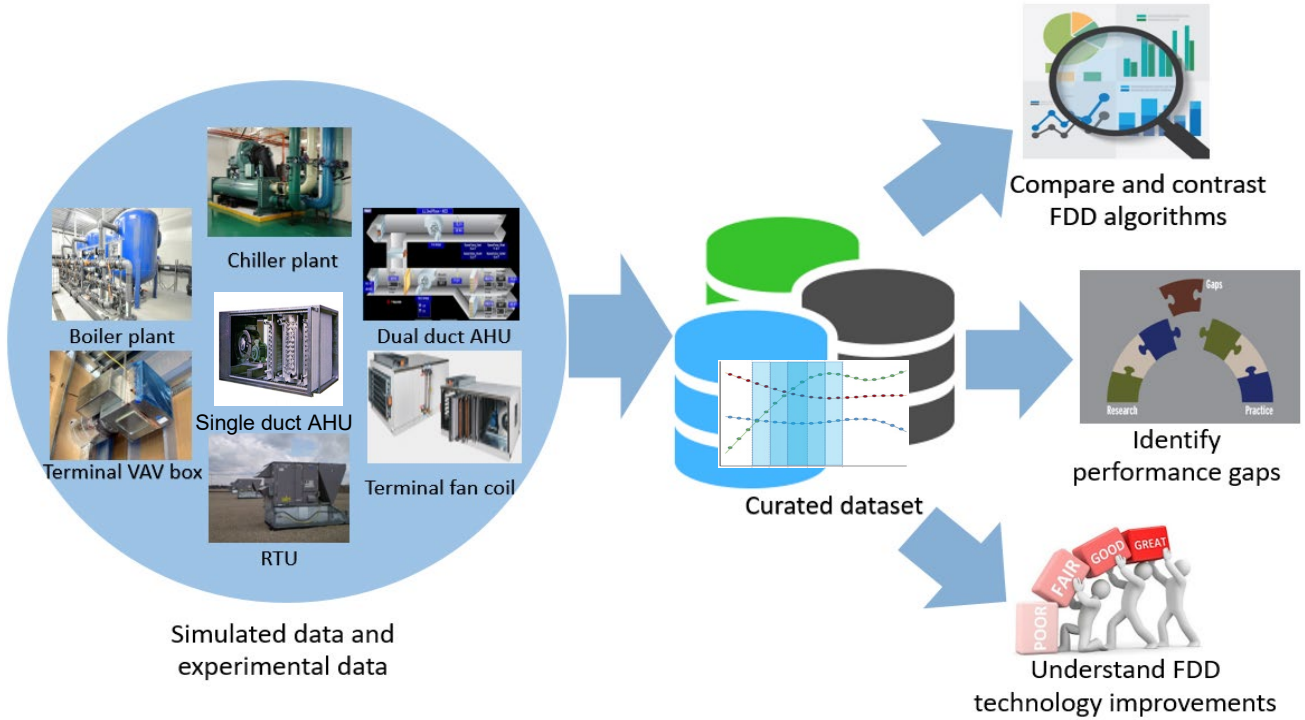
AFDD: Test Datasets and Prioritization Methods



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Project Summary

Timeline:

Start date: October 1, 2019

Planned end date: Sept 30, 2022

Key Milestones

1. FDD dataset curation and validation; FY20
2. Fault prioritization state of art and gaps; FY21
3. FDD dataset benchmark case studies; FY22

Budget:

Total Project $ to Date:

- DOE: $1.2 million
- Cost Share: $0

Total Project $:

- DOE: $1.775 million
- Cost Share: $0

Key Partners:

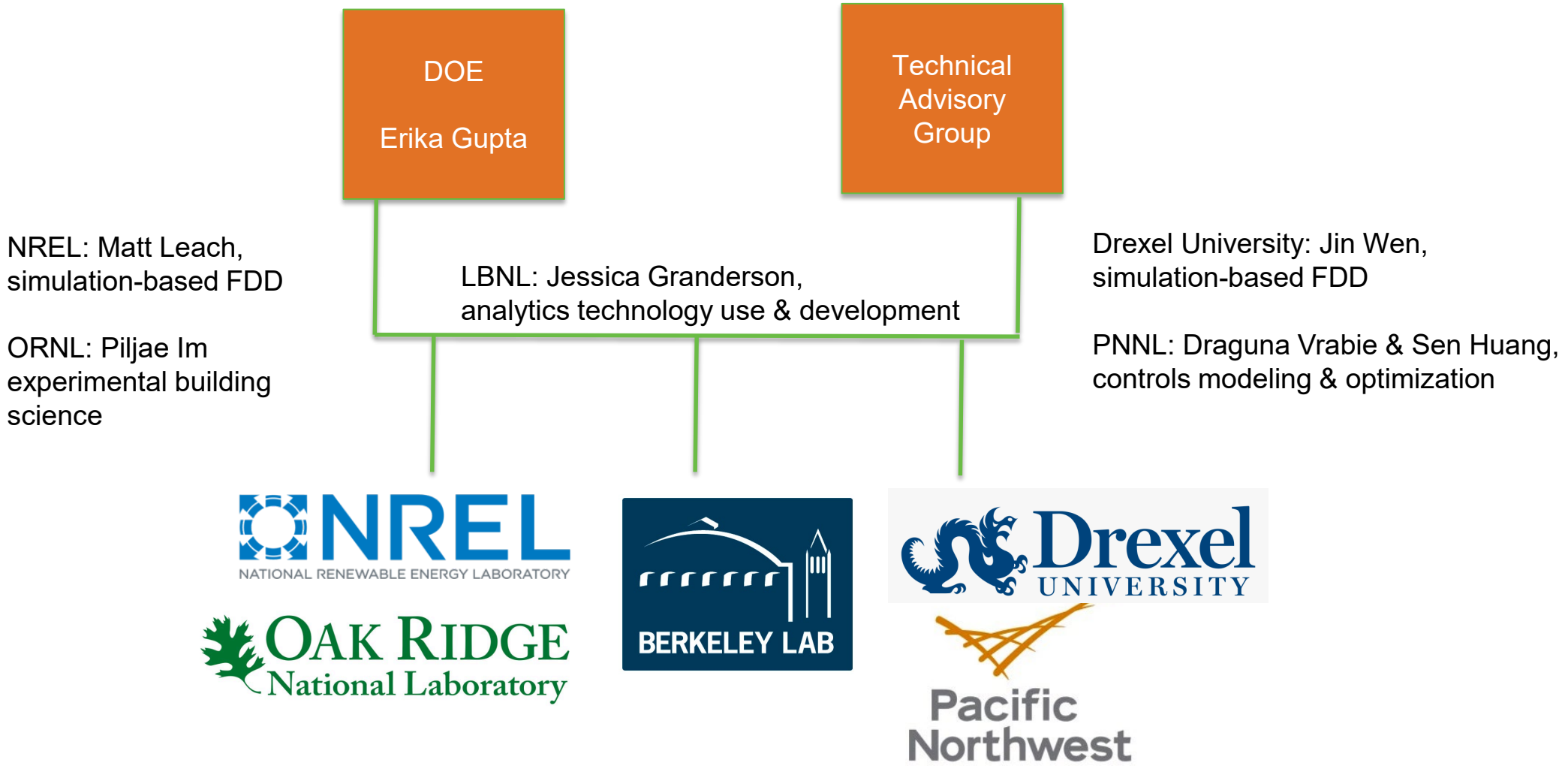
Drexel University
Pacific Northwest National Laboratory
National Renewable Energy Laboratory
Oak Ridge National Laboratory
11 Technical Advisory Group Members

Project Outcome:

- **Primary**: Create world's largest publicly available dataset for evaluating fault detection and diagnostics (FDD) algorithm accuracy

- **Secondary**: Provide guidance for FDD users and recommendations for future R&D to enhance fault prioritization

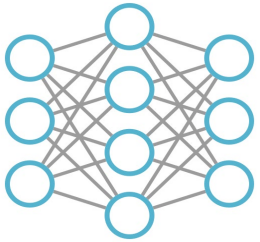
Team



Multi-organizational collaboration

Challenge

- Leading-edge users using FDD to enable ~9% portfolio savings[1]



