



An Open, Cloud-Based Platform for Whole-Building Fault Detection and Diagnostics

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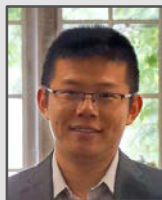
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DOE AFDD Project Portfolio

Controls



Analytics



**Active AFDD
and Adaptive
Controls**



**Model-Based, Whole-Building
AFDD Platform & Algorithms
(This Project)**



**AFDD Market Deployment &
Algorithm Evaluation**

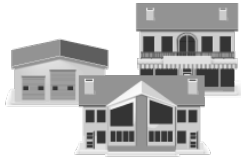
Smaller Buildings



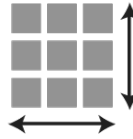
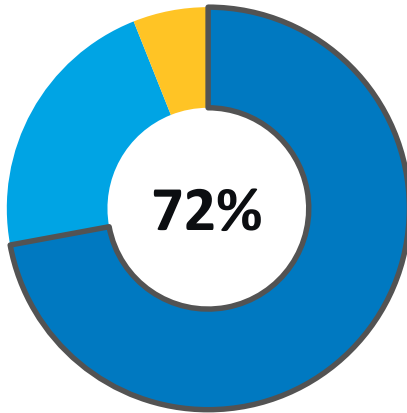
Larger Buildings

Project Goal: Develop cost-effective automated fault detection and diagnosis algorithms for small commercial buildings

