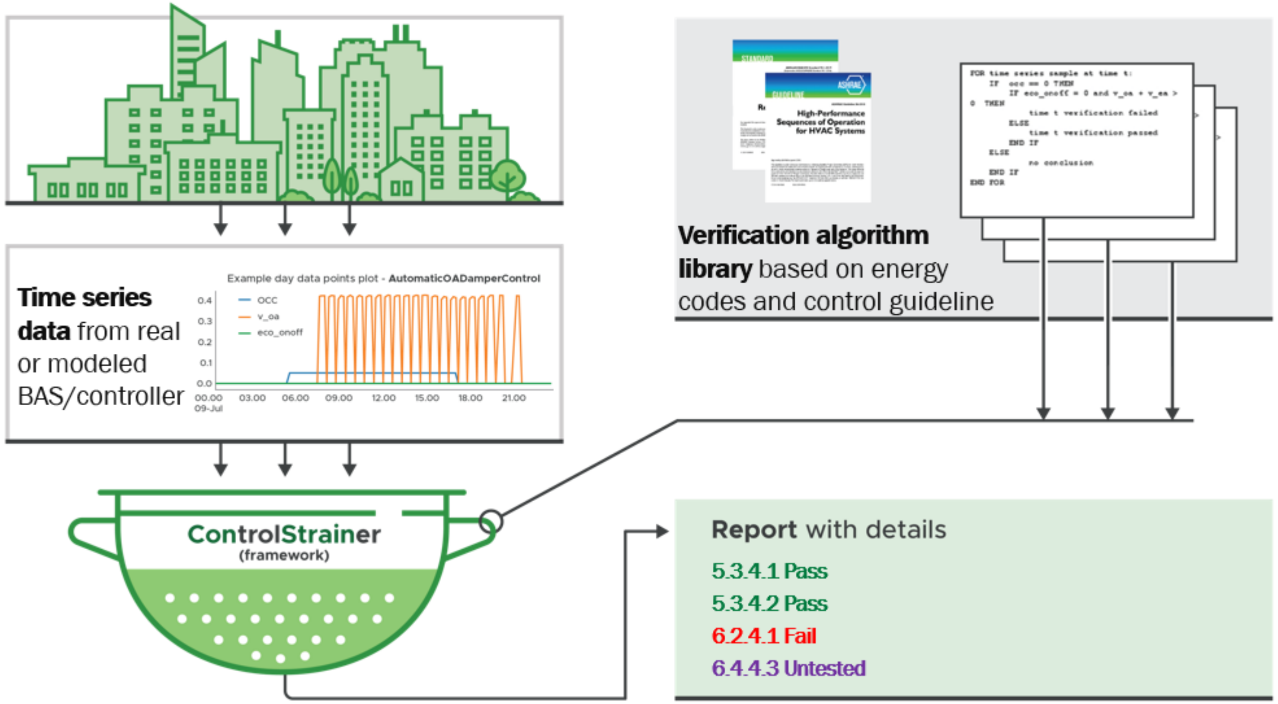
Control Strainer: A Data-driven Control Verification Framework



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Project Summary

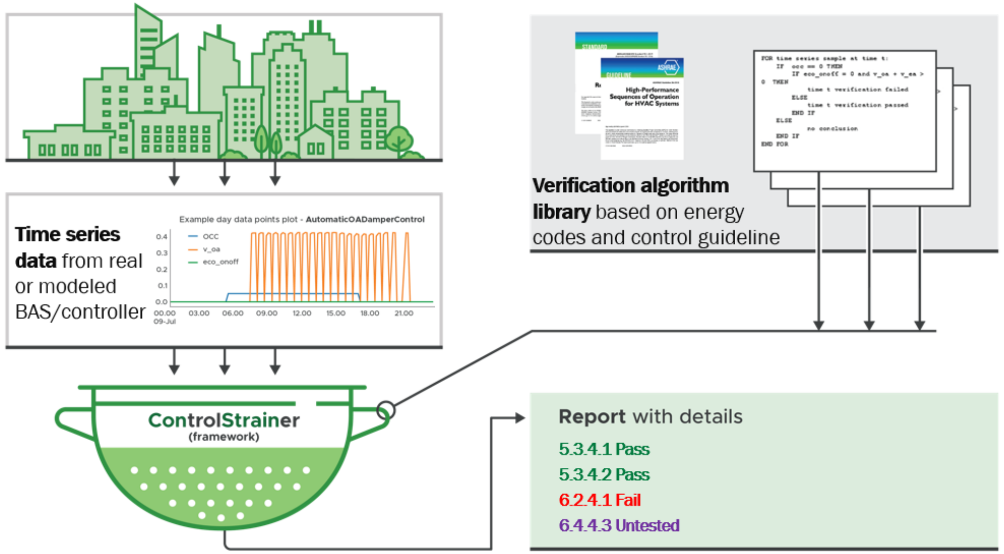
Objective and outcome

- To enable fully automated control verification by developing a data-driven knowledge-integrated framework.
- This solution is targeted for the commercial building stock: both existing buildings and new construction.
- Open-source framework is developed and tested via simulated and real building data in collaboration with industry stakeholder.