- As data science comes to buildings, explosion of interest in advanced analytics approaches
  - 100s of peer reviewed articles, continuous development

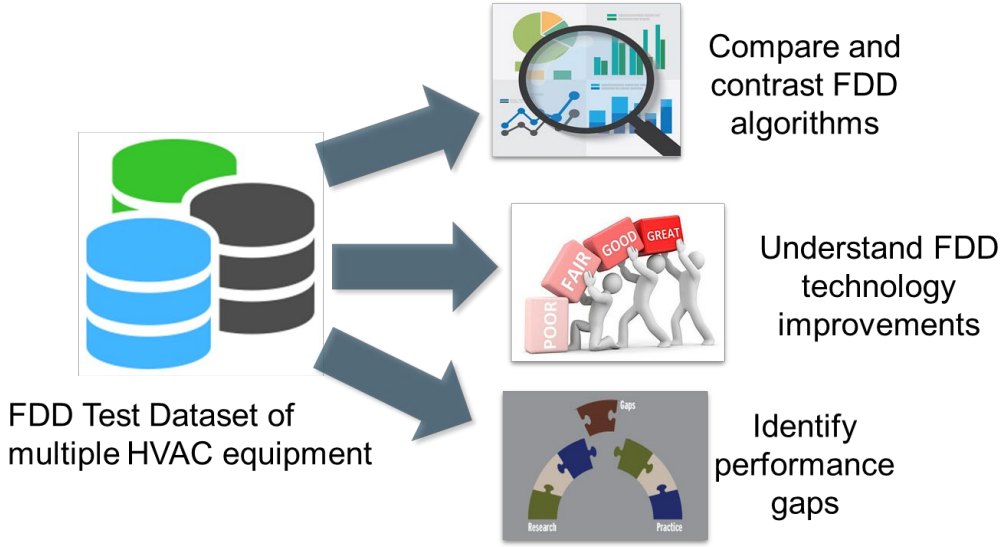
- ~$6B building analytics market, one of the fastest growing markets
- Users, researchers have limited common test datasets to evaluate performance, train/test solutions
  - What is good, are we improving, where do we focus our efforts?

- Although leading-edge users derive strong value from FDD technology, they lack robust techniques to manage large volumes of faults

1. Kramer H, Lin G, Curtin C, Crowe E, Granderson J, Proving the Business Case for Building Analytics, Better Buildings, U.S. Department of Energy, 2020

Project Goals

- Create the world's largest publicly available test dataset for FDD performance evaluation to facilitate innovations
  - Time series of HVAC operational data (e.g. temp., pressure, control signal) under a diversity of operating conditions, combined information on the presence and absence of faults and associated intensity
  - Span a large number of commercial-building HVAC systems

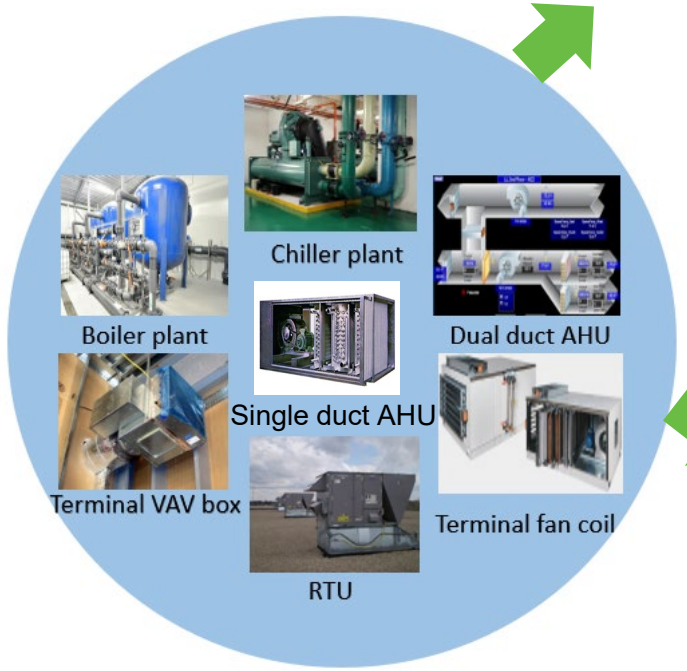


- Provide guidance for FDD users to prioritize faults, and recommendations for future R&D for analytical solutions