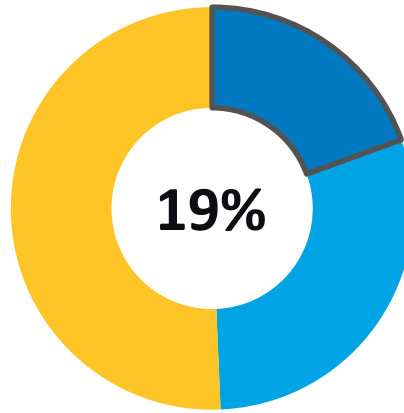
U.S. Small Commercial Buildings



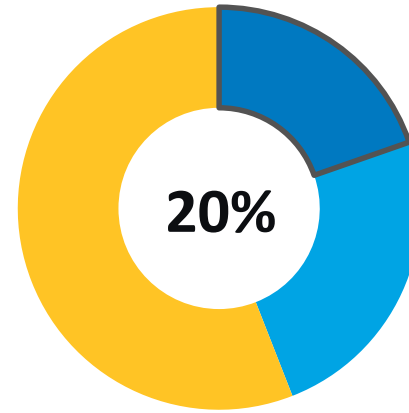
Number of Buildings



Floor Area



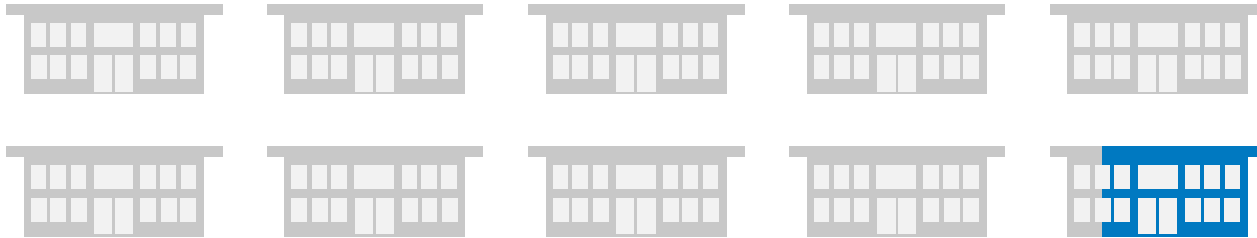
Energy Use



● ≤ 10,000 ft²

● 10,001–50,000 ft²

● > 50,000 ft²

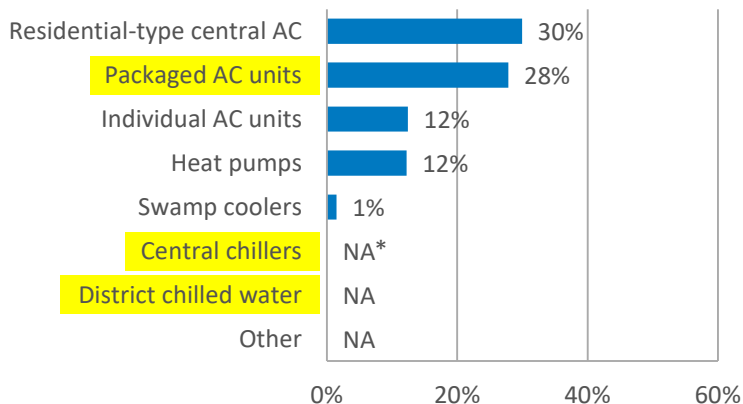


**Automation Systems In
Small Commercial Buildings**