Team and Partners

PNNL: Conceptualization, framework development, verification library development, application test case development, semantic modeling

LBNL: Semantic modeling, framework testing,



Status

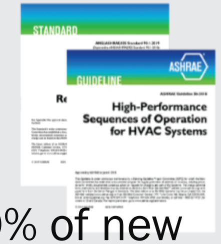
Performance Period: FY2020-FY2023

DOE budget: $825k, Cost Share: $0k

- ✓ Milestone 1: Automated control performance testing for simulated and real building.
- ✓ Milestone 2: Performing 100+ tests in parallel
- ✓ Milestone 3: Vendor-neutral API

Problem - Urgent Need to Verify Control

Controls Advanced in Codes and Guideline



- **90.1**: Since 2004, ~30% of new requirements controls-related [1]
- **Guideline 36**: Advanced sequences require expertise to interpret, implement, and verify

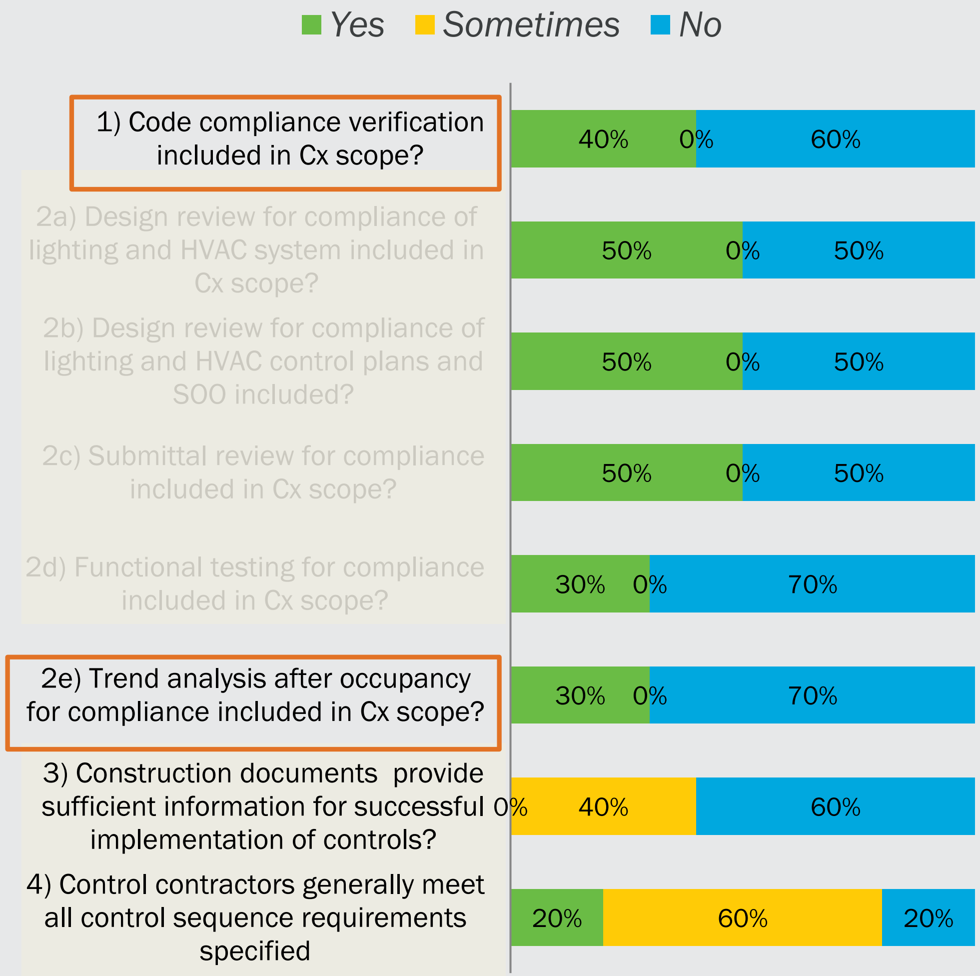
Saving potential: Installing known, properly tuned control sequences can cut commercial building energy use by ~29%, saving 4-5 quads [2]

Only 50% of observed buildings have controls correctly configured to meet energy code requirement [1]

[1]. Rosenberg, M. I., Hart, P. R., Hatten, M., Jones, D., & Cooper, M. (2017). *Implementation of Energy Code Controls Requirements in New Commercial Buildings* (No. PNNL-26348). Pacific Northwest National Lab, Richland, WA

[2]. Fernandez, N. E., Katipamula, S., Wang, W., Xie, Y., Zhao, M., & Corbin, C. D. (2017). Impacts of commercial building controls on energy savings and peak load reduction (No. PNNL-25985). Pacific Northwest National Lab, Richland, WA

Commissioning Agent Responses [1]



* Cx = commissioning

Problem - Challenges in Current Verification Process

DESIGN
Incomplete/poorly written sequences

INSTALLATION
Improper integration (Cx)

OPERATION
Improper changes to the sequences

Human error can affect the control system at each stage of the building life cycle [1].

Lack of systematic interpretation of energy codes and control guidelines regarding how control shall be verified.

Building energy codes control requirements are sometimes **unverifiable.**

Manual control verification is **ad-hoc, error-prone, incomplete, and time-consuming.**

[1] Torabi, N., Gunay, H. B., O'Brien, W., & Barton, T. (2022). Common human errors in design, installation, and operation of VAV AHU control systems–A review and a practitioner interview. Building and Environment, 109333.

How should I verfiy this control requirement?

