Evaluation of Fault Prevalence in Commercial Buildings

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Project Summary

Timeline:

Start date: 10/1/19

Planned end date: 9/30/22

Key Milestones

1. Midpoint review: partners engaged, technical work on track (12/20/20)
2. Initial review of study data collected to date is conducted and confirms quality and sufficiency needs for priority faults and systems (3/15/21)
3. Fault prevalence metrics have been calculated for all targeted fault types in Study Design (9/20/21)

Key Partners:

Pacific Northwest National Lab
University of Nebraska-Lincoln
7 Data Partners (6 FDD tool developers + 1 building owner)
11 Technical Advisory Group Members

Targeted HVAC Equipment Types

AHU: Air Handler

ATU: Air Terminal Unit

RTU: Rooftop HVAC Unit

Budget:

Total Project $ to Date:

- DOE: $884k
- Cost Share: $0

Total Project $:

- DOE: $1500k
- Cost Share: $0

Project Outcome:

- Conduct the efficiency community's most comprehensive study ever on the prevalence of HVAC faults in commercial buildings in the U.S. (AHUs / ATUs / RTUs)
- This will support acceleration of FDD deployment in commercial buildings, improvement of FDD fault detection algorithms, improvements to HVAC system reliability
- Ultimate goal is to meet long term energy and carbon reduction goals.

FDD Defined

Fault Detection & Diagnostics (FDD) tools analyze building automation system data to identify HVAC faults

Team

- >10 years building data analytics research
- >$5m Annual research budget for EMIS R&D
- Extensive network of FDD developers & users

- Data collection experience at PNNL/Federal sites
- >$5M annual R&D budget for controls/analytics
- Experience developing and commercializing FDD

- Researched building technologies since 1987
- Led 10 HVAC fault/FDD projects
- Deep R&D experience in industry and academia

Activity	LBNL	PNNL	UNL
PM and Partner Engagement	X		
Data Cleaning / Normalization	X		X
Data/Metric Specifications	X		
Analysis Code Development	X	X	X
Code Infrastructure / Review		X	
Data QC	X		
Field Studies			X
Data Analysis	X	X	X
Dissemination	X	X	X

Challenge

Problem Definition:

- 18% of U.S. energy use is consumed by commercial buildings[1], with ~40% of that going to HVAC
- In aggregate, HVAC faults in U.S. commercial buildings have been estimated to waste 0.7 quads of energy annually (worth nearly $14 billion)
- Past studies on HVAC faults have used relatively limited datasets, inconsistent analysis approaches
- Lack of reliable HVAC fault prevalence data has been documented as a key barrier to owners and operators who use automated fault detection and diagnostics (FDD) technology, as well as researchers and developers

- FDD software is an important tool for elevating commercial buildings' performance to meet DOE's long term climate goals; what can a building owner expect when installing FDD?

- **Key questions:**
  - Which fault types are most common?
  - Which components suffer faults most frequently?
  - How many faults are likely to be triggered monthly/annually in any given building?
  - What key drivers affect fault prevalence? (e.g., building type, climate zone, time of year)

[1] EIA 2020

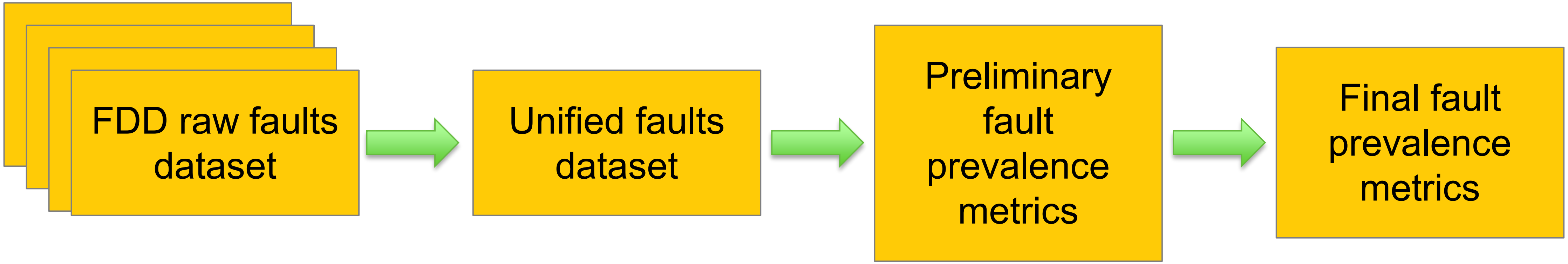
Approach: Overview

[1] Obtain FDD faults' data from multiple sources

[2] Convert all raw data into unified / standardized dataset

[3] Calculate and analyze key metrics from unified data

[4] Publish results based on statistical analysis, review of key drivers, verification activities



