Forecasting and Dynamic Real-Time Optimization of a Campus District Energy System using PI

Dr. Kody Powell and Dr. Pratt Rogers

THE UNIVERSITY OF UTAH

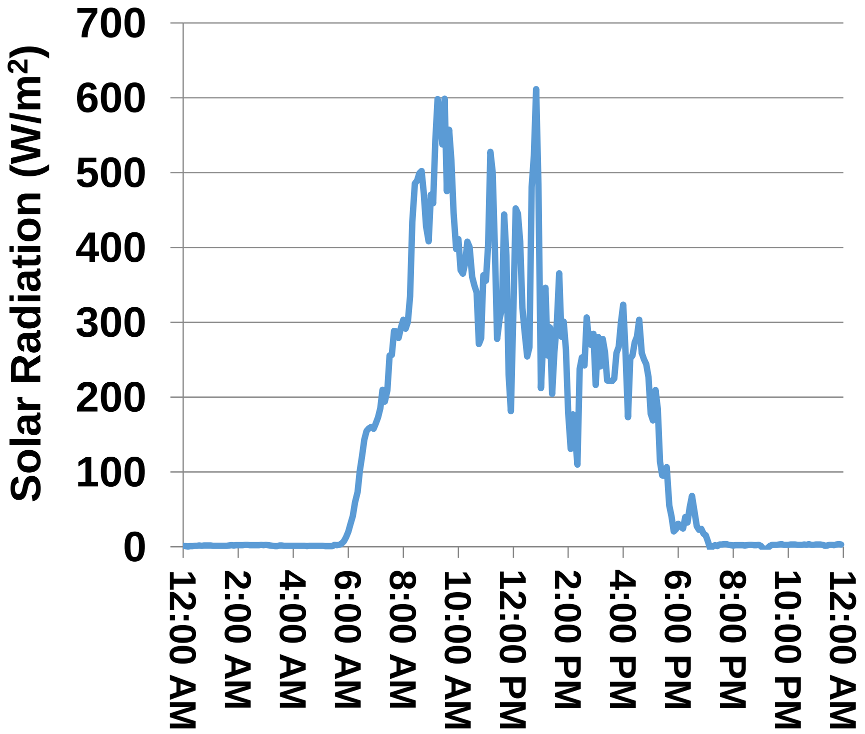
About Me: Kody Powell, Ph.D.

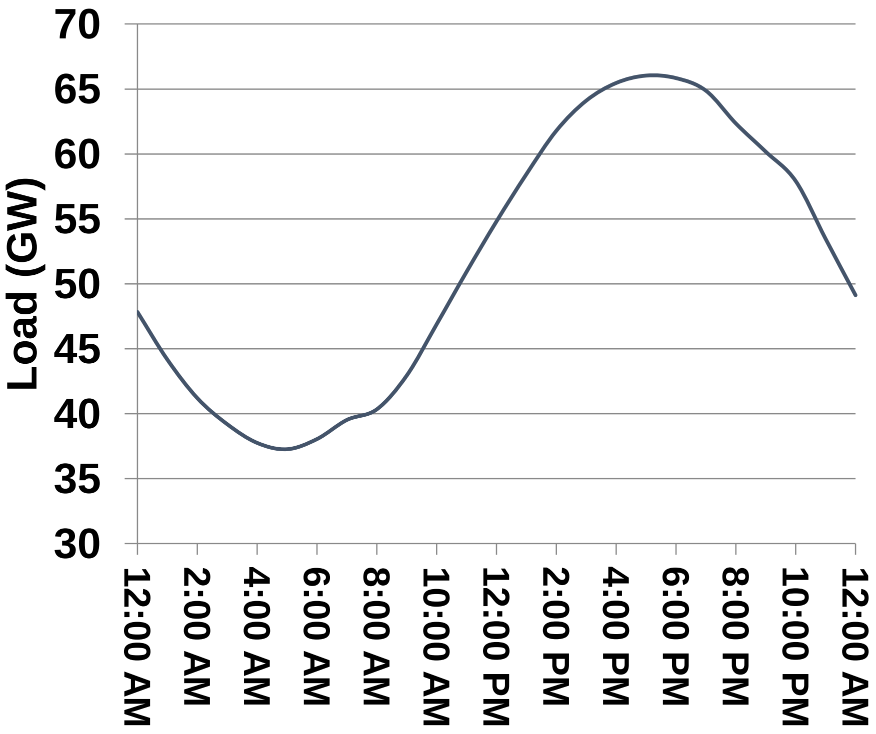
- University of Utah – Dept. of Chemical Engineering
  - Previously ExxonMobil Research and Engineering
- Automation and Optimization **Researcher**
- Research focus on energy systems and smart grid
  - Solar energy
  - Distributed energy
  - Manufacturing/process systems
  - Building energy management
  - **Energy Storage**
- My goals as a professor and researcher
  - Develop technology for systems to be “smarter”
  - Develop engineers with applicable skill sets for the market
- Warning: I am a PI novice

About Me: Pratt Rogers, Ph.D.

- University of Utah – Dept. of Mining Engineering
  - Previously MISOM Technologies
- Analytics and Operations Engineering **Researcher**
- Research focus on
  - Socio-technical systems: people, processes, technology
  - Machine learning and analytics nexus
  - Management safety and production systems
- My goals as a professor and researcher
  - Operationalize cool technology
  - Develop engineers with applicable skill sets for the market

The Fundamental Problem



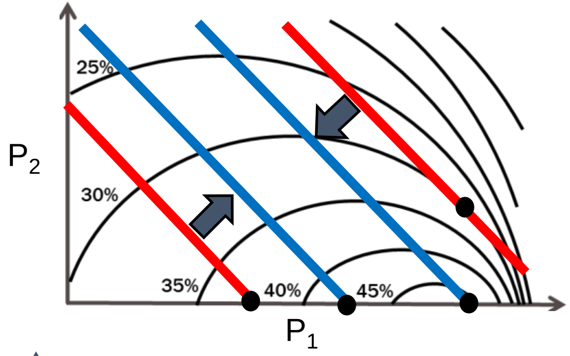


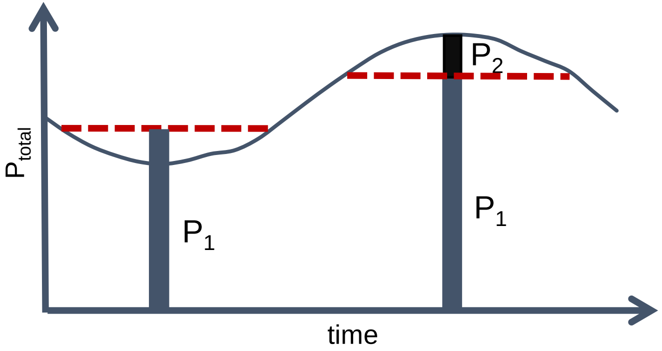
The Solution(s)

- Energy Storage
  - Large scale
    - Heavy lifter
  - Distributed
  - Thermal Energy storage
    - “Heat things up and cool them down”
- Intelligent Systems
  - Powerful can be smart too

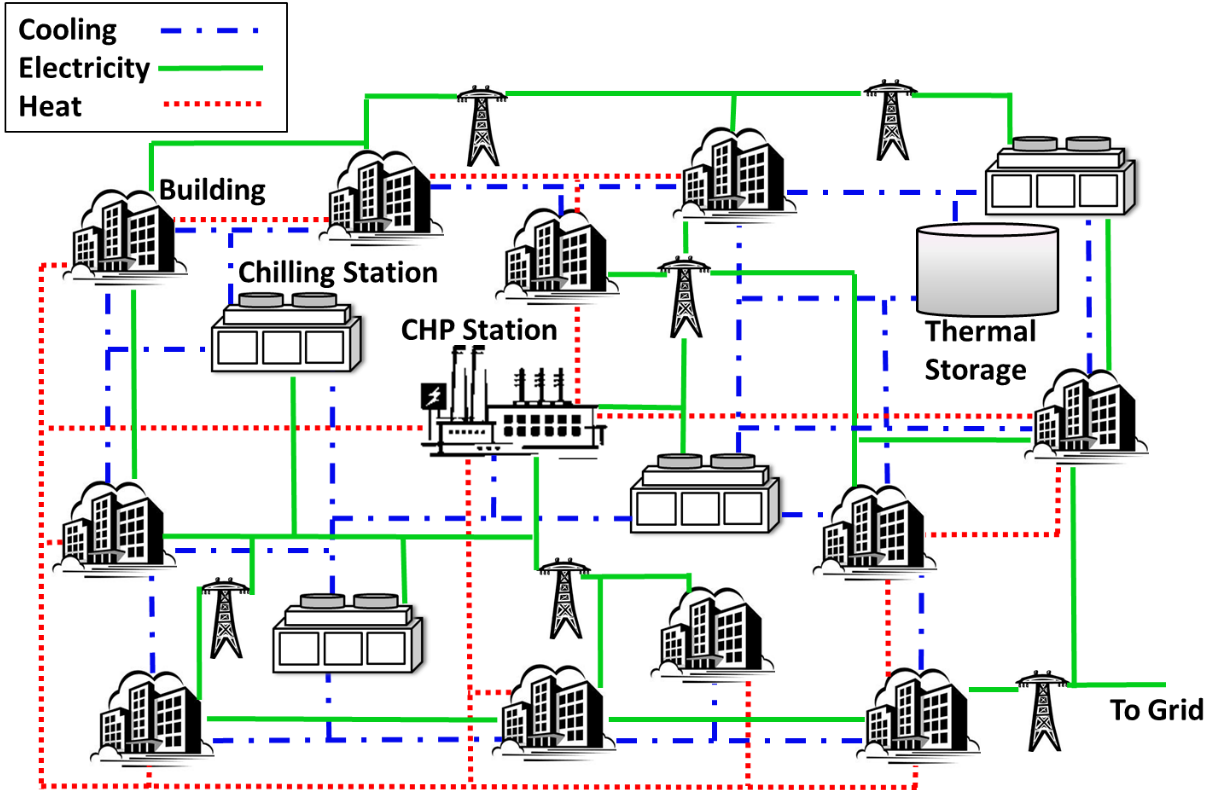
Smart Energy Storage

- Constraints
  - $P_1+P_2=P_{total}$
  - DOF=1
- Dynamic optimization
  - DOF=infinite
  - Discretize
  - Flexibility
  - Blessing and curse of dimensionality