EXAMPLE

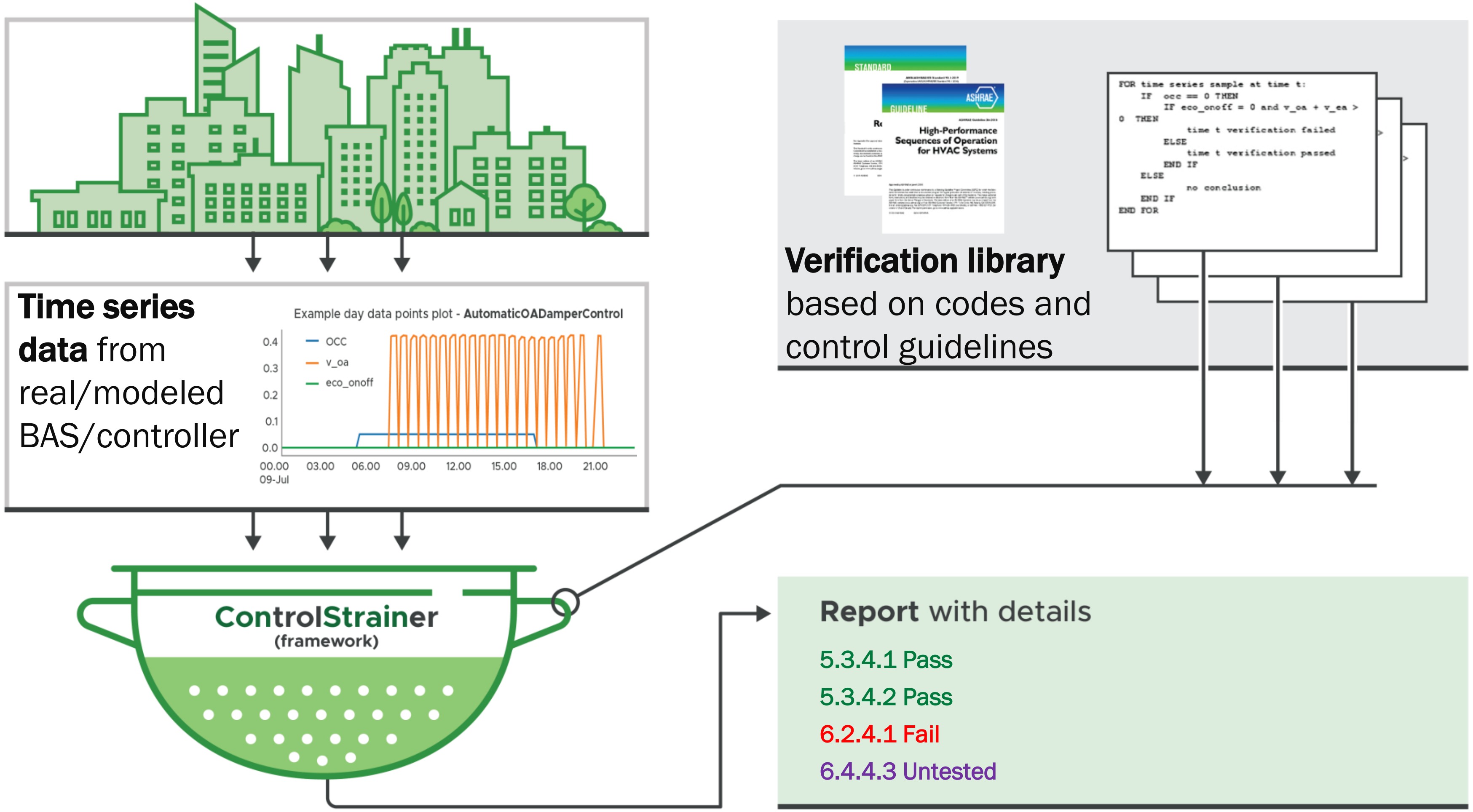
6.4.3.5 Heat Pump Auxiliary Heat Control

Heat pumps equipped with internal electric resistance heaters shall have **controls that prevent supplemental heater operation** when the heating load **can be met by the heat pump** alone during both steady-state operation and setback recovery. Supplemental heater operation is permitted during outdoor coil defrost cycles. *(ASHRAE 90.1-2016)*

Building Energy Codes

Vision

A **data**-driven **knowledge**-integrated framework that **automatically verify** that controls function as intended. Applications to compliance, commissioning, and BPS.



Overall Plan

Phase 1: (FY20-22) (basic technology research)

- Initial development of the framework
- Proof of concept
- Preliminary test cases

Phase 2: (FY23-25) (research to prove feasibility)

- API development, testing with industry partners
- Expansion of the library to cover all control requirements in 90.1 and Guideline 36
- Fully implementation of semantic information integration
- Initial deployment

Phase 3: (FY26-beyond) (development & demonstration)

- Industry deployment
- Continuous maintenance based on practitioner feedback

Industry/stakeholder engagement
FY23 Q4 Host workshops for **ConStrain** testing with potential users (from both building modelers and building operators)

Stakeholders / Interested Parties

Actual Building Operation
Building operator, Cx Agents, analysts (GSA, TRC, Edo, MacDonald-Miller)

Building modeling and simulation engines
EnergyPlus, Modelica, other BEM tools that simulate HVAC operation and control

Building analytics tools
TSPR, DOE prototype building models

Other relevant projects
OpenBuildingControl, BOPTEST

Communities reach out
ASHRAE

Alignment and Impact

DOE/BTO

- Increase the code compliance rate for controls (currently ~50%) – bringing control systems into compliance is probably the most effective upgrade we can apply to existing buildings at scale in the near term.
- Reduce cost and improve effectiveness of commissioning (Cx) going forward.
- “Close the loop” of digitized control delivery from design to the operation.