Big data …

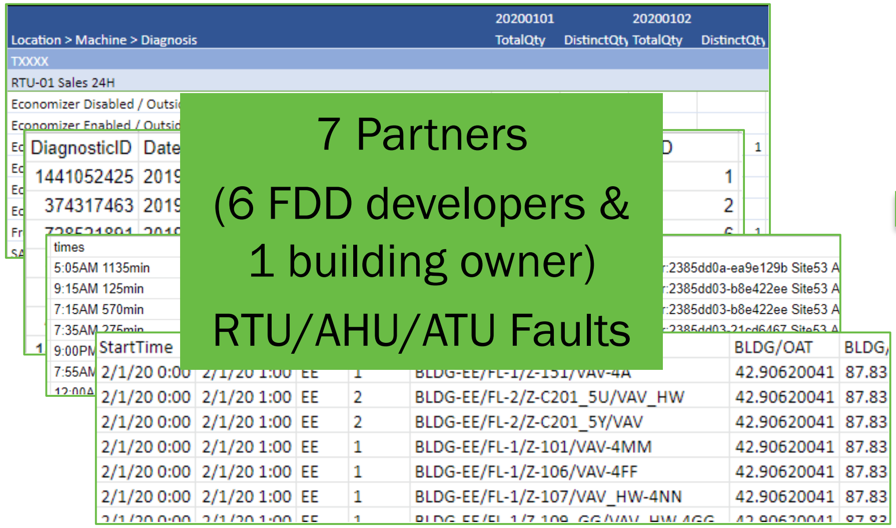
… consistent data …

… exploratory results …

… reliable results …

Approach: Data Cleaning, Unification, QC

FDD tools' raw data



Binary Daily Format ('BDF')
(>14 million rows!)

	Fault record	Building ID	Equipment ID	Date	Fault name raw	Fault name mapped
	0	C0001	RTU-68	20180101	SAT Too High Condition	RTU-SAT-Abnormal
	1	C0001	DHU-4	20180101	ZAT Drift: Heating Not Activated	VAVUNIT-ZAT-Drift
	2	C0001	RTU-105	20180102	Zone Air Dew Point Reading Exceeds 53	VAVUNIT-ZAT-Unspecified
	3	C0001	RTU-68	20180102	SAT Too High Condition	RTU-SAT-Abnormal
	4	C0001	DHU-4	20180102	ZAT Drift: Heating Not Activated	VAVUNIT-ZAT-Drift
	5	C0001	RTU-54	20180103	Setpoint Not Met - ZAT - Over Cooling - Occupied	VAVUNIT-ZAT-Abnormal
	6	C0001	RTU-86	20180103	Setpoint Not Met - ZAT - Over Cooling - Occupied	VAVUNIT-ZAT-Abnormal
	7	[illegible]	RTU-105	[illegible]	[illegible] Air Dew Point Reading Exceeds 53	[illegible]

Tagged by fault / equipment

Indicates fault presence on a specific date

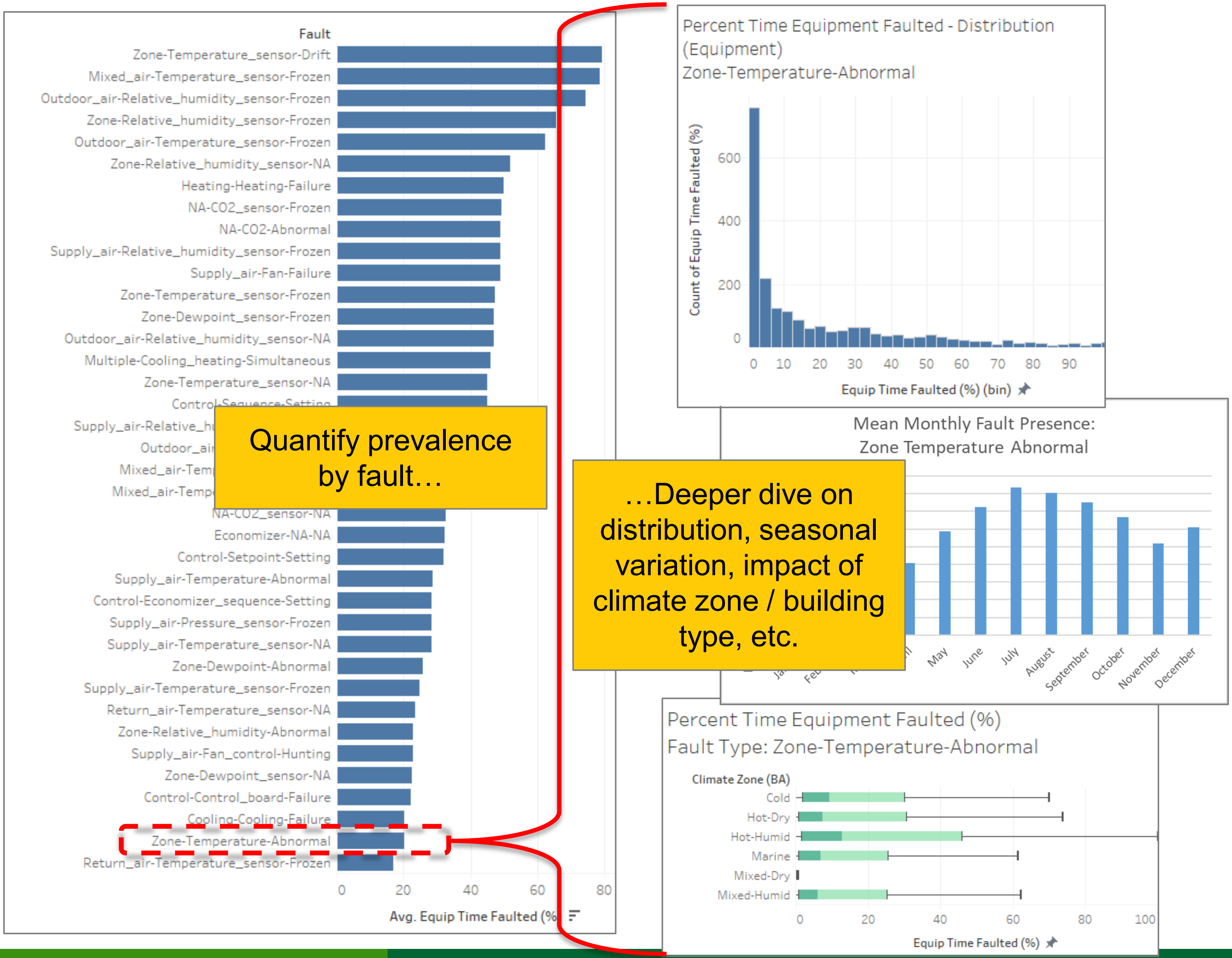
Consistent fault taxonomy

Key Risks	Mitigation
Data gaps/duplication	QC reports identify patterns/anomalies
Proving absence of fault (e.g., fault rule not applied, component doesn't exist)	Partner collaboration; metadata report review; QC reports
Small sample size	Highlight/exclude results where subset is small (e.g., isolating a specific climate zone and building type)
Pandemic affects fault prevalence	Exclude data after December 2019
False alarms	Verification activities

