Towards a Big Data-enabled Digital Twin for Large-Scale Infrastructure Planning

ICAS Emerging Technology Forum 2019

September 9th, 2019

Dimitri Mavris, Ph.D.

Director, Aerospace Systems Design Laboratory (ASDL)

Langley Distinguished Regents Professor

Boeing Endowed Regents Professor for Advanced Systems Analysis

School of Aerospace Engineering

Georgia Institute of Technology

Georgia Tech Aerospace Systems Design Laboratory

Digital Twin – Key Concepts

- "An integrated multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin." (DAU Glossary)
- A Digital Twin is created through a combination of
  - **Data:** sensors data, model data and domain knowledge
  - **Subject matter expertise**
  - **Modeling:** physics-based models (electrical, hydraulic, etc.), simulation/kinematic models, discrete-event, etc.
- Mirrors replication of a physical asset; Mimics its **structure**, **context** and **behavior; connects different value chains**
- Provides a window to the past and present states and conditions of the physical asset
- Dynamic in nature: is **constantly updated with data coming from the system/physical asset** → When coupled with the right level of intelligence, allows us to look into the future

Towards A Digital Campus

GT Campus as a Digital Twin of a System of Systems

Endgame: Campus of the Future

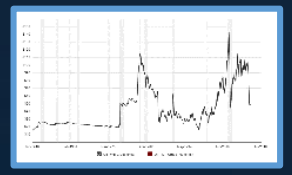
A Multi-layered System of Systems

- Georgia Tech
- *Human Activities*
- *Built Environment*
- *Energy & Water*
- *Enviro. Footprint*
- *Security*
- *Supply Chain*
- *IT Infrastructure*
- *Mobility*
- *Ecological Services*

Desired qualities

Sustainable

Resilient


Rising Energy Costs


Weather Threats


Emergency Events


Cyber Threats

Adaptable


Campus Growth


Emerging Tech

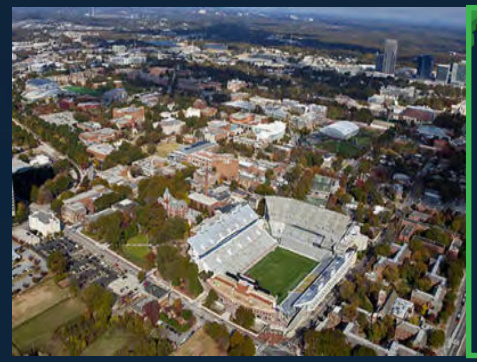

Engaged Stakeholders

Changing Policy

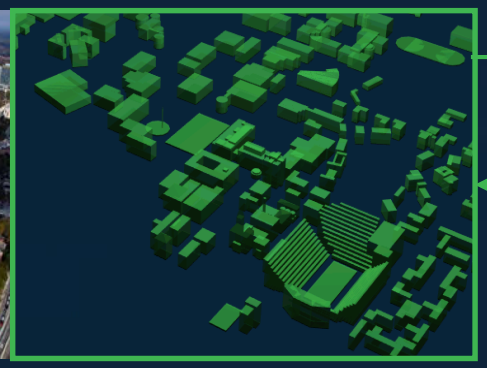
Evolving Cityscape

Vision: Digital Twin of Georgia Tech Campus

A Real World System of Systems



Digital Twin of the System of Systems



- *Planning / Construction*
- *Renovation / Maintenance*
- *Sustainability / Optimization*
- *Event Analysis / EVAC*

Decision Support

Interactive Visualization

Data Fusion

GIS

- *Areas of Interest*
- *Lands / Roads*
- *Buildings*
- *Infra. Networks*

Data

- *Metadata*
  - *BIM / Occupancy*
  - *Space Usage*
  - *Resources*
  - *Services*
- *Sensor Measurements*
  - *Weather*
  - *Consumptions (Energy / Water)*
  - *Communication / Social Media*
  - *Traffic / Parking*
  - *Crime / Safety*

Analytics

- *Statistics*
- *Machine Learning*
- *Predictive Analytics*

Modeling & Simulation

- *Physics-Based Tools*
- *System Dynamics*
- *Discrete Event Simulation*
- *Agent Based Modeling*

Digital Twin for System of Systems consists of mutually interacting multiple layers

Geographic Information Layer

Traffic & Mobility Layer

Energy Layer (Campus HVAC System)

Energy Layer (Electrical Grid System)

Security Layer

Campus Service Layer

Towards A Digital Campus

Focus on Infrastructure & Energy

Smart Campus: Targeted Capabilities

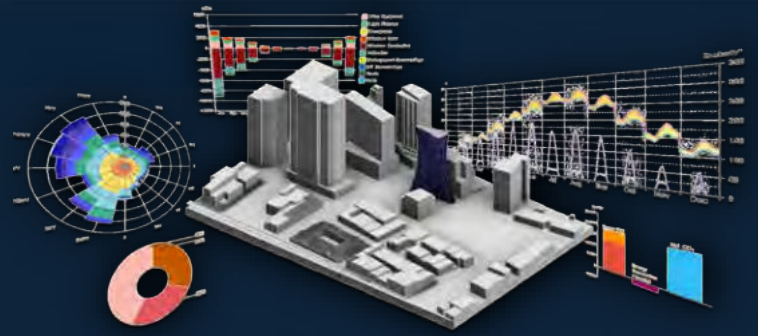
Running Campus Smartly

Focus: Existing campus, improving it as it is

Goals: Cost avoidance, energy savings, reliability, safety

Planning Campus Smartly

Focus: Future campus, Future scenario forecasting



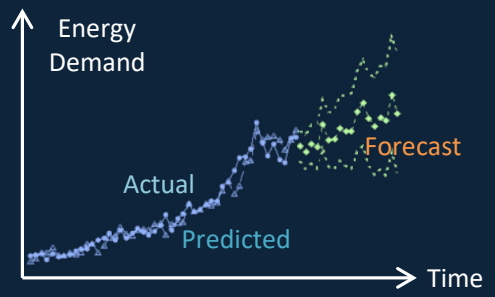
Goals: Data-driven decision making, strategic gaming, etc.

