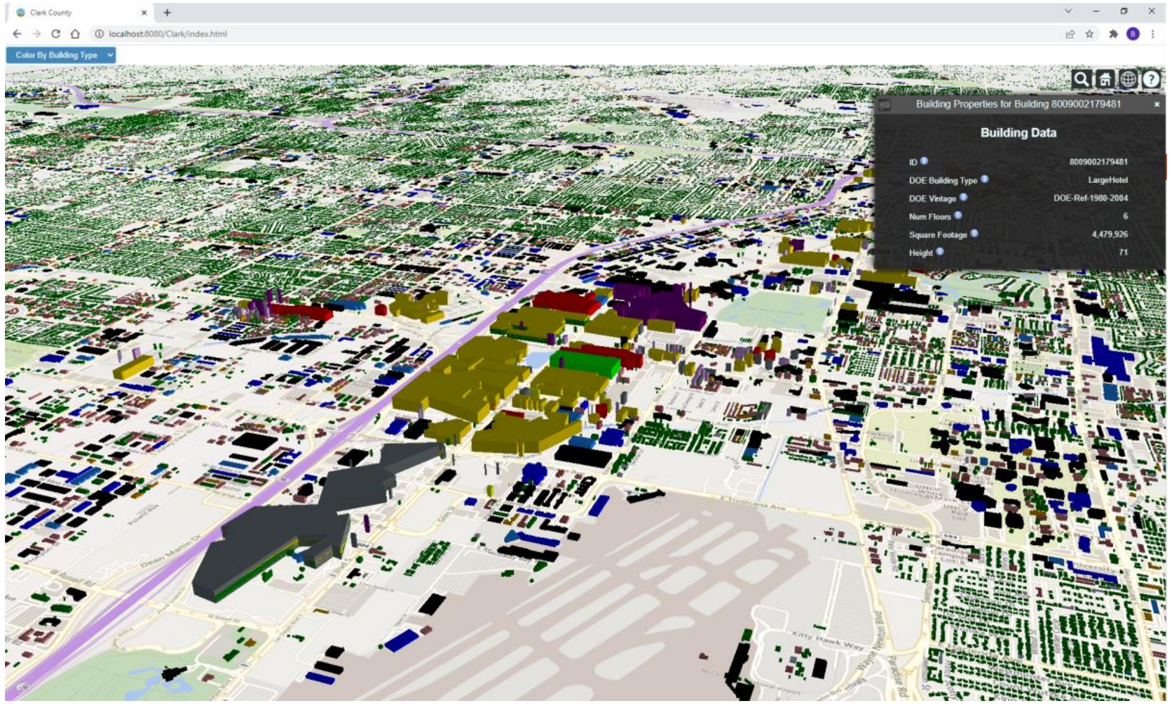
- AutoBEM takes set of building properties as inputs
  - Building Footprint
  - Building Height
  - Building Type
  - Building Age
- AutoBEM develops building energy models using OpenStudio and simulates Models using EnergyPlus
- Internal characteristics and other building properties (occupancy, equipment, insulation, etc.) determined non-intrusively by building type and year built

OpenStudio

EnergyPlus



DOE Prototype Buildings



Clark County (Las Vegas) Modeling Example

Automatic Detection and Building Energy Model Creation (AutoBEM)

Data Sources

- Imagery (satellite, aerial)
- Street-level imagery
- Cartographic layers
  - Elevation, GIS
- Tax assessors
- Ranking of descriptors
  EE and Demand impacts
  (281–4,617 per building type)

Class	Object	Field	Default	Minimum	Maximum	Distribution	Type	Group	Constraint
Sizing:Parameters		Heating Sizing Factor	1.33	0.931	1.729	uniform	float		
Sizing:Parameters		Cooling Sizing Factor	1.33	0.931	1.729	uniform	float		
Lights	Core_bottom_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Core_mid_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Core_top_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
...	...	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
Lights	Perimeter_top_ZN_4_Lights	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0001	
ElectricEquipment	Core_bottom_PlugMisc_Equip	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0002	
...	...	Watts per Zone Floor Area	10.76	7.532	13.988	uniform	float	G0002	
ElectricEquipment	Core_bottom_Elevators_Equip	Design Level	32109.89011	22476.92	41742.86	uniform	float		
Exterior:Lights	Exterior Facade Lighting	Design Level	14804	10362.8	19245.2	uniform	float		
ZoneInfiltration:DesignFlowRate	FirstFloor_Plenum_Infiltration	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	
...	...	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	
ZoneInfiltration:DesignFlowRate	TopFloor_Plenum_Infiltration	Flow per Exterior Surface Area	0.000302	0.000211	0.000393	uniform	float	G0003	

Data comparison matrix

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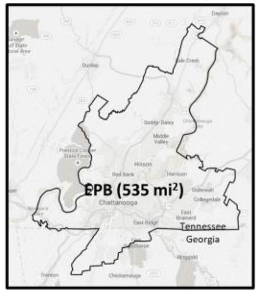
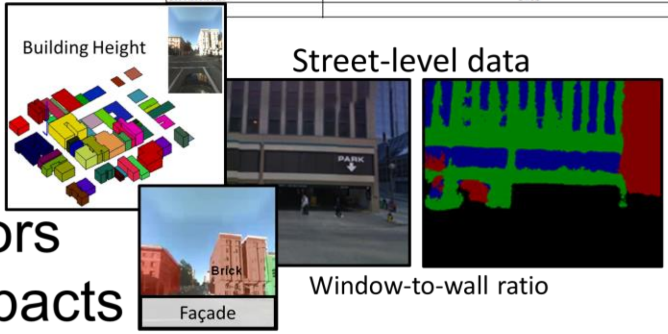
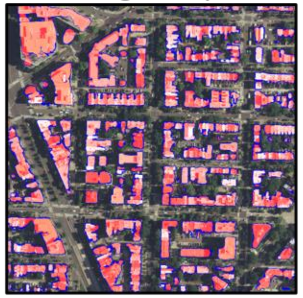
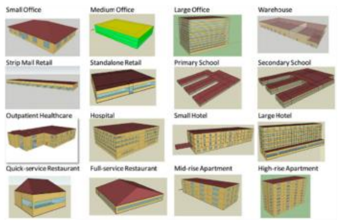
Occupancy