Excerpt of example QC report, used to identify data anomalies

Fault name	201901	201902	201903	201904	201905
RTU-Zone-Relative_humidity_sensor-Frozen	1.4	-0.6	-0.5	-1.1	-2.0
RTU-Zone-Temperature-Abnormal	12.6	12.0	12.1	12.3	13.3
RTU-Outside_air-Temperature_sensor-Frozen	3.0	2.1	2.2	1.3	1.2
RTU-Supply_air-Temperature-Abnormal	6.4	4.7	5.1	4.0	3.8
RTU-Economizer-Sequence-Setting	7.9	7.9	8.5	7.0	3.2
RTU-Supply_air-Temperature_setpoint-Rule_Ab	12.5	10.0	12.1	8.8	5.6
RTU-Zone-Temperature_sensor-Unspecified	15.2	13.7	15.1	15.2	16.1
RTU-Outside_air-Airflow-Abnormal	1.3	0.0	-0.4	-1.1	-1.8
RTU-Supply_air-Temperature_sensor-Frozen	-0.1	-0.1	-0.3	-0.3	0.0
RTU-Zone-Relative_humidity-Abnormal	0.2	0.5	0.4	0.3	1.1
RTU-Zone-Temperature_sensor-Frozen	-12.1	-11.6	-13.5	-14.0	-14.4
RTU-Compressor-Unassigned-Unspecified	1.7	3.4	2.4	2.5	3.9

Approach: Fault Prevalence Metrics (Example)



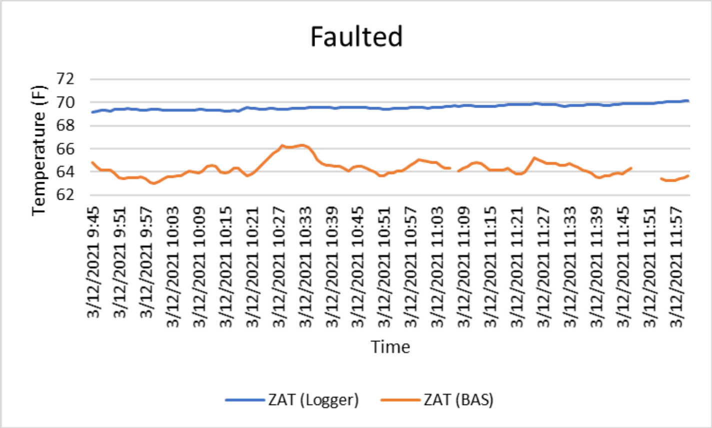
Metrics address key questions:

- **Which faults are most often observed to be present?**
- **What percentage of units are observed to be faulted at any given point in time?**
- **How many faults are observed to be present each month for a given building type?**

Approach: Verification

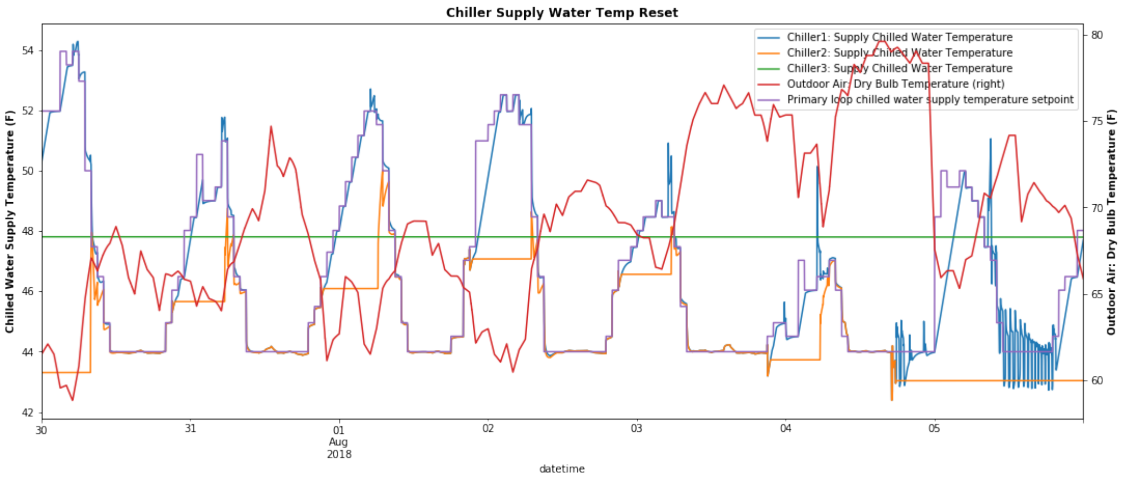
Verification activities mitigate risk of FDD fault reporting error (i.e., false positive, false negative)

1. Field Visits: Compare FDD results to manual inspection and data loggers (sample of sites)



2. Ground truth testing FDD algorithms (separate Berkeley Lab project)

- Time series HVAC operational data with known faults and their associated intensity, to be used for benchmarking FDD algorithms
- Data on false positive/negative can be used to apply uncertainty bounds on fault prevalence study results



Impact

Fault Prevalence study results

Building owners/ managers
- Stronger business case
- Allocate adequate O&M resources

→ Increased market demand

FDD developers
- Increased focus on key FDD functionality gaps
- Improve interpretability of fault reports

→ Improved analytics tools

HVAC designers / component manufacturers
- Prioritize reliability improvements

→ Increased HVAC system reliability

Researchers
- Develop new functionality on solid empirical foundation

→ Accelerated R&D

DOE Goal

Triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels.