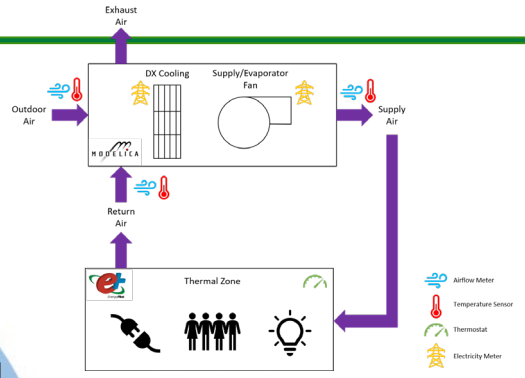
Approach

FDD test dataset

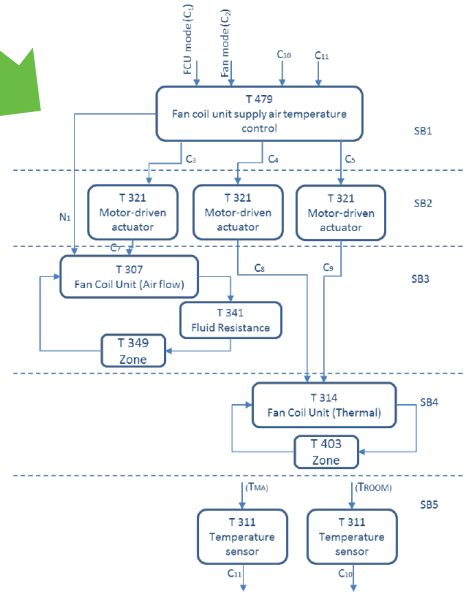
- Develop data curation plan
  - 7 HVAC systems/equipment
  - Each system 5-15 common faults, 4 severities
  - Simulation data captures a full 365 days of operation, 1-min interval



Lab experiments of RTU



Modelica-EnergyPlus simulation of chiller plant, boiler plant, RTU and single duct AHU

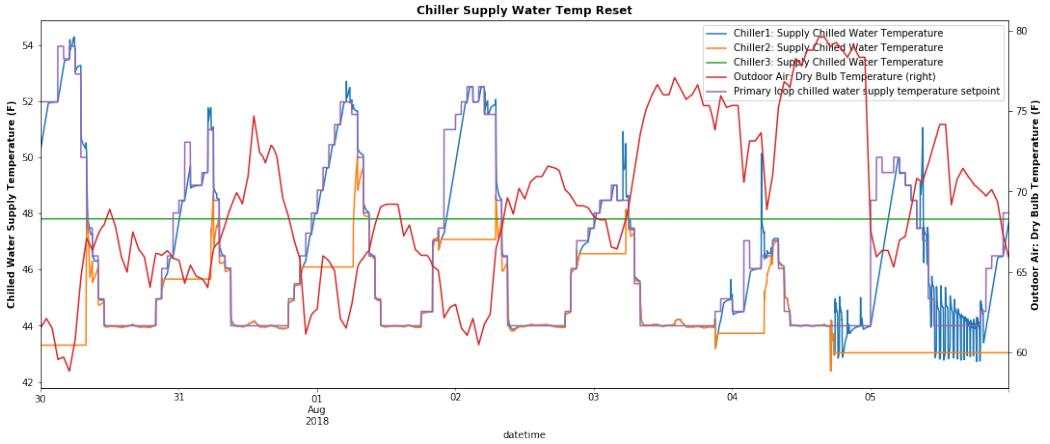


HVACSIM+ simulation of dual duct AHU, fan coil, and terminal VAV box

Approach

FDD test dataset

- Develop data curation plan
- Develop data validation and ground truth assessment protocols
  - System info and control sequence documentation
  - Data format and quality
    - Data naming convention, time interval, completeness, data limit, missing data
  - Fault-free ground truth validation
    - System operates following control sequence
    - Measurements meet setpoints
  - Faulty ground truth validation
    - Check against expected fault symptoms defined from literature review