Building footprints





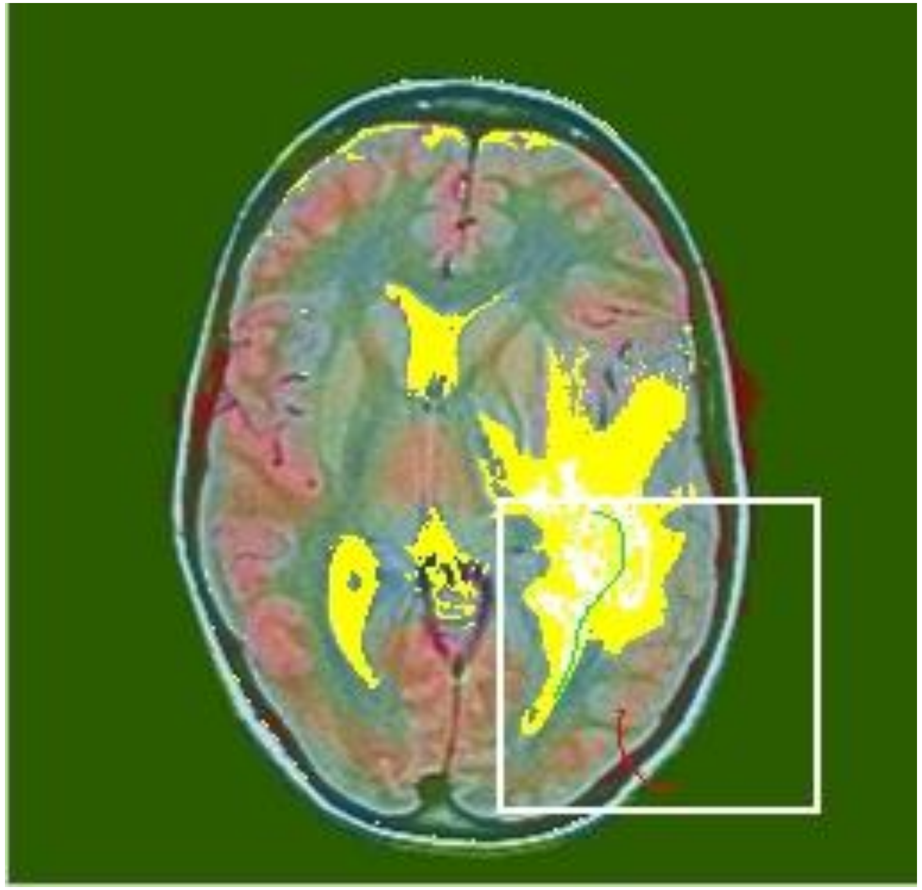
Software Tools

- Occupancy (every 90m)
- Aerial - best footprints
- Street - height, type, WWR
- LiDAR - geometry
- GIS - database API
- Building type
- Model generator
- Fastest buildings simulator
- Web-based visual analytics

Result: Simulated buildings for any area of interest that match 15-minute electrical data more accurately than most manually created models

Retinal Fusion and Human/Computer Training originated from MIT's Lincoln Lab

DEMO



Full Results

Detailed Results

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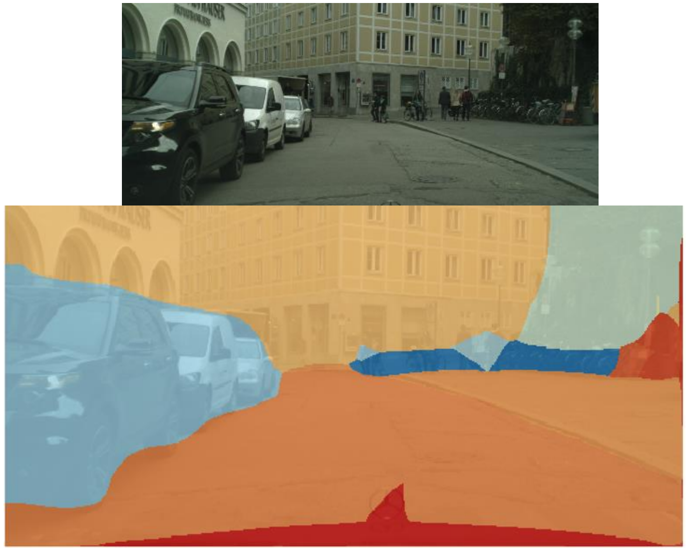
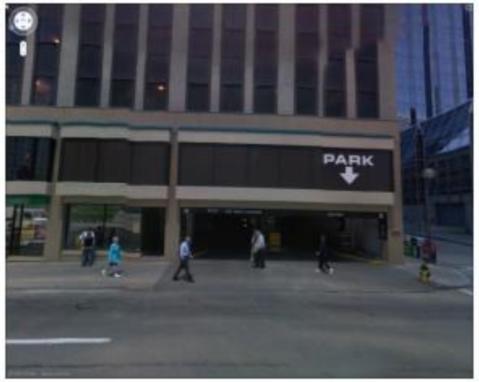
Computer Vision – street-level imagery

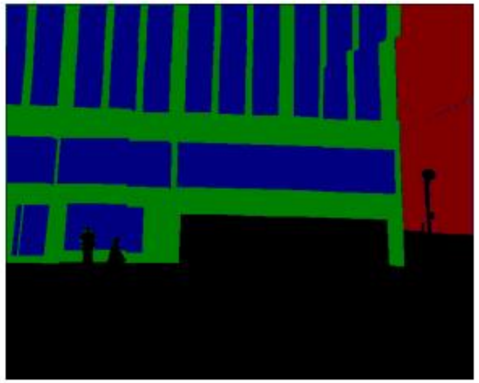
Façade Type



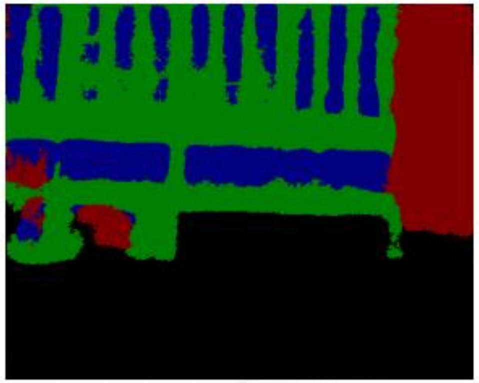
Windows (blue)
Façade (green)
Street/open (black)
Other building (red)