Projected impact from expanded deployment of FDD

With 9% savings[1], FDD adoption by 10% of eligible buildings[2] can result in 54TBtu[3] annual source energy savings ($0.5b)[3]

[1] Median savings for FDD users, based on Smart Energy Analytics Campaign
[2] Commercial buildings >100,000 sq.ft.
[3] Based on CBECS data

Progress: Data Received

Data*

- Data received from 6 partners so far (1 pending)
- 1,526 buildings (50 pending)
  - 8,140 RTUs
  - 3,729 AHUs
  - 44,572 ATUs
- >14 million rows of fault data

Fault record	Building ID	Equipment ID	Date	Fault name mapped
0	C0001	RTU-68	20180101	RTU-SAT-Abnormal
1	C0001	DHU-4	20180101	VAVUNIT-ZAT-Drift
2	C0001	RTU-105	20180102	VAVUNIT-ZAT-Unspecified
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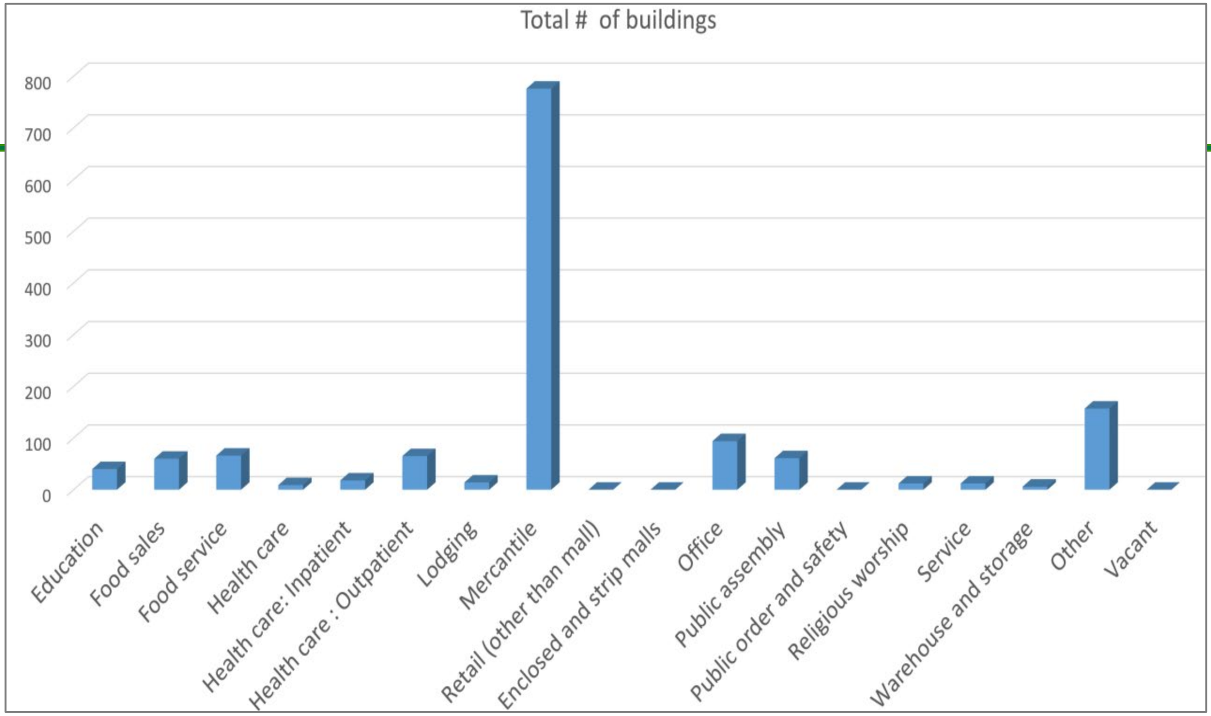

