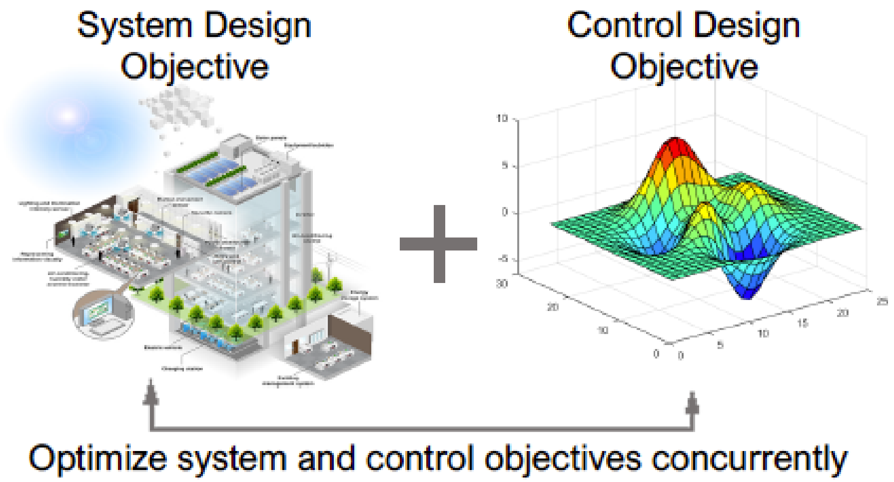
Co-Design of HVAC Systems and Controls for Energy-Flexible Buildings



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Presenter: Arnab Bhattacharya

Project Summary

Timeline

Start date: 10/01/2019

Planned end date: 09/30/2021

Key Milestones

- ✓ Document current design practice for building HVAC and control retrofit (met 12/2019)
- ✓ Develop and implement scalable co-design optimization methodology under uncertainty (met 12/2020)
- ✓ Implement and demonstrate co-design optimization methodology for the integrated system (met 06/2021)

Budget

Total Project $: 700K

- DOE: $700K
- Cost Share: $0

Key Partners

Paul Ehrlich, Building Intelligence Group

Project Outcomes

1. Scalable co-design framework and methodology for integrated building HVAC systems and onsite energy assets
2. Templating higher-fidelity system level models for design optimization
3. Demonstrated co-design benefits for chiller plant and community energy system use-cases

Team

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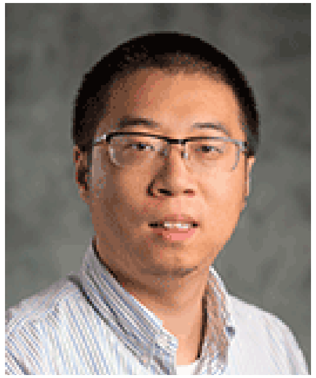

Sen Huang

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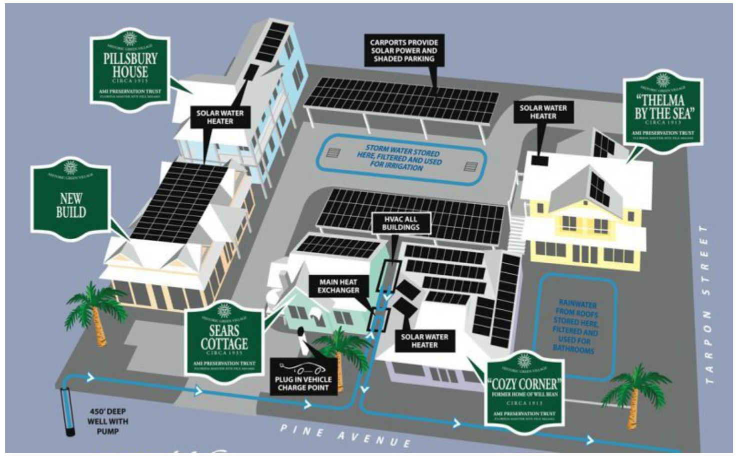
Paul Ehrlich