Input image



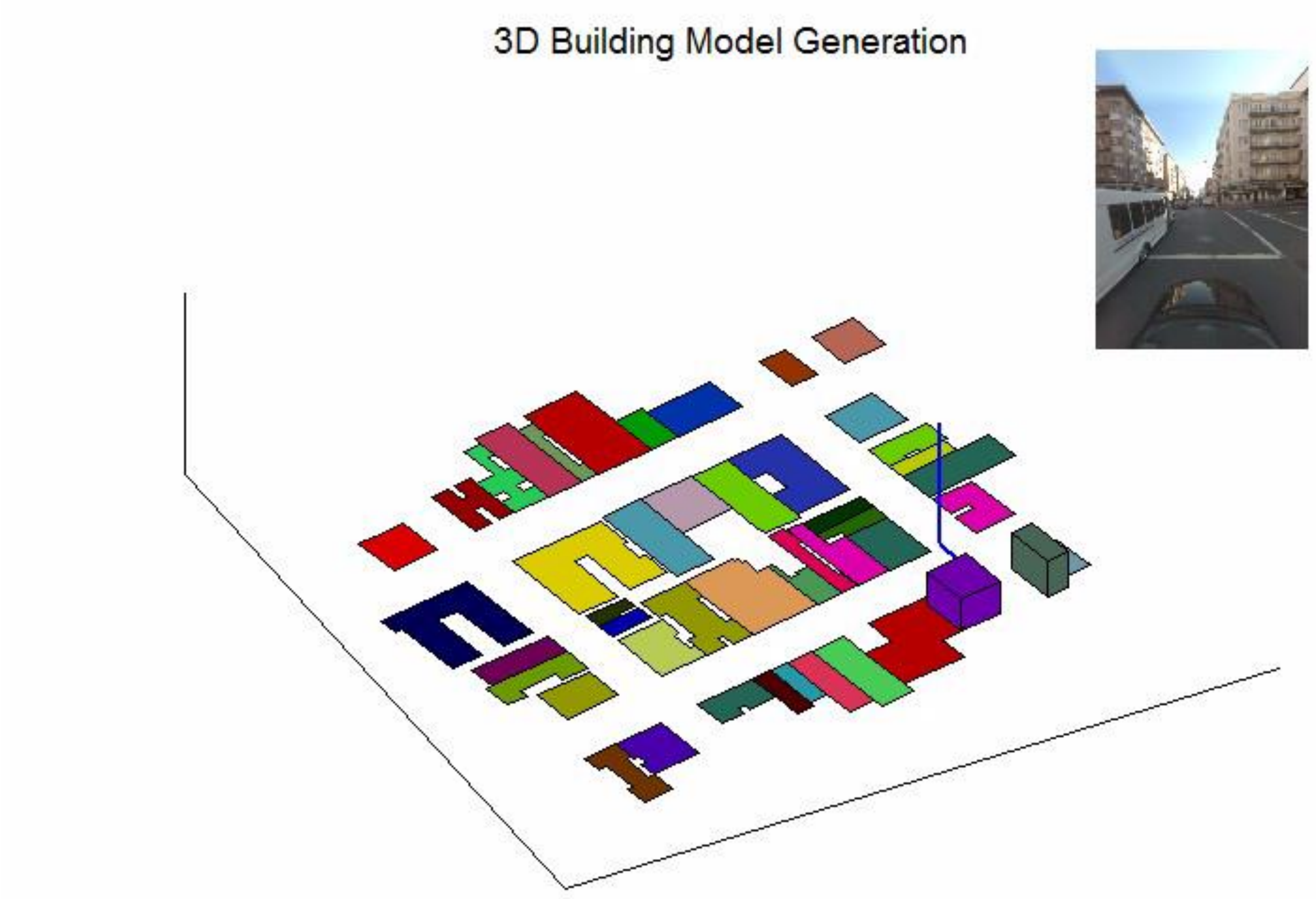
Ground truth



Model output

Window-to-wall ratio

Jiangye Yuan



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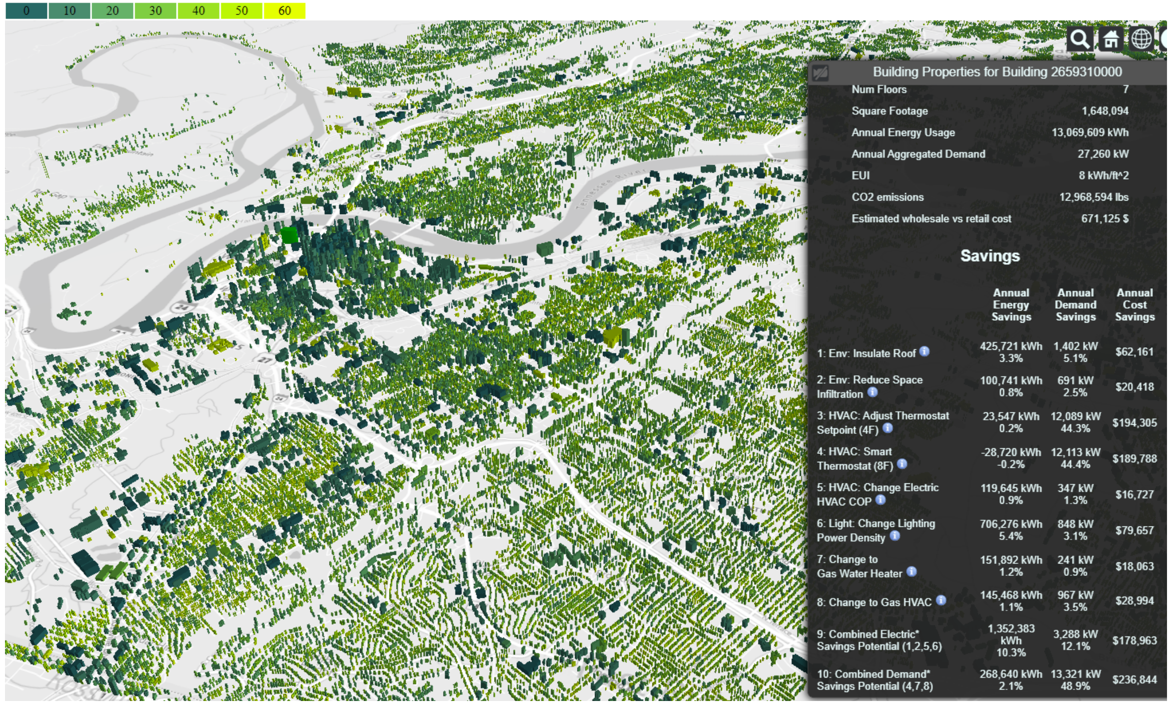
Overview of Building Technologies (simulated in every building)