 $\leq 10,000 \text{ ft}^2$

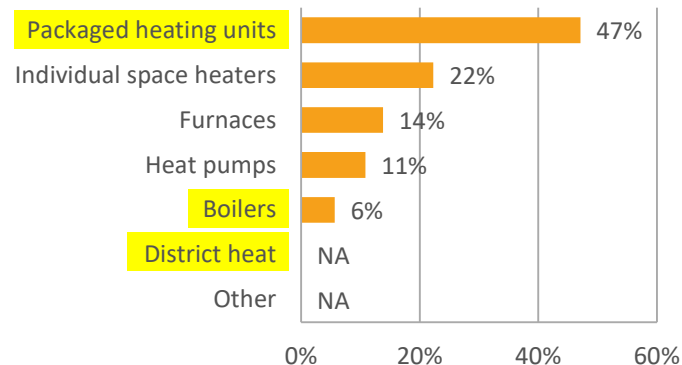
8%

Small Buildings HVAC&R Equipment

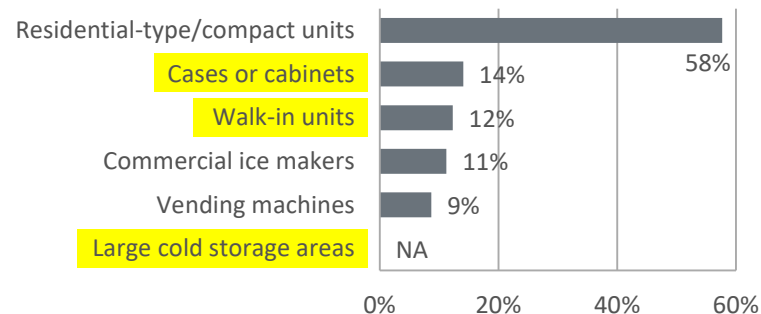
Cooling Equipment



Heating Equipment



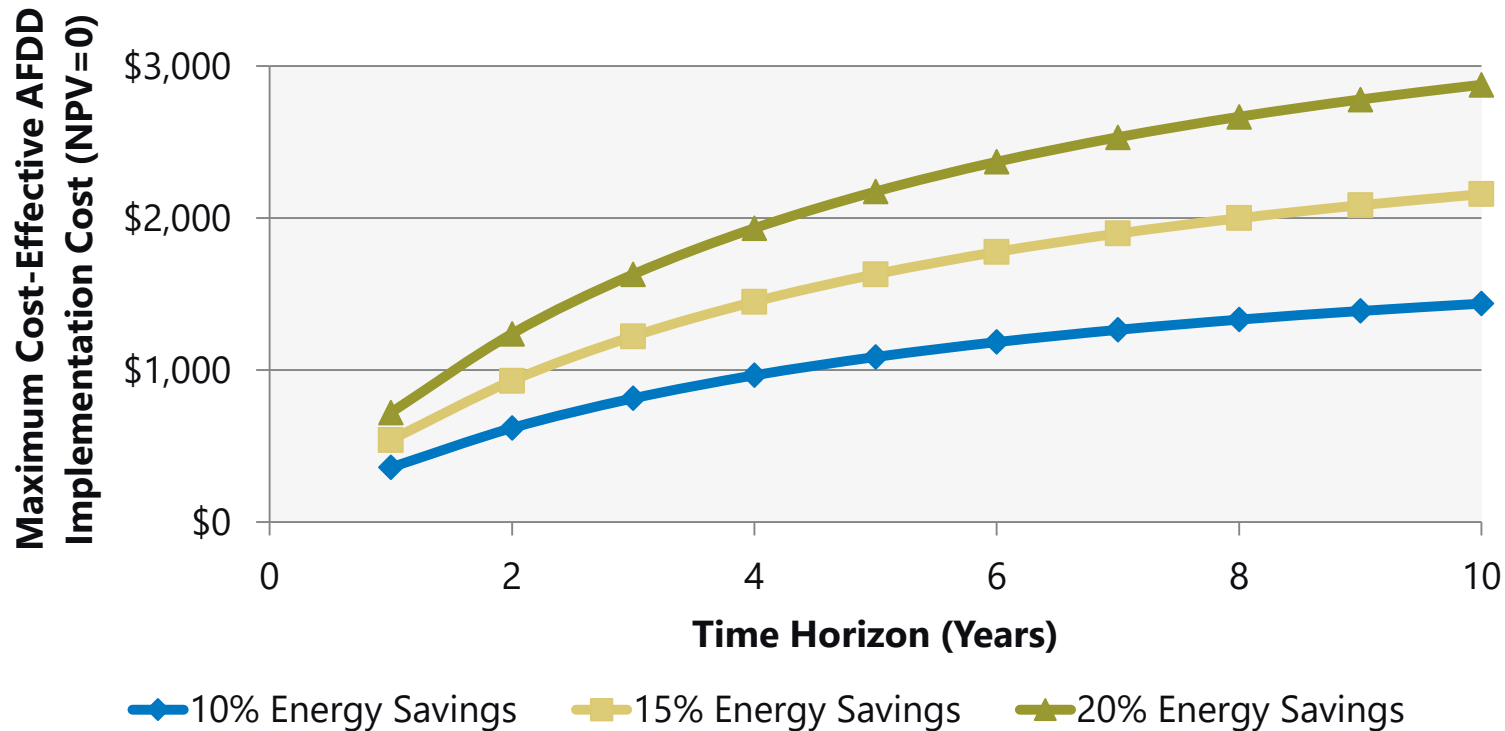
Refrigeration Equipment



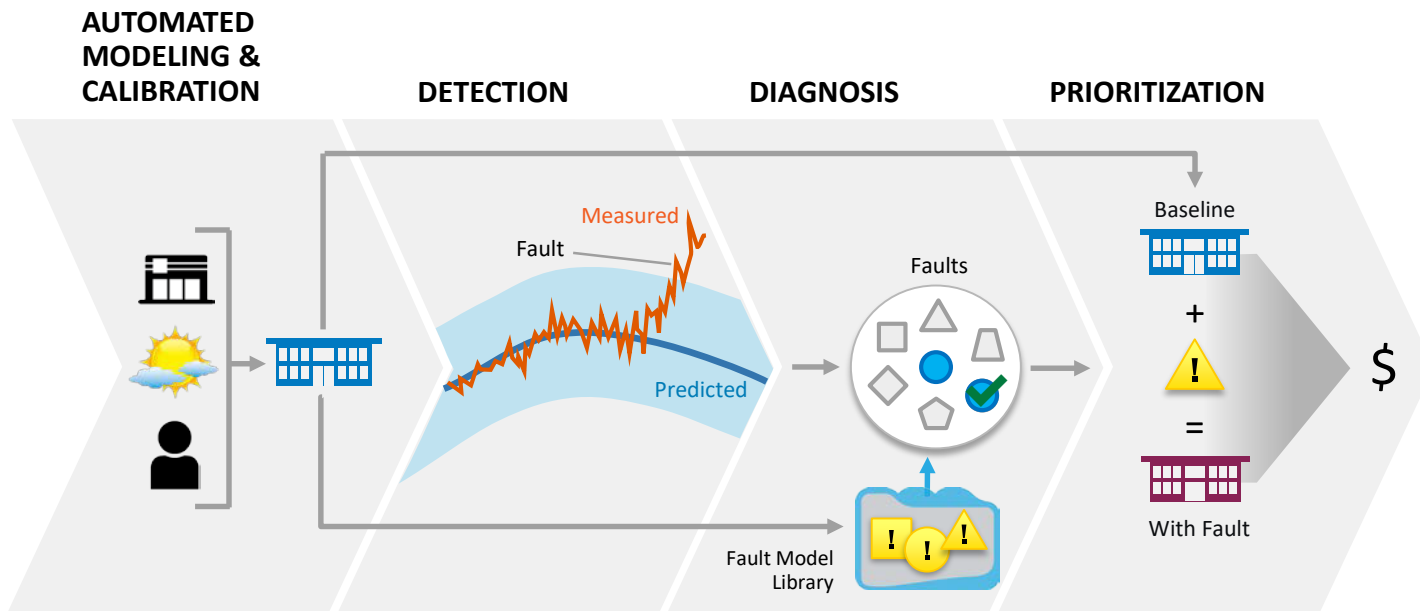
*NA values = No data or no estimate due to small sample size