Fault-free validation: supply temp is higher at low outside air temp, and vice-versa, temp meets setpoints

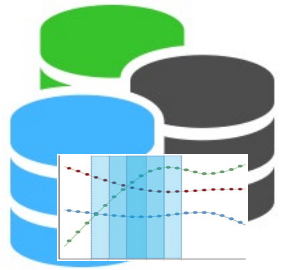
Approach

FDD test dataset

- Develop data curation plan
- Develop data validation and ground truth assessment protocols
- Synthesize and validate dataset across all contributors

Input Scenarios			
Fault Type		Fault Intensity	Method of Fault Imposition
Room Temperature	Sensor bias	-4 °C, -2°C, +2 °C, +4 °C	Add bias to sensor output
Reheat valve	Stuck	Full Open	Assign a fixed simulated controlled device position
		Full Closed	
		Partial Open 20%, 50%, 80%	
	Leaking	20%, 50%, 80% of the max flow	Assign a fixed simulated controlled device minimum position
VAV damper	Stuck	Full Open	Assign a fixed simulated controlled device position
		Full Closed	
		Partial Open 20%, 50%, 80%	
Room air temperature control sequence unstable		100 to 0.1	Decrease proportional band (increase controller gain kp) until unstable
Room VAV damper control unstable		9.99 to 99999	Increase controller gain kp until unstable
Unfaulted			NA

Example faulted or unfaulted test cases of terminal VAV box



FDD Test Dataset

Approach

FDD test dataset

- Develop data curation plan
- Develop data validation and ground truth assessment protocols
- Synthesize and validate dataset across all contributors
- Conduct benchmark case studies
  - Verify the efficacy of the test dataset
  - Inform the architecture/infrastructure needs for public release of the dataset
  - Illustrate the types of insights gained from use of the dataset
- Make available to public for ongoing use

Approach

Scope of fault prioritization study

- Literature review
  - Targeted system, equipment, and faults
  - Fault prioritization categories and approaches
  - Research needs and knowledge gaps

- FDD tech. developers and users survey
  - Current state of art
  - Display of prioritization results in FDD tool
  - Fault prioritization categories and metrics
  - Fault prioritization process in facility or portfolio
  - Research needs and knowledge gaps

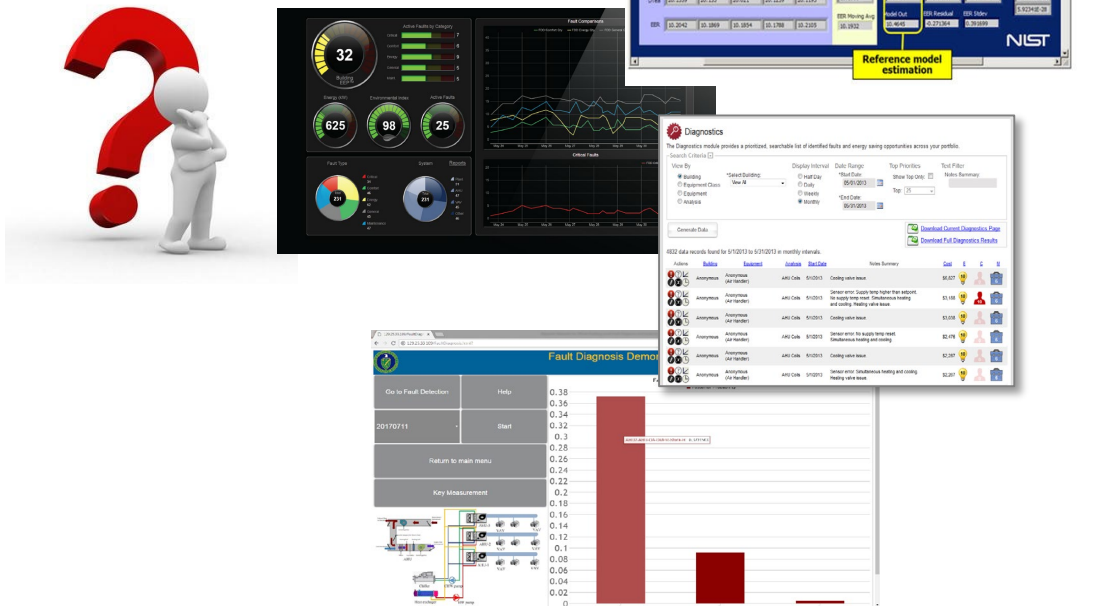
1. Technical article [Research audience]