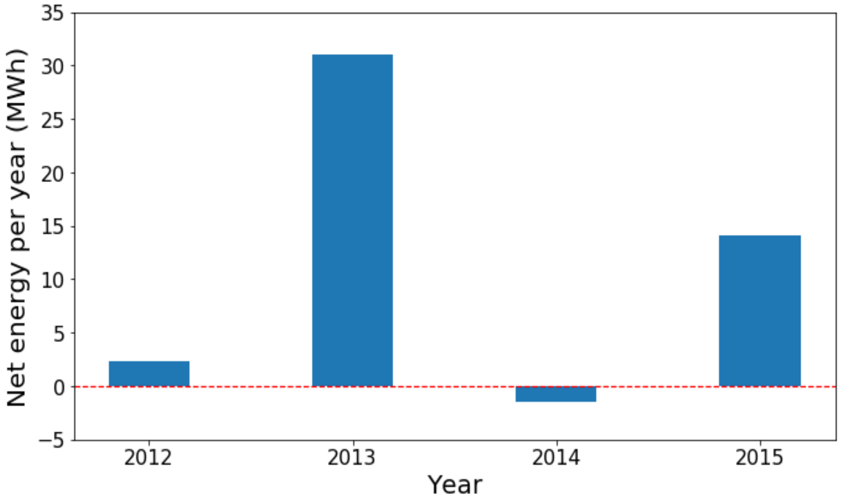
Current Design Practice and Challenges

- Current HVAC design practice is sequential or iterative at best
- Modeling step is often skipped; when done it is primarily for equipment sizing
- Little effort given to control design
- Sub-optimal system designs and increased up-front costs (e.g., over-sized equipment, post-deployment changes)

Historic Green Village: Mixed-Use Community in Florida



Commissioned 2012 and achieved net-zero in 2014 after post-deployment PV additions



Current design practice

Requirements

↓

Limited Model Development

↓

System and Equipment Selection

↓

Control Design

↓

Complete Design Documents

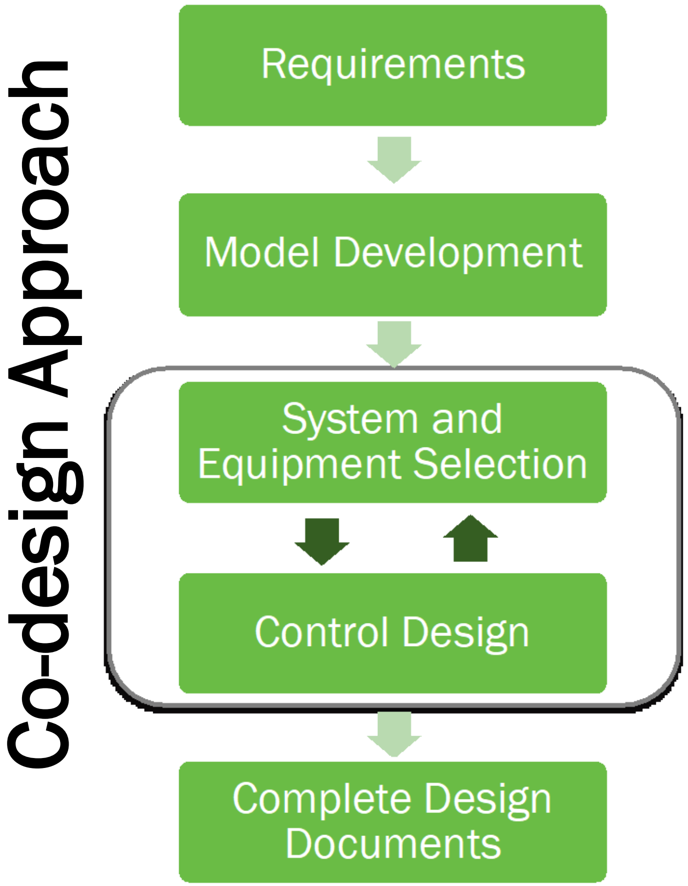
Challenges and Opportunities

- Buildings are becoming more complex; integrated building systems with significant intersystem couplings that are less understood
- Increased need to design and operate buildings for multiple objectives e.g., thermal comfort, energy efficiency, energy decarbonization, demand flexibility in support of grid operation and building resilience
- Limited tools for incorporating and evaluating control options early in the project design cycle

Approach: Co-design

Survey questionnaire and telephone interview with building research and industry experts

- Interviewees agree on the control co-design potential to realize added value.
- Unified agreement on the need to quantify co-design benefits