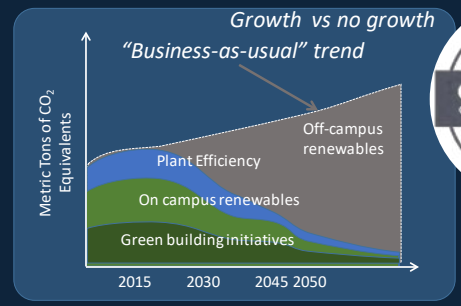
Smart Campus Data Analytics & Simulations support decision making at several horizons

Present → Near Future → Mid-Term Future → Long-Term Future

Initiatives Align with Decision-Making Horizons

	Running Campus Smartly		Planning Campus Smartly	
Planning Horizons	Present & Near Future		Mid-Term Future	Long-Term Future
	Situational Awareness	**Operations Optimization**	**Technology Integration Studies**	**Strategic Planning**
	Explore the Data	Benchmark Performance	Detect Faults & Degradation	Forecast BAU Loads	Explore Alt. Operations	Infuse New Technologies	Design Sys. Architectures	Game Scenarios	Develop Roadmaps





Ultimate Goals	*Intelligently monitored campus*	*Self-optimizing, resilient campus*	*"Virtual Campus" experimental facility*	*Revolutionary planning tools*

Digital Architecture (DA) of Smart Campus

Physical Campus

Ecosystem

Interface

Infrastructure
- Energy Supply Networks
- Transit Systems
- IT/IoT Layers
- ...

Database
- Mechanical Measurements
- Video Streams
- Weather Forecast Data
- Traffic API
- ...

Analysis Tools
- Usage Pattern Analysis
- Predictive Analytics
- ...

Simulators
- Dymola/Modelica
- SUMO (Simulation Urban Mobility)
- ...

Digital Twins

Energy & Water DSM
- Cooling Demand DSM
- Plant-A DSM
- Plant-B DSM
- Operation Policy DSM

Energy & Water Digital Thread
- Daily Ops
- Maint.
- Optimization
- Expansion Planning

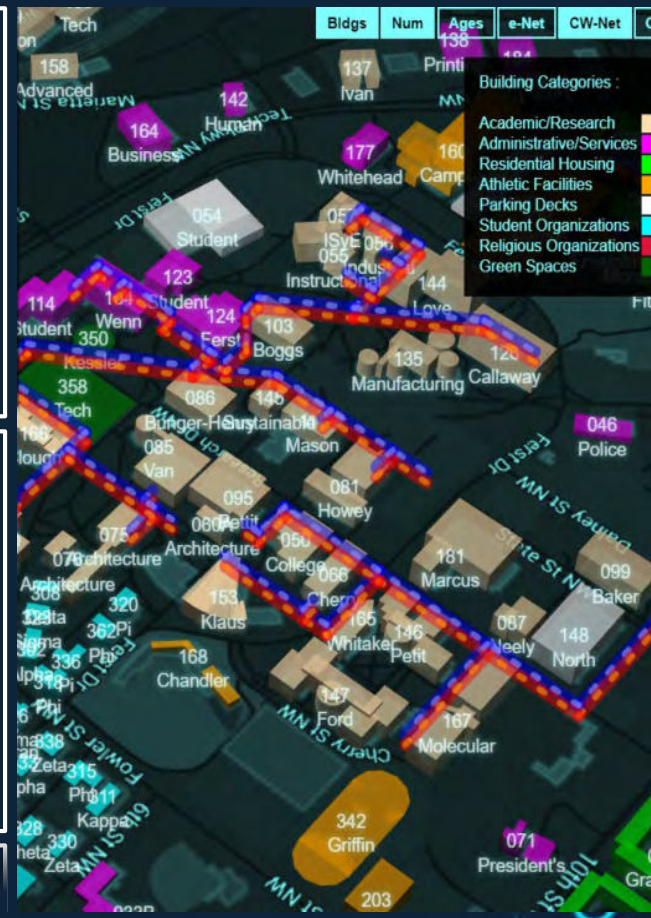
Safety & Mobility DSM
- Mobility Demand DSM
- Vehicle Traffic DSM
- Pedestrian Traffic DSM
- Traffic Law Enforcement

Safety & Mobility Digital Thread
- Traffic Mgmt.
- Safety Assurance
- Flow Easement
- Emergency Response

Campus Services DSM

Campus Services Digital Thread

Digital Campus



Massive Data Available

Sensor data, collected and overlaid onto a digital facsimile of campus, to support infrastructure monitoring and planning

ASDL started with access to:

Meso-scale: 20,000 streams

Data from 150+ buildings & 2 plants
Archived every 15 min for >7 years

- Energy & water metering
- People counters on newer entryways

…cleaned, normalized, and mapped to drive:

Macro-scale Situational Awareness

- Campus-level visualizations
- Baselining for detecting degradation
- Modeling to project future scenarios

…soon to be supplemented with

Micro-scale data streams

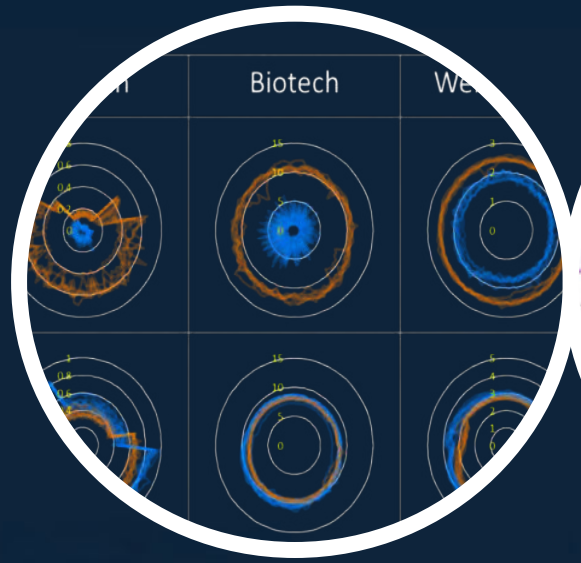
- ~10k end points per building
  - Internal temp, air quality
  - HVAC hardware states
- IoT sensors from maker spaces
- Mobile device locations, anonymized

Creating this digital version of campus required that ASDL:

Map & verify data sources Tap into data streams and databases Clean erroneous data	Normalize data by weather and campus schedule Interpret data with help from GT Facilities Management engineers