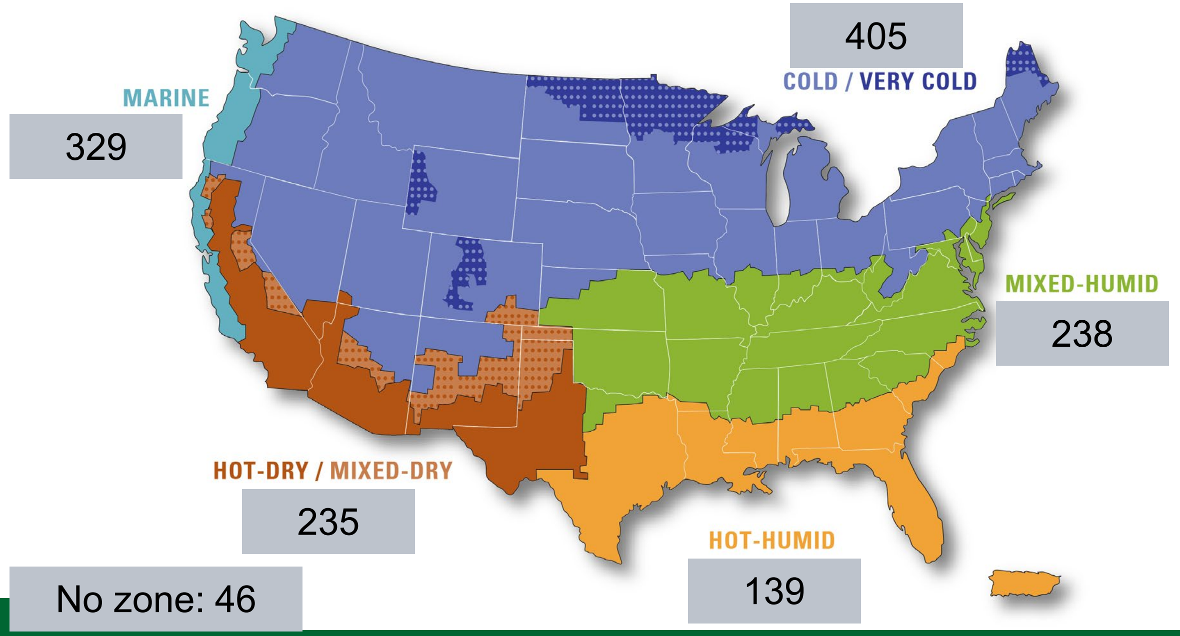

* Data will be used to calculate metrics; data will not be made public

Progress: QC and Metrics Development

QC

- Data QC complete for all received data

Fault name	201901	201902	201903	201904	201905
RTU-Zone-Relative_humidity_sensor-Frozen	1.4	-0.6	-0.5	-1.1	-2.0
RTU-Zone-Temperature-Abnormal	12.6	12.0	12.1	12.3	13.3
RTU-Outside_air-Temperature_sensor-Frozen	3.0	2.1	2.2	1.3	1.2
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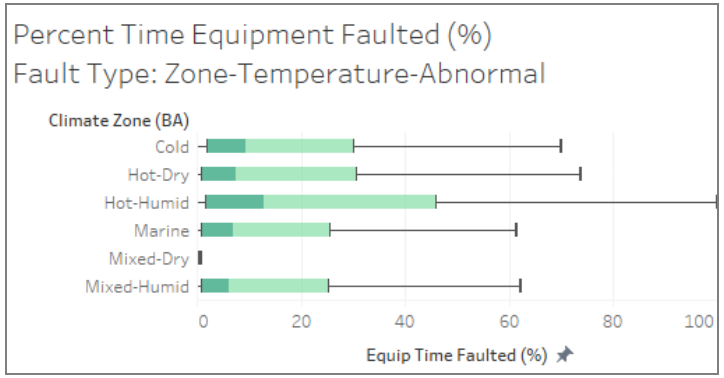
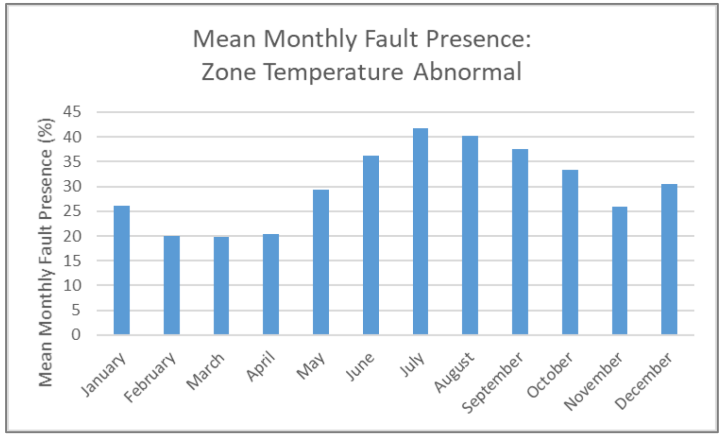
RTU-Zone-Temperature_sensor-Unspecified	15.2	13.7	15.1	15.2	16.1
RTU-Outside_air-Airflow-Abnormal	1.3	0.0	-0.4	-1.1	-1.8
RTU-Supply_air-Temperature_sensor-Frozen	-0.1	-0.1	-0.3	-0.3	0.0
RTU-Zone-Relative_humidity-Abnormal	0.2	0.5	0.4	0.3	1.1
RTU-Zone-Temperature_sensor-Frozen	-12.1	-11.6	-13.5	-14.0	-14.4
RTU-Compressor-Unassigned-Unspecified	1.7	3.4	2.4	2.5	3.9