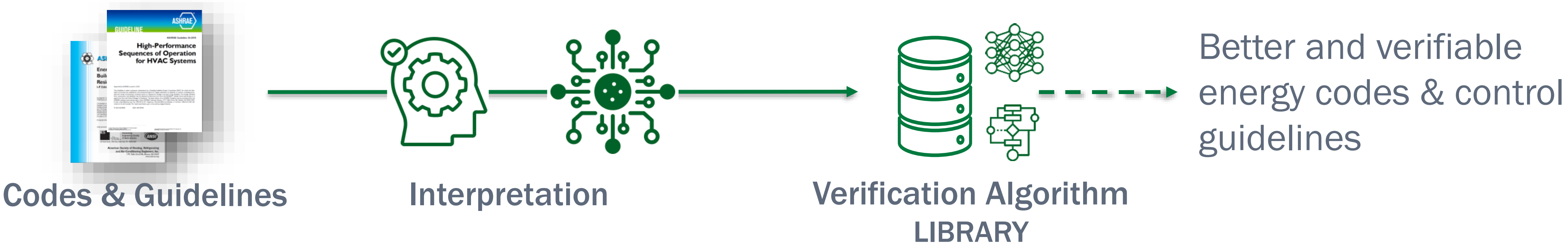
ConStrain provides value to different industry stakeholders

- Cx agent – reduce effort and cost, while increasing rigor
- Building operator – implement Continuous Commissioning (CCx) to avoid performance drift
- AHJ – achieve better compliance rates for control provisions in code
- Mechanical engineer/energy modeler – ensure that chosen systems and their controls will comply with code.
- Energy code/control guideline developer -- identify ambiguity in code languages.
- BEM software developer -- identify control related issues in simulation engine.

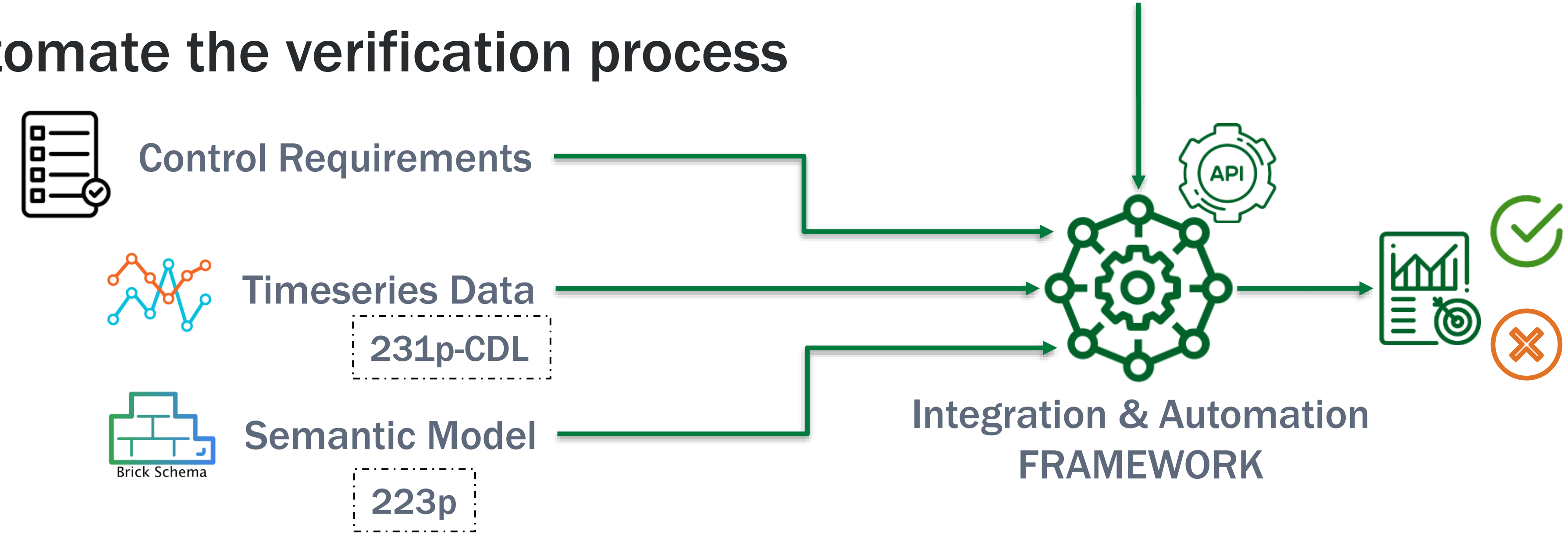
Cx Agent | Operator | AHJ | Modeler | Simulation Engine | Energy Codes

Approach – Overview

- Develop the library of control verification algorithms



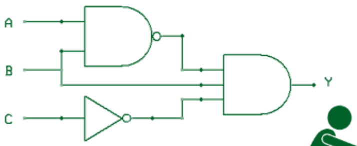
- Automate the verification process



Approach – Verification Library

- **Reviewed control requirement in energy codes and control guidelines.**
  - ASHRAE Standard 90.1
  - International Energy Conservation Code (IECC)
  - Guideline 36

- **Identified three methods to carry out verification [1].**
  - Logical expressions
  - Procedural knowledge
  - Machine learning-based verification



EXAMPLE

Interpret code language into pseudo code and python script

6.4.3.4.2 Shutoff Damper Controls (90.1-2016)

…Ventilation outdoor air and exhaust/relief dampers shall be capable of and configured to *automatically shut off* during preoccupancy building warm-up, cooldown, and setback, except when ventilation reduces energy costs or when ventilation must be supplied to meet code requirements.