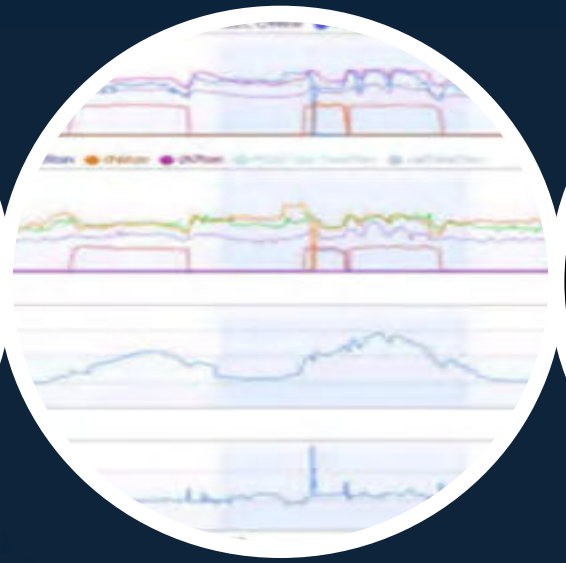
DIGITAL TWIN – ANALYTICAL CAPABILITIES

Descriptive



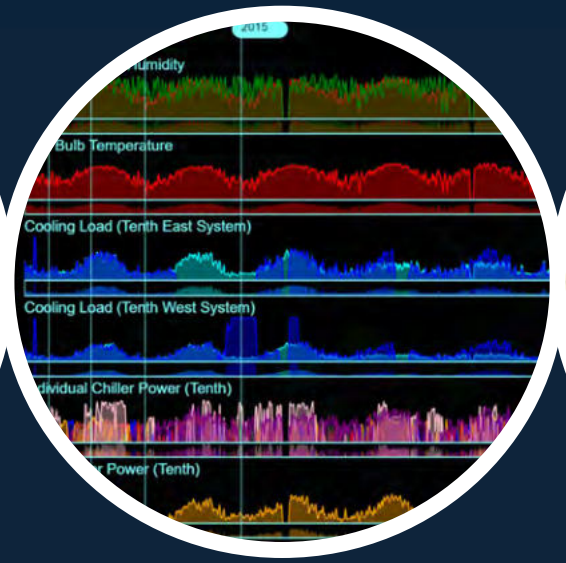
"What happened"
"What is happening?"

Diagnostics



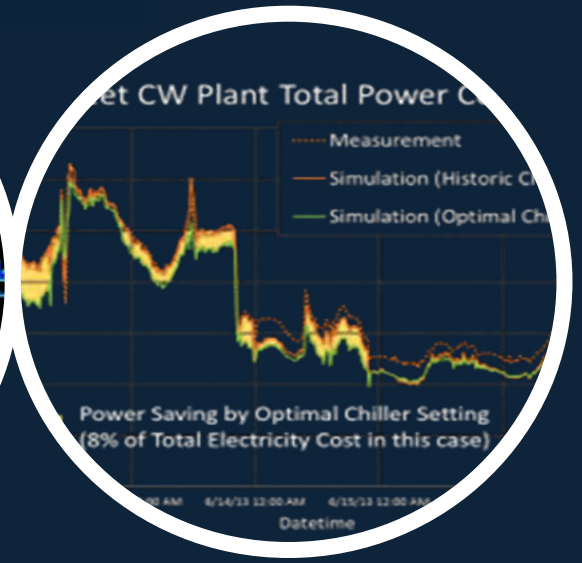
"Why did it happen?"

Predictive



"What is likely to happen?"

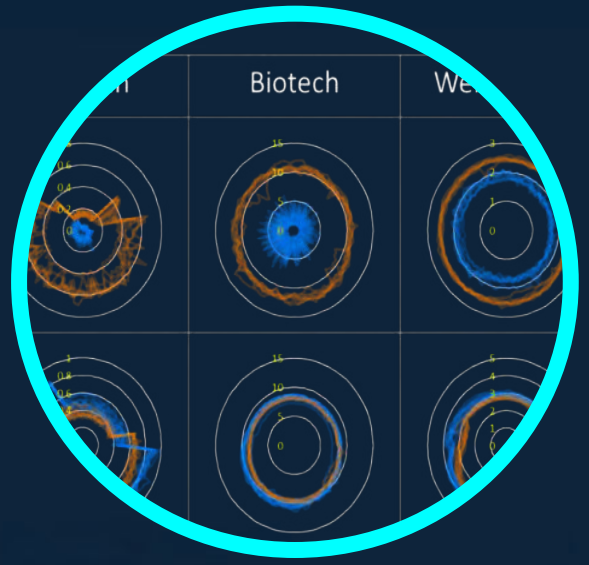
Prescriptive



"How to act in response?"

DIGITAL TWIN – ANALYTICAL CAPABILITIES

Descriptive

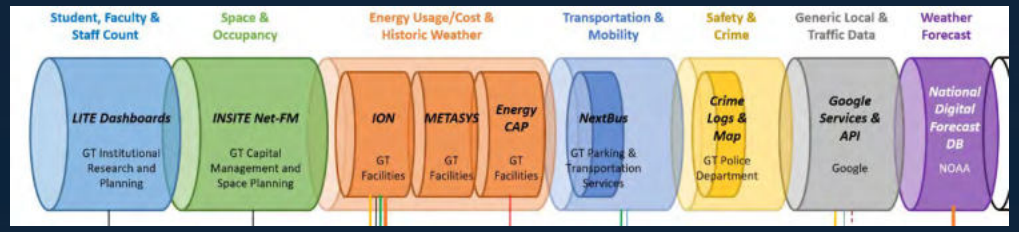


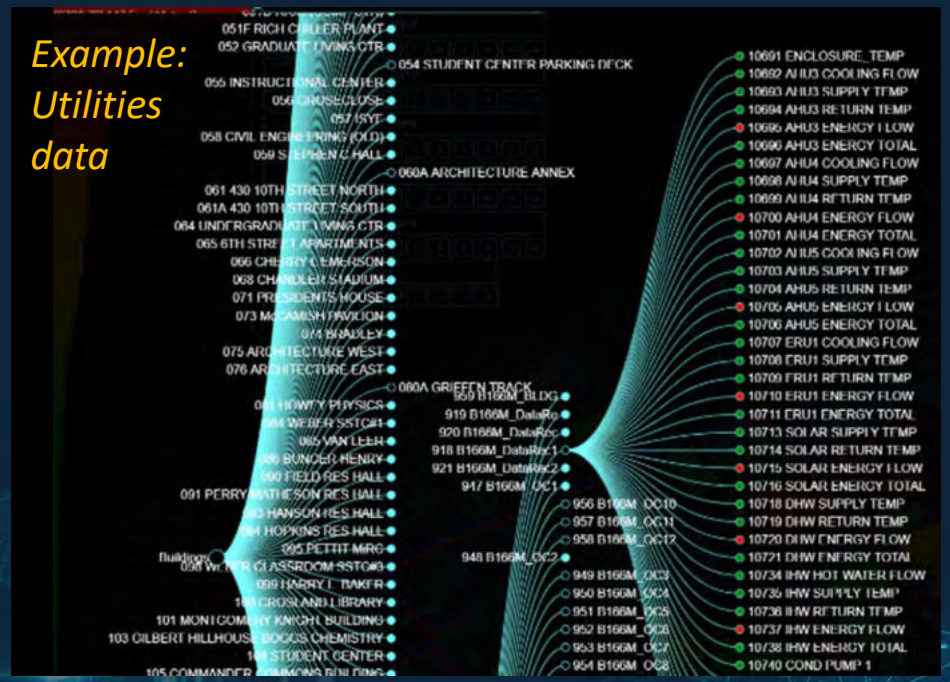
- Focus on summarizing and visualizing historical data to provide insights into the past and present
- Provides necessary context and foundation for further analysis
- Seeks answer about “What happened/What is happening?”