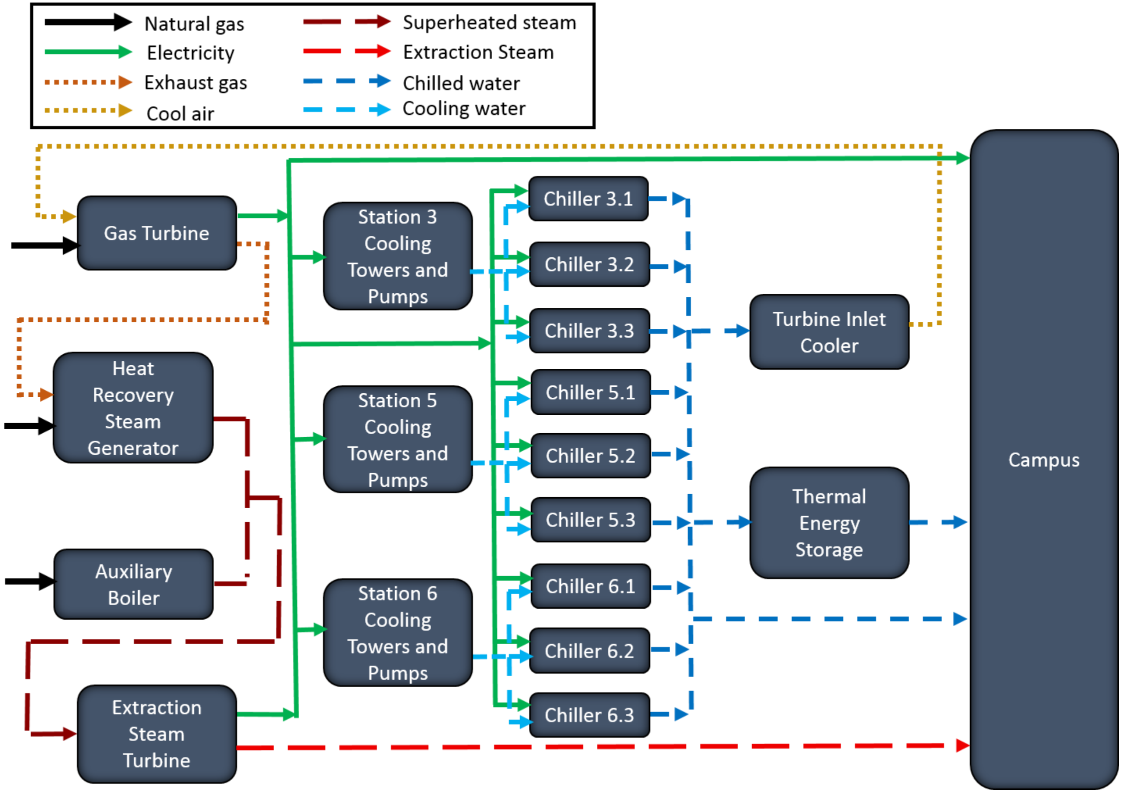




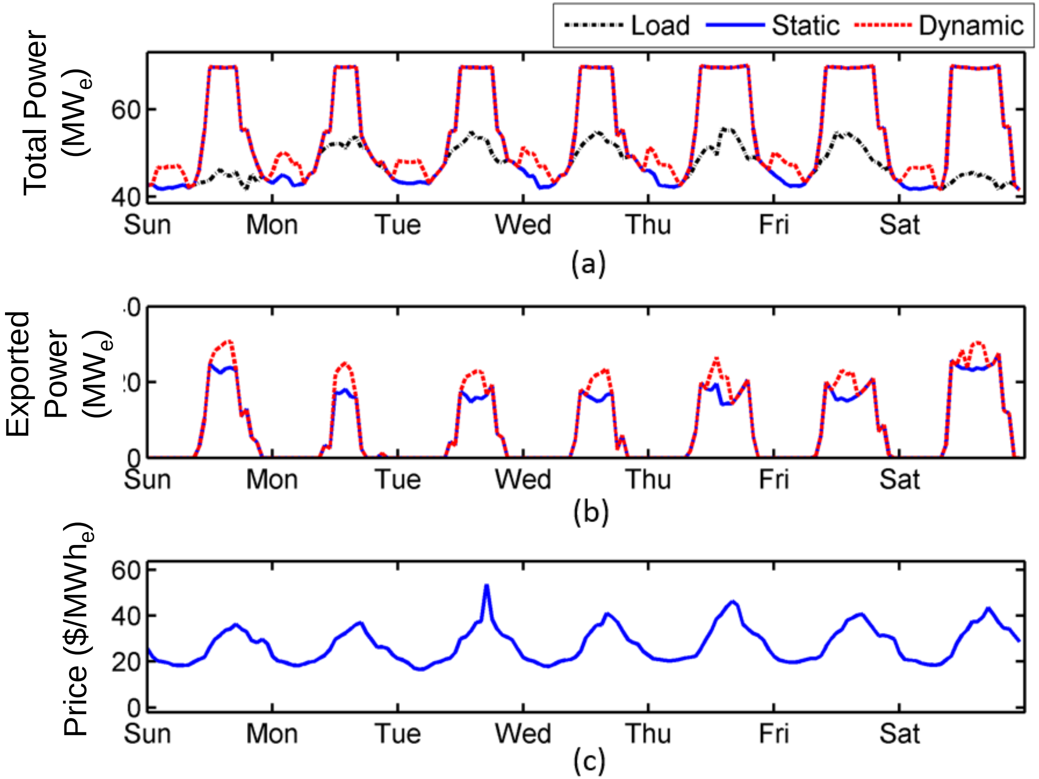
Energy System Optimization



Complete System Model

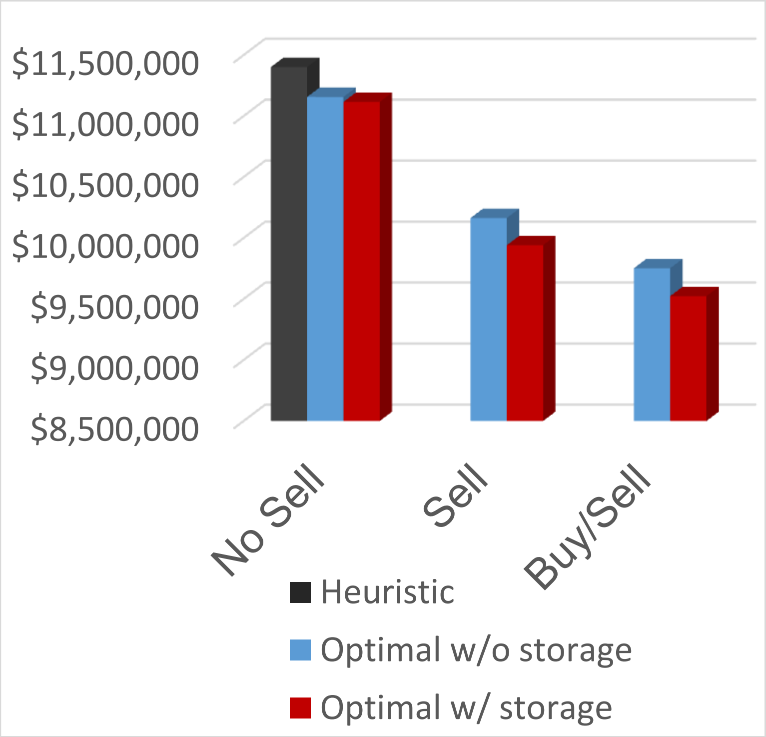


Results: Grid Interconnection Example



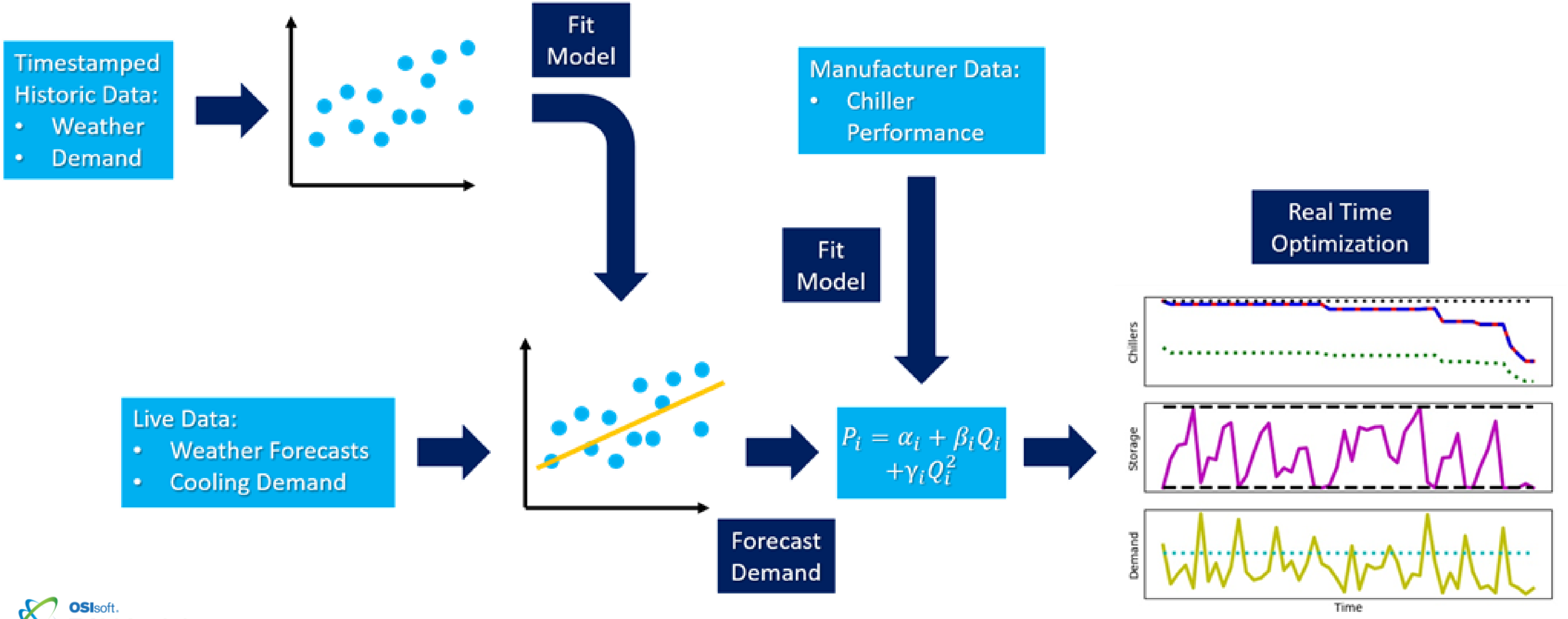
Summary of Results

- 2.2% savings by optimizing
- Marginal benefit using storage for efficiency
- +6 MW_e peak capacity
- Storage beneficial in market conditions
  - Additional 2.2-2.4% savings
- $1.9 M (16.5%) savings overall

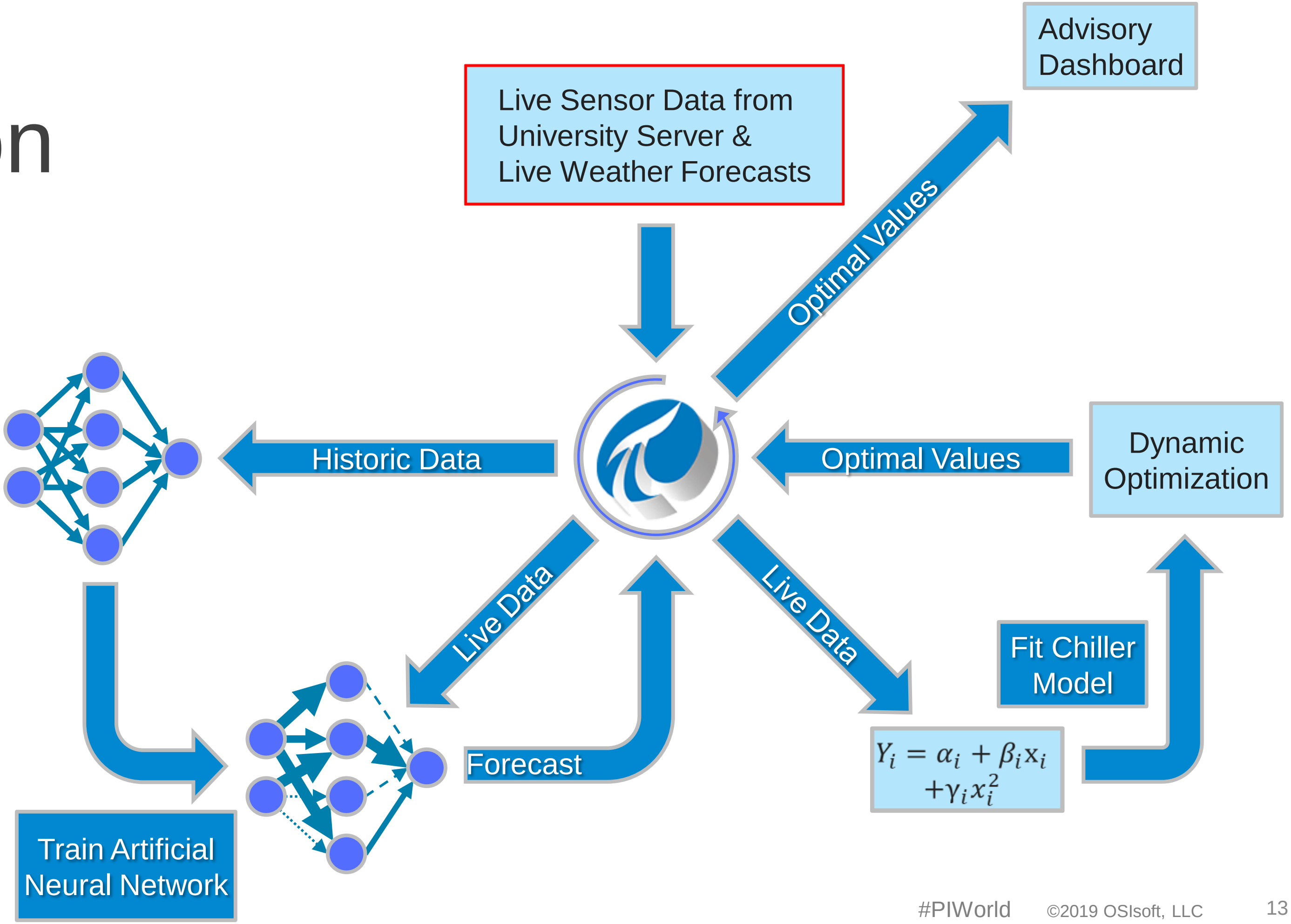


How Do We Make Theoretical Results A Reality?

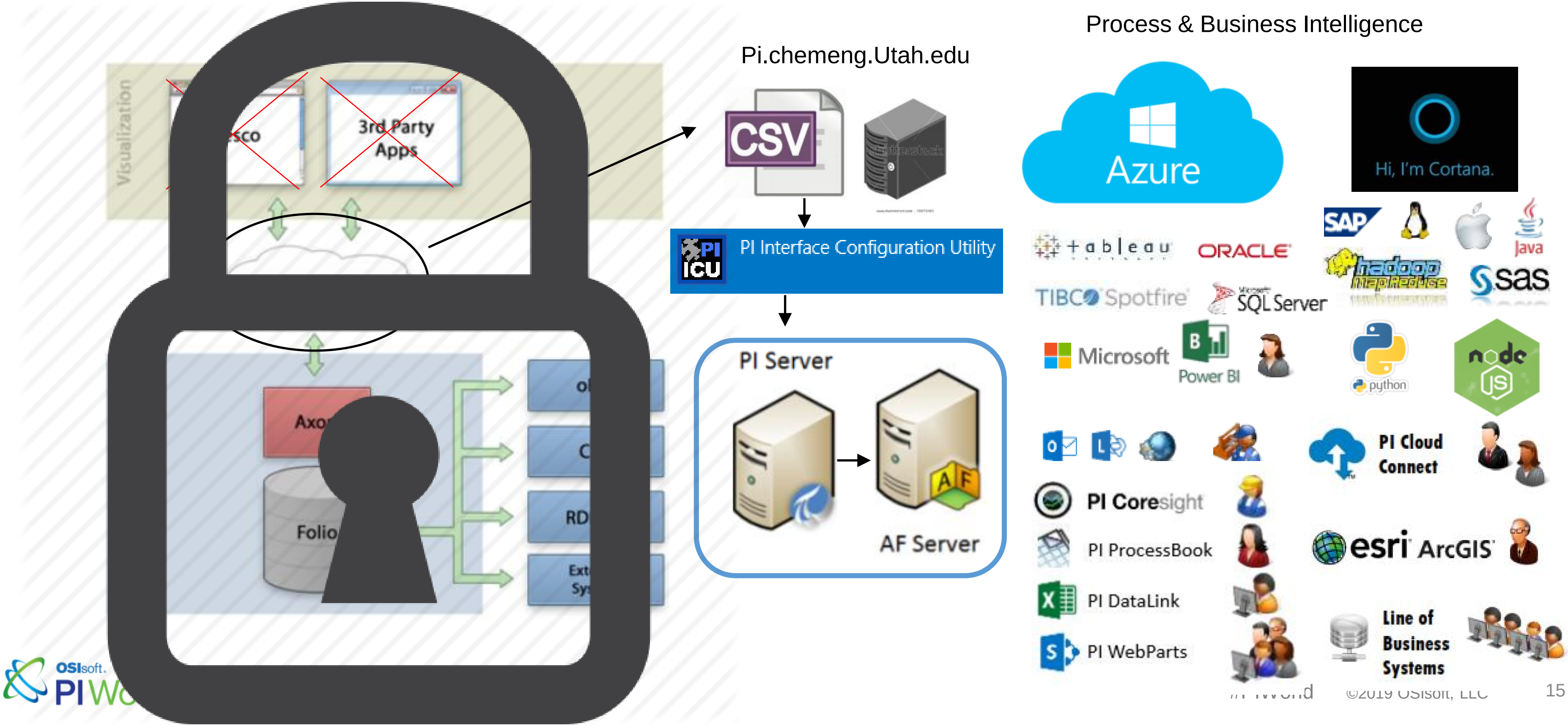
Building an Optimization Application Around PI