#	Description	Category	Value	Source
1	Insulate Roof	Envelope	R-16.12 to R-28.57	IECC-2012
2	Reduce Space Infiltration	Envelope	Reduce 25% from vintage	EnergyStar whole-house
3	Adjust Thermostat Setpoint (4F)	HVAC	4°F 2 hrs prior to peak	EPB
4	Smart Thermostat (8F)	HVAC	8°F 4 hrs prior to peak	EPB
5	Change Electric HVAC COP	HVAC	COP to 3.55 (heating) 3.2 (cooling)	IECC-2012
6	Change Lighting Power Density	Lighting	LPD 0.85 W/ft^2	IECC-2012
7	Change to Gas Water Heater	Water	Efficiency 80% (assumes electric)	IECC-2012
8	Change to Gas HVAC	HVAC	Efficiency 80% (assumes electric)	IECC-2012

AutoBEM Chattanooga

- 15-Minute electricity use was shared for more than 178,000 building electrical meters in Chattanooga, TN area.
- AutoBEM **empirical validation** was done by comparing these meters measured electricity use to AutoBEM simulation results
- Several analyses were conducted on these models
  - Energy saving technologies
  - Demand saving technologies
  - Climate scenarios
  - Microgrids
- Models can be augmented with real building properties from building owner to significantly improve model performance

DEMO



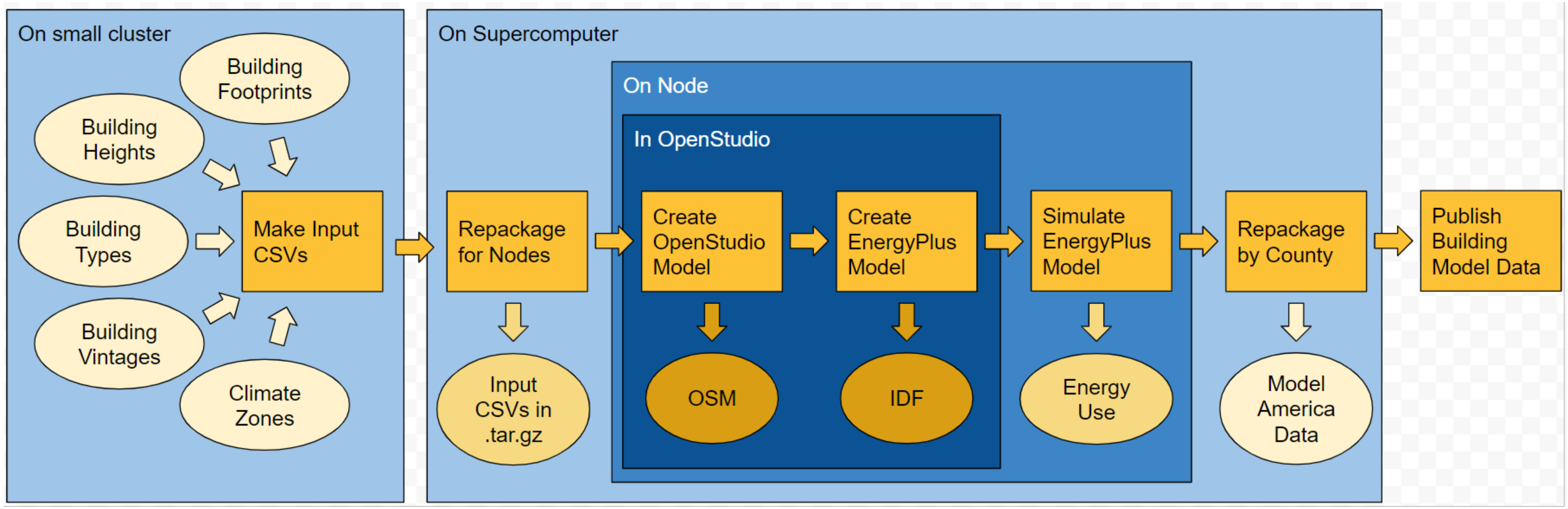
Chattanooga (TN) Modeling Example Visualization

bit.ly/virtual_epb

Model America

- Building data for more than 125 million buildings
  - Microsoft building footprints
  - JAXA convolutionally interpolated height data
  - GAIA urban sprawl data
  - Building type heuristics, PNNL DOE prototype construction weights

45 million core-hours (2021) and 51 million core-hours (2022) on Argonne's Theta supercomputer



Building simulation at scale

Simulation Engine and Analysis Platform
U.S. Dept. of Energy
$100+M, 1995–?

EnergyPlus

OpenStudio

Free, open-source (GitHub), community support
100 – 2,000 improvements per building

Theta is the world's fastest buildings energy model (BEM) simulator

Use over 80% of the HPC resource

125M US buildings could be simulated in 2 weeks

8M simulations of DOE prototypes (270 TB)

Titan supercomputer

CPU Cores	Wall-clock Time (mm:ss)	Data Size	EnergyPlus Simulations
16	18:14	5 GB	64
32	18:19	11 GB	128
64	18:34	22 GB	256
128	18:22	44 GB	512
256	20:30	88 GB	1,024
16,384	26:11	5.6 TB	65,536
32,768	31:29	11.5 TB	131,072
65,536	44:52	23 TB	262,144
131,072	68:08	45 TB	524,288

Theta supercomputer

CPU Cores	Wall-clock Time (mm:ss)	Data Size	EnergyPlus Simulations
57,344	20:44	440 GB	229,376
114,688	28:20	880 GB	458,752

1,068,813 bldgs/hr
6 utilities/hour

45 million core-hours (2021) and 51 million core-hours (2022) on Argonne's Theta supercomputer

Scalable Computing

- 1,068,813 buildings/hour – generated, simulated, results stored
- Building energy modelers - $150/hr
- Model levels and cost at Architectural, Engineering, Const. (AEC) firm

Model Quality	Typical Time	Cost
Basic	2 days	$2,400
Functional	1 week	$6,000
Detailed	2 weeks	$12,000

- AutoBEM on HPC - $6.4 billion and 20,554 person-years worth of work… completed in 1 hour on supercomputers