Preparing Big Data

Answers: "What Happened?"

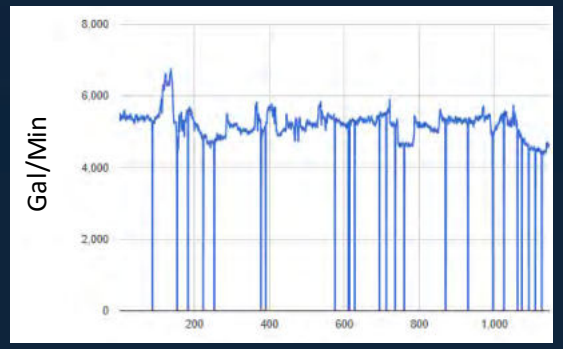
Map data repositories





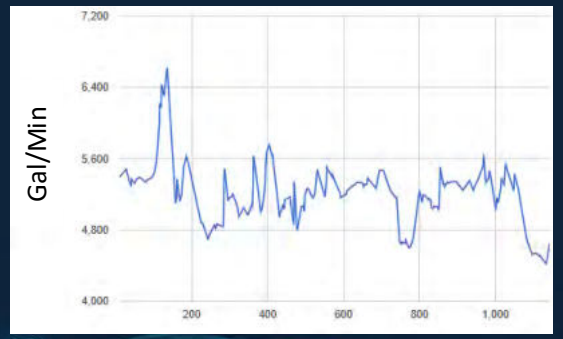
Clean data sets

Problem data

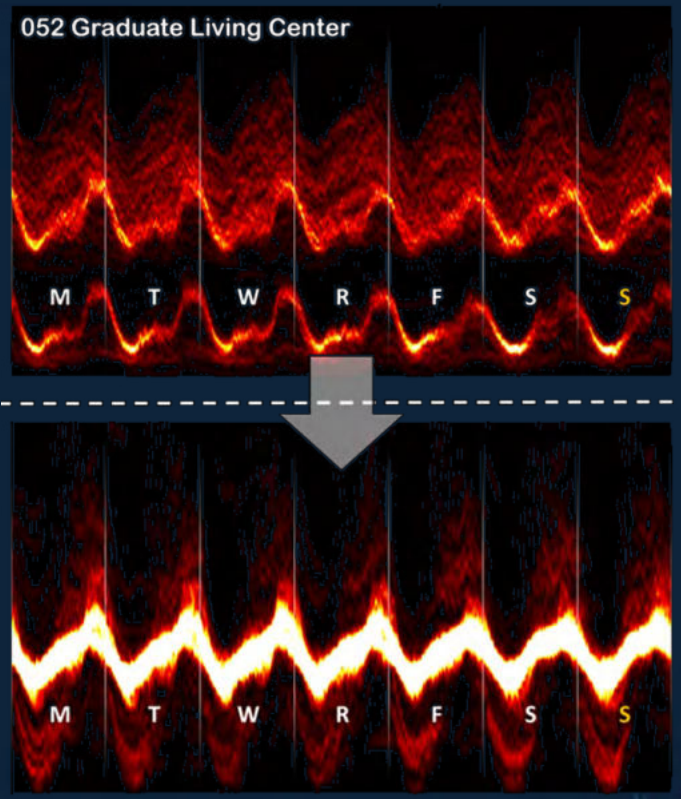


Anomaly treatment

Corrected data



Normalize & extract features

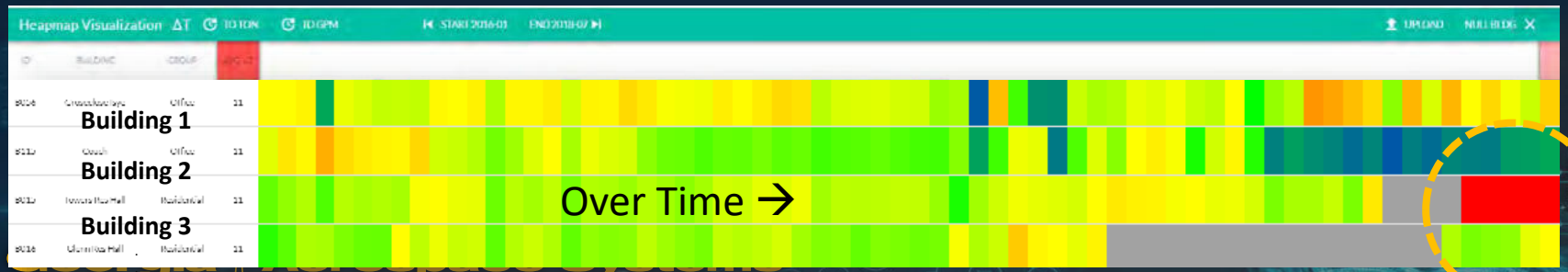


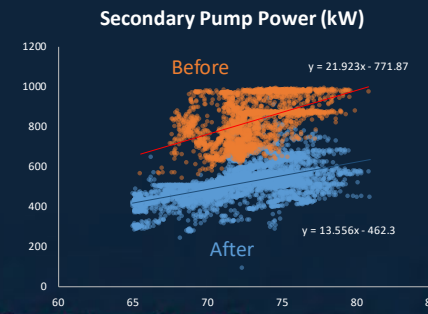
Visualizing Data for Infrastructure

Answers: "What Happened?"

Value Propositions:

- Common Operating Picture for team discussion
- Cost avoidance, identifying inefficiency





Visualizing Data From Many Domains

Answers: "What Happened?"