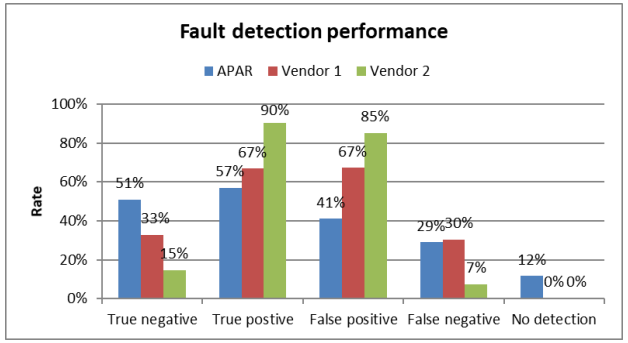
2. Best practice heuristics [FDD user audience]

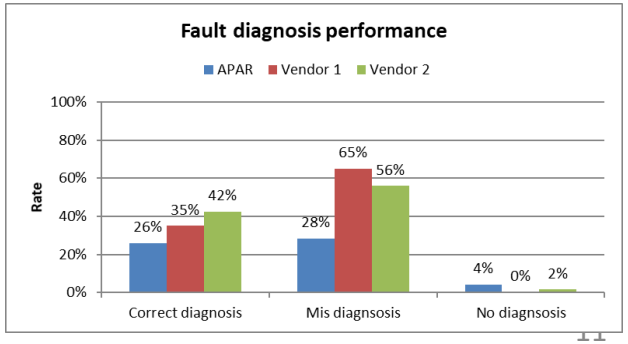
3. Future R&D recs for analytical methods [Labs/DOE audience]

Impact

- Improve the development and validation of FDD technology
- Promote long-term technical progress to improve effectiveness







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

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

[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: FDD Test Dataset

- 6 systems, in total 76151 day-long test cases

System		No. of day-long test cases	No. of fault types	Data Type	Contributor
Dual-duct air handler unit		20075	15	HVACSIM+ simulation	Drexel University
Terminal fan coil		17520	17		
Fan-Powered Terminal VAV box	Parallel	10950	10		
	Series	10950	10		
Chiller plant		10220	10	Modelica-EnergyPlus simulation	PNNL
Boiler plant		6205	5		
Rooftop unit (RTU)		63	4		NREL
RTU		168	3	Experiments	ORNL

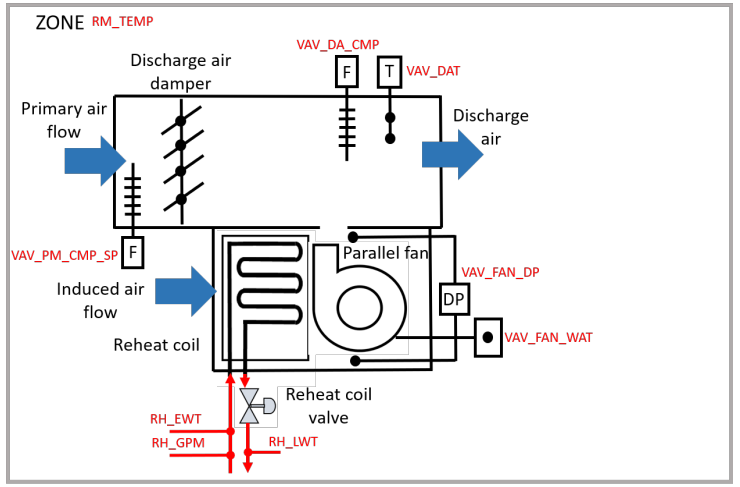
Progress: FDD Test Dataset Documentation