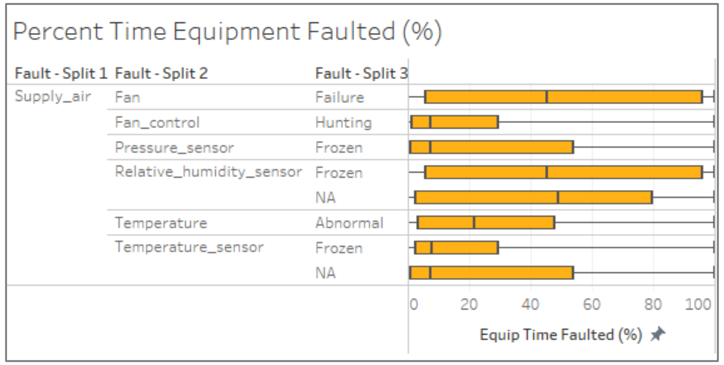
C0012	C-RTU00158	0	0	0	0	0	0	0	0	0	0	0	0
C0012	C-RTU00159	0	0	0	0	0	0	0	0	0	0	0	0
C0012	C-RTU00160	0	0	0	0	0	0	0	0	0	0	0	0
C0012	C-RTU00164	0	0	0	0	0	0	0	0	0	0	0	0
C0012	C-RTU00167	0	0	0	0	0	0	0	0	0	0	0	0
C0012	C-RTU00153	100	89.29	96.77	100	80.65	63.33	19.35	32.26	6.67	41.94	96.67	35.48
C0012	C-RTU00157	83.87	92.86	96.77	73.33	61.29	36.67	6.45	0	0	35.48	86.67	22.58
C0012	C-RTU00156	100	96.43	100	100	100	66.67	32.26	6.45	3.33	16.13	90	32.26
C0012	C-RTU00161	96.77	85.71	100	100	93.55	66.67	19.35	0	0	0	0	0
C0012	C-RTU00165	96.77	89.29	83.87	93.33	58.06	20	9.68	0	0	0	0	0
C0012	C-RTU00162	100	82.14	96.77	96.67	93.55	66.67	38.71	16.13	0	0	86.67	38.71
C0012	C-RTU00166	100	85.71	100	100	96.77	53.33	25.81	38.71	20	48.39	96.67	32.26
C0012	C-RTU00168	100	96.43	100	100	100	70	54.84	48.39	23.33	48.39	100	38.71
C0012	C-RTU00163	100	96.43	96.77	96.67	100	76.67	19.35	0	0	0	0	0
C0012	C-RTU00154	83.87	71.43	93.55	100	100	100	90.32	32.26	63.33	67.74	100	38.71
C0012	C-RTU00155	90.32	92.86	100	93.33	87.1	83.33	38.71	48.39	10	25.81	73.33	32.26

Metrics

- 5 Metrics Defined & Coded:
  - Monthly Fault Presence
  - Average Monthly Fault Presence
  - Mean Faults per Building per Month
  - Percent Equipment Faulted
  - Percent Time Equipment Faulted

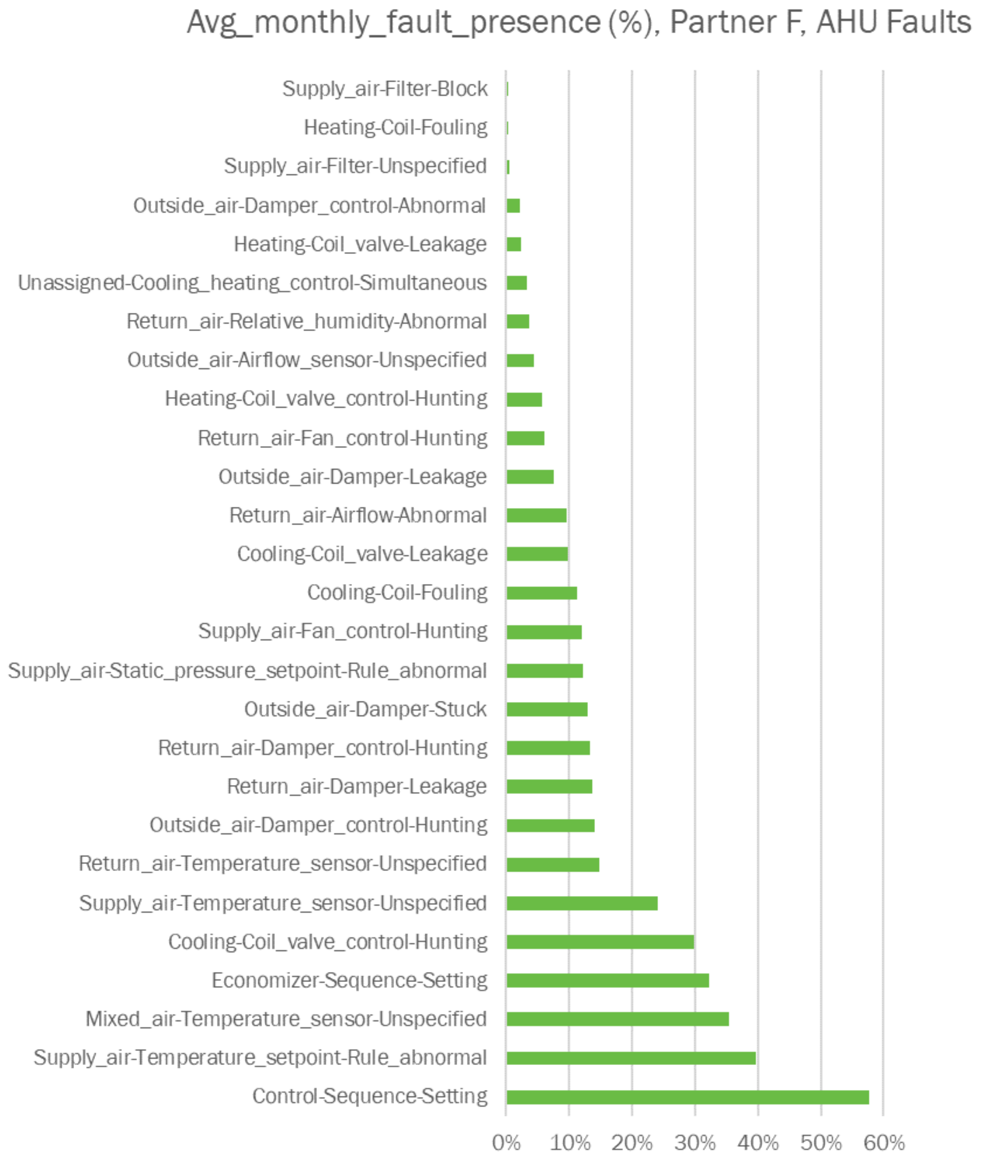






Progress: Preliminary Results (example)