Value Proposition: Discovery of interactions between systems-of-systems

Energy Consumption (KWh, KWh/m²)

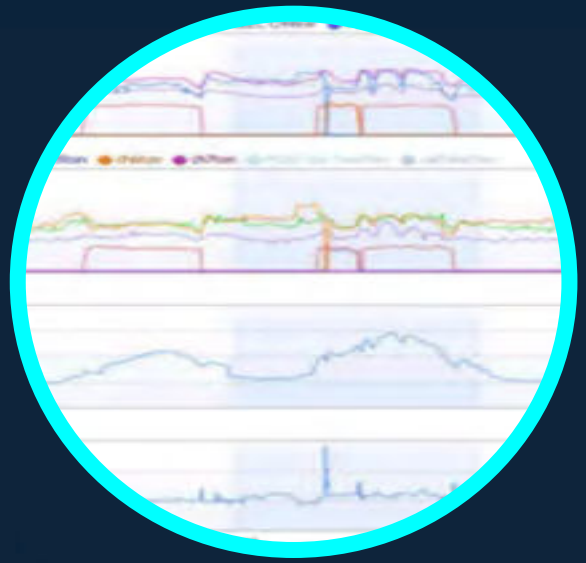
Safety (Incidents)

CO_2 Footprint ($KgCO_2$)

Construction Activity & Costs ($)

DIGITAL TWIN – ANALYTICAL CAPABILITIES

Diagnostics



- Drill down into the data, identify correlations and dependencies, and identify patterns for the purpose of identifying causes
- Seeks answer about "Why did it happen?"

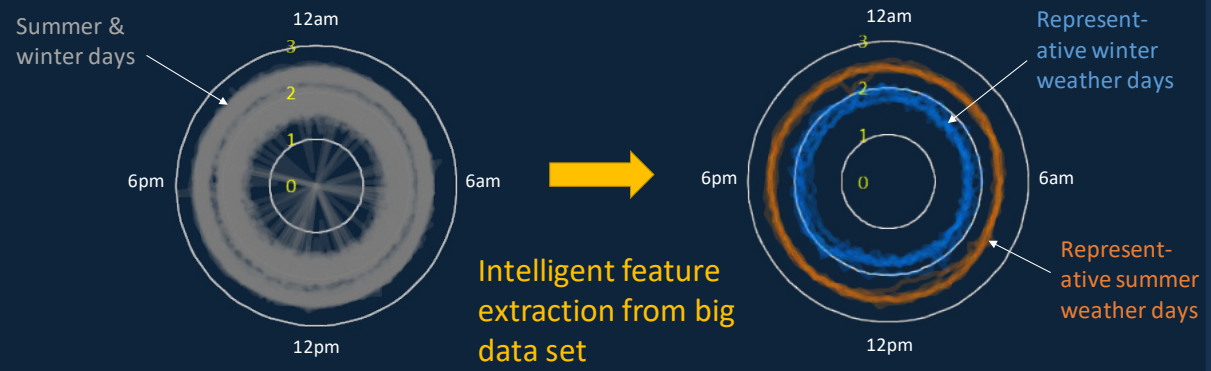
Extracting Features

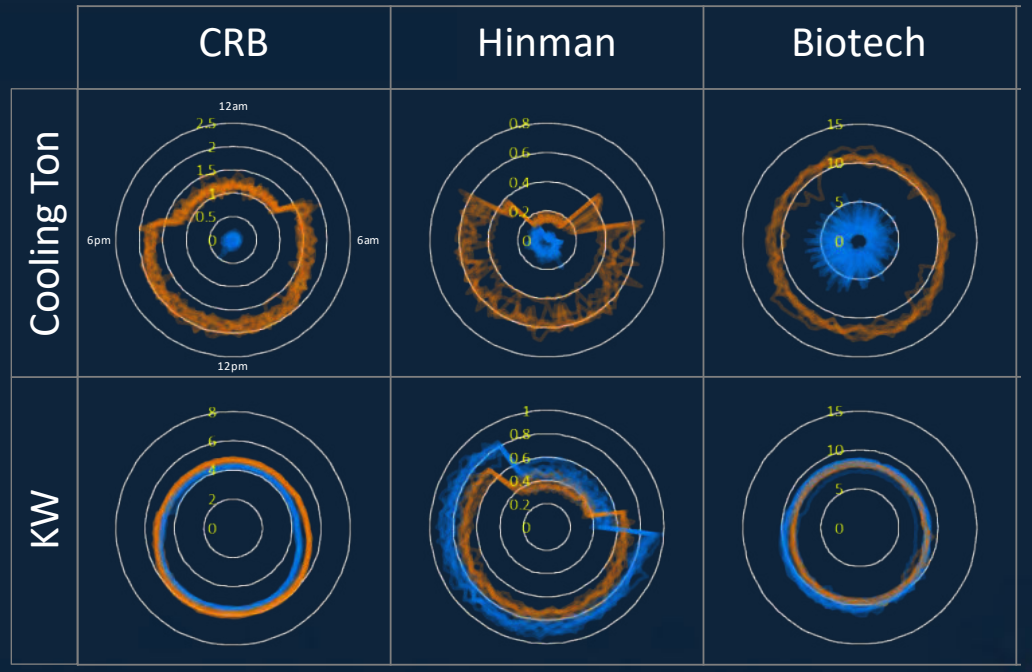
Answers: "Why did it happen?"

- SMEs identify performance signatures & root causes

Data Treatment to Find Signatures

Cooling Ton Data, Around the Clock

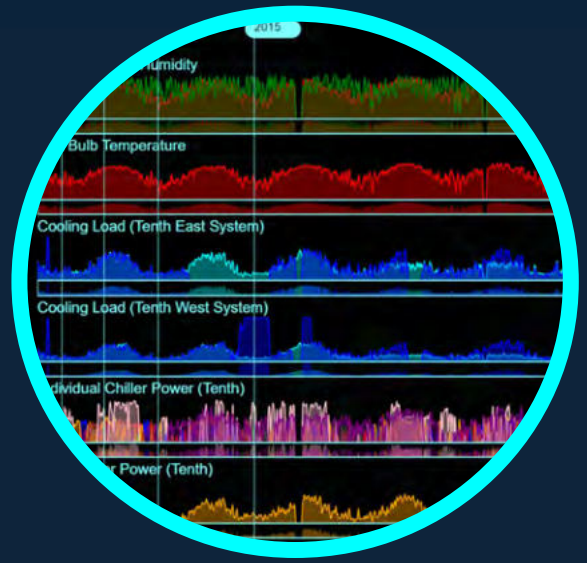




DIGITAL TWIN – ANALYTICAL CAPABILITIES

Predictive

- Leverages descriptive and diagnostic analytics to predict future trends
- Probabilistic in nature
- Seeks answer about “What is likely to happen?”