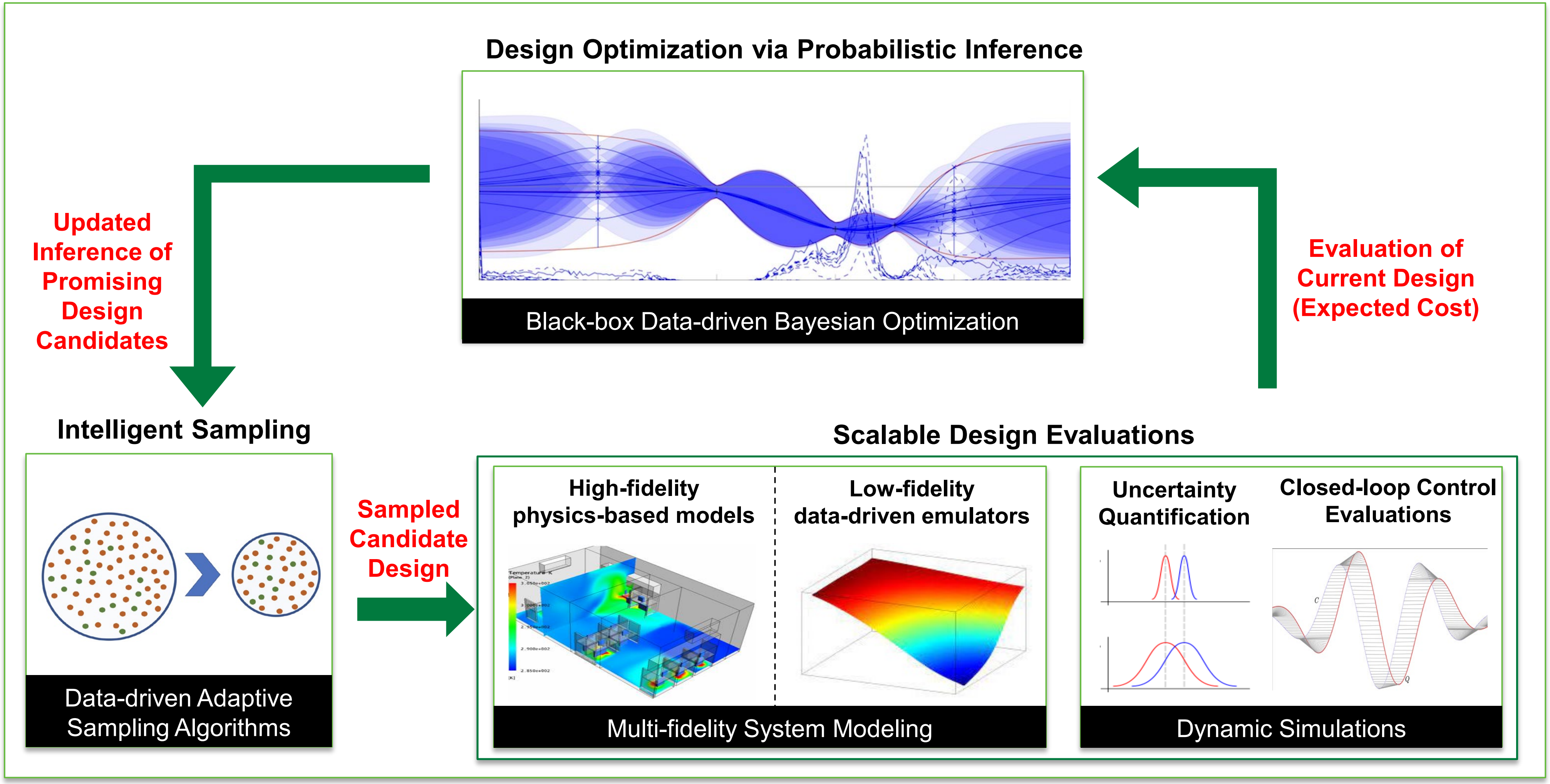


Features to Enhance Scalability and Accuracy of Codesign

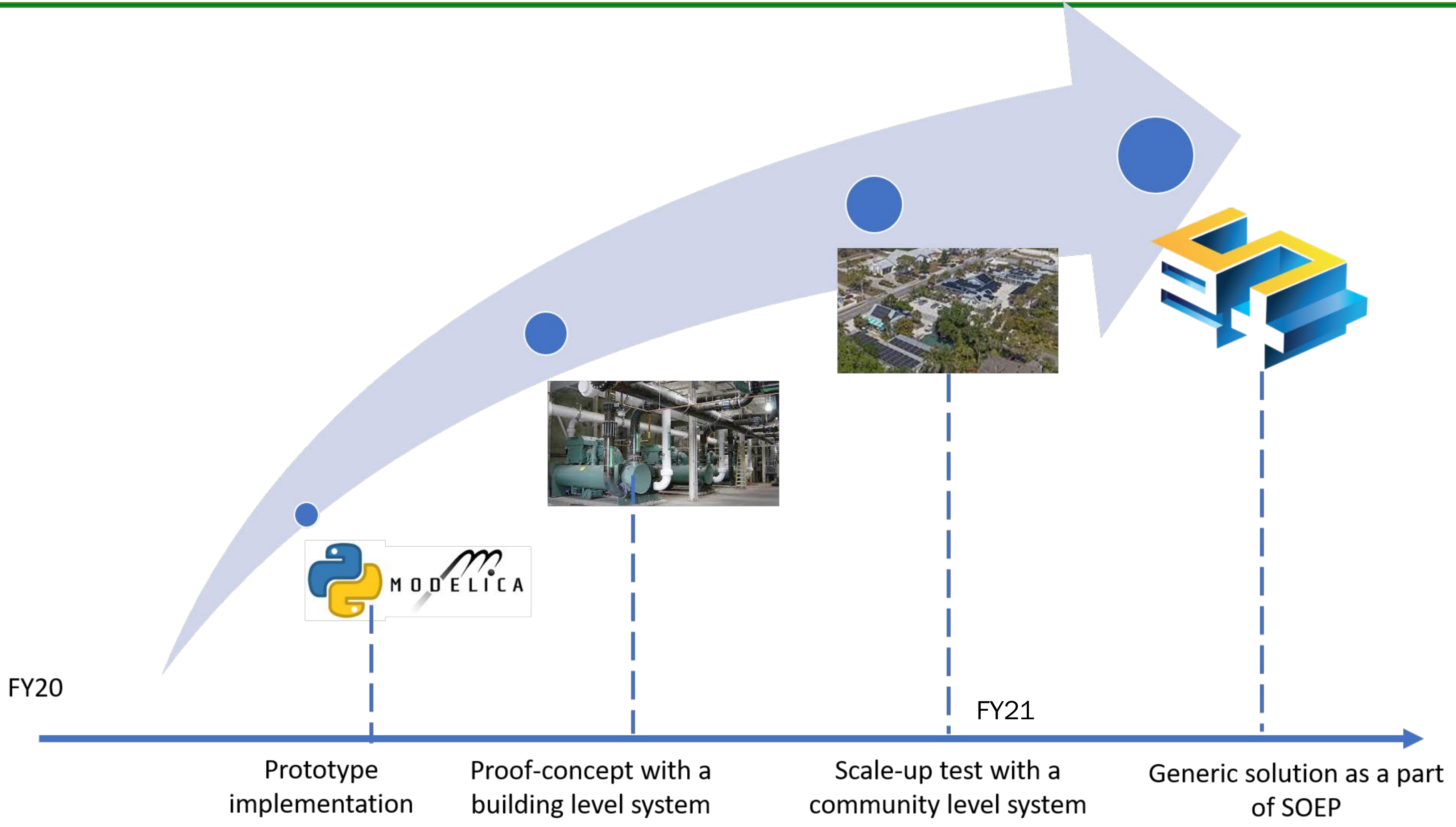
Approach	Description
Multi-fidelity models	Effectively utilize data and models of varying fidelity. Leverage complementary research efforts (e.g., BEM - Spawn of E+, Control specifications and sequences – Guidelines 13/36)
Simulation-based Bayesian Optimization	Machine-learning-based optimization, no analytical models required, intelligent sampling