Pseudo Code

```
if Occ <= 0 + tol
  if eco_onoff = 0
and (m_oa > tol or
m_ea > tol)
    return false
  else
    return true
  endif
else
  return untested
endif
```

Python Script

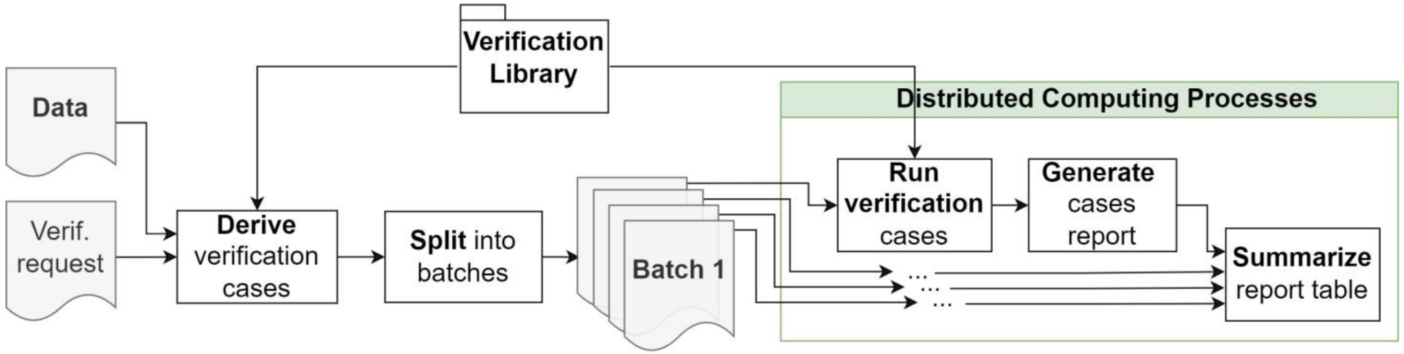
```python
from checklib import RuleCheckBase

import numpy as np


class AutomaticOADamperControl(RuleCheckBase):
    points = ["o", "eco_onoff", "m_oa", "m_ea",
    "tol_o", "tol_m_oa", "tol_m_ea"]

    def automatic_oa_damper_check(self, data):
        if data["o"] < data["tol_o"]:
            if data["eco_onoff"] == 0 and (
                data["m_oa"] >= data["tol_m_oa"]
                 or data["m_ea"] >= data[
                "tol_m_ea"]
            ):
                return False
            else:
                return True
        else:
            return np.nan

    def verify(self):
        self.result = self.df.apply(lambda d:
        self.automatic_oa_damper_check(d), axis=
        1)
```


[1] Chen, Y., Lerond, J., Lei, X., Rosenberg, M. and Vrabie, D., A Knowledge-based Framework for Building Energy Model Performance Verification. Proceedings of Building Simulation 2021: 17th Conference of IBPSA, 2021

Approach – A Parallel Verification Process

- **Developed a parallel process to handle many verification cases simultaneously.**
  - Real building data can easily have 100+ verification cases (See Example).

- **Parallel verification workflow**



A **verification case** is defined to verify one control action for a specific controller (e.g., to verify zone temperature reset in Room 101)

Example: PNNL's Systems Engineering Building has 33 thermal zones, 5 AHUs, 3 FCUs

Each zone:

1. Temperature setback control
2. Temperature setpoint dead band
3. Off hour control

Each AHU:

1. Supply Air Temperature Control
2. Economizer High Limit
3. Integrated Economizer Control
4. Shutoff Damper Controls
5. VAV Static Pressure Sensor Location

The number of verification cases adds up quickly.

Approach: End-to-End Workflow (SAT Reset Example)

Preprocess data → Setup cases to verify → Default verification / Users can add custom checks → Run selected checks → Report

Time-series data 

Semantic mode 

Library metadata

```
} library.json > {} SupplyAirTempReset
"SupplyAirTempReset": {
    "library_item_id": 1,
    "description_brief": "Cooling supply air temperature
    "description_detail": "Multiple zone HVAC systems mu
    "description_index": [
        "Section 6.5.3.5 in 90.1-2016"
    ],
    "description_datapoints": {
        "T_sa_set": "AHU supply air temperature setpoint
        "T_z_coo": "Design zone cooling air temperature"
    },
    "description_assertions": [
        "Max(T_sa_set) - Min(T_sa_set) >= (T_z_coo - Mir
    ],
    "description_verification_type": "rule-based",
    "assertions_type": "pass"
},
```

Case definition

```
"no": 2,
"run_simulation": false,
"simulation_IO": {…
},
"expected_result": "pass",
"datapoints_source": {
    "idf_output_variables": {
        "T_sa_set": {
            "subject": "VAV_2 Supply Equipment Out
            "variable": "System Node Setpoint Temp
            "frequency": "detailed"
        }
    },
    "parameters": {
        "T_z_coo": 24.0
    }
},
"verification_class": "SupplyAirTempReset"
```

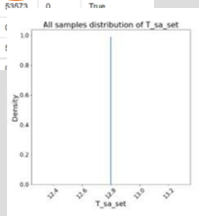
Verification logic (.py)