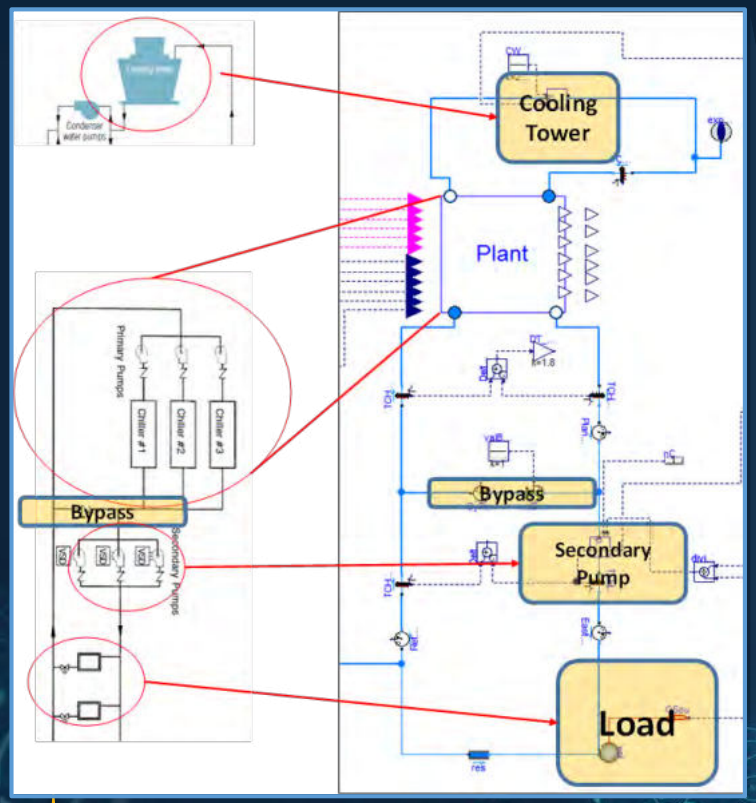


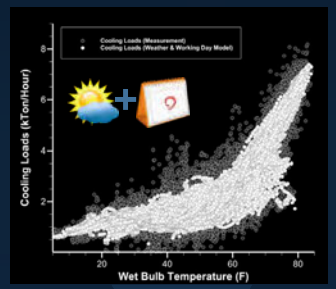
Predictive Modeling Capabilities

Plants

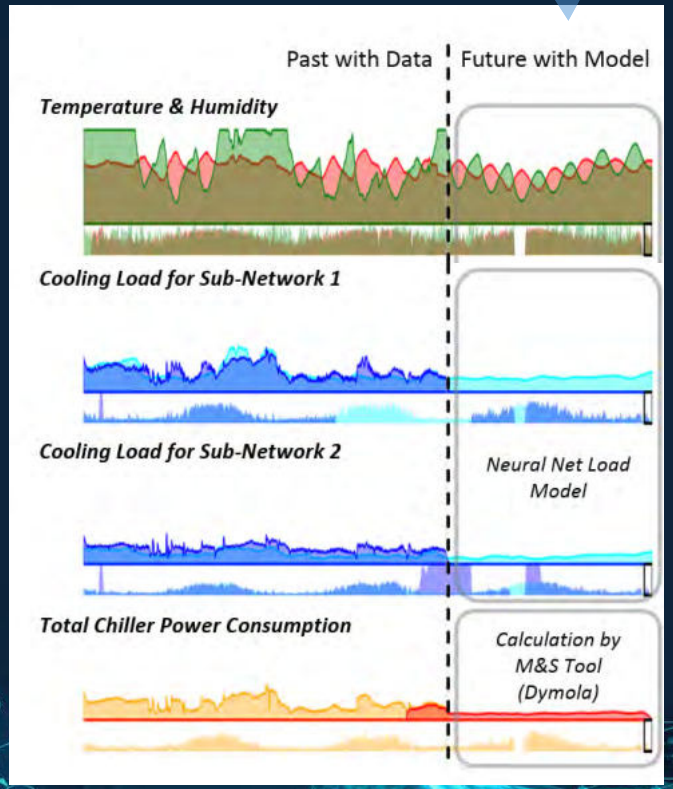
- Calibrated, physics-based models to forecast loads for chiller plant energy

Chiller Plant model (Modelica)





Load model (Neural Net)



Value Proposition:

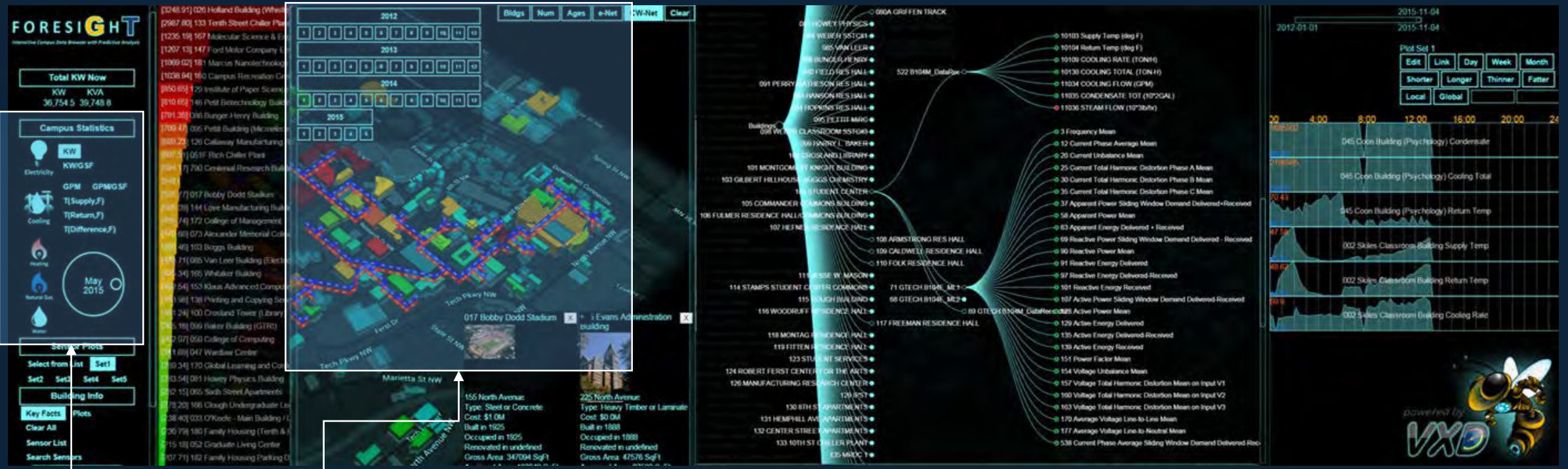
- Forecasting future demand and system response