Building an Optimization Application around PI



Skyspark PI System Connection

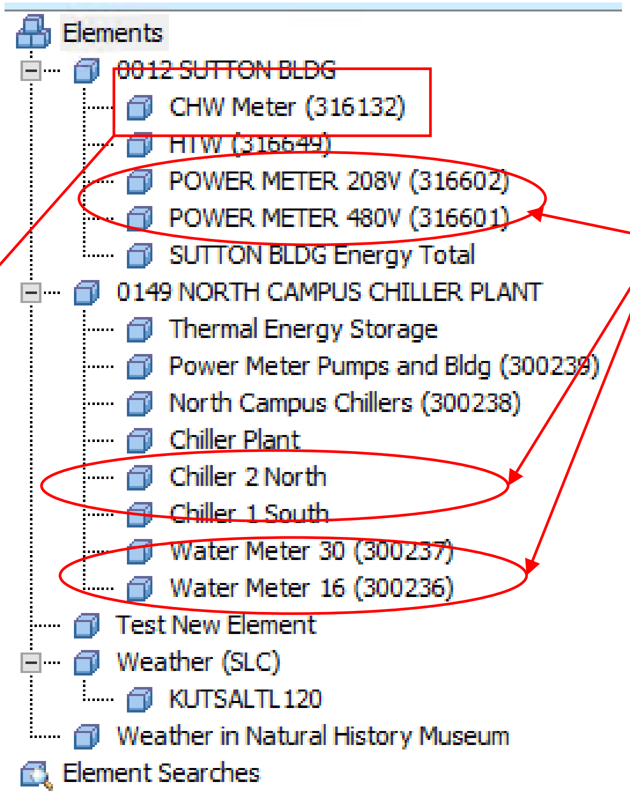


The PI System and current data

- Element Hierarchy – Tree Structure
- All names kept consistent with Haystack Terminology
- Multiple Attributes for each Element
- Templates
- Tags

Current Day Total_b	16636928
Daily Energy Value_a	22678016 Btu
Energy Month Total	6598860 Btu
Energy Rate	0 Btu/h
Energy Total Mode 1	5.94393E+09 Btu
Energy Total Mode 1 Status	OK
Five day avg_c	23703244.8 Btu
Return Temperature	53.94992 °F
Supply Temperature	53.94501 °F

Tag for each data source



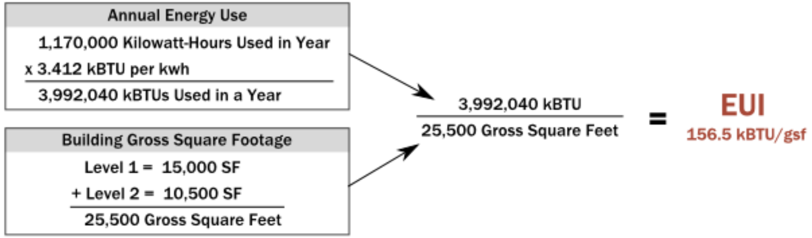
Templates

Advanced calculations in PI AF

Calculating a Building's EUI

A school contains a main floor consisting of 15,000 square feet, a second floor consisting of 10,500 square feet. The school used 1,170,000 kilowatt-hours of power during the year in question. Kilowatt-hours is multiplied by 3.412 to obtain kBTUs, therefore 1,170,000 * 3.412 = 3,992,040 kBTUs. This is divided by the total square footage of 25,500 square feet for an Energy Use Intensity of 3,992,040 / 22,500 = 156.5 kBTU/sf.

Using PI Unit Conversions to Measure Energy Use Intensity (EUI)



https://www.archtoolbox.com/materials-systems/sustainability/energy-use-intensity.html

Energy

Filter

Name	Abbreviation	Class	Origin	Canonical	Reference
British thermal unit	Btu	Energy	Unknown	1055.05585262 J	1055.05585262 J
calorie	cal	Energy	Unknown	4.1868 J	4.1868 J
EUI	kBtu/Ft2	Energy	Unknown		Btu = (1000*91000/365) * EUI, kBtu/Ft2 = Btu / (1000*91000/365)
gigajoule	GJ	Energy	Unknown	1000000000 J	1000000000 J
gigawatt hour	GWh	Energy	Unknown	3600000000000 J	3600000000000 J
joule	J	Energy	Unknown	1 J	
kilocalorie	kcal	Energy	Unknown	4186.8 J	1000 cal
kilojoule	kJ	Energy	Unknown	1000 J	1000 J
kilowatt hour	kWh	Energy	Unknown	3600000 J	3600000 J
megajoule	MJ	Energy	Unknown	1000000 J	1000000 J
megawatt hour	MWh	Energy	Unknown	3600000000 J	3600000000 J
million British thermal unit	MM Btu	Energy	Unknown	1055055852.62 J	1000000 Btu
million calorie	MMcal	Energy	Unknown	4186800 J	1000000 cal
watt hour	Wh	Energy	Unknown	3600 J	3600 J
watt second	Ws	Energy	Unknown	1 J	1 J

External Data Sources

WEATHER UNDERGROUND

– 3 minute current weather conditions

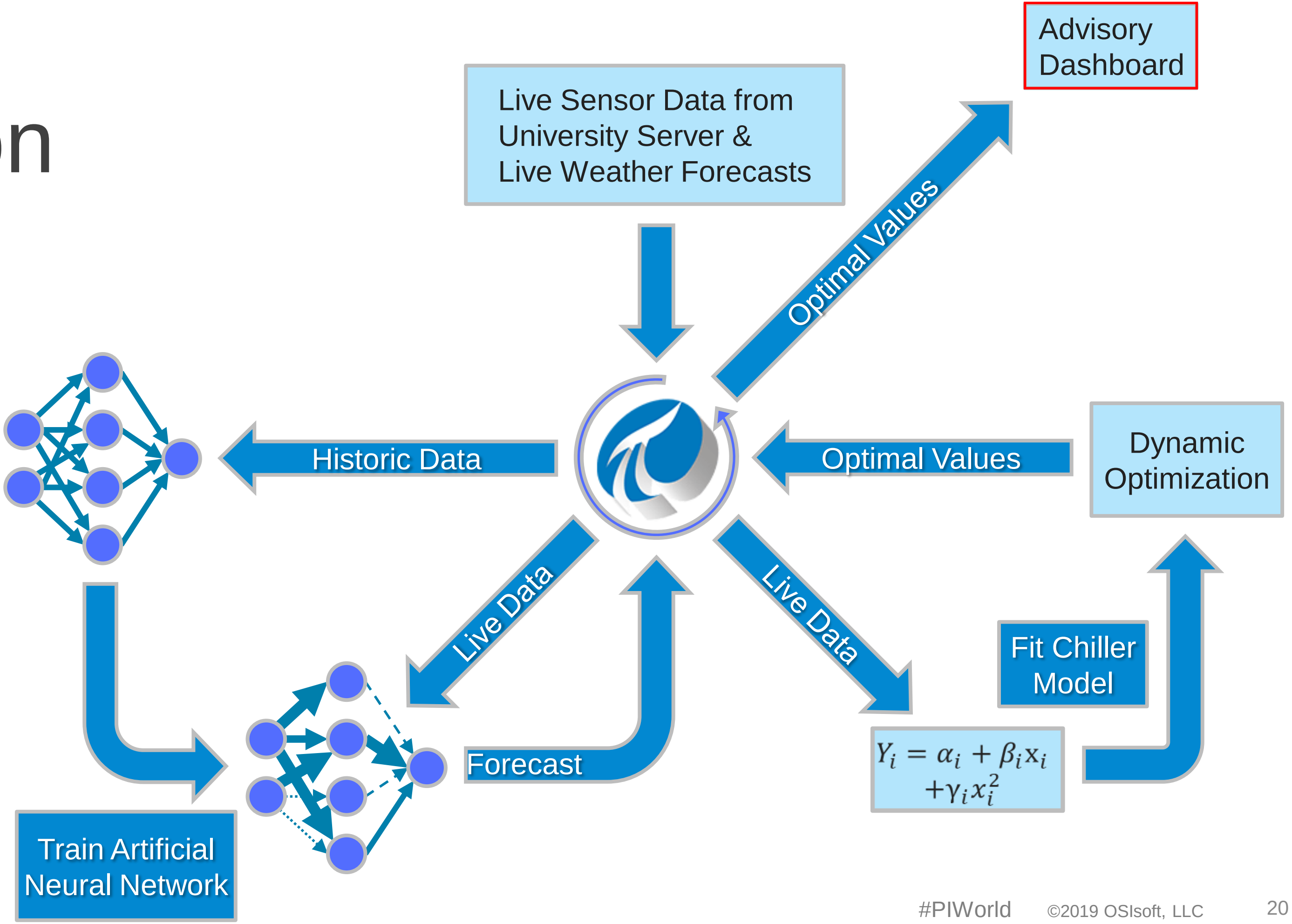
– Hourly forecasts

– Heating Degree Days

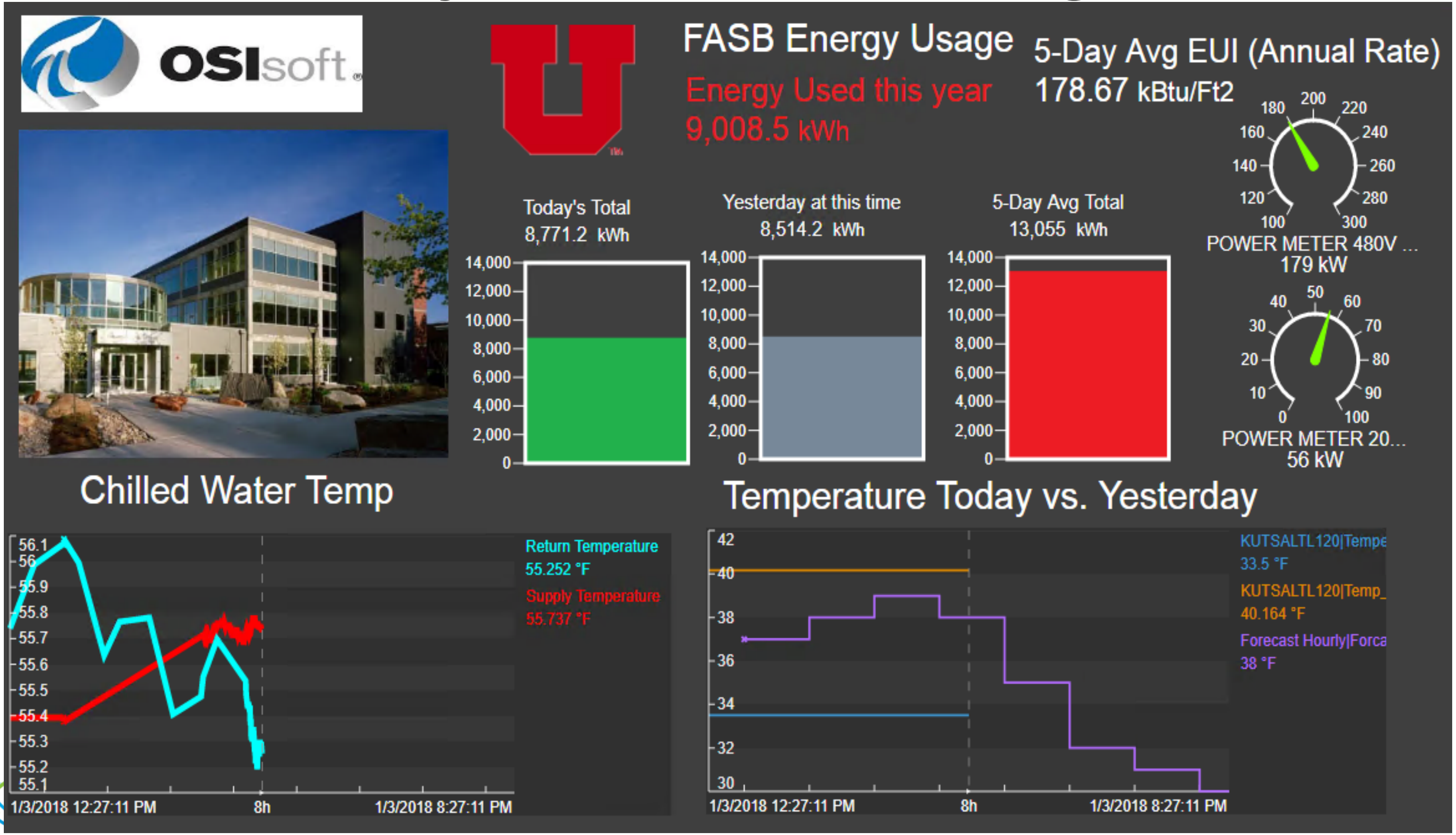
DATA.GOV

- Forecasted Electricity demand for the region
- Current electric demand for the region
- Current air pollution (PM2.5, O_3, NO_2, & CO)