Data documentation in pdf

- An overview of the data set
- Building and system information
  - System type and diagram
  - Control sequences
  - Data points
- Input scenarios for faulted and fault-free conditions
  - Fault types
  - Fault intensities
  - Method of fault imposition
  - Fault occurred time

Data stored in Google Drive

- Each dataset is provided in a set of the csv files
- Each file represents a fault with a specific intensity



Data Point Name	Description	Unit
For each room:		
RM_TEMP	Room Temperature	°F
RMCLGSPT	Room Cooling Setpoint	°F
RMHTGSPT	Room Heating Setpoint	°F
RH_VLV	Reheating Coil Valve Position	%Open
RH_VLV_DM	Reheating Coil Valve Position (command)	%Open
RH_GPM	Reheating Coil Water Flow Rate	GPM
RH_EWT	Reheating Coil Entering Water Temperature	°F
RH_LWT	Reheating Coil Leaving Water Temperature	°F
VAV_DAT	VAV Discharge Air Temperature	°F
VAV_DMPR	VAV Damper Position	%Open
VAV_PM_CFM_SP	VAV Primary Air Flow Rate Setpoint	CFM
VAV_PM_CFM	VAV Primary Air Flow Rate	CFM
VAV_FAN_CS	VAV Fan Status (On/Off)	
VAV_FAN_DP	VAV Fan Differential Pressure	in. WG
VAV_FAN_WAT	VAV Fan Power	Watts

Diagram and data points summary of parallel flow fan powered terminal air unit

Progress: Scope of Fault Prioritization Study

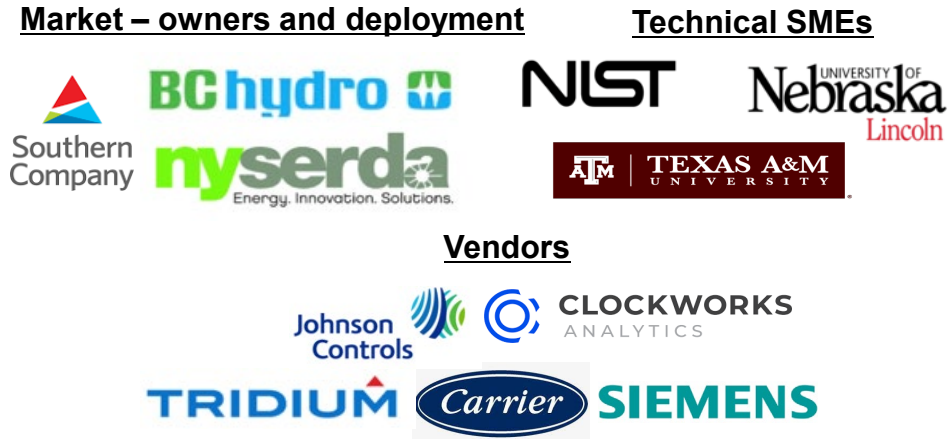
- Reviewed 41 publications and interviewed 8 FDD tech. providers and users
- Prioritization is an important research topic, key to overcome data overload and to encourage action
- Common prioritization categories; energy, comfort, maintenance impacts and fault duration

Interviewed FDD tech. providers and users

- Customizable prioritization to meet the needs of different user groups (e.g. facility O&M team, facility engineers, energy manager, etc.)
- Knowledge gaps/research needs
  - Provide a database of repair costs/labor hrs
  - Improve rules for integration of multiple faults
  - Provide dynamic, customized energy impact results for a specific building or equipment

Stakeholder Engagement

- Progress recap:
  - FDD test dataset curation and validation across 6 systems
  - Literature review and stakeholder survey of fault prioritization
  - Engaged stakeholder TAG with deep subject matter expertise