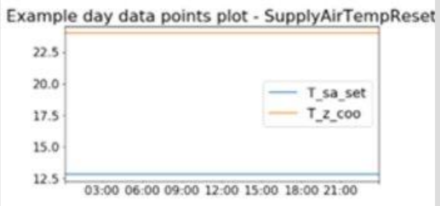
```
class SupplyAirTempReset(RuleCheckBase):
    points = ["T_sa_set", "T_z_coo"]

    def verify(self):
        t_sa_set_max = max(self.df["T_sa_set"])
        t_sa_set_min = min(self.df["T_sa_set"])

        self.result = (t_sa_set_max - t_sa_set_min) >= (
            self.df["T_z_coo"] - t_sa_set_min
        ) * 0.25 * 0.99  # 0.99 being the numeric threshold
```

Verification Results:

Case No.	Verification Class	Sample #	[illegible]	Fail #	Verification Passed?
1	SupplyAirTempReset	53573	53573	0	True
2	SupplyAirTempReset	52978	[illegible]	[illegible]	[illegible]
3	SupplyAirTempReset	53573	[illegible]	[illegible]	[illegible]
4	SupplyAirTempReset	52978	[illegible]	[illegible]	[illegible]

6.5.3.5 (no SAT reset found)





Case report

GitHub Repository: https://github.com/pnnl/ConStrain

Approach – Barriers, Challenges, and Risks

Adoption challenges:

- Insufficient industry interest to drive wide adoption and integration in existing market available systems and tools.
- Framework flexibility to satisfy the diverse needs and configurations of the entire commercial building stock.

Mitigation strategies:

✓ Test the framework with both simulated dataset and real building dataset.

✓ Formed a **technical advisory panel** to engage the industry and academia from the start of the project to inform the development process.

✓ Quarterly check-ins and updates with industry stakeholders, and sustained engagement with PNNL's Technology, Deployment & Outreach Office to identify early adopters in industry.

Progress – Verification Algorithm Library

	Control Items	FY21	FY22	FY23
AHU	6.5.3.5* Supply Air Temperature Control	Yes		
	6.5.1.1.3 Economizer High Limit	Yes		
	6.5.1.3 Integrated Economizer Control	Yes		
	6.4.3.4.2 Shutoff Damper Controls		Yes	
	6.5.3.2.3 Fan Static Pressure Reset Controls		Yes	
	6.5.3.2.2 VAV Static Pressure Sensor Location		Yes	
	6.4.3.4.4 Ventilation Fan Controls		Yes	
Plant	6.5.4.4 Hot Water Temperature Reset	Yes		
	6.5.4.4 Chilled Water Temperature Reset	Yes		
	6.5.5.2.1 Economizer Humidification System Impact -- Water-side Economizer		Yes	Focus on ASHRAE Guideline 36
	6.4.3.5 Heat Pump Supplemental Heat Lockout		Yes	
	6.5.5.2.2 Heat Rejection Fan Variable Flow Controls		Yes	
	6.5.2.2.3 Water Loop Heat Pump Heat Rejection Controls		Yes	
SWH	7.4.4.3 Service Water-heating System Controls-outlet Temperature Control		Yes	
Zone	6.4.3.1.2 Zone Temperature Control - Dead Band	Yes		
	6.4.3.3.2 Zone Temperature Control - Setback Controls	Yes		
	6.4.3.3 Off Hour Automatic Temperature Setback And System Shutoff		Yes	
	6.4.3.3.5 Guest Room Control		Yes	

** Section number (e.g., 6.5.3.5) is based on ASHRAE 90.1-2016*

Selection of the control verification is based on **energy impact** from the list of control requirements identified by Rosenberg et al. (2017)

Rosenberg, Michael I., et al. *Implementation of Energy Code Controls Requirements in New Commercial Buildings*. No. PNNL-26348. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2017.