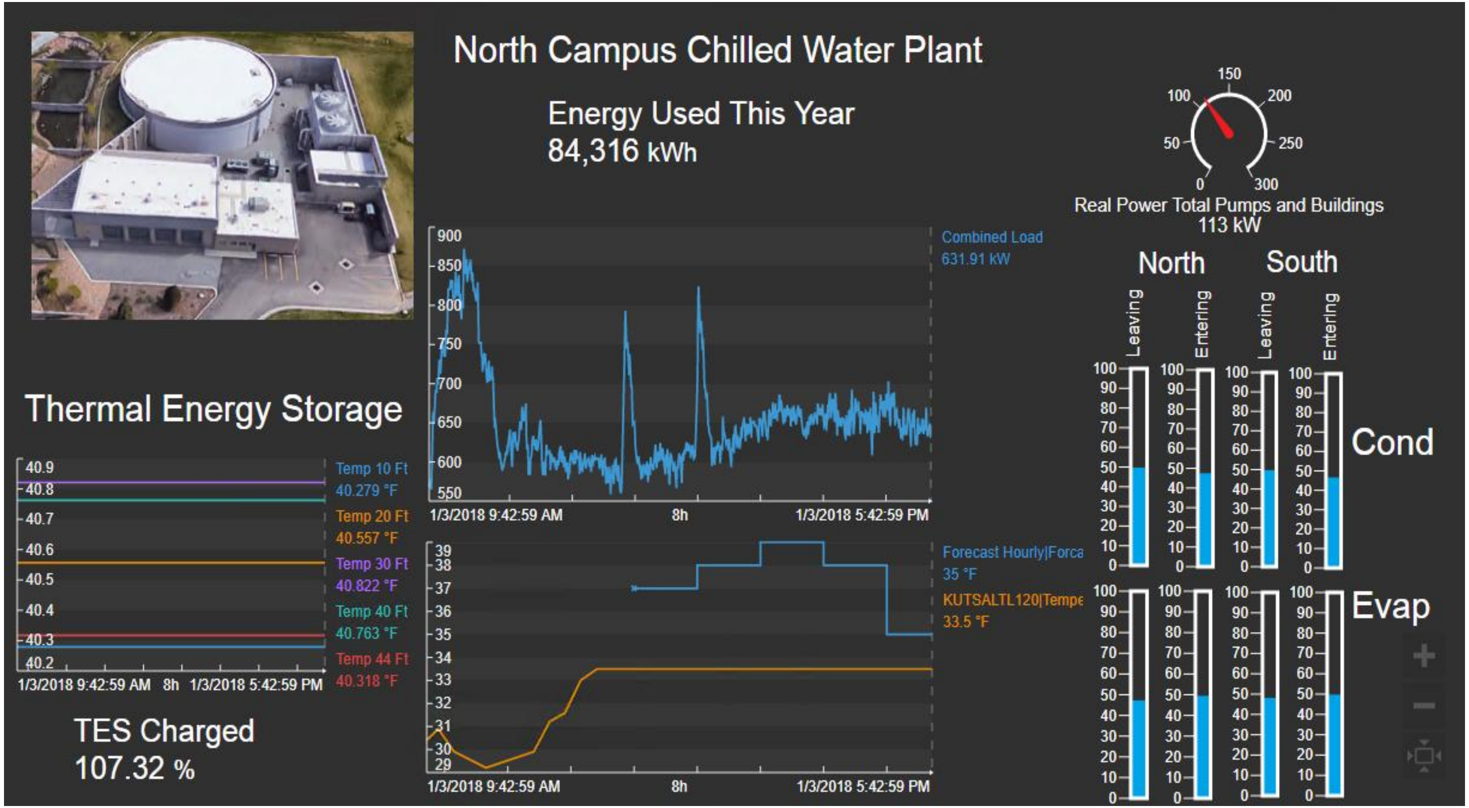
Building an Optimization Application around PI



Data Analytics – Visualizing EUI



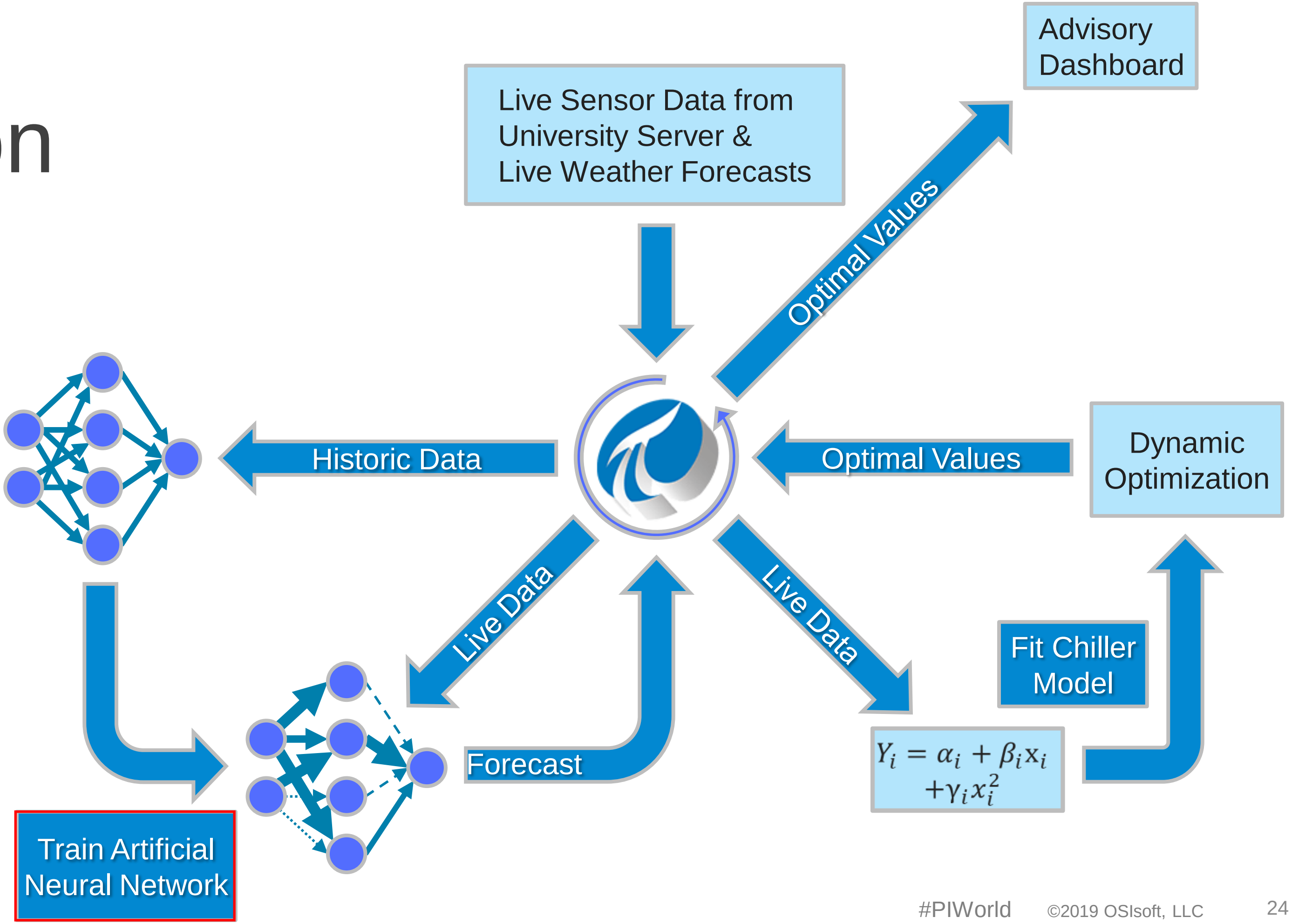
Data Analytics – Visualizing EUI



Analyses

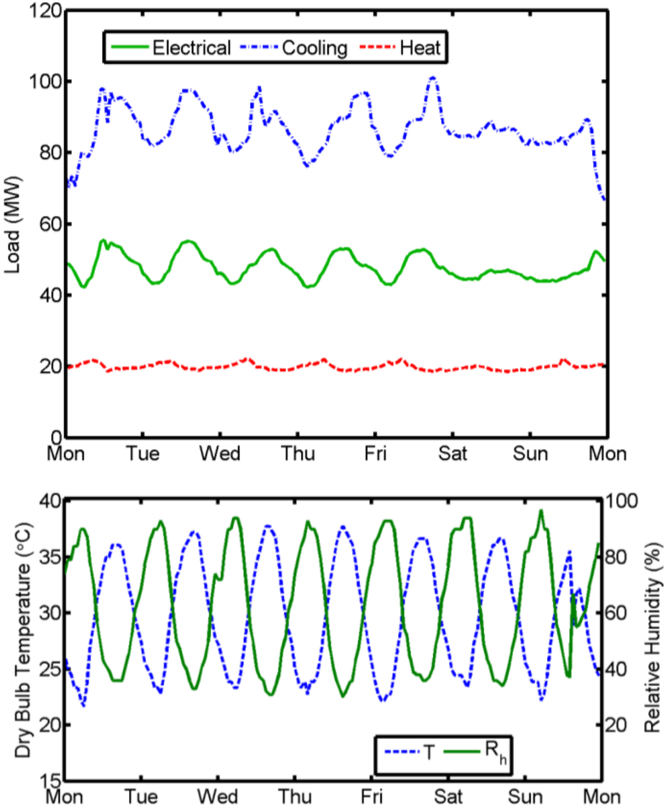
- PI System Analyses – simple
  EUI (Annual Rate)
  Heating Degree Days
  Energy Load
- Python Integration – complex
  Dynamic Load Forecasting

Building an Optimization Application around PI

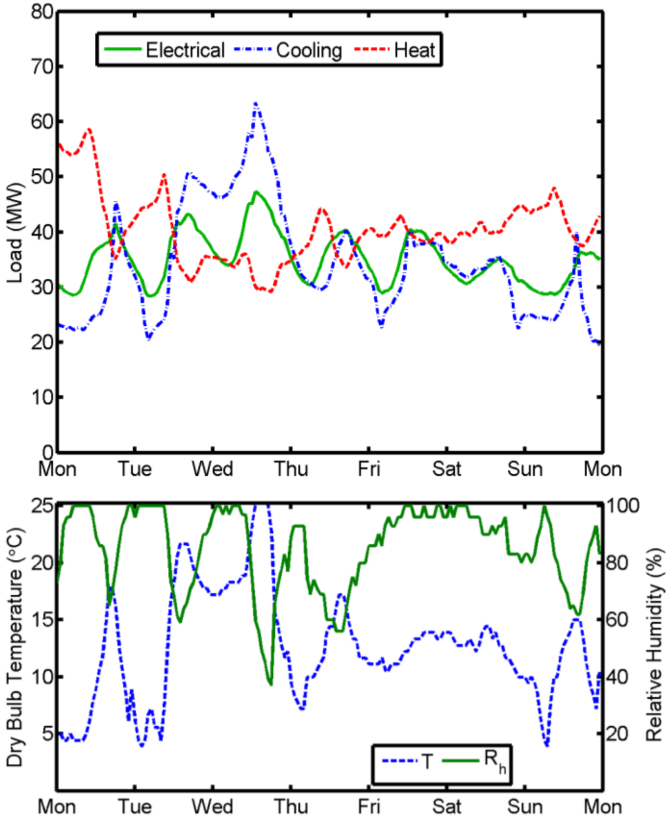


System Loads

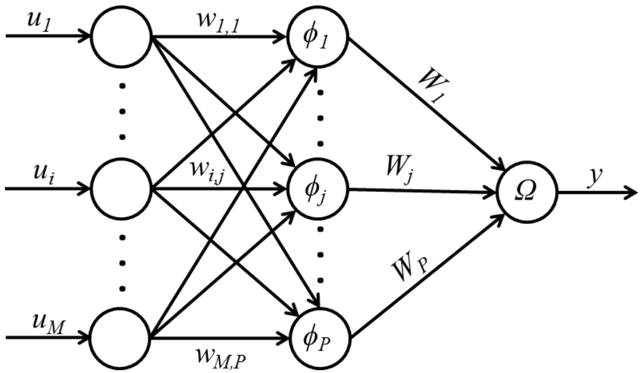
August

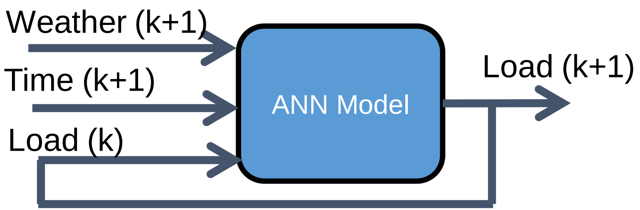


February



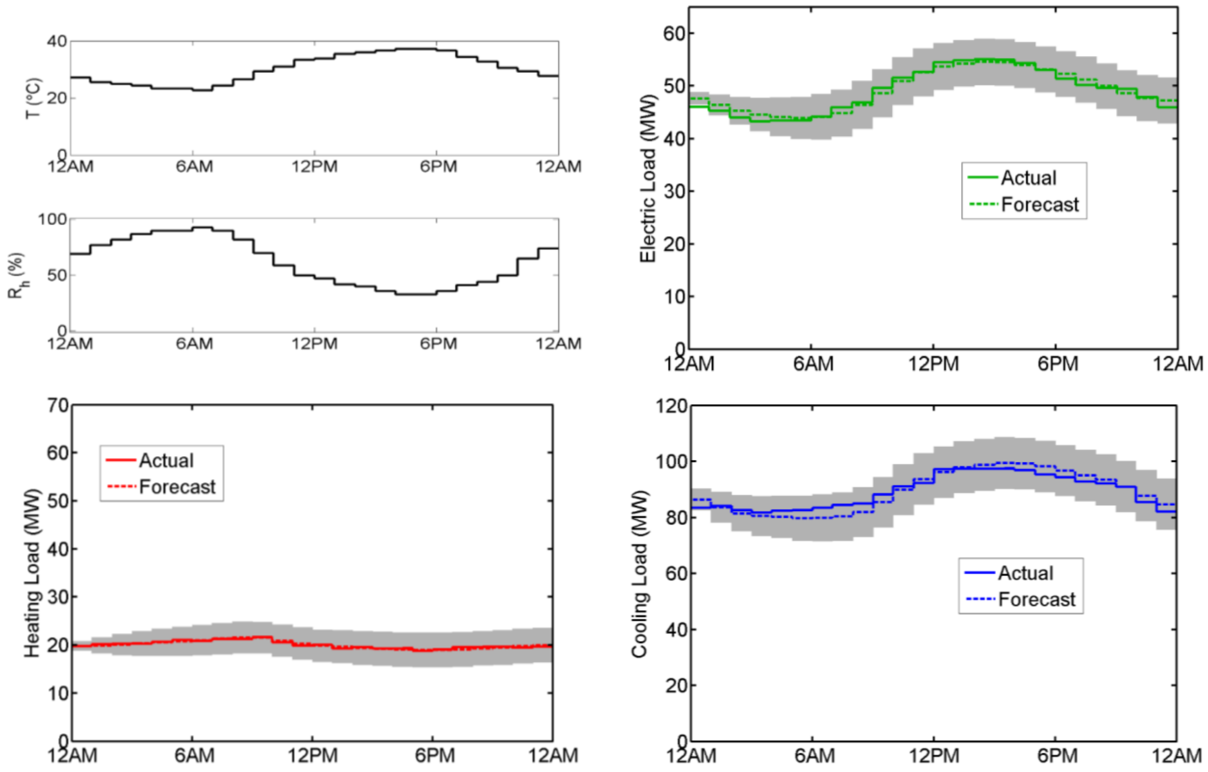
Using AI: Load Forecasting with Recurrent Neural Networks