Uncertainty quantification and integration	Expand beyond typical design days, Incorporate uncertainties in modeling and exogeneous inputs, and validation over annual operational scenarios,

Approach : Iterative Framework and Elements

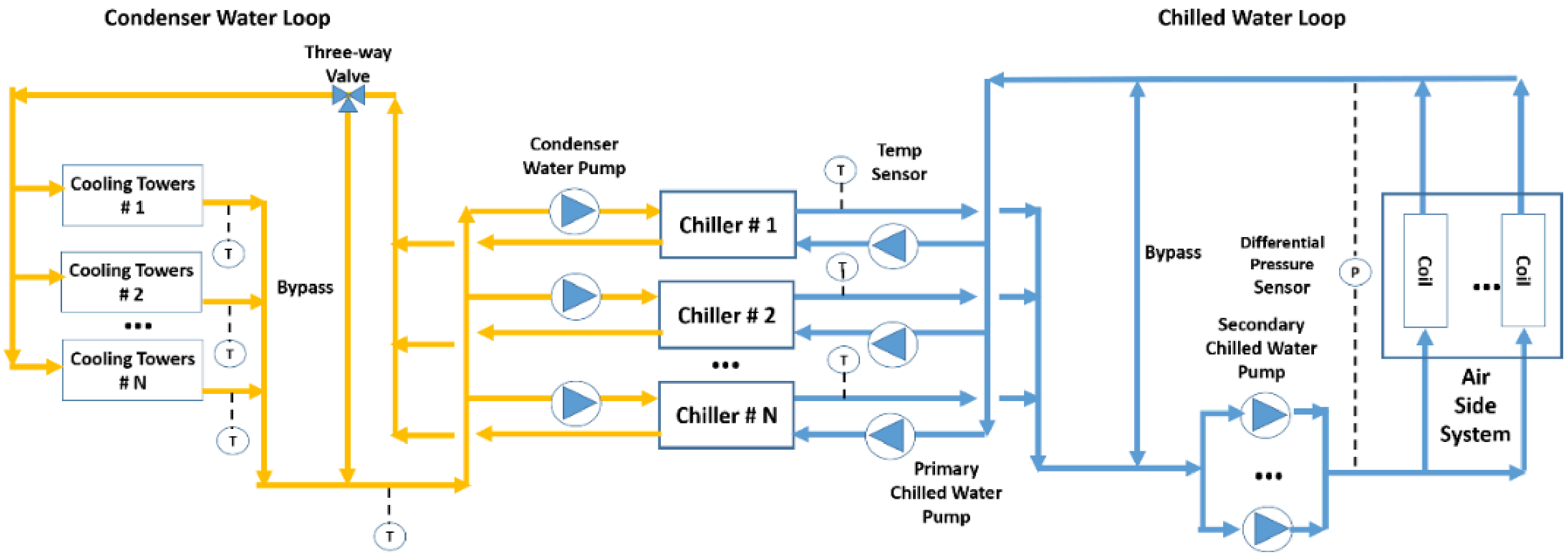
Automated machine learning-based co-design framework leveraging advances in multi-fidelity methods, sampling, and probabilistic surrogate models to identify high-quality designs without any “human-in-the-loop”