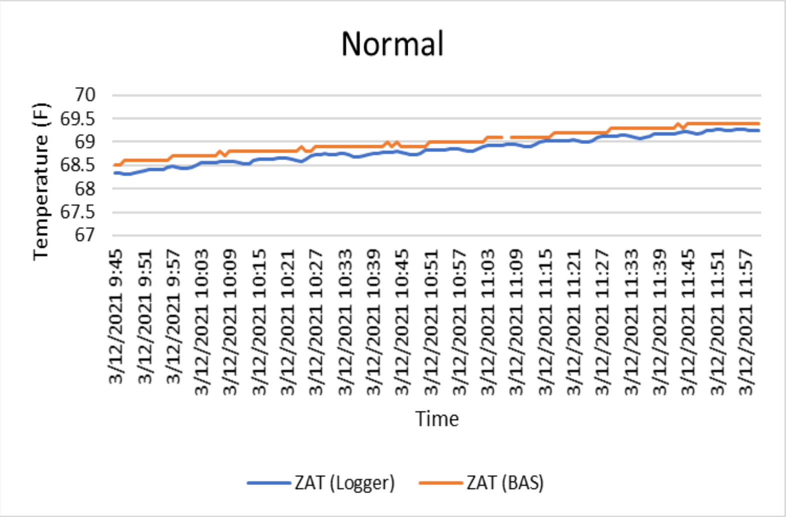
- 27 AHU Fault types reported
- Top 10 faults account for 73% of overall "fault_months"
- Top 10 ranges from 13% - 58% Avg Monthly Fault Presence
- 4 Sensor-related faults
- 8 Economizer-related faults
- 7 Coil-related faults
- Location/Section
  - Outside Air: 5
  - Mixed Air: 1
  - Return Air: 6
  - Supply Air: 5
  - Cooling Coil: 3
  - Heating Coil: 3
  - Control: 1

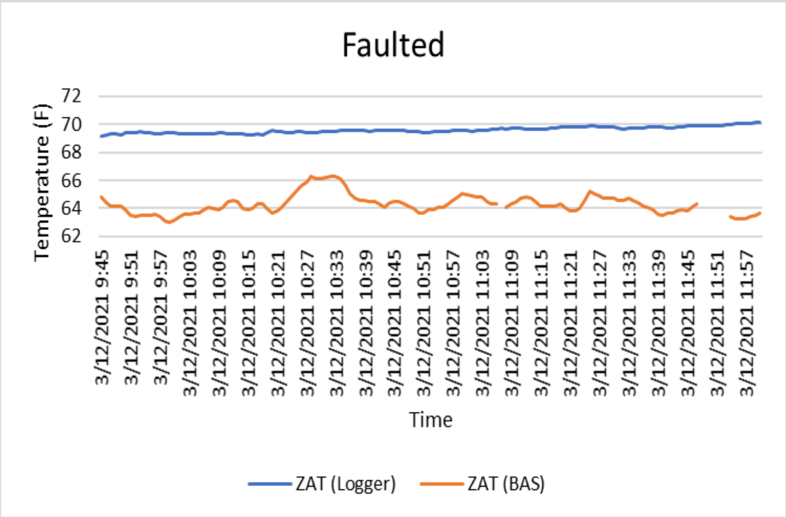


- Ongoing results review for all faults, all metrics, all data partners
- Distribution & sample size analysis ongoing
- Iterative review of metric specifications and taxonomy application
- Ongoing communications with data partners on data interpretation

Progress: Field Validation

Example:
Fault: RTU-Zone-Temp_Sensor-Drift
Detection Method: Comparing BAS and Logger Values
Detection Threshold: 2°F
 # Units Faulted: 3 out of 11 (27%)





- **3 site visits to date**
- **Data analysis in progress (not yet cross-checked to FDD results)**
- **Insufficient data for applying confidence bounds around FDD analysis results, but insights gained regarding potential error**
- **Key issue: Need to determine best way to increase confidence in sensor-related faults. Options:**
  - Exclude some faults' data
  - Request more thorough inventory data for BAS sensors
  - Cross-check BAS trend data
  - Ignore if found to be low impact
- **Overarching issue: Pandemic limits travel and availability of sites to visit**