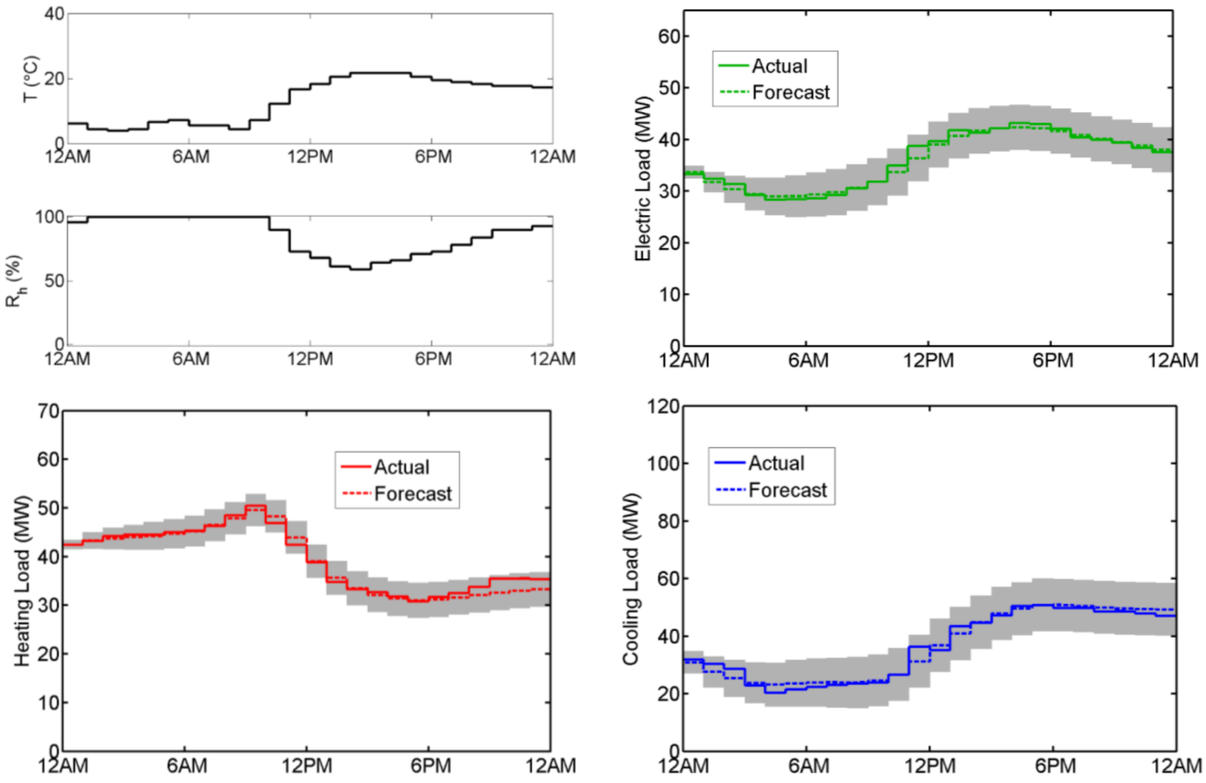


Adjusted R^2 values	Cooling	Heating	Electrical
Static Neural Network (weather only)	0.906	0.820	0.808
Static Neural Network (weather and time)	0.945	0.942	0.910
Linear ARX (weather only)	0.911	0.932	0.749
Linear ARX (weather and time)	0.936	0.948	0.850
NARX (weather only)	0.948	0.977	0.864
NARX (weather and time)	0.964	0.986	0.933