Progress: Flexible Modeling



Progress: Chilled Water Plant Retrofit Use-Case



- ➢ Flexible high fidelity chiller plant model
- ➢ Combination of chillers with different sizes and functionalities
- ➢ Co-simulation between EnergyPlus and Modelica

Design objective

- Minimize chiller capital cost, energy and operational cost, peak-power demand and penalty cost for cooling demand violation, over a set of representative design days

Design variables

- System design: number of chillers in the plant and capacity of each chiller
- Control design: chiller staging and sequencing - switching (on/off) temperature thresholds

Progress: Chilled Water Plant Co-design Results

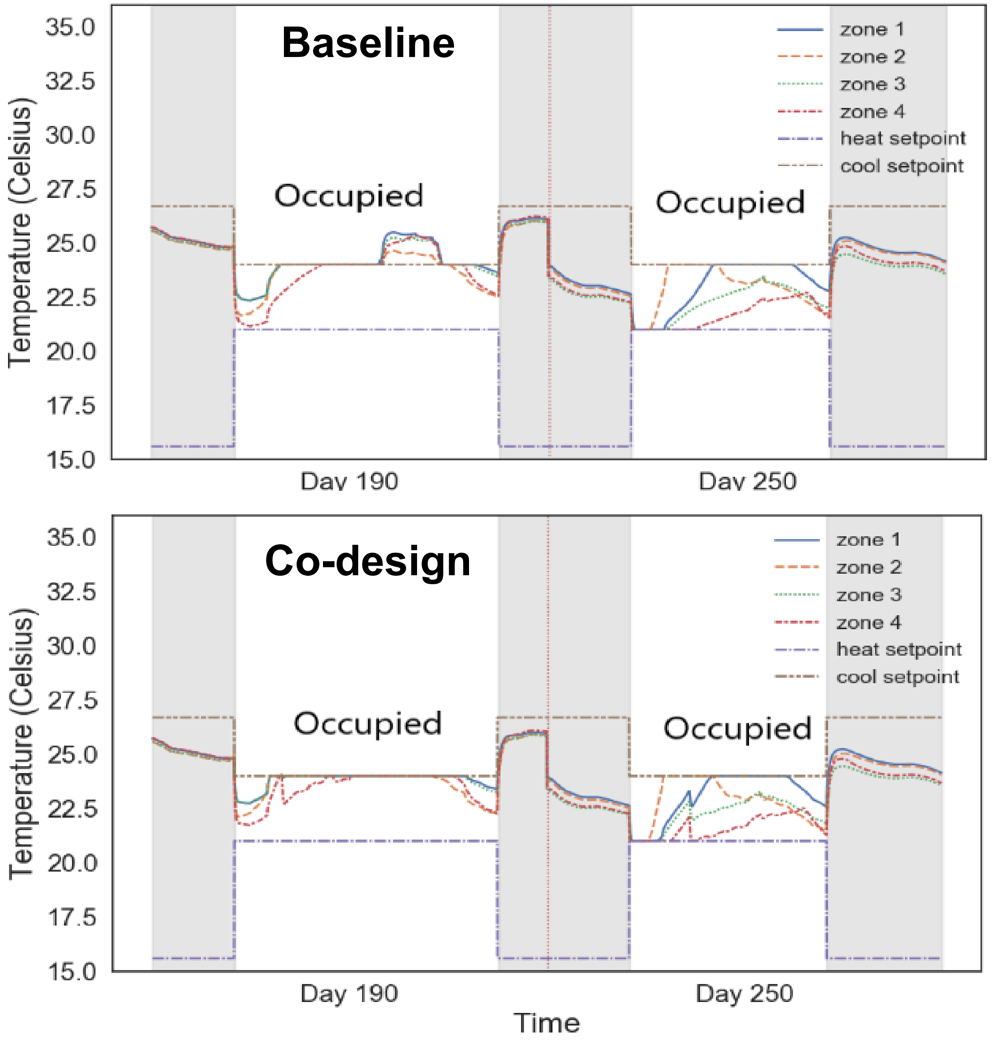
Co-designed system results in capital cost savings ($0.7M), annual energy savings (33%), peak-load reduction (56%) and improved thermal comfort.