Example:
Given a weather forecast…

…predict the energy usage of the central chiller plants to meet the thermal demand

FORESIGHT Predictive Campus Browser

Interactive, visual-analytics based campus data browser, supporting real-time situational awareness, campus-level energy usage monitoring and model-based energy usage predictions, based on real time data streams

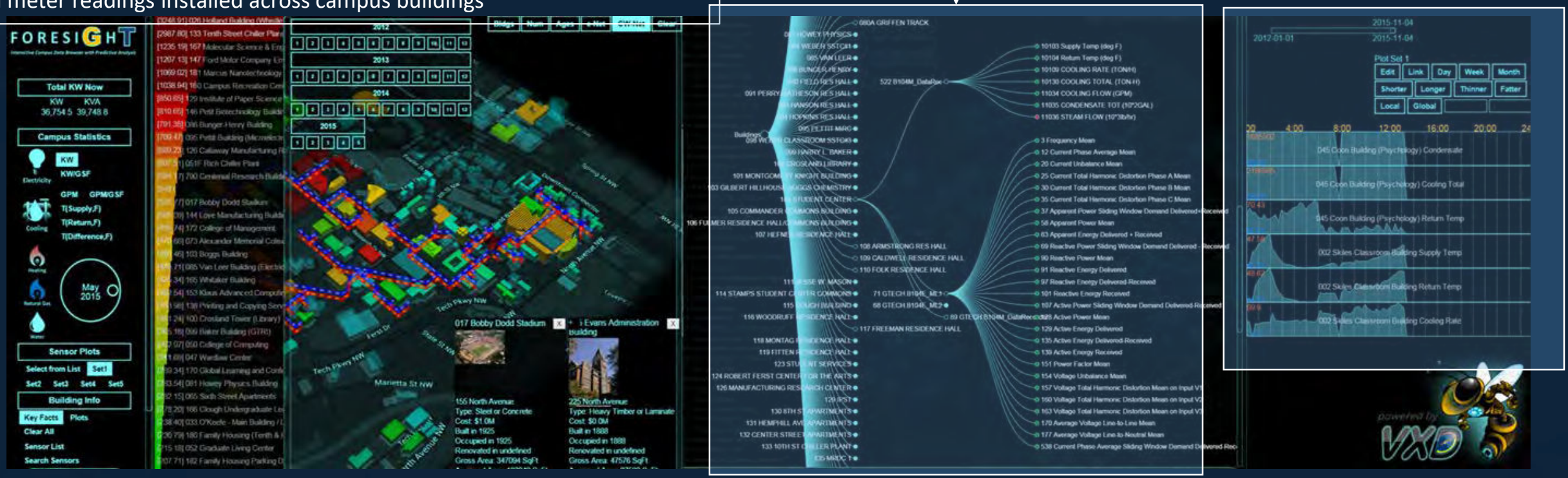


User can navigate through time/campus location and observe past energy performance trends for any building of interest

FORESIGHT Predictive Campus Browser

Interactive, visual-analytics based campus data browser, supporting real-time situational awareness, campus-level energy usage monitoring and model-based energy usage predictions, based on real time data streams

Real-time measurements and historic data queried from repositories maintained by campus facilities, and is sourced from sensor measurements and meter readings installed across campus buildings



FORESIGHT Predictive Campus Browser

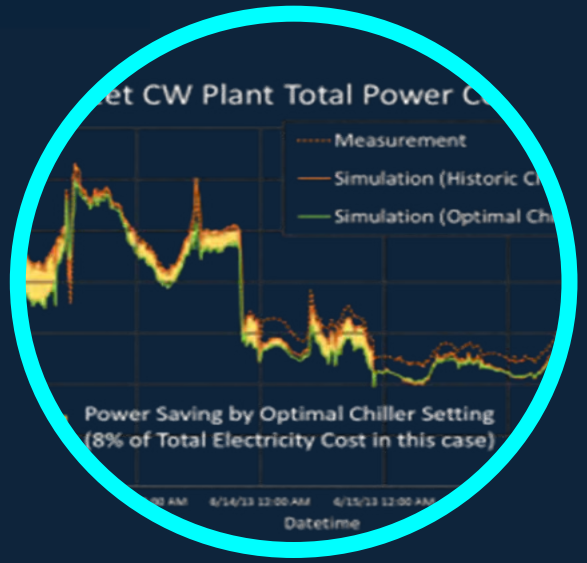
Interactive, visual-analytics based campus data browser, supporting real-time situational awareness, campus-level energy usage monitoring and model-based energy usage predictions, based on real time data streams

Comprehensive prediction capability for campus-wide energy usage that includes varying energy demand, accounts for total campus cooling load fluctuations, and utilizes weather forecast data

DIGITAL TWIN – ANALYTICAL CAPABILITIES

Prescriptive

- Integrates data, mathematical models (optimization, etc.) and business rules to advises on possible outcomes / recommends one or more courses of action
  → Support decision making
- Seeks answer about "How to act in response?"

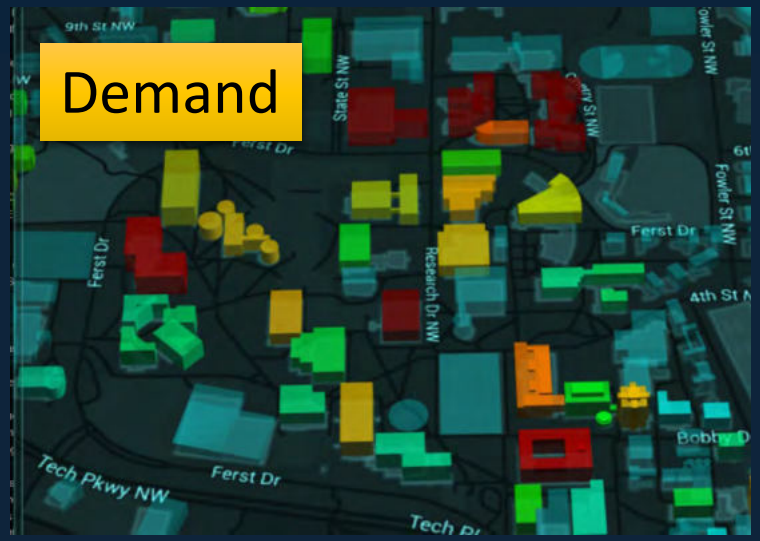


Answers: "How to act in response?"