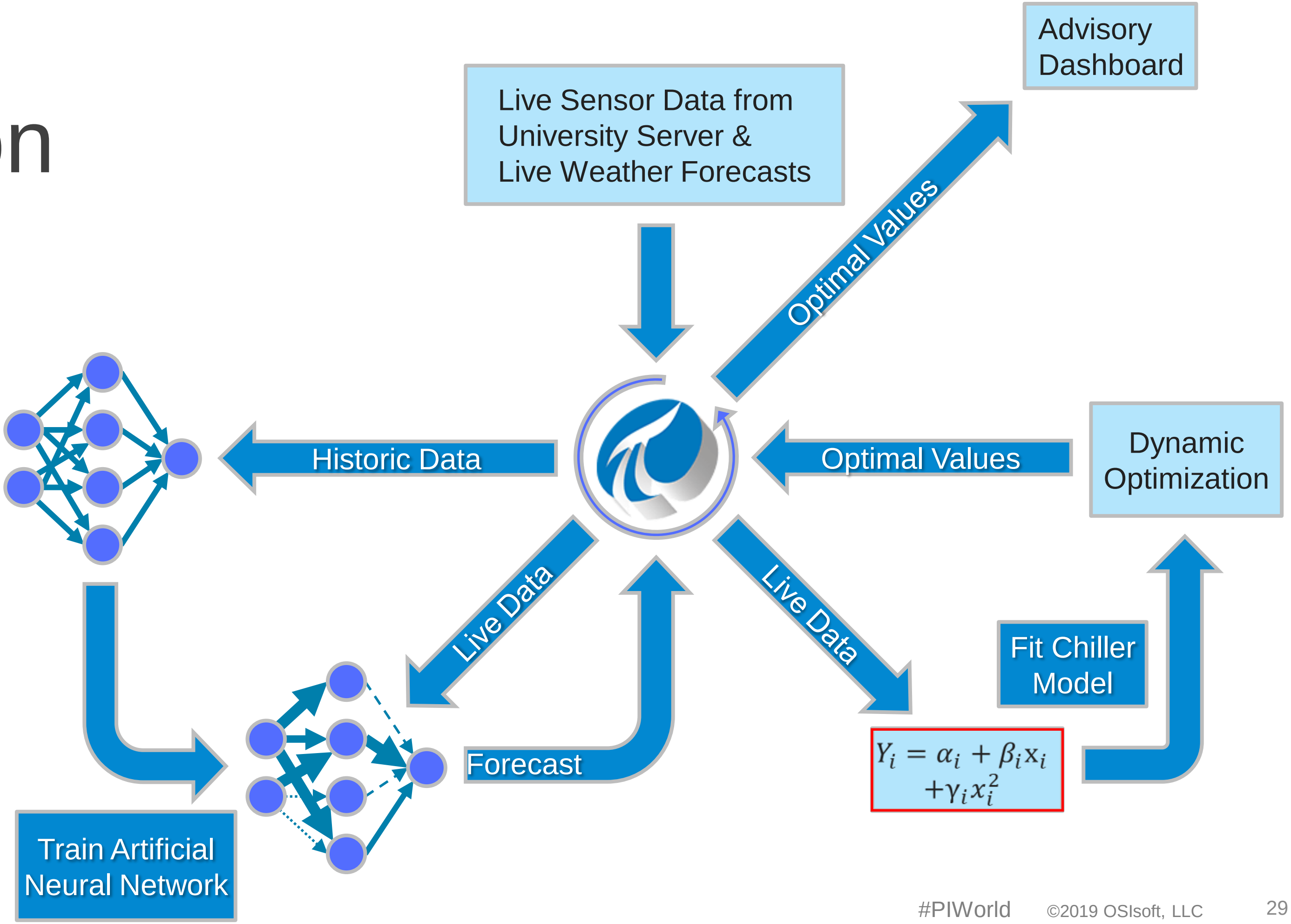
Forecast Results: August



Forecast Results: February

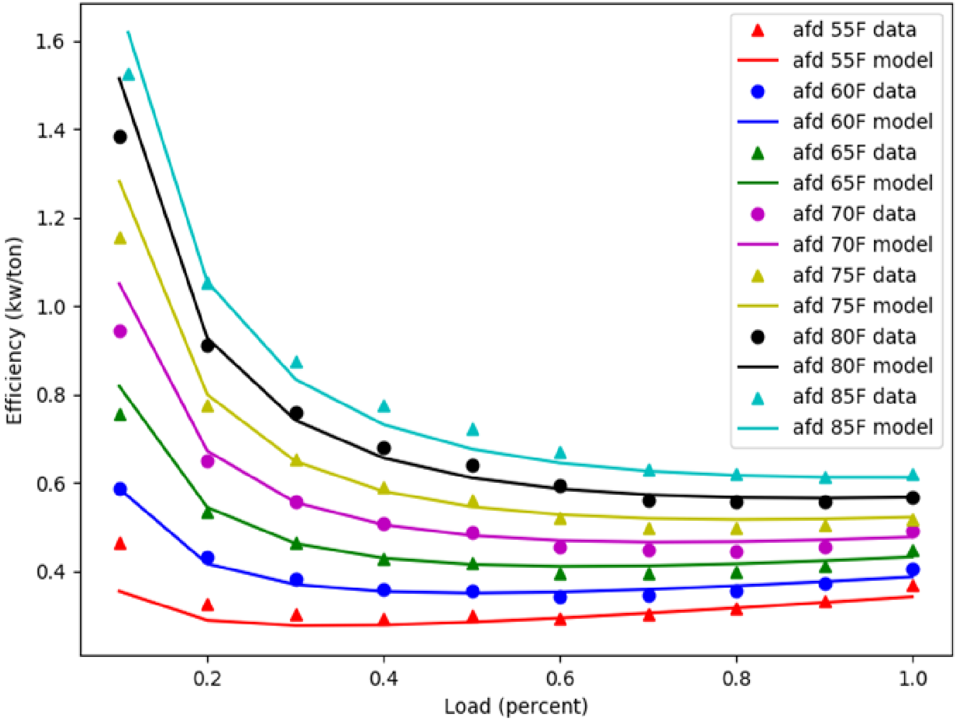


Building an Optimization Application around PI

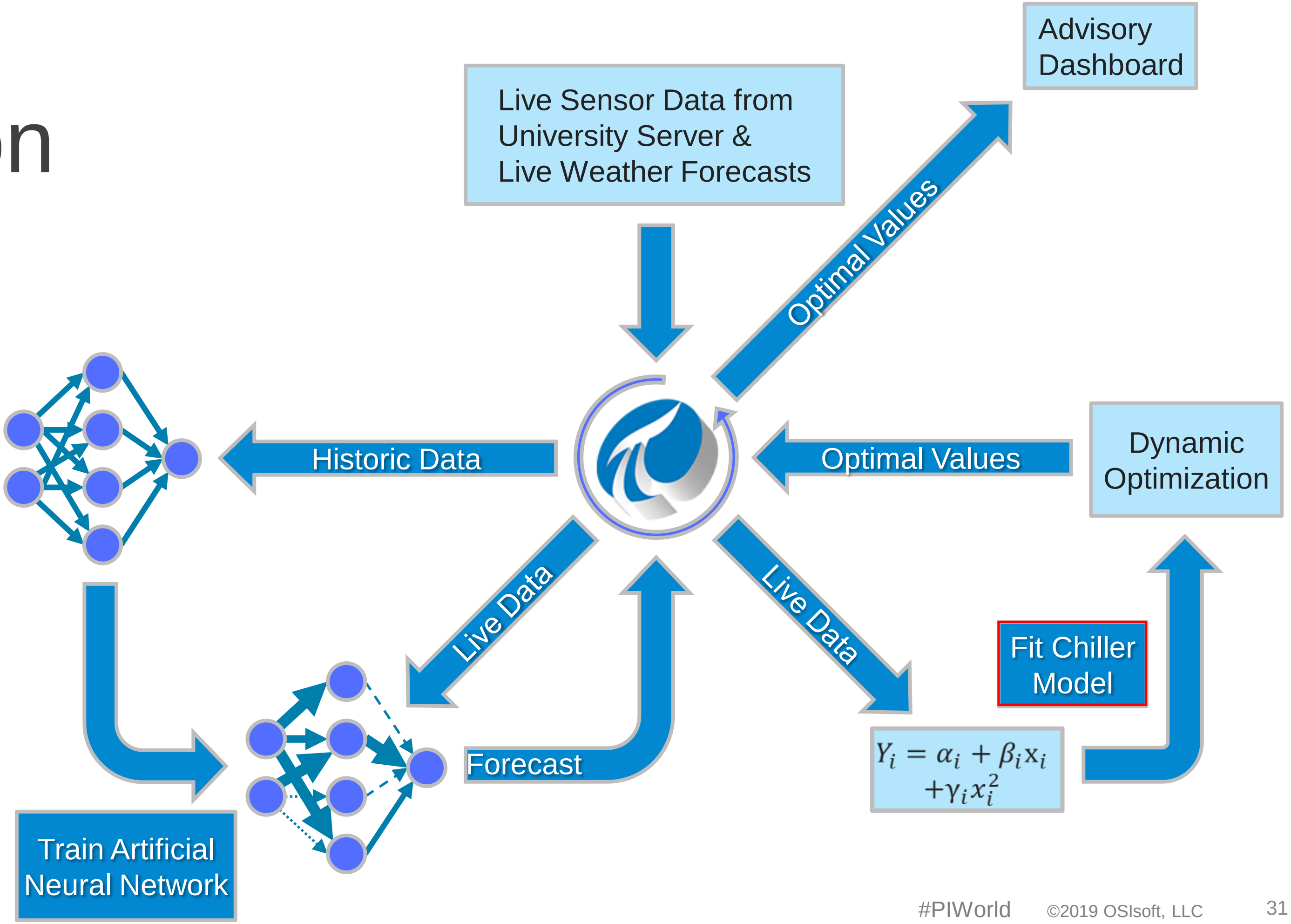


Modeling with Manufacturing Data

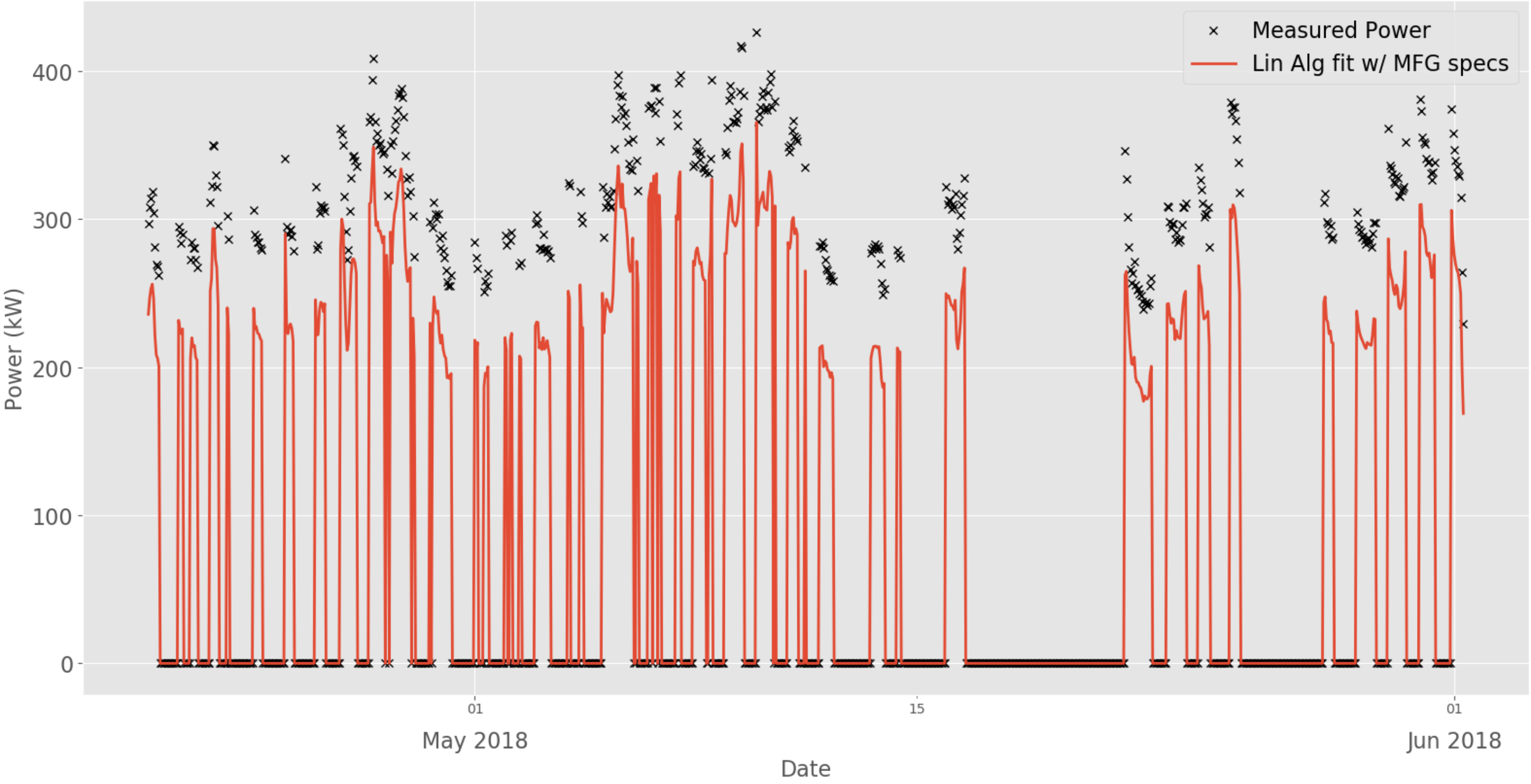
- Need to determine unknown parameters of chiller model generally
- Use data from manufacturer to fit chiller performance
- Put model in quadratic form to speed up optimization



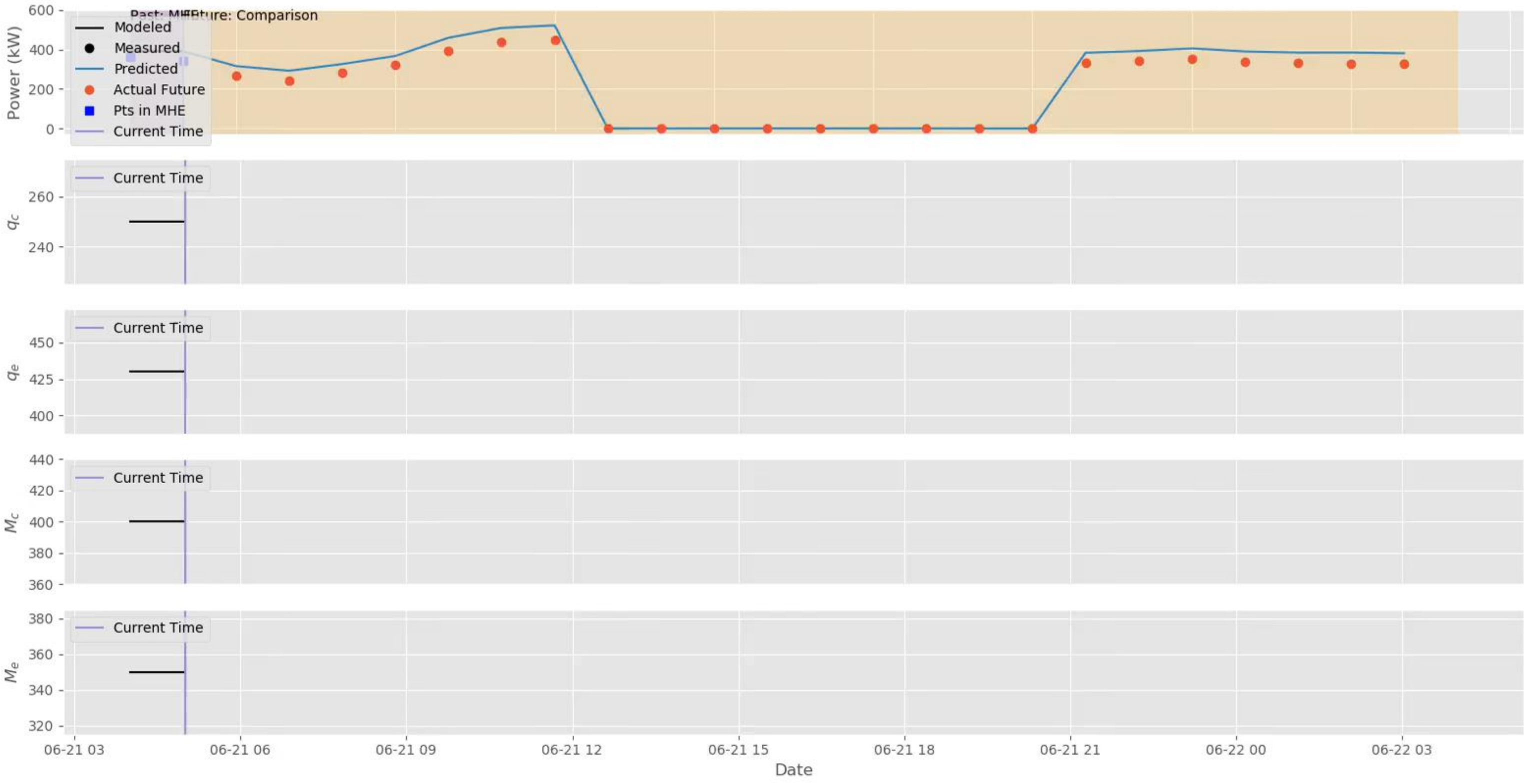
Building an Optimization Application around PI