Net Present Value Analysis: 5,000 ft² Building

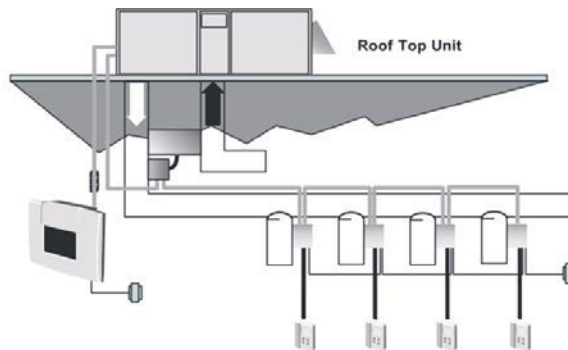
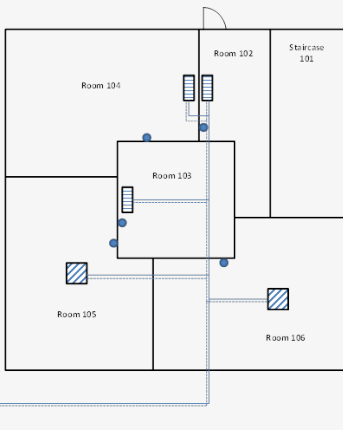
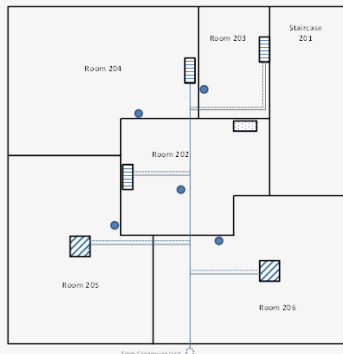
Annual Cost of Capital: 10% | Cost of Energy: \$1.80/ft² | Annual Subscription Cost: 15% of Purchase Price



Research Approach



Case Study: ORNL FRP #2



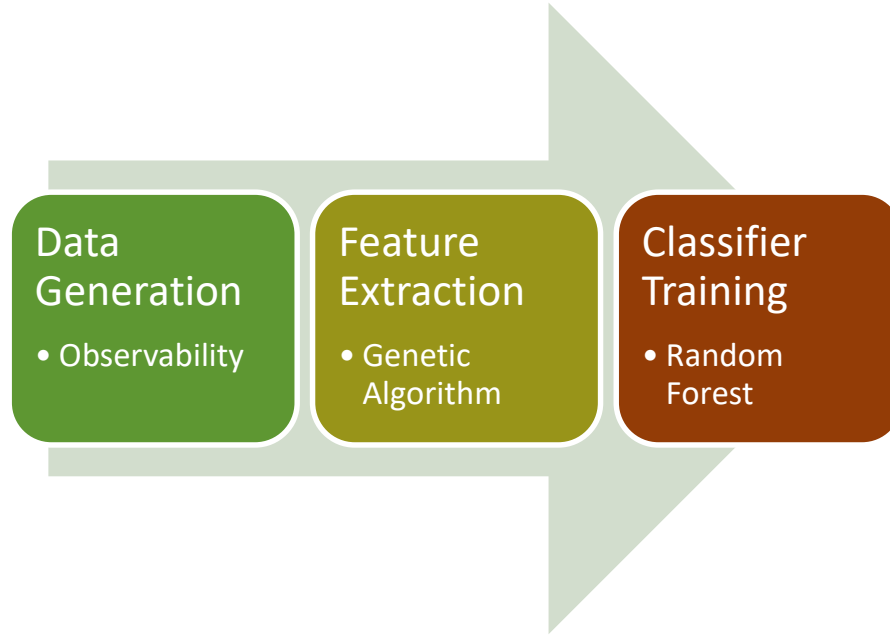
Flexible Research Platform (2-Story)

Oak Ridge National Laboratory

- Dedicated experimental facility (not occupied)
- 3,200 ft²
- Resembles 80's era office building
- RTU + VAV system (10 zone)