Model-Based Scenario Exploration: Energy Demand vs. Supply

- Calibrated, physics-based models used to plan playbooks & responses

1 Given a weather forecast & cooling demand → …how should plant chillers be optimally staged?



2 …where does it make sense to curtail load? ← If a chiller went offline unexpectedly…

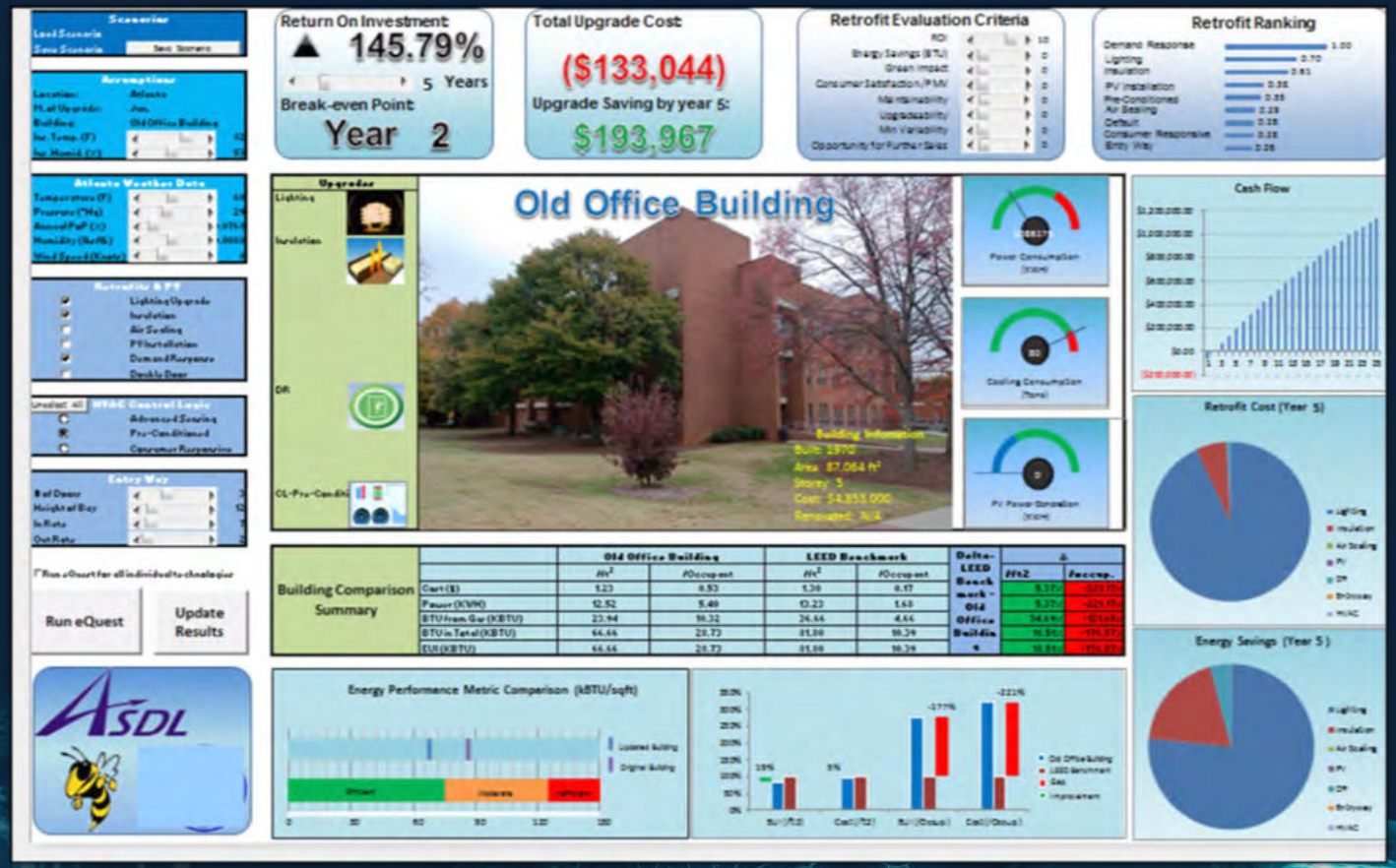
Value Propositions:

- Optimization of efficiency
- Playbooks for resilient response

Answers: "How to act in response?"

Model-Based Scenario Exploration: Upgrade Portfolios

- Calibrated, physics-based models used to rank choices for retrofitting buildings



A tool to answer:

- For an existing system in need of energy retrofits,
- given a set of technology candidates,

→ What should I invest in?

→ And what are their: ROI, Payback period, Energy savings, etc.

  - Either: absolutely, normalized per ft^2, compared to best in class, etc.

Digital Twin of a System-of-Systems

LEADER-X: Campus as Experimental Apparatus

Goal: Elevate ASDL's Smart Campus platforms into a Living Testbed for scientific study of socio-cyber-physical systems

Vision: a test bed with parallel facets:

1 "Digital twin" virtual test facility

Calibrated models, update with real conditions

Used to:

- Plan out and run virtual experiments
- Create multiple instances in parallel, for comparison
- Prove-out proposed changes before implementing
- Create a baseline for understanding real measurements?

2 Real test facility

the instrumented, connected campus

Used to:

- Run parallel experiments on
  - Infrastructure
  - Community response shaping
- Calibrate the virtual apparatus

Questions to Address:

- With a campus as your test bed, how would you design living experiments to characterize the complex interactions between technology, infrastructure, and people? *Relevant to understanding Smart Cities, mobility systems, human space habitats, etc.*
- How good are the current measurements of your experimental instrument? *i.e., What can already be done with current campus data sets, for selected case studies?*
- What other data would you collect, i.e., what sensors to add would improve it?

Thank You


NASA
FedEx
Flight From To Depart Arrive
4525 ATL MEM 8:59PM 9:47PM
2354 MEM PHL 1:05AM 2:48AM
4852 LAX MEM 8:47PM 9:11PM
TECH
EDS
New Material
Structure
Propulsion
Emission
New Technology
Noise
Aero-dynamics