Progress – Applications with Simulated Data & Result

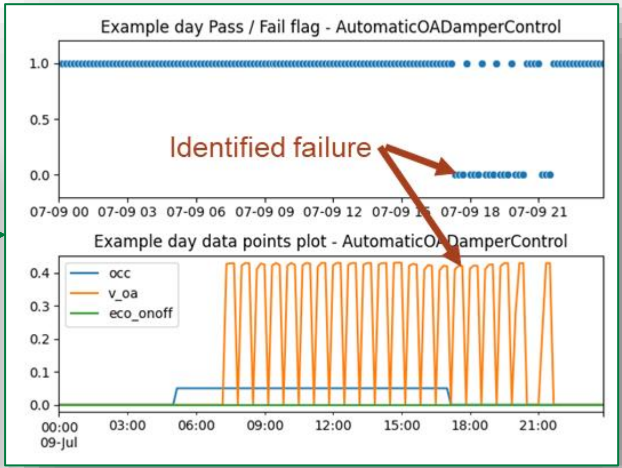
Dataset: Building simulation models

Result Summary Table

Case No.	Verification Class	Sample #	Pass #	Fail #	Failure Ratio	Failure Severity	Priority Ranking from report	Priority	Verification Passed?
1	SupplyAirTempReset	53573	53573	0	0.0	0.0	4	0.0	True
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.28	4	0.28	False
3	SupplyAirTempReset	53573	53573	0	0.0	0.0	4	0.0	True
4	SupplyAirTempReset	52978	0	52978	1.0	0.28	4	0.28	False
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	IntegratedEconomizerControl	106488	0	106488	1.0	1.264	N/A	1.264	False
7	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	True
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.291	False
9	CHWReset	52560	40157	12403	0.236	0.044	9	0.01	False
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	9	[illegible]	False
11	NightCycleOperation	8760	145	134	0.48	0.023	N/A	0.011	False
12	AutomaticOADamperControl	52560	52250	310	0.006	0.002	2	0.0	False
14	HeatRejectionFanVariableFlowControlsCells	53573	53573	0	0.0	0.0	10	0.0	True
15	ServiceWaterHeatingSystemControl	148330	0	148330	1.0	1.648	8	1.648	False
17	VentilationFanControl	8760	8760	0	0.0	0.0	N/A	0.0	True
18	WLHPLoopHeatRejectionControl	52560	52560	0	0.0	0.0	11	0.0	True
19	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	N/A	N/A	True
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	True
21	HeatRejectionFanVariableFlowControl	1	[illegible]	0	[illegible]	0.0	N/A	0.0	True
22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
23	ZoneHeatingResetDepth	8760	8760	0	0.0	0.0	N/A	0.0	True
24	ZoneCoolingResetDepth	8760	8760	0	0.0	0.0	N/A	0.0	True
25	VAVStaticPressureSensorLocation	21601	12983	8618	0.399	0.429	N/A	0.171	False

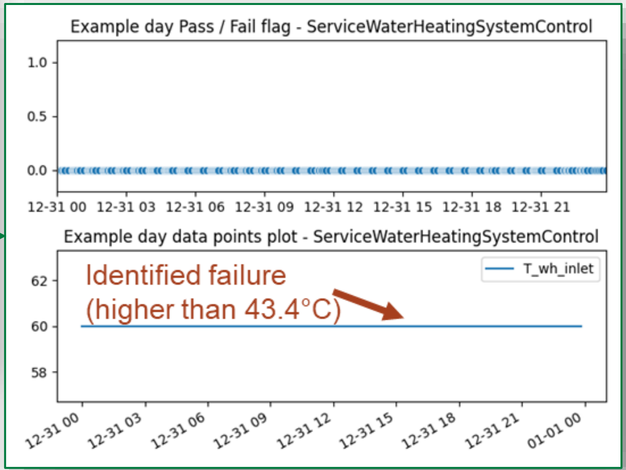
6.4.3.4.2 Shutoff Damper Controls
Ventilation outdoor air and exhaust/relief dampers shall be capable of and configured to automatically shut off during preoccupancy *building warm-up*, *cooldown*, and *setback*, except when *ventilation* reduces *energy* costs or when *ventilation* must be supplied to meet code requirements.

7.4.4.3 Outlet Temperature Controls
Temperature controlling means shall be provided to limit the maximum temperature of water delivered from lavatory faucets in public facility restrooms to 110ºF (43ºC).



Failed: Outdoor air flow rate was non-zero and night cycling was not operating correctly.

Simulation engine error.



Failed: Water heater setpoint temperature schedule was set to 60ºC, which is greater than 43ºC.

Model input error.

Progress – Applications with Real Building Data & Result

Dataset: OpenEI Dataset, LBNL Building 59[1]

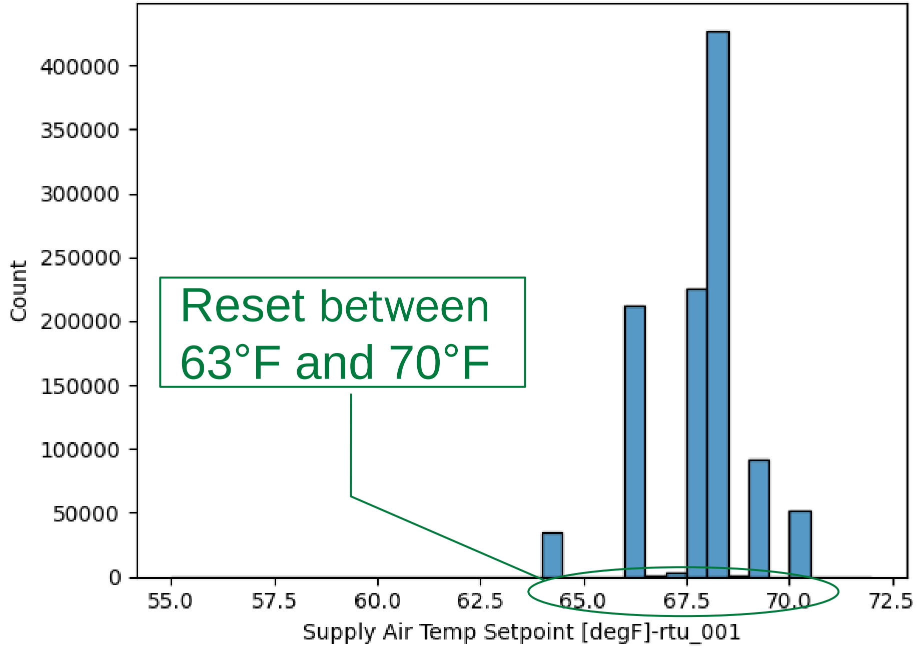
Control Verification item:
6.5.3.5 Supply Air Temperature Reset Controls
Multiple zone HVAC systems shall include controls … to automatically reset the supply air temperature …The controls shall reset the **supply air temperature at least 25%** of the difference between the **design supply air temperature** and **the design room air temperature.**

```
schema > {} library.json > {} SupplyAirTempReset
{
    "SupplyAirTempReset": {
        "library_item_id": 1,
        "description_brief": "Cooling supply air temperature reset scale (25%)",
        "description_detail": "Multiple zone HVAC systems must include controls
        "description_index": [
            "Section 6.5.3.5 in 90.1-2016"
        ],
        "description_datapoints": {
            "T_sa_set": "AHU supply air temperature setpoint",
            "T_z_coo": "Design zone cooling air temperature"
        },
        "description_assertions": [
            "Max(T_sa_set) - Min(T_sa_set) >= (T_z_coo - Min(T_sa_set)) * 0.25"
        ],
        "description_verification_type": "rule-based",
        "assertions_type": "pass"
    },
```

Assumptions: current verification algorithm needs design zone cooling air temperature, which is unavailable within this dataset. Based on zone thermostat setpoints, assumed 73ºF.