Annual Performance

Design	Baseline Design	Co-design (2 chillers)
Capacities (kW)	2184, 2184	531, 2799
Switching Thresholds	0.95	0.95
Energy (MWh)	1286.85	855.38
Peak Load (kW)	1241.59	539.77
Capital Cost ($)	1.69 million	0.99 million

Thermal comfort

Day	Design	Maximum discomfort (ºC)
190	Baseline	2.053
	Co-design (2 chillers)	0.543
250	Baseline	0.002
	Co-design (2 chillers)	0.001

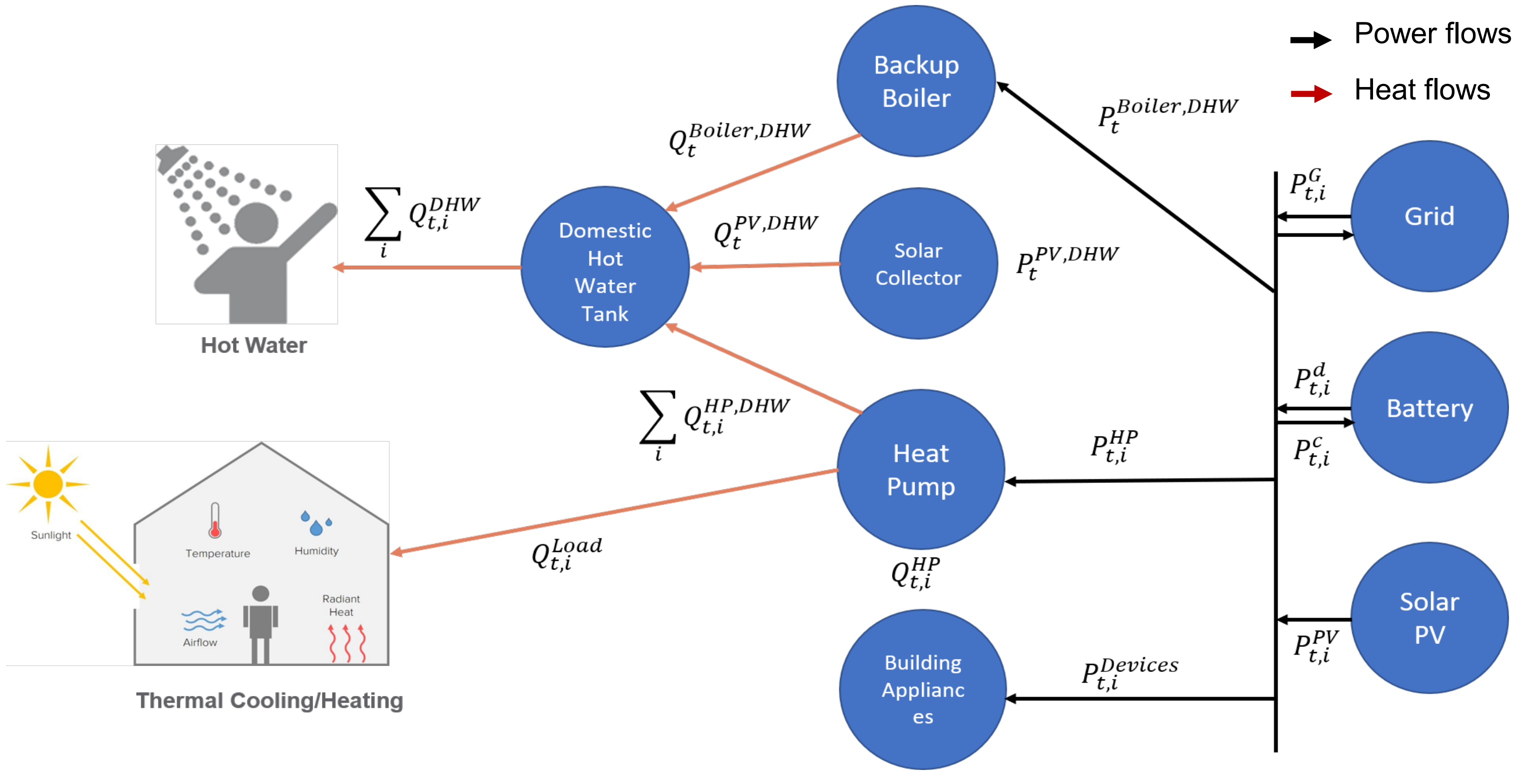


Progress: Multi-Buildings and Community Energy Systems

Mixed-Community Use-Case: Historic Green Village (HGV), Anna Maria Island, Florida