Nation-scale…

- **Automatic Building Energy Modeling (AutoBEM) software**
  - Related publications: **bit.ly/AutoBEM**
- **Model America** data - free model of every U.S. building (**bit.ly/ModelAmerica**)
  - OpenStudio (v3.1.0) and EnergyPlus (v9.4)
  - State_county.zip (requires free Globus Connect Personal); location-specific requires NDA
  - New, Joshua R., Adams, Mark, Bass, Brett, Berres, Anne, and Clinton, Nicholas (2021). "Model America – data and models of every U.S. building." ORNL Constellation, https://doi.ccs.ornl.gov/ui/doi/339, April 14, 2021.
- 125,714,640 buildings, 124,276,332 simulated,122,930,327 (97.8%) shared
- Dynamic archetypes of models and floor area multipliers for any geographical region
- In last 1.5 years (since 1/1/21): 22 NDAs (1 free dataset), 5 funded CRADAs, 9 CRADAs proposed, leveraged in many other proposals

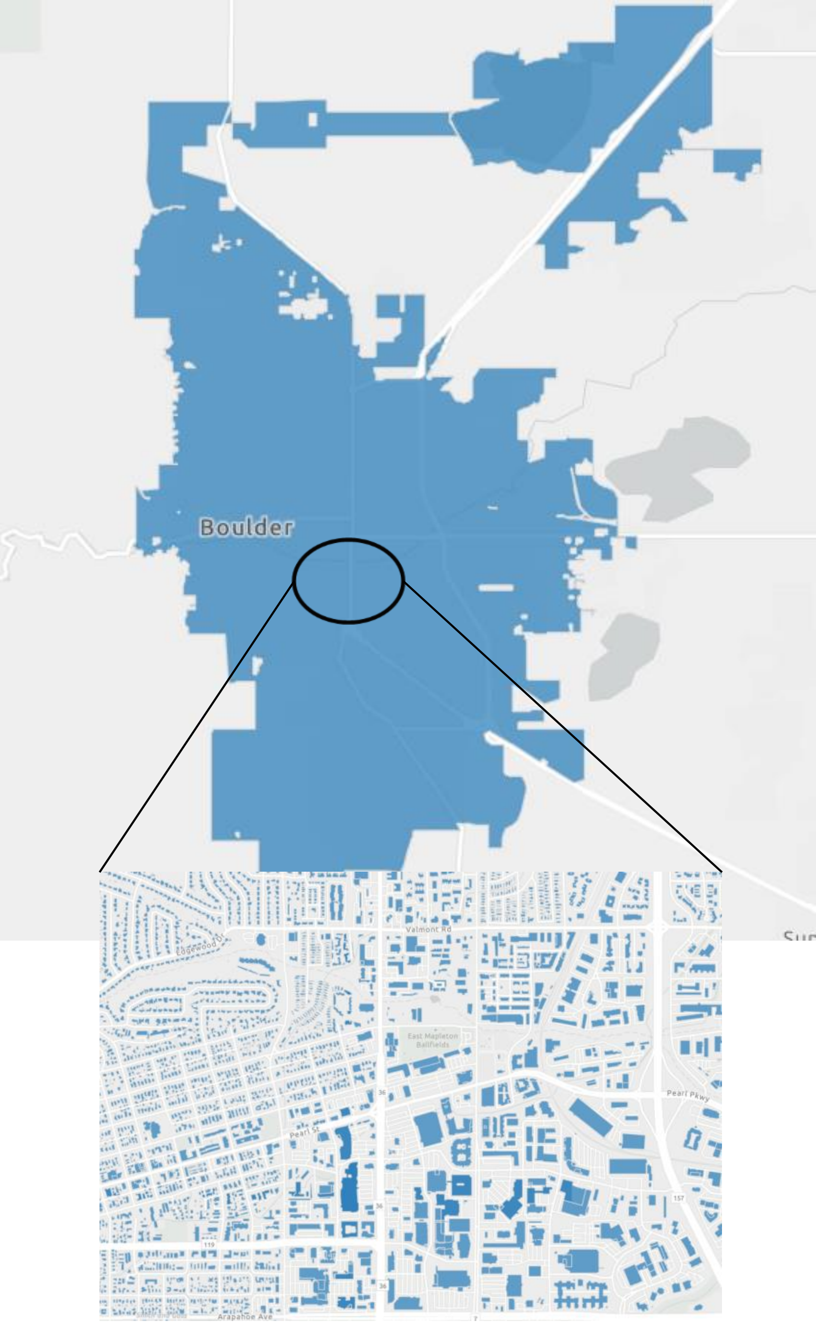
Dynamic Archetypes

- Model with median EUI selected for each building type/vintage combination
- Dynamically construct floor space multiplier (all buildings / median-EUI bldg.)
- 29,230 Boulder, CO buildings represented by 60 models

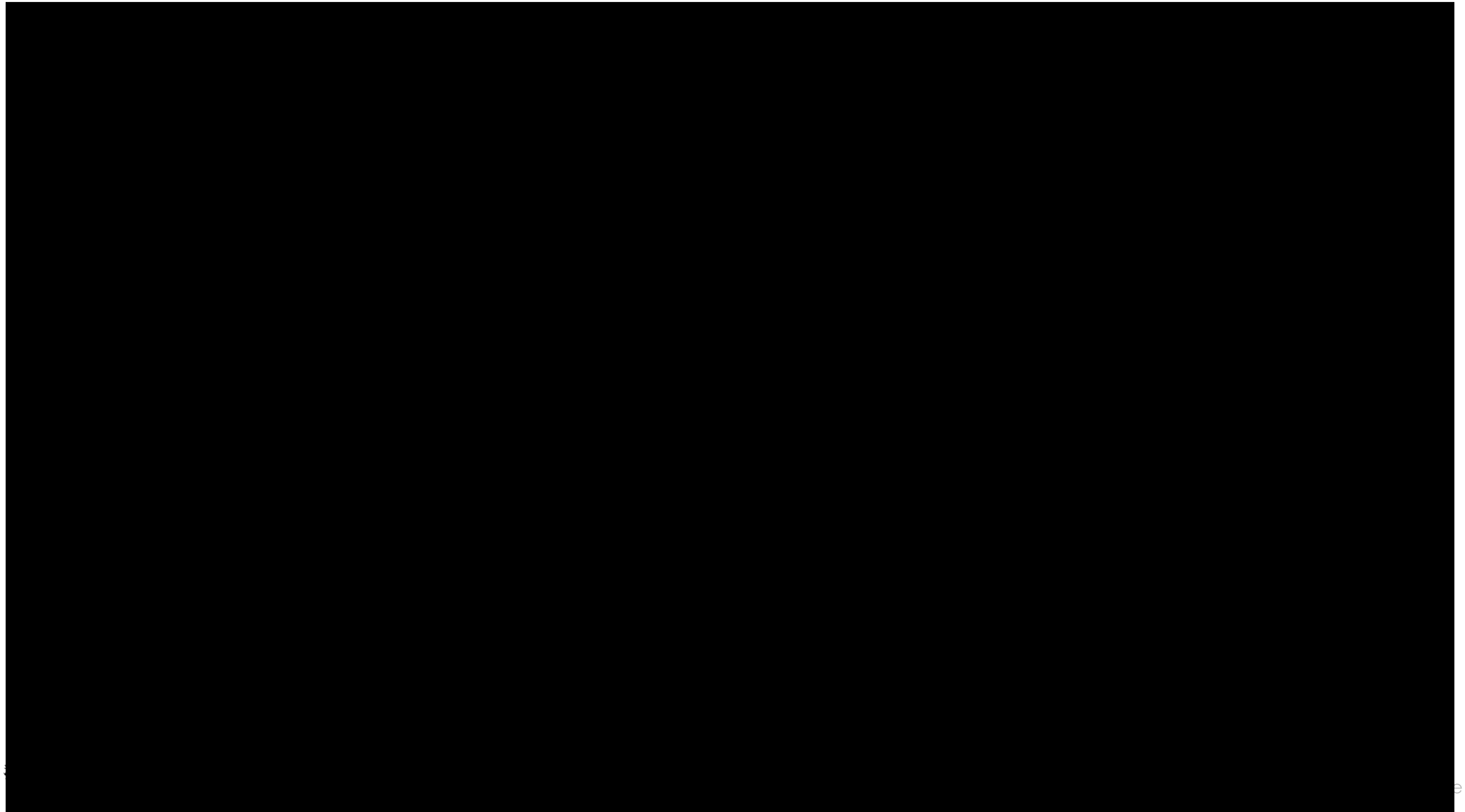
	AutoBEM Original	Dynamic Archetypes
Total Electricity (TWh)	1.29	1.36
Total Natural Gas (TWh)	1.77	1.92
Total Energy (TWh)	3.06	3.27