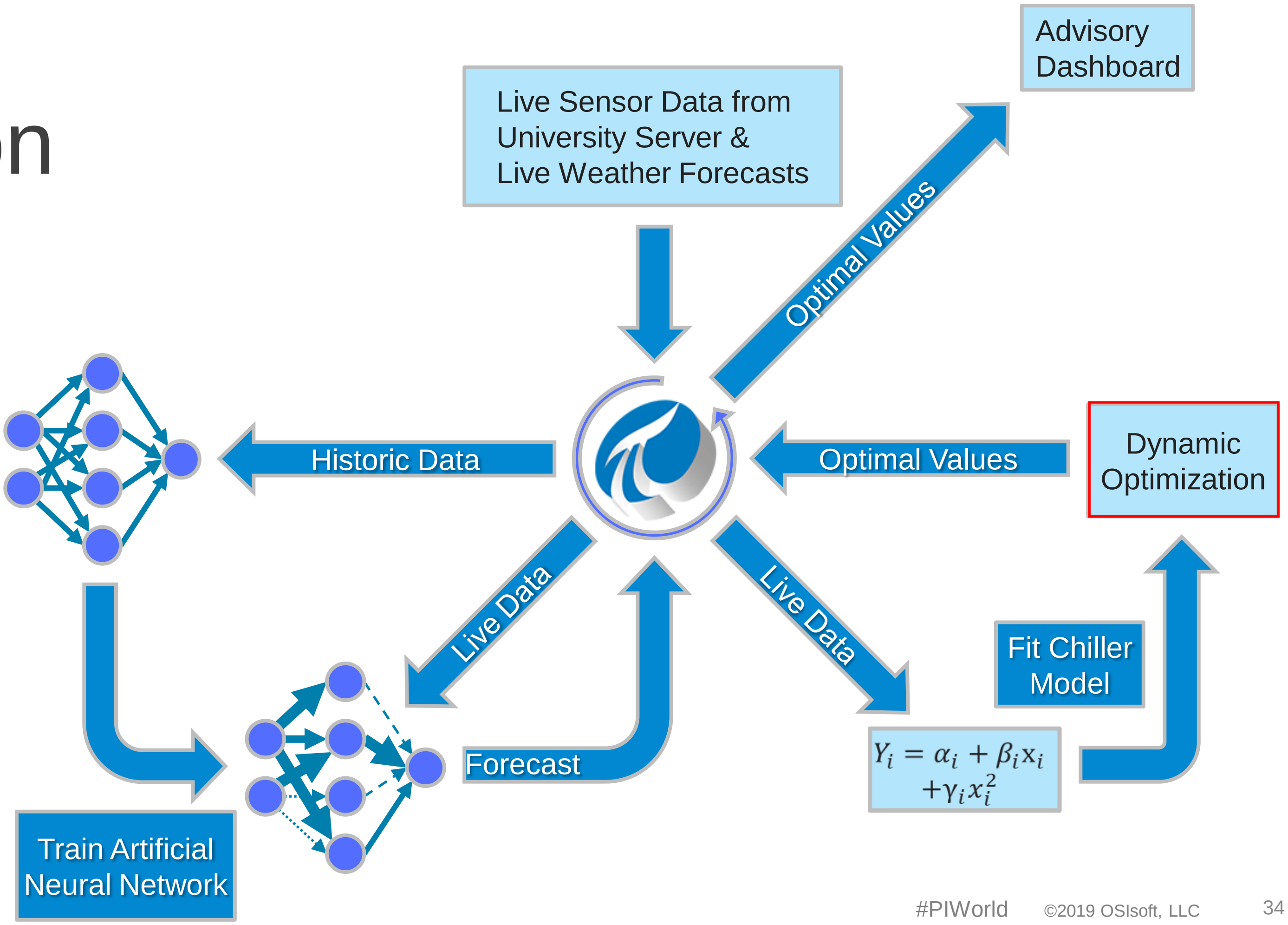
Comparing the Model to PI Data



Dynamic fitting with Moving Horizon Estimation

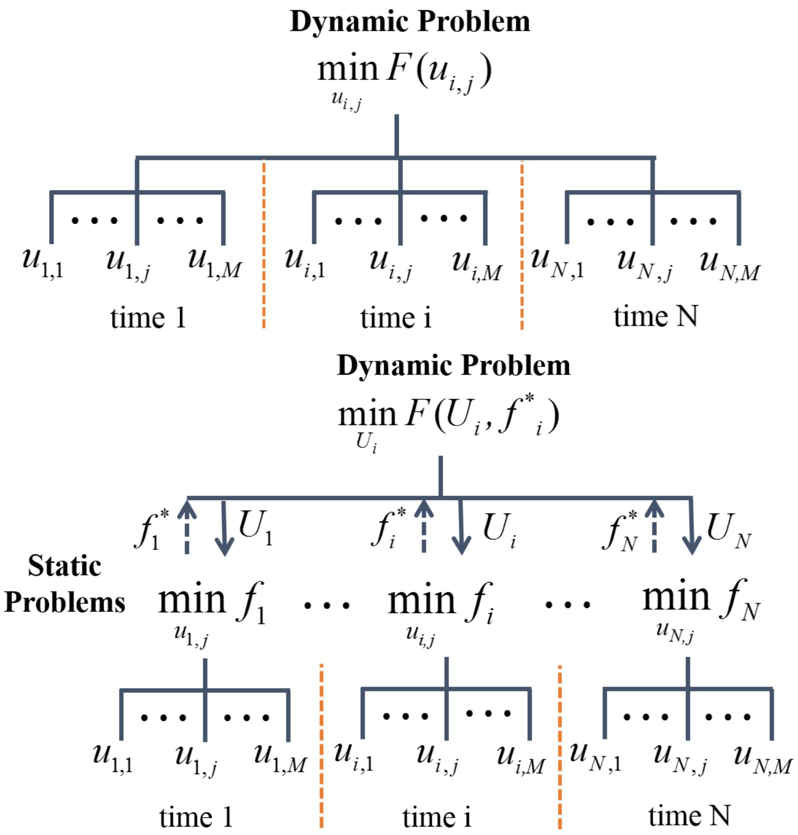


Building an Optimization Application around PI

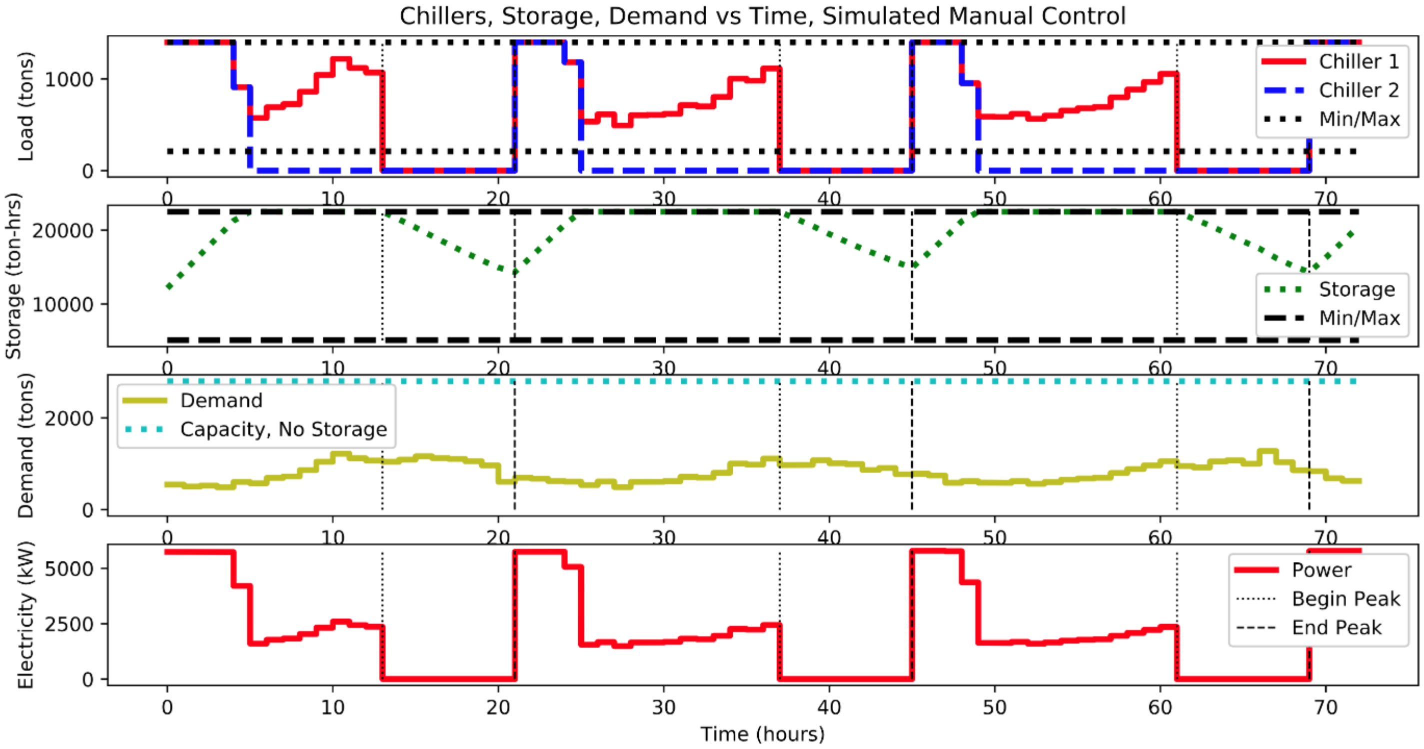


Dynamic Decoupling Approach

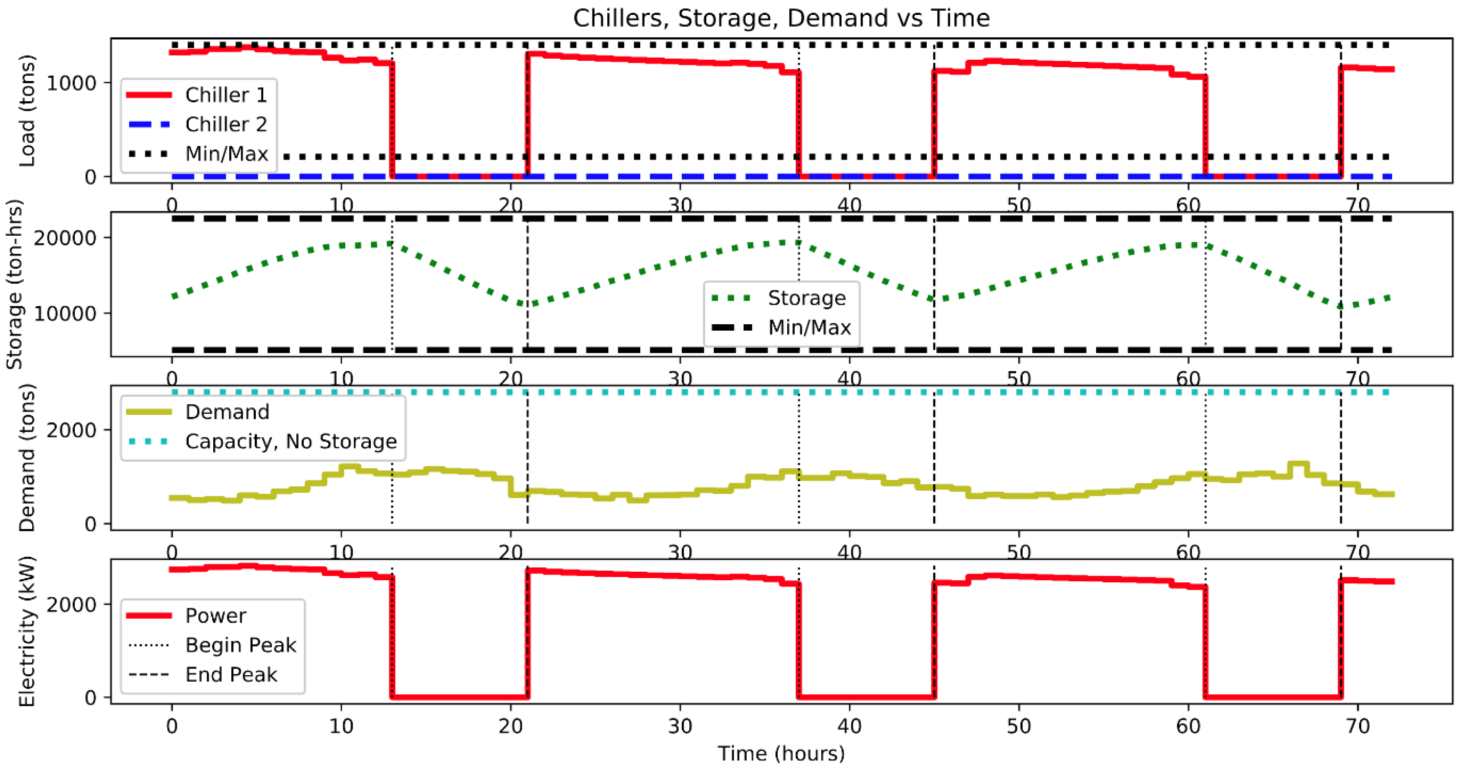
- Combinatorial complexity
- Dynamic problem "guesses" how much energy to store / extract
- Static problems report back
- Back and forth iteration until convergence
- Static problems – MINLPs with convex relaxations
- Static problem solved 1,000-5,000 times



Manual Operation



Dynamically Optimized Operation



Summary of Results

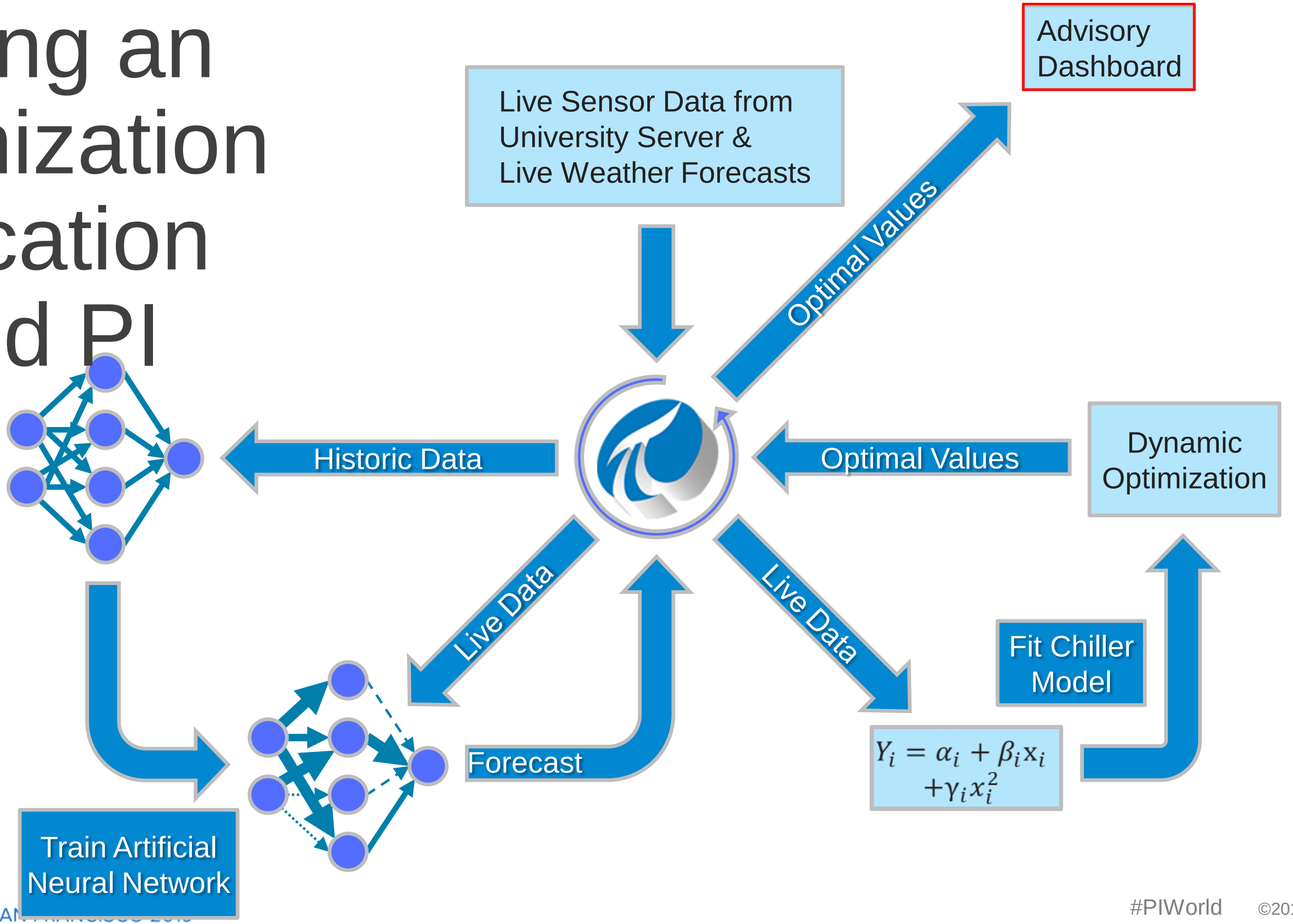
- Dynamic optimization algorithm *predicts* 16.5% cost savings
- Still need to close the loop
  - Make savings a reality

	QPHAC	Manual	BnB
4-h	$190.30 (0.150 s)	$246.68 (~ 0 s)	$165.53 (38 s)
8-h	$580.89 (0.150 s)	$632.11 (~ 0 s)	$557.20 (13 min)
12-h	$1248.68 (0.167 s)	$800.55* (~ 0 s)	$961.61 (24 min)
24-h	$871.63 (0.150 s)	$1314.80 (~ 0 s)	Did not converge†
72-h	$4257.48 (0.184 s)	$5097.72 (~ 0 s)	Did not converge†

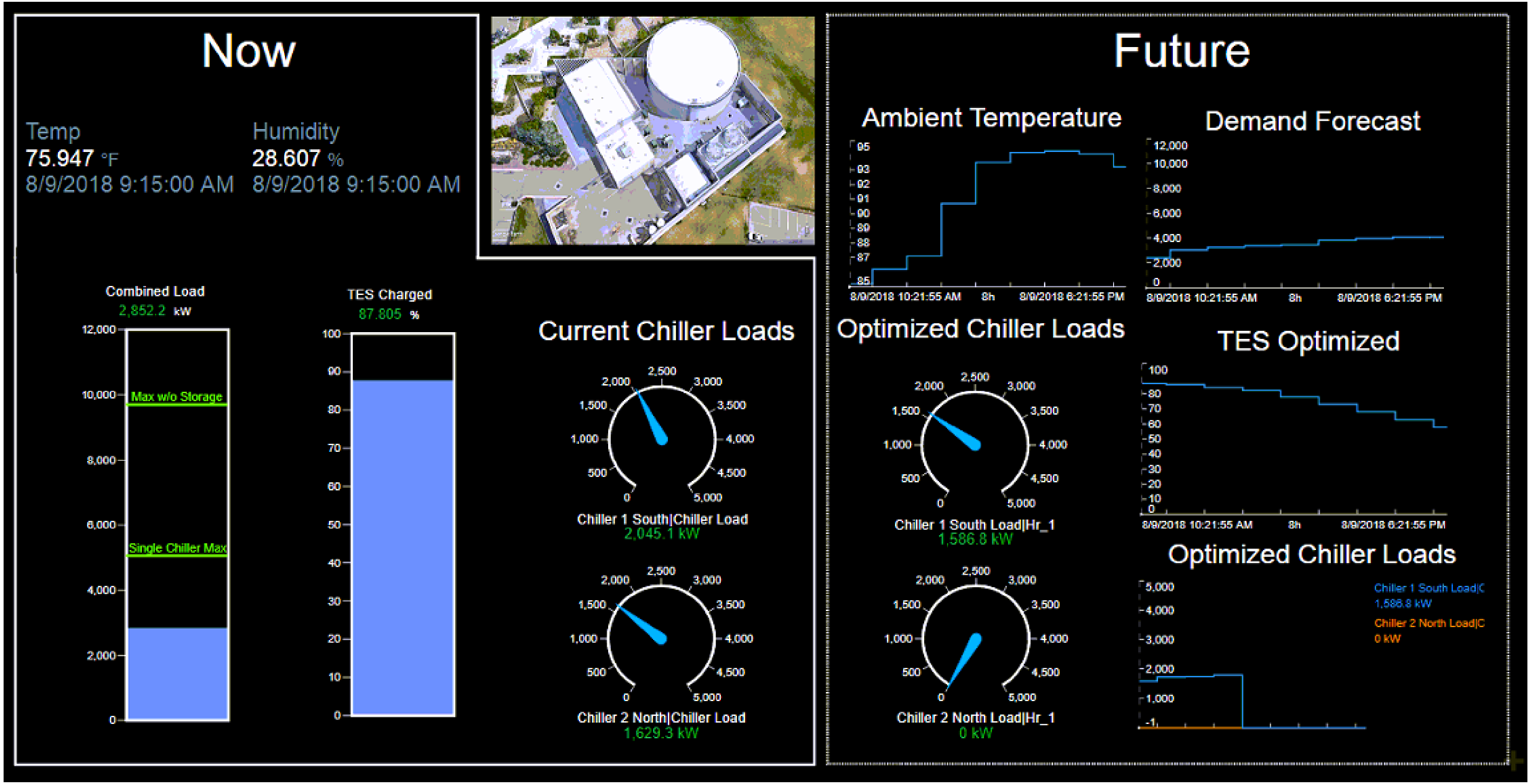
*The 12-h time window manual control was unable to achieve the starting energy storage