We modeled this facility in OpenStudio / E+

Automated AFDD Pipeline



Data Generation



Training Data

25 Fault Measures
6 climate zones (TMY3)
1 year

Testing Data

25 Fault Measures
1 climate zone (AMY3)
1 year

```

air_handling_unit_fan_motor_degradation:0:1
air_handling_unit_fan_motor_degradation:0:2
air_handling_unit_fan_motor_degradation:0:3
based_economizer_sensor_mixed:1-3
based_economizer_sensor_mixed:1-2
based_economizer_sensor_mixed:1-1
based_economizer_sensor_mixed:1:1
based_economizer_sensor_mixed:1:2
based_economizer_sensor_mixed:1:3
based_economizer_sensor_oat:1-3
based_economizer_sensor_oat:1-2
based_economizer_sensor_oat:1-1
based_economizer_sensor_oat:1
based_economizer_sensor_oat:2
based_economizer_sensor_oat:2
based_economizer_sensor_outdoor_rh:1-3
based_economizer_sensor_outdoor_rh:1-2
based_economizer_sensor_outdoor_rh:1-1
based_economizer_sensor_outdoor_rh:1
based_economizer_sensor_outdoor_rh:2
based_economizer_sensor_outdoor_rh:3
based_economizer_sensor_return_rh:1-3
based_economizer_sensor_return_rh:1-2
based_economizer_sensor_return_rh:1-1
based_economizer_sensor_return_rh:1
based_economizer_sensor_return_rh:2
based_economizer_sensor_return_rh:3
based_economizer_sensor_return:1-3
based_economizer_sensor_return:1-2
based_economizer_sensor_return:1-1
based_economizer_sensor_return:1
based_economizer_sensor_return:2
based_economizer_sensor_return:3
condenser_fan_degradation:0:1
condenser_fan_degradation:0:2
condenser_fan_degradation:0:3
condenser_fouling:0:1
condenser_fouling:0:2
condenser_fouling:0:3
condenser_fouling:0:4
condenser_fouling:0:5
duct_fouling:10
duct_fouling:20
duct_fouling:30
economizer_opening_stuck:0:5
economizer_opening_stuck:1
excessive_infiltration:10
excessive_infiltration:20
excessive_infiltration:30
excessive_infiltration:40
hvac_setback_error_delayed_onset:1
hvac_setback_error_delayed_onset:2
hvac_setback_error_delayed_onset:3
hvac_setback_error_early_termination:1
hvac_setback_error_early_termination:2
hvac_setback_error_early_termination:3
hvac_setback_error_no_overnight_setback:TRUE
improper_time_delay_setting_in_occupancy_sensors:1
improper_time_delay_setting_in_occupancy_sensors:2
improper_time_delay_setting_in_occupancy_sensors:3
lighting_setback_error_delayed_onset:1
lighting_setback_error_delayed_onset:2
lighting_setback_error_delayed_onset:3
lighting_setback_error_early_termination:1
lighting_setback_error_early_termination:2
lighting_setback_error_early_termination:3
lighting_setback_error_no_overnight_setback:TRUE
liquid_line_restriction:0:1
liquid_line_restriction:0:2
liquid_line_restriction:0:3
non_standard_charging:0:1
non_standard_charging:0:2
non_standard_charging:0:3
oversized_equipment_at_design:10
oversized_equipment_at_design:20
oversized_equipment_at_design:30
oversized_equipment_at_design:40
oversized_equipment_at_design:50
presence_of_non_condensable:0:1
presence_of_non_condensable:0:2
presence_of_non_condensable:0:3
presence_of_non_condensable:0:4
presence_of_non_condensable:0:5
presence_of_non_condensable:0:6
return_air_duct_leakages:0:1
return_air_duct_leakages:0:2
return_air_duct_leakages:0:3
supply_air_duct_leakages:0:1
supply_air_duct_leakages:0:2
supply_air_duct_leakages:0:3
thermostat_bias:1
thermostat_bias:2
thermostat_bias:3
thermostat_bias:1
thermostat_bias:2
thermostat_bias:3