https://github.com/ORNL-BTRIC/AutoBEM-DynamicArchetypes

- 589,586 Clark County (Las Vegas) bldgs. via 129 archetypes
  - New, Joshua R., Bass, Brett, Adams, Mark, and Berres, Anne (2021). "Model America - Clark County (Vegas) extract from ORNL's AutoBEM (Version 1.1) [Data set]." Zenodo, doi.org/10.5281/zenodo.4552901, Feb. 16, 2021. [Data]
  - New, Joshua R., Bass, Brett, Adams, Mark, and Berres, Anne (2021). "Clark County (Vegas) Archetypes from ORNL's AutoBEM [Data set]." Zenodo, doi.org/10.5281/zenodo.4552901, Mar. 21, 2021. [Data]



AutoBEM inside – GSHP tool (analytics for any US bldg.)



Open discussion

- Measures – share AutoBEM's measures for NEAT/MHEA analysis
- Simulation – 1M sims/hr for comparative analysis NEAT versions; energy (kWh), demand (kW), emissions ($CO_{2\text{-}eq}$), and savings ($)
- ModelAmerica – web-based map API, select building via address, AutoBEM-generated model, modify form inputs
  - Carbon – EnergyPlus with EPA's EGRID or NREL's Cambium to report carbon emissions related to building energy use. Utility-scale report for Carbon Dioxide (CO_2), Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x), Nitrous oxide (N_2O), and Methane (CH_4).
- Dashboard – live and on-demand analytics, deployment stats for potential vs. actual impact in any geographical area
- Climate change – IPCC weather data fTMY for climate impacts and non-energy benefits

Discussion

Joshua New, **Ph.D., CEM, PMP, CMVP, CSM, IREE**
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Building Technologies Research and Integration Center (BTRIC)
Oak Ridge National Laboratory