Co-design model: Validated with data from the HGV

Co-design scenario: Heat recovery via ground source heat pump to preheat domestic hot water



Design Objectives

Minimize Initial investment cost of DHW + HPs + Battery, total energy consumption, thermal imbalance of DHW and space conditioning loads, battery SOH (~# of cycles)

Progress: Multi-Buildings and Community Energy Systems

Co-design led to capital cost savings (~20%), annual energy savings (>3 MWh), improved cooling demand satisfaction, and reduced battery degradation (~30%)

Variable Type	Variable Name	Baseline Design	Co-design
Plant Design	Boiler Capacity	350 kW	250 kW
	Tank Capacity	3 m^3	4 m^3
	Battery Capacity	120 kWh	100 kWh
Control Design	Temperature Thresholds	25ºC, 28.88ºC	23.46ºC, 26.99ºC
	Min SOC, Max SOC	0.10, 0.90	0.27, 0.83
	Battery charge and discharge rates	200 kW, -400 kW	100 kW, -400 kW
	Time window for battery discharge	7 am, 6 pm	12 pm, 7 pm

Capital Investment	Baseline Design	Co-design
Boiler	$42,928	$32,057
Battery	$43,400	$36,200
Hot Water Tank	$743	$924
Total Cost	$87,071	$69,181

Control Cost	Baseline Design	Co-design
Annual DHW Energy Consumption	13.16 MWh	13.15 MWh
Annual HP Energy Consumption	153.62 MWh	150.56 MWh
Max supply-temperature deviation	0.95ºC	0.67ºC
Battery State of Health	292	205

Benefits and Impact

- Improved design can reduce up-front project costs while meeting or exceeding energy efficiency goals
- Identification of cheaper, smarter design solutions will accelerate market adoption and societal impacts
- Codesign benefits apply to all building types; both retrofit and new building constructions
  - U.S. retrofit market is valued at $124.2 billion (2020) and expected to grow to $182.9 billion by 2027
  - Potential of over $1 trillion in energy savings over a 10-year period
- Use of high-fidelity modeling can readily be used as a system operations tool (i.e., digital twin) to make operational decisions for demand flexibility

Mid- to Long-term Impact

HVAC design tools with enhanced capability for control specifications and co-optimization

Overall reduction in up-front project costs and risks while enabling delivery of high performing GEB

ET Programmatic Alignment

- Expand utilization and effectiveness of building energy models
- Connections to other BTO related work including OBC and support for semantic information (ASHRAE 223P and 231P)
- Exploratory work towards the identified long-term sensors and control R & D opportunity

Stakeholder Engagement

Early-Stage Project

November 2019 – January 2020:

- Questionnaire Survey and telephone interview with building experts from Research and Industry
- Engaged on current design practice, value proposition and use-case selection

May 2021

- Raymond Kaiser, LEED and sustainability consultant for HGV design project

ASHRAE

Integrated Building Design

ASHRAE Technical Committee 7.1

Broad dissemination of project and its outcomes

- ASHRAE Winter Conference, 2021
- American Control Conference, 2021
- Trade magazine articles – Project Haystack Connection and Engineered Systems
- Control Co-Design of Commercial Building Chiller Plant using Bayesian Optimization." Energy and Buildings, 2021.