```

Uninformative Sensor

Informative Sensor

Poor Fault Observability

Good Fault Observability

1.0

0.8

0.6

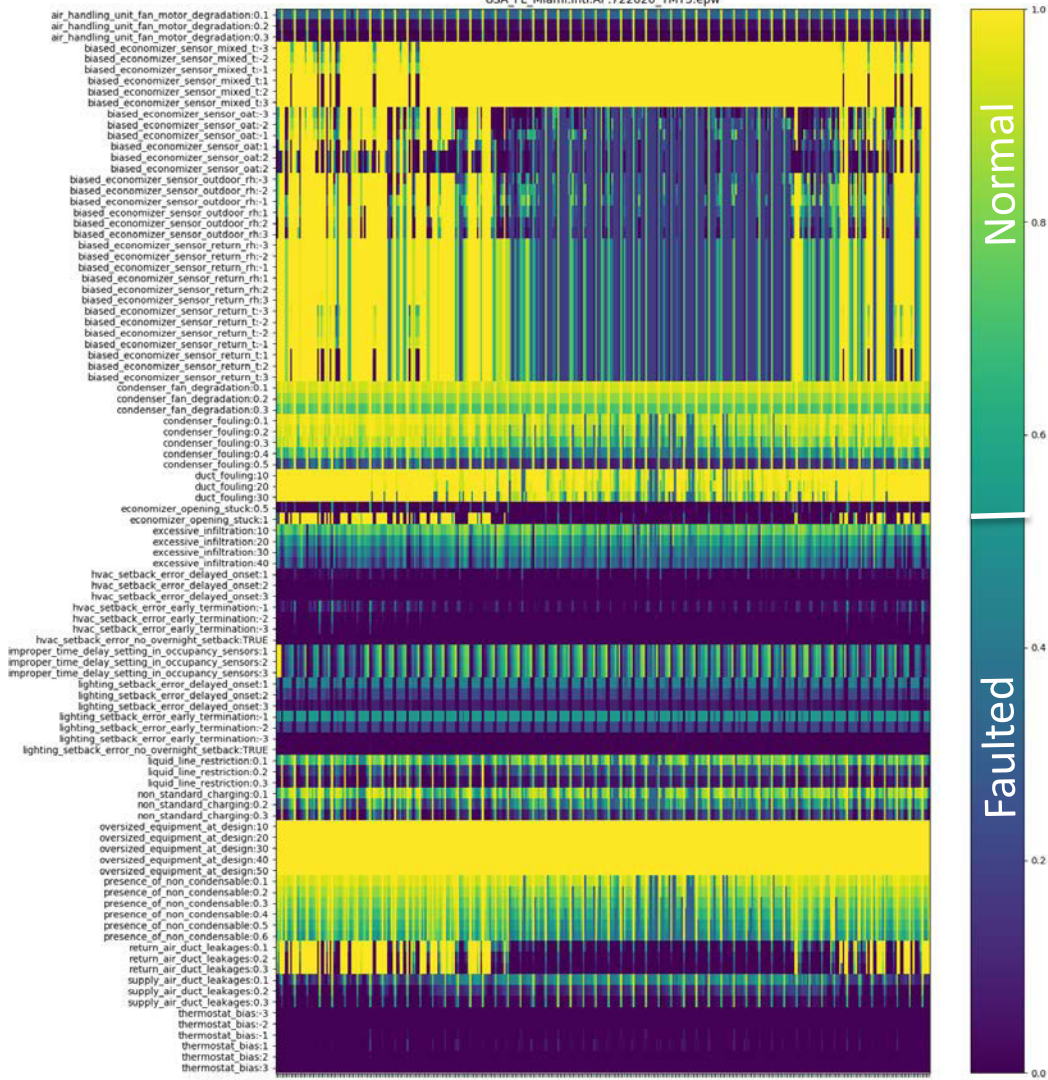
0.4

0.2

0.0

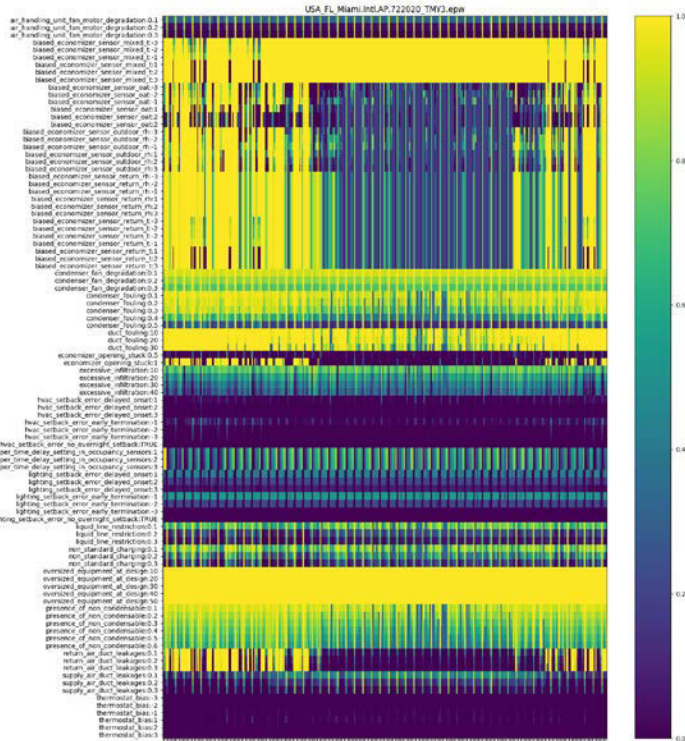
Ground Truth

Recommend that ground truth label of faulted state be based on observability criterion, rather than an energy/performance threshold