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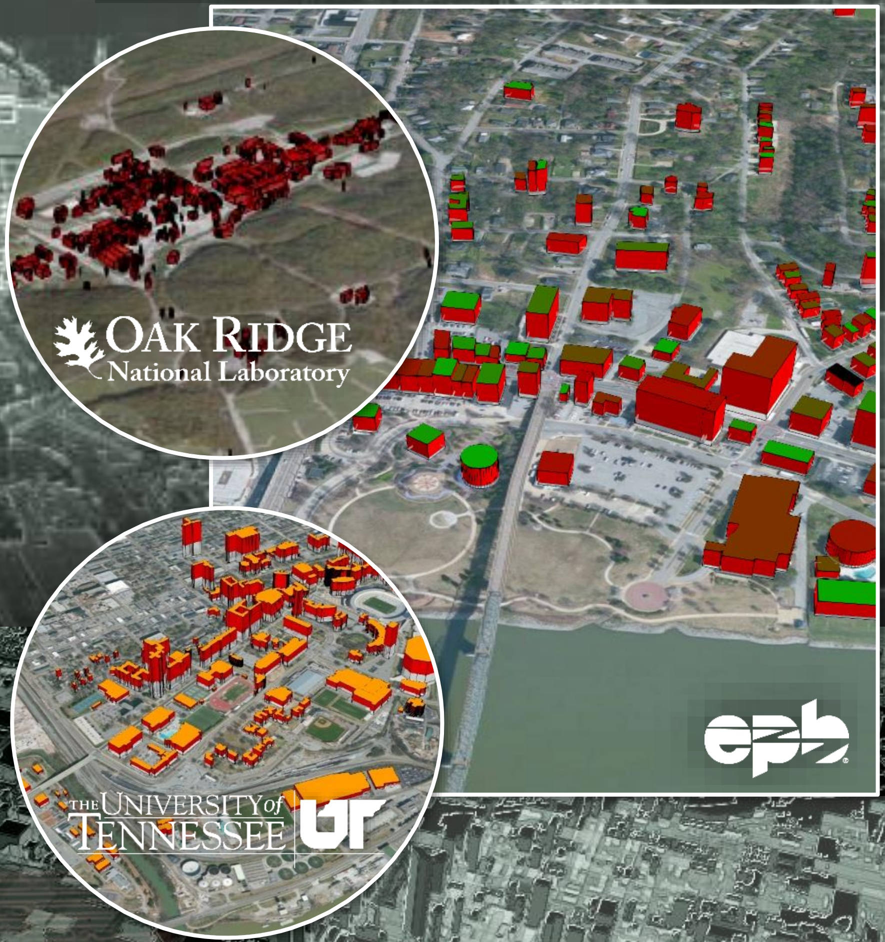
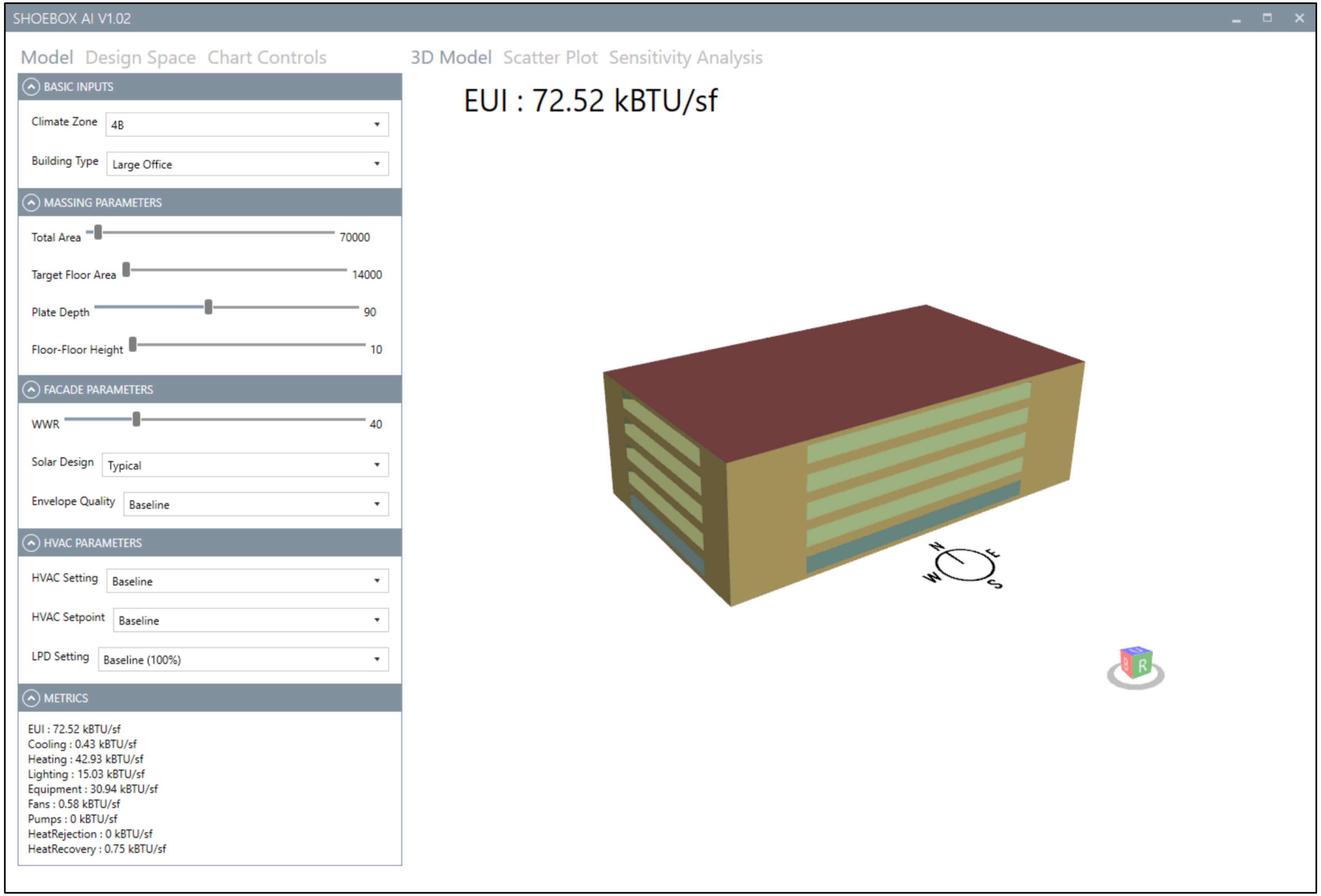
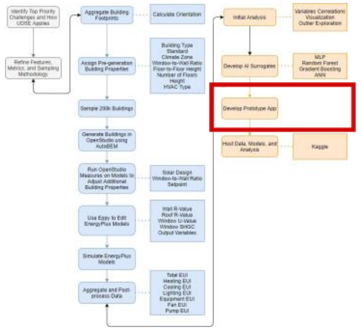
HPC Tools for Modeling and Simulation
Capturing building energy consumption