Result:

Verification passes → confirmed that AHU supply air temperature is reset based on outdoor air temperature or representative building loads.



[1] Data source: Hong, T., and Luo, N., Lawrence Berkeley National Laboratory Building 59, Berkeley, CA. United States. 2021 DOI: 10.25584/1763770

Lessons Learned

- The process of **interpreting** control requirements in codes and guidelines into verification algorithms **evaluates** the **formality and ambiguity** of energy code and control sequence language.
- The **collection of data points** for verification needs can serve as the **minimum requirement** for BAS trending and data acquisition.
- Testing with data sets from both **actual buildings** and **simulation models** further informs the **robust design** of the ConStrain verification framework.

EXAMPLE 1: Identify ambiguity issue

6.4.3.5 Heat Pump Auxiliary Heat Control

Heat pumps equipped with internal electric resistance heaters shall have controls that prevent supplemental heater operation when the heating load can be met by the heat pump alone during both steady-state operation and setback recovery. Supplemental heater operation is permitted during outdoor coil defrost cycles.(ASHRAE 90.1-2016)

What does "can be met" mean? In 5 minutes? In an hour?

EXAMPLE 2: Data matrix to inform minimum trending

Data Point	Verification items			
	Supply Air Temp Reset	Economizer High Limit A	Economizer High Limit B	Integrated Economizer Control
AHU supply air temperature setpoint	•			
Design zone cooling air temperature	•			
Return air temperature			•	
OA dry bulb temperature		•	•	
OA dry bulb upper threshold		•		
Cooling demand				•
OA airflow rate		•	•	•
OA minimum airflow setpoint		•	•	•

ConStrain Summary

- A data-driven knowledge-integrated framework that automates verification of control based on energy codes and control guidelines.

- Provides benefits to different stakeholders: commissioning agents, building operators, building owners, mechanical engineers and energy models, BEM software developers, energy code developers.

- More verification algorithms will be developed, and more tests will be conducted in real buildings with stakeholders targeting deployment.

Thank You

Performing Organization(s), PNNL, LBNL
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WBS # 3.2.6.67

REFERENCE SLIDES

Project Execution

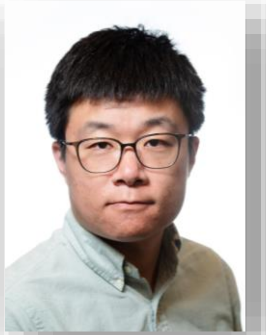
	FY2020				FY2021				FY2022				FY2023			
Planned budget	75k				200k				250k				300k			
Spent budget	75k				193k				215k				188k			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work																
Q4 Milestone: Initial development of automated verification framework and test via a case study.																
Q1 Milestone: Form a small panel to advise the automated control performance verification framework development																
Q3 Milestone: Developed a preliminary version of the control performance verification library																
Q4 Milestone: Demonstration and testing of automated verification framework via building simulation models																
Q2 Milestone: In-parallel evaluation process developed for analyzing large scale (100+) models/cases simultaneously																
Q3: An expanded control performance verification library that covers the key requirement selected from 90.1																
Q4: Documentation of a set of key performance indicator (metrics) for control performance verification																
Current/Future Work																
Q2 Milestone: Development of a vendor neutral API for using ANIMATE.																
Q3 Milestone: Expanded control verification library that include the key control specifications from Guideline 36																
Q4 Milestone: Development of local loop control verification algorithms for building system.																
Q4 Milestone: Host workshop for ANIMATE with potential users (from building modelers and building operators)																

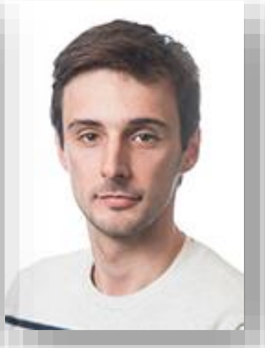
- Go/no-go decision points

Team

Project team includes experts in **energy codes, building energy modeling, control, semantic modeling.**

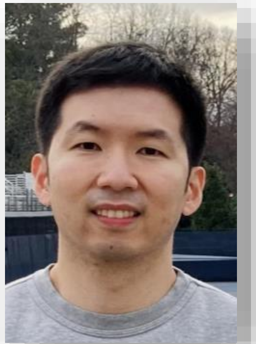

Yan Chen


Xuechen Lei

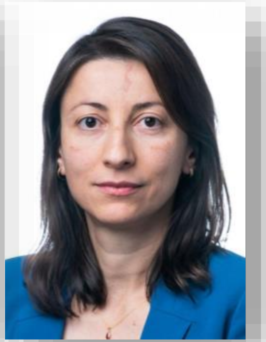

Jeremy Lerond


Michael Wetter


Anand Prakash


Yun Joon Jung


Mike Rosenberg


Draguna Vrabie

Pacific Northwest NATIONAL LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

Engaging with subject matter experts, industry stakeholders and earlier adopters.

EERE/BTO goals

The nation's ambitious climate mitigation goals

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

EERE/BTO's vision for a net-zero U.S. building sector by 2050