†The 24-h and 72-h BnB failed to converge after over 24 h of computation

Building an Optimization Application around PI



PI Vision Dashboard



Future Work

- More verification and validation
- Human-in-the-loop operation
  - Advisory mode using PI Vision
- Close the loop
- Stochastic + dynamic optimization
  - Account for model uncertainty using probabilistic methods

Next Steps:

- Nexus of ML and BI Analytics
  - Operationalize ML
- Educating next gen
  - Data infrastructure, analytics, computational intelligence, …

Acknowledgements

- OSISoft and John Matranga
- Utah office of Science Technology and Research (USTAR)
- Aaron Young, Landen Blackburn, Titus Quah
- University of Utah Facilities Management Group

謝謝 KEA LEBOHA

TAPADH LEIBH 고맙습니다

DZIĘKUJĘ CI

БАЯРЛАЛАА MISAOTRA ANAO

NGIYABONGA

GRÀCIES

SALAMAT

OBRIGADO شكرا

TEŞEKKÜR EDERIM

DANKIE TERIMA KASIH DANKON TANK TAPADH LEAT

KÖSZÖNÖM

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GO RAIBH MAITH AGAT

MAHADSANID

HVALA ХВАЛА ВАМ

БЛАГОДАРЯ GRACIAS

THANK YOU

TEŞEKKÜR EDERIM

ТИ БЛАГОДАРАМ

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DI OU MÈSI

RAHMAT MERCI

GRAZZI ÞAKKA ÞÉR ありがとうございました

FALEMINDERIT

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MATUR NUWUN

CẢM ƠN BẠN UA TSAUG RAU KOJ

WAZVIITA ТИ БЛАГОДАРАМ

СИПОС

Appendix Slides

Modeling the Chillers

First Principles Model of a Chiller by Gordon, Ng, and Chua:

$$P = \frac{Q}{\mathrm{COP}} = -Q + \left(\frac{T_c^{\mathrm{in}}}{T_e^{\mathrm{out}}}\right) Q + \left(\frac{q_e T_c^{\mathrm{in}}}{T_e^{\mathrm{out}}} - q_c\right) + \left(\frac{q_e}{M_c T_e^{\mathrm{out}}}\right) \left(\frac{q_e T_c^{\mathrm{in}}}{T_e^{\mathrm{out}}} - q_c\right) + \left(\frac{Q^2}{T_e^{\mathrm{out}}}\right) \left(\frac{T_c^{\mathrm{in}}}{T_e^{\mathrm{out}}}\right) \left(\frac{1}{M_c} + \frac{1}{M_e}\right)$$
$$+ Q \frac{\frac{q_c}{M_e} + \frac{q_e T_c^{\mathrm{in}}}{T_e^{\mathrm{out}} M_c} + \left(\frac{T_c^{\mathrm{in}} q_e}{T_e^{\mathrm{out}}} - q_c\right)\left(\frac{1}{M_c} + \frac{1}{M_e}\right)}{T_e^{\mathrm{out}}}$$

Gordon, J. M., Ng, K. C., & Chua, H. T. (1995). Centrifugal chillers: thermodynamic modelling and a diagnostic case study. International Journal of refrigeration, 18(4), 253-257.

Modeling the Chillers

First Principles Model of a Chiller by Gordon, Ng, and Chua:

$$P = \frac{Q}{COP} = -Q - \left(\frac{T_c^{in}}{T_e^{out}}\right) Q - \left(\frac{q_e T_c^{in}}{T_e^{out}} - q_c\right) + \left(\frac{q_e}{M_c T_e^{out}}\right)\left(\frac{q_e T_c^{in}}{T_e^{out}} - q_c\right) + \left(\frac{Q^2}{T_e^{out}}\right)\left(\frac{T_c^{in}}{T_e^{out}}\right)\left(\frac{1}{M_c} + \frac{1}{M_e}\right)$$
$$+ Q \frac{\frac{q_c}{M_e} + \frac{q_e T_c^{in}}{T_e^{out} M_c} + \left(\frac{T_c^{in} q_e}{T_e^{out}} - q_c\right)\left(\frac{1}{M_c} + \frac{1}{M_e}\right)}{T_e^{out}}$$

Gordon, J. M., Ng, K. C., & Chua, H. T. (1995). Centrifugal chillers: thermodynamic modelling and a diagnostic case study. International Journal of refrigeration, 18(4), 253-257.

Optimization Problem Formulation

- Objective: Minimize total cost

$$\min_{u_i} F = \sum_i \left[C_f \left(W_{f,GT,i} + W_{f,\mathrm{HRSG},i} + W_{f,\mathrm{BR},i} \right) - C_{e,i} P_{net,i} \right] (\Delta t)$$

- Decision variables

$$u_i = \left[Q_{3.1} \cdots Q_{6.3}\ \delta_{3.1} \cdots \delta_{6.3}\ Q_{TIC}\ \theta_{IGV}\ W_{f,GT}\ W_{f,\mathrm{HRSG}}\ W_{f,\mathrm{BR}}\ W_{s,EXT}\ P_{net} \right]^T$$

- Load constraints

$$P_{GT,i} + P_{ST,i} - P_{net,i} \geq L_{E,campus,i} + \sum P_{ch,i} + \sum P_{aux,i}$$

$$\sum_j Q_{i,j} - Q_{TES,i} \geq L_{C,i} + Q_{TIC,i}$$

$$W_{S,\mathrm{EXT,i}} \geq L_{H,i}$$

Assumptions

- One-hour time intervals
- Steady-state models for all generation equipment
  - Max settling time ~ 15 minutes
- 24-hour time horizon
  - Storage capacity ~ 2-6 hours full load
- Discrete dynamics for storage

$$E_{TES,i} = E_{TES,i\text{-}1} + \left(Q_{TES,i} - E_{loss,i}\right)\Delta t$$

$$Q_{TES,i} = \sum_{j} Q_{i,j} - \left(L_{C,i} + Q_{TIC,i}\right)$$

Dynamic Optimization Problem Summary

- Mixed-integer Nonlinear Program (MINLP)
- 600 decision variables
- 216 binary constraints

$$\delta_j \in [0,1]$$

$$\delta_j Q_{j,\mathrm{lo}} \le Q_j \le \delta_j Q_{j,\mathrm{hi}}$$

- Original Approach: Full MINLP solved using BONMIN solver
  - 27-hour solve time (2.5 GHz processor)
  - Curse of dimensionality
  - Equipment chatter

Data Management Spring 2019

Objective

- Business rules
- Data characterization
- Data visualization

OSIsoft Resources:
YouTube Videos
Regional Seminars
AF Public Library
Templates
Tech Support
OSI mentors
…

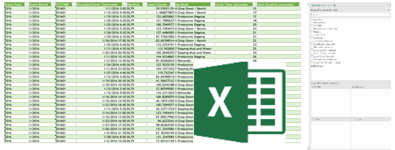
Data

- Fleet events and cycles
- Crush plant
- Equipment health

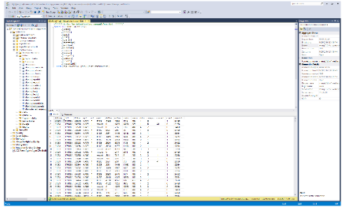
Students

- Mining, chemical, graduate, undergraduate
- Expand disciplines in future courses

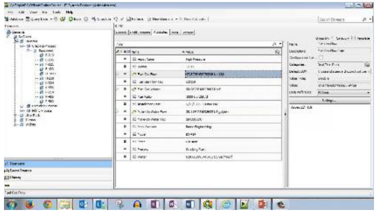
Connecting engineering and operational standards to business rules



Excel tables & pivot



SQL tables & views

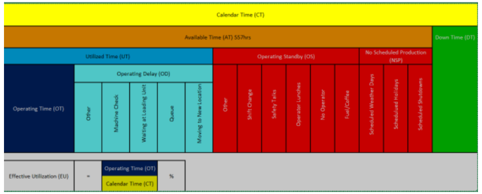


PI AF / Event Frames

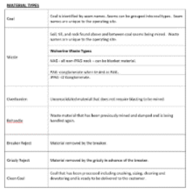
Business rules to engineering standards

Business rules to engineering standards

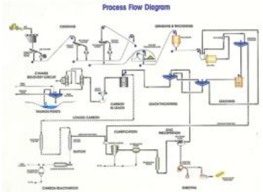
Business rules to engineering & operational standards



Time Usage Model

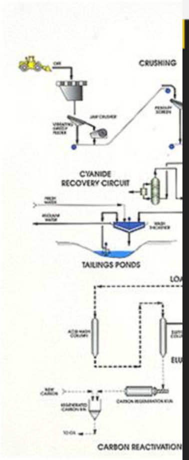


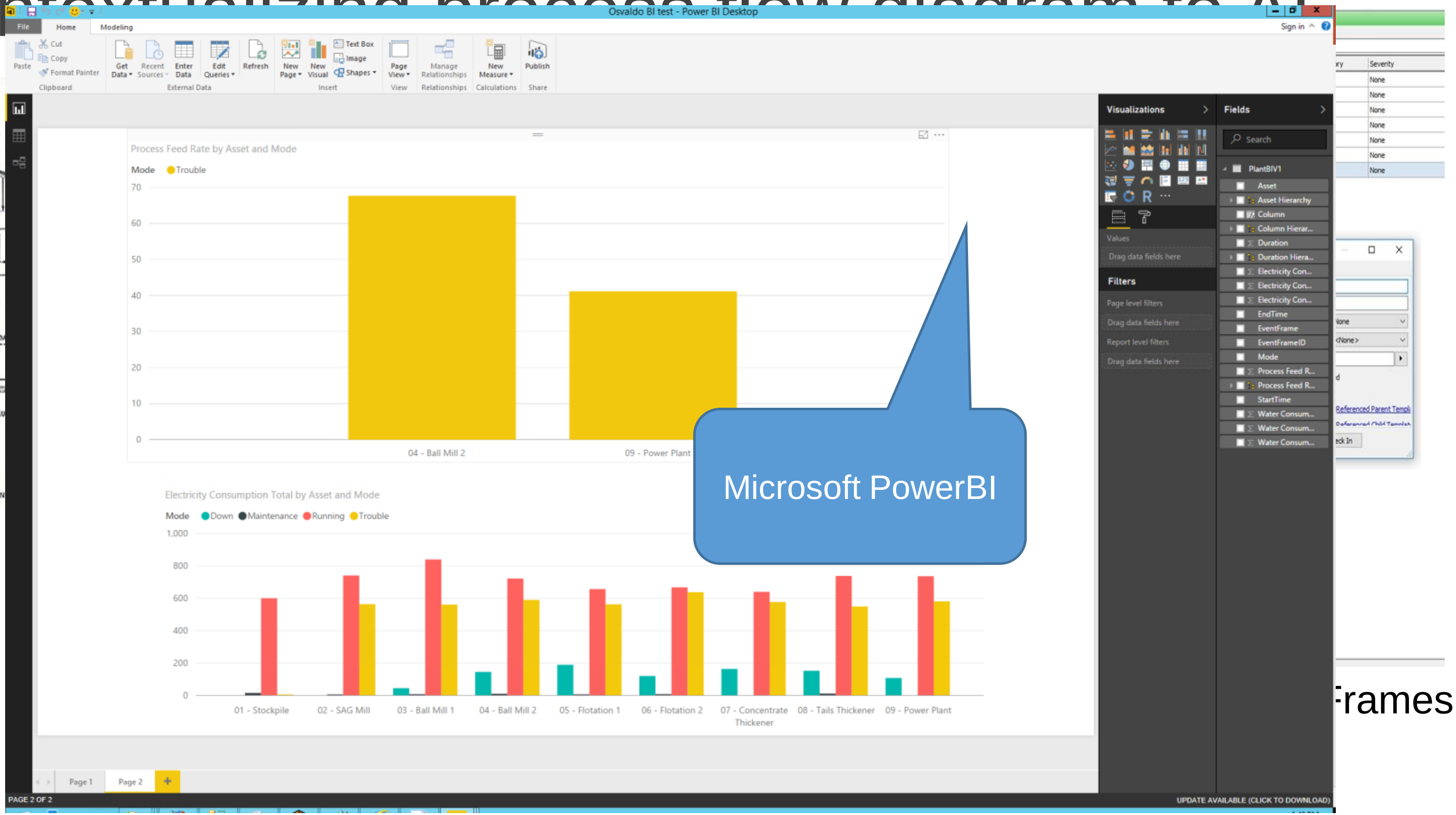
Material Hierarchy



Process Flow Diagram

Contextualizing process flow diagram to AF





Frames

Initial lessons learned

- Introduce concepts gradually
  - I do, we do, you do approach
- Infrastructure always a challenge
- Business rules first, visualization second
  - Visualizations important business rules foundational
- Students are enjoying it!