Feature Extraction

Observable Faults



Sensor Selection by Genetic Algorithm

Keep Winners

Encode: 1001010110

0 – Sensor not selected
1 – Sensor selected

Fitness function
- $w_1 \times (\text{CDDR}) + w_2 \times (\# \text{ of sensors})$

Evaluate: Fitness Function

Mutate: 1101010110



Multiclass Classification Challenge

Features

room_204_zone_air_relative_humidity [%]_mean
room_204_zone_air_relative_humidity [%]_sum

rooftop_supply_fan_fan_electric_energy [W]_mean
rooftop_supply_fan_fan_electric_energy [W]_sum
rooftop_supply_fan_fan_electric_energy [W]_max
rooftop_supply_fan_fan_electric_energy [W]_std

rooftop_mixed_air_outlet_system_node_temperature [C]_mean
rooftop_mixed_air_outlet_system_node_temperature [C]_sum
rooftop_mixed_air_outlet_system_node_temperature [C]_std
rooftop_mixed_air_outlet_system_node_temperature [C]_min

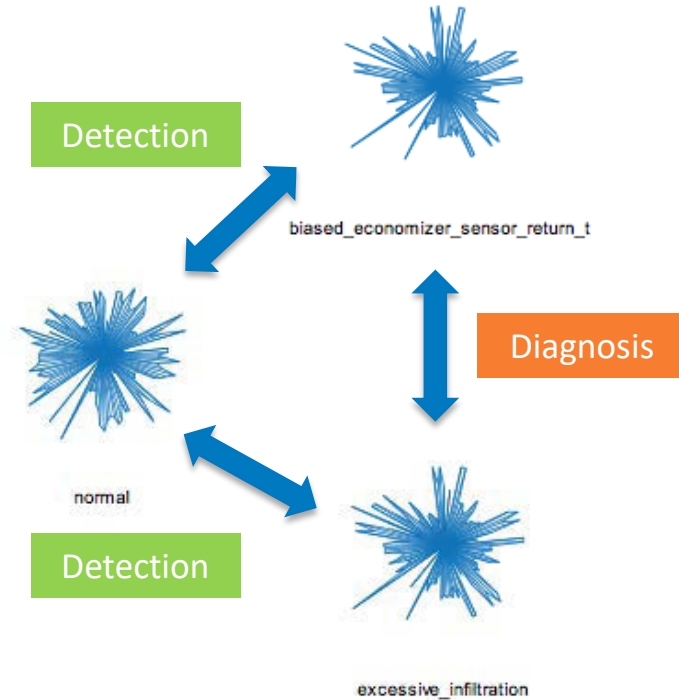
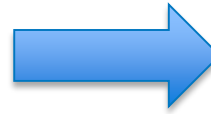
room_201_zone_mean_air_temperature [C]_min

2f_plenum_zone_mean_air_temperature [C]_min

gas_facility [W]_sum
gas_facility [W]_max
gas_facility [W]_std
gas_facility [W]_mean

heating_gas [W]_mean
heating_gas [W]_max
heating_gas [W]_sum
heating_gas [W]_std

25 informative sensors
7 maximally informative sensors
20 input features



Remaining Challenges & Paths Forward

Goal	Challenge	Potential Solution
Automated data generation	Generating data with enough load variation	Building load normalization methods
Improved diagnostic capability	Automatically generating informative features	Include feature types for: <ul style="list-style-type: none">• Building hysteresis• Fault sensitivity• Cyclic pattern recognition
Fast feature generation	Compute for observability and genetic algorithm is intensive	<ul style="list-style-type: none">• Code optimization• Run-time parallelization