Contributed Article

Co-Design a New Process to Improve Control System Design and Delivery

Pacific Northwest

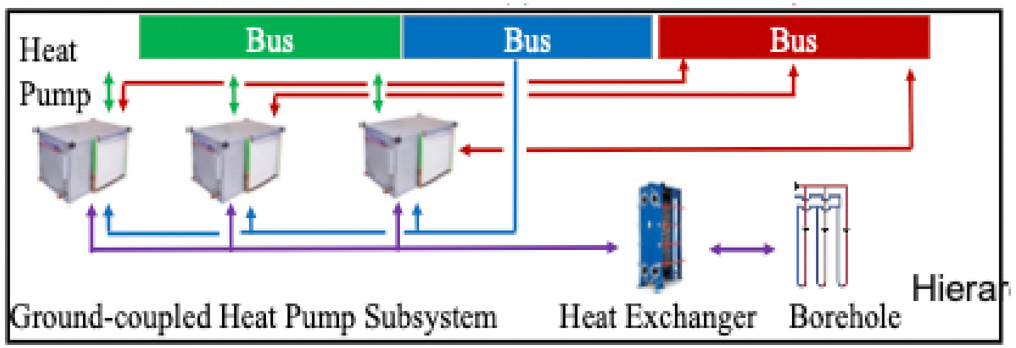
BUILDING INTELLIGENCE GROUP LLC

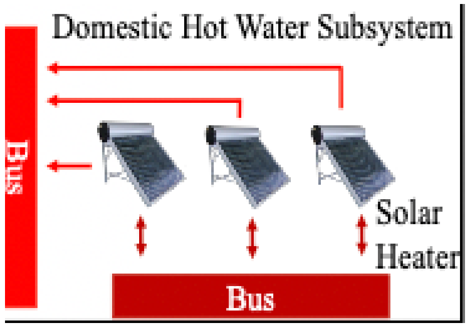
"The vision of grid-interactive energy-efficient buildings will be realized through effective integration of energy savings and automated demand response technologies enabled by advanced building energy management systems with two-way grid interacting capabilities."

Remaining Project Work

1. Complete uncertainty analysis and integration for robust HGV co-design use-case

2. Complete evaluation of additional HGV configurations
   - Ground source HP loop complemented with cooling tower for heat rejection
   - Domestic hot water subsystem alternatives (e.g., replace thermal solar with additional PV panels)





Concluding Remarks

Achieved project outcomes

- Developed of a scalable co-design optimization framework and methodology for integrated building HVAC systems and onsite energy assets
- Developed flexible higher-fidelity, system-level, modeling templates for co-design experimentation
- Demonstrated co-design application and benefits for two retrofit use-cases
- Showed that co-design results in lower capital cost and operational cost (improved energy efficiency and thermal comfort)

This proof-of concept project paves the way for future work:

- A series of standards, easy-to-use tools and templates for both co-design and verification, allowing designers to readily apply control co-design methodology
- Framework for new and innovative projects (e.g., energy decarbonization) that doesn’t readily fit into templates
- Workforce training

Thank You

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REFERENCE SLIDES

Publications and Presentations

1. A. Bhattacharya, Vasisht S.S., S. Huang, H. Sharma, V.A. Adetola, and D.L. Vrabie. " Control Co-Design of Commercial Building Chiller Plant using Bayesian Optimization." Energy and Buildings, 2021 https://doi.org/10.1016/j.enbuild.2021.111077
2. Vasisht S.S., A. Bhattacharya, S. Huang, H. Sharma, V.A. Adetola, and D.L. Vrabie. "Co-Design of Commercial Building HVAC using Bayesian Optimization. IEEE American Control Conference, June 2021.
3. V. Adetola. “Better Together: Co-design for the Win”. ASHRAE Winter Conference Seminar 10. Feb 9, 2021.
4. V. Adetola and P. Ehrlich. “Co-design a new process to improve control system design and delivery. " *Haystack Connections*. Issue 8, Fall 2020. pages 42-46. PNNL-SA-158438
5. V. Adetola and P. Ehrlich. Solving the built environment’s controls conundrum. Engineered Systems magazine. November 2020. https://digital.bnpmedia.com/publication/?m=11646&i=678234&p=26&oly_enc_id=9775D1291356A9T

Project Budget

Project Budget: $700k
Variances: None
Cost to Date: $625K.
Additional Funding: None planned

Budget History					
10/1/2019 – FY 2020 (past)		FY 2021 - 9/30/2021 (current)		FY 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$450K	$0	$250K	$0	$0	$0

Project Plan and Schedule

Project Schedule								
Project Start: 10/1/2019	Completed Work							
Projected End: 09/30/2021	Active Task (in progress work)							
	Milestone/Deliverable (Originally Planned)							
	Milestone/Deliverable (Actual)							
	FY2020				FY2021			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work								
Q1 Milestone: Document current design practice for building HVAC and control retrofit								
Q2 Milestone: Specify retrofit case study								
Q3 Milestone: Complete building equipment and optimization models								
Q4 Milestone: Co-design formulation and optimization algorithms are specified and implemented for a building HVAC retrofit								
Q1 Milestone: Co-design optimization methodology under uncertainty developed								
Q2 Milestone: Co-design optimization methodology implemented for integrated system use-case (HVAC, Storage and Local generation)								
Q3 Milestone: Co-design approach and improved performance demonstarted for integrated system -use case								
Current/Future Work								
Q4 Milestone: Disseminate technical and economic benefits of Co-design								