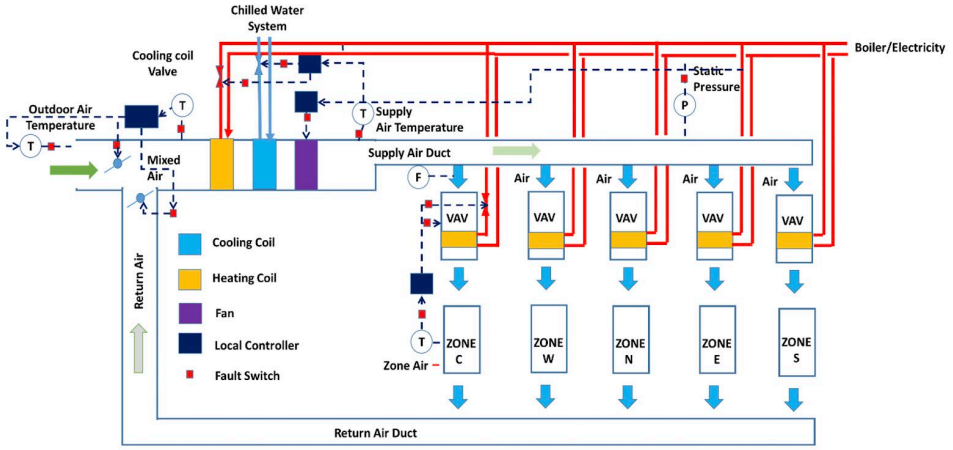


Industry Technical Advisory Group

  - Engaged and contributed to international research collaboration Annex 81 project "Data-Driven Smart Buildings".

Remaining Project Work: FDD Test Data Creation

- Simulated data set with Modelica-EnergyPlus model
  - Multi-zone AHU-VAV system with typical controls configuration
- ORNL experimental data set
  - ORNL Flexible Research Platform
  - Summer conditions
- Merge with existing data sets to expand scope of coverage



Remaining Project Work: Public Availability

- Finalize fault prioritization scoping study outcomes

- Work with FDD developers and researchers (2 tech. providers, 4 researchers from U.S., Australia, and Italy) to generate benchmark case studies

- Disseminate FDD test data set for wide industry awareness and ongoing use
  - Where is data set stored, how is it formatted, how is it accessed?
  - What infrastructure facilitates use and how is it maintained?

Data repo, Q&A forum

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $600K/yr FY20-FY21, $575k FY22
Variances: No variances from original planned budget
Cost to Date: Spending on track, $514K of $600K spent through July 2021

Budget History					
Oct 1, 2019– FY 2020 (past)		FY 2021 (current)		FY 2022 – Sep 30, 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$600k	0	$600k	0	$575k	0

Project Plan and Schedule

Project Schedule									
Project Start: October 1, 2019		Completed work							
Project End: September 30, 2022		Active Task (in progress work)							
	◆	Milestone/Deliverable (Actual)							
	Status	**FY 2020**				**FY 2021**			
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									
FY20 Q1: Based on engineering knowledge of system behavior in the presence of each fault type, develop data validation and ground truth assessment protocols and demonstrate them on a subset of data.	Completed	◆							
FY20 Q2:Initial data validity and quality check	Completed		◆						
FY20 Q3 GNG decision: Verify that 75% of data collected to date have valid ground truth and usable measurement points for FDD algorithms to run against.	Completed			◆					
FY20 Q4: Synthesize dataset across all contributors, covering 6 systems, and >45,000 test cases; merge with the data from Phase I.	Completed				◆				
Current work									
FY21 Q1:Hold initial conversations with 4-7 FDD developers to line up interest to participate in case studies.	Completed					◆			
FY21 Q2:Prepare an article documenting the expanded dataset curation and validation (from FY19&FY20 Q1); summarize FDD prioritization methods from literature review.	Completed						◆		
FY21 Q3:Document state the of commercial FDD prioritization methods based on discussion with 7-15 FDD users and developers; identify gaps and needs associated with the current state of the art	Completed							◆	
FY21 Q4:For each partner contributor, document Y3 data curation plan including: facility/model descriptions; fault types, severities, and conditions; and methods to	Ongoing								◆
FY21 Q4:GNG decision: Case study progress and use as additional data validity and quality check	Ongoing								◆