Thank you

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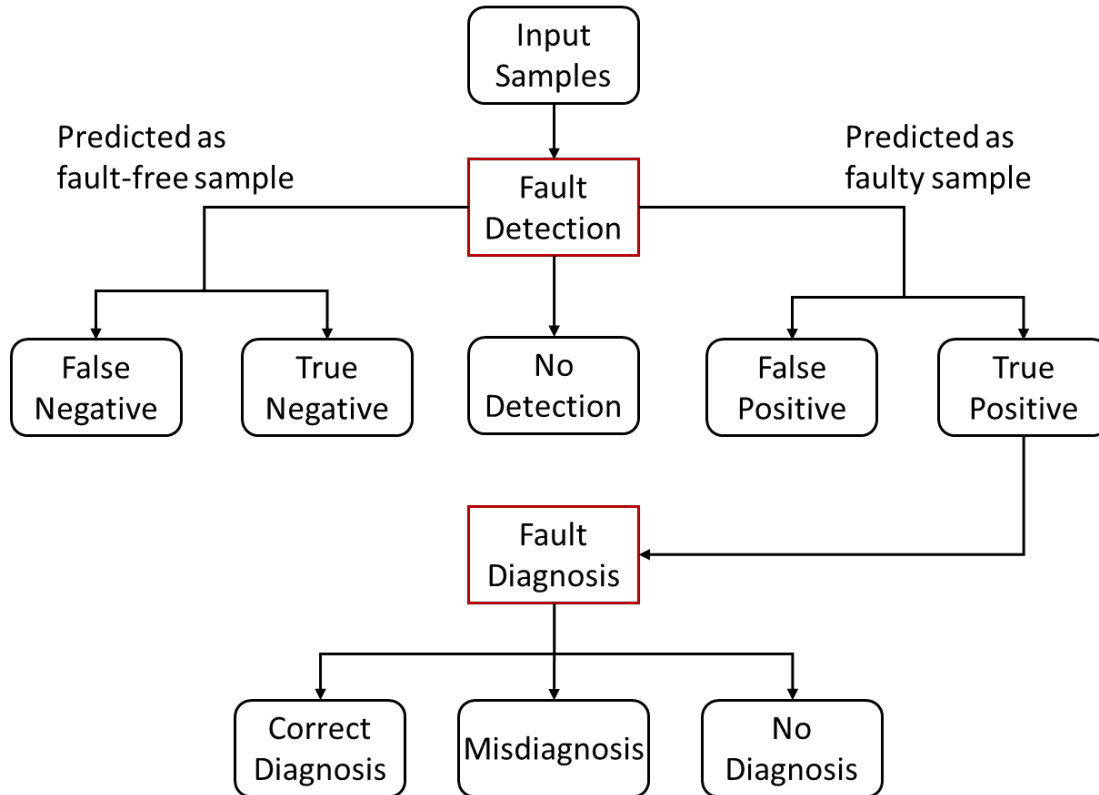


References

(EIA) U. S. Energy Information Administration. 2012. “Commercial Building Energy Consumption Survey (CBECS).” www.eia.gov/consumption/commercial/.

Frank, Stephen, Xin Jin, Daniel Studer, and Amanda Farthing. 2018. “Assessing Barriers and Research Challenges for Automated Fault Detection and Diagnosis Technology for Small Commercial Buildings in the United States.” Draft submitted for publication.

Evaluation: Protocol Outcomes



Evaluation: Confusion Matrix

			Protocol Output (Prediction Condition)					Prediction Condition Negative (no fault detected)	No Detection
			Predicted Condition Positive				No Diagnosis		
			Fault 1	Fault 2	Fault 3	No Diagnosis			
Ground Truth (True Condition)	Condition Positive	Fault 1	Correct diagnosis (CD ₁)	Misdiagnosis (MD _{1,2})	Misdiagnosis (MD _{1,3})	No diagnosis (ND ₁)	False negative (FN ₁)	No detection positive (ND _{P,1})	
		Fault 2	Misdiagnosis (MD _{2,1})	Correct diagnosis (CD ₂)	Misdiagnosis (MD _{2,3})	No diagnosis (ND ₂)	False negative (FN ₂)	No detection positive (ND _{P,2})	
		Fault 3	Misdiagnosis (MD _{3,1})	Misdiagnosis (MD _{3,2})	Correct diagnosis (CD ₃)	No diagnosis (ND ₃)	False negative (FN ₃)	No detection positive (ND _{P,3})	
	Condition Negative (No Fault)	False positive (FP)				True negative (TN)	No detection negative (ND _N)		

Evaluation: Combined Detection & Diagnosis Rate (CDDR)

Combined Detection & Diagnosis Rate: Fault i

$$\text{CDDR}_i = \frac{\text{CD}_i}{\text{CD}_i + \sum_{j=1, i \neq j}^N \text{MD}_{i,j} + \text{ND}_i + \text{FN}_i + \text{ND}_{P,i}}$$

Number of Samples where ground truth = fault i

Combined Detection & Diagnosis Rate: Overall

$$\text{CDDR} = \frac{\text{TN} + \sum_{i=1}^N \text{CD}_i}{\sum_{i=1}^N \left(\text{CD}_i + \sum_{j=1, i \neq j}^N \text{MD}_{i,j} + \text{ND}_i + \text{FN}_i + \text{ND}_{P,i} \right)}$$

Number of Samples where ground truth = any fault