Stakeholder Engagement

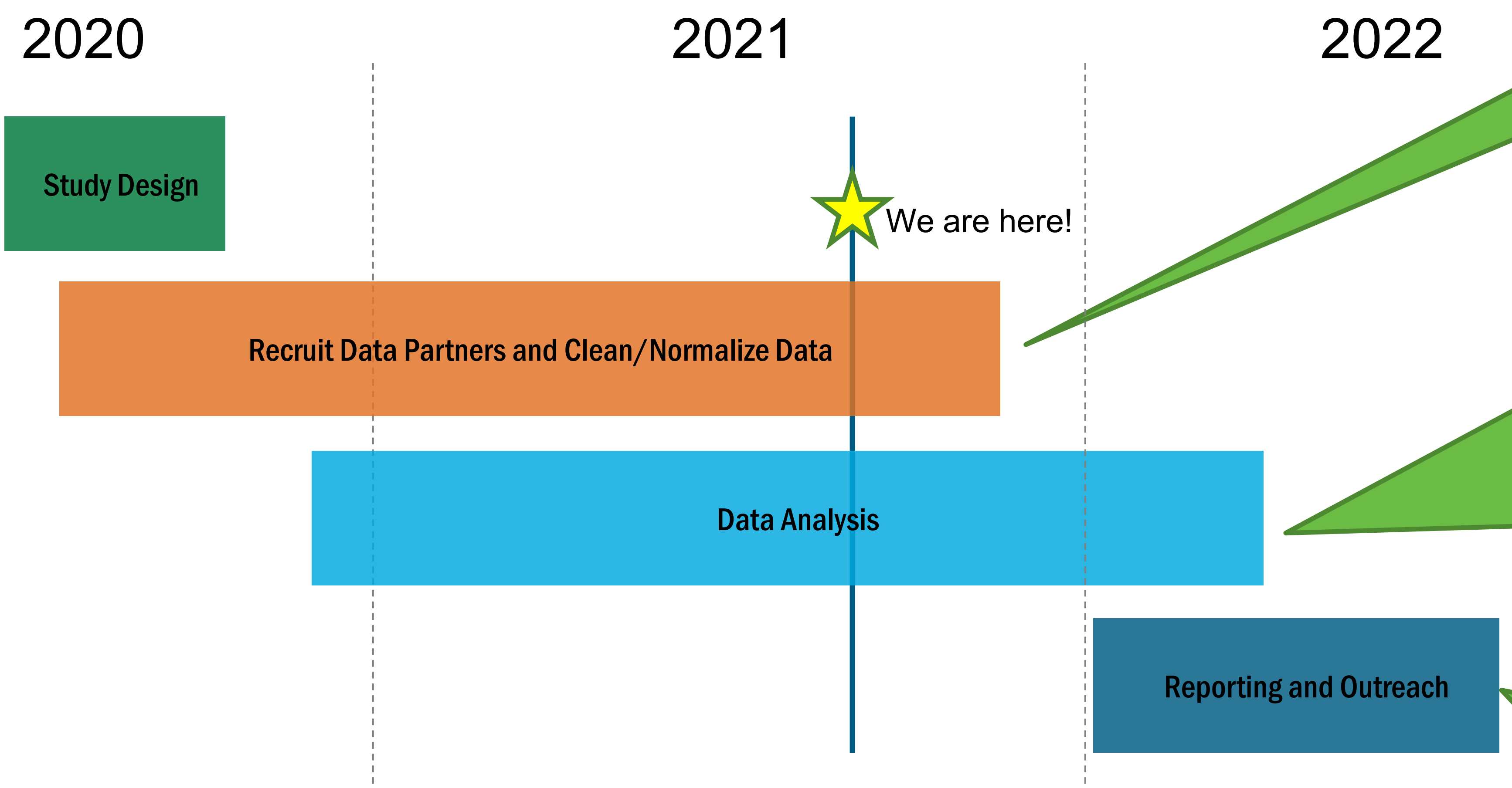
Technical Advisory Group Participating Organizations
BC Hydro
Carrier
Clockworks Analytics
CopperTree Analytics
Hydro Quebec
JCI
NYSERDA
SkyFoundry
Southern Co
Texas A&M
Tridium

Outreach to date:

- ACEEE Summer Study paper (2020)
- Purdue Conference Paper (2021)
- ASHRAE Conference Presentation (2021)
- Co-authored journal paper in *Science and Technology for the Built Environment*
- Journal paper submitted to *Energies*

- *Close ongoing collaboration with 7 data partners (6 FDD tool developers & one building owner)*

Remaining Project Work



- Integrate final data sets

- Complete and integrate verification outputs
  - Field verification
  - FDD Algorithm's ground truth testing
- Develop combined results across all data partners
- Statistical analysis of results
  - Correlation with key drivers
  - Sample size / precision
  - Representativeness

- Outreach
  - Conference papers
  - Journal papers
  - Webinars

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $1500k
Variances: Not applicable
Cost to Date: $884k
Additional Funding: Not applicable

Budget History					
FY 2020 (start date 10/1/19)		FY 2021* (current)		FY 2022 (planned end date 9/30/22)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$431k	$0	$658k	$0	$411k	$0

* FY21 spend to date, plus projection thru end of year

Project Schedule

Project Start: 10/1/19

Projected End: 9/30/22

- Completed Work
- Active Task (in progress work)
- Milestone/Deliverable (Originally Planned)
- Milestone/Deliverable (Actual)

Task	FY2020				FY2021				FY2022			
	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	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												
Draft study design is documented for review by DOE and partners and/or TAG.												
Preliminary analysis of data from pilot study from four or more sites is documented.												
Data cleaning and mapping methods developed for pilot study are found to be scalable within project resources for application to the full study dataset; study design is refined based on pilot findings, and documentation demonstrates that pilot findings merit continuation of full study.												
~Midpoint status review for Task 3 (implement study) and project as a whole, shows that partners remain engaged, research management processes are functioning, and technical work is on track. Feedback on analysis results to has been documented.												
Initial review of study data collected to date is conducted and confirms quality and sufficiency needs for priority faults and systems. Robust approach to cataloging results has been developed, and approach has been developed for drawing out key conclusions from analysis results.												
Ongoing review of data collected to date is conducted and confirms quality and sufficiency needs for fault prevalence estimates. Data verification activities/results provides preliminary basis for documenting confidence in study results												
Current/Future Work												
Preliminary plots and metrics from full study are generated, showing that fault prevalence estimates meet study accuracy targets.												
Drafts of dissemination materials, are prepared for DOE and/or TAG review.												
Results finalized and project close-out conducted with DOE and/or TAG.												