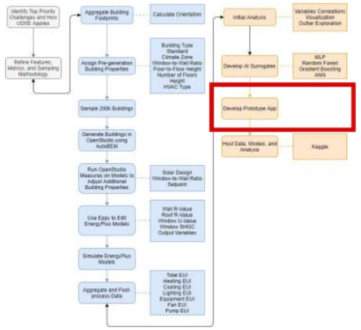


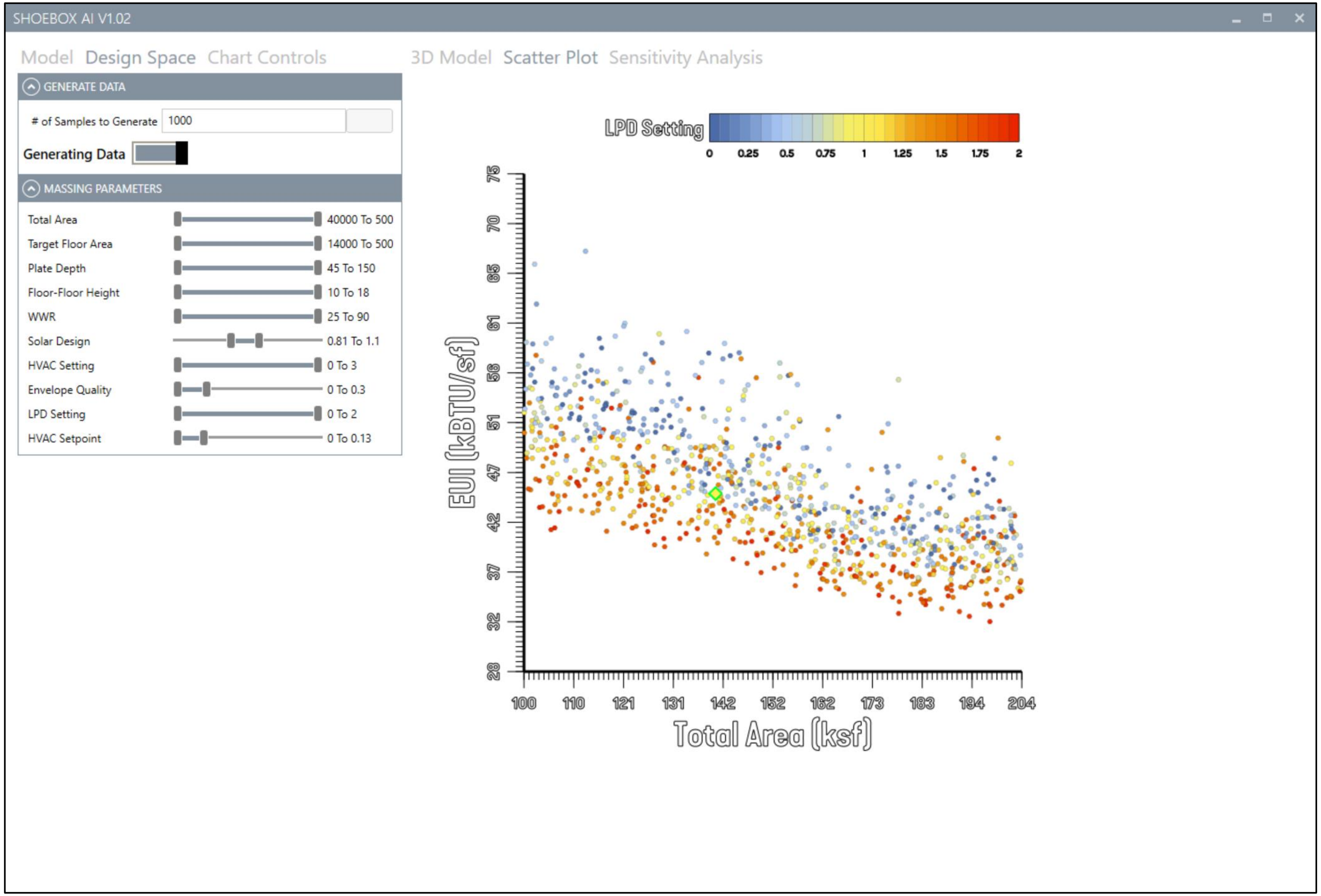
Prototype App: Single Design





Prototype App: Design Space Exploration





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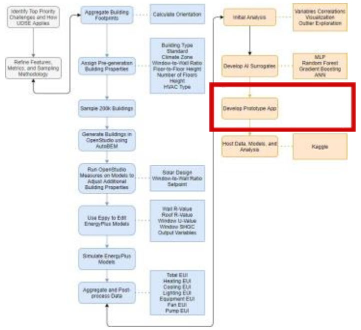
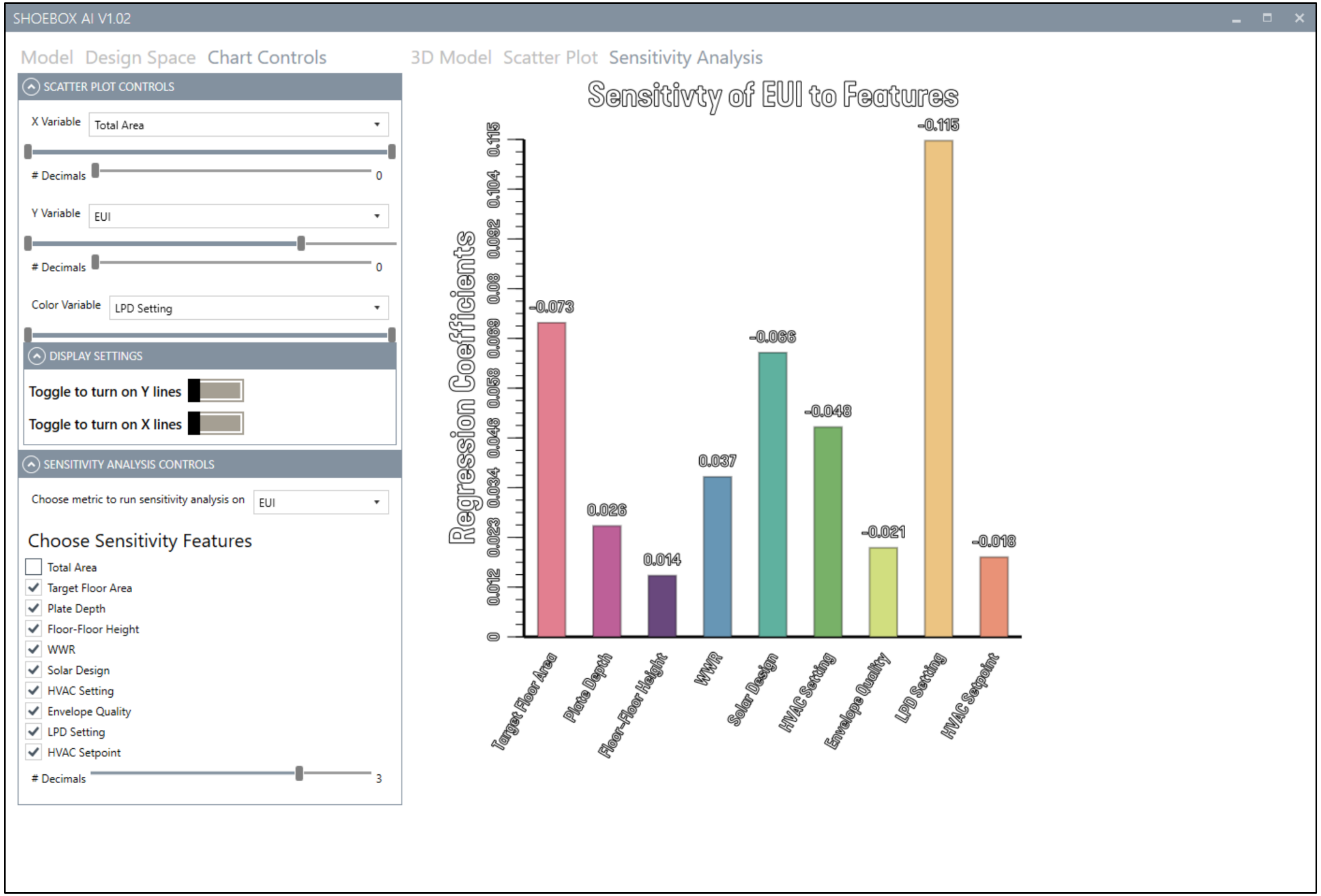
Prototype App: Real-time Analytics





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Future uses for AutoBEM's Model America

The promise of a more safe, secure, and sustainable country in which to live and work...