CONSORTIUM for
BUILDING ENERGY
INNOVATION

FINDINGS

The Consortium for Building Energy Innovation

CBEI is focused on generating impact in the small and medium-sized commercial buildings (SMSCB) retrofit market. CBEI is comprised of 14 organizations including major research universities, global industrial firms, and national laboratories from across the United States who collaborate to develop and demonstrate solutions for 50% energy reduction in existing buildings by 2030. The CBEI FINDINGS series highlights important and actionable technical, application, operation and policy research results that will accelerate energy efficiency retrofits when applied by various market participants. CBEI views these FINDINGS as a portal for stakeholders to access resources and/or expertise to implement change.

RTU AFDD Impact Evaluation and Optimal Service Scheduling

The savings are due to early detection and repair of common component level and system level faults that can degrade energy performance. To achieve significant national benefit, it would be necessary to implement integrated **Automated Fault Detection and Diagnostics (AFDD)** in the majority of **rooftop units (RTUs)** in the field. As a first step, this work is targeted to the high-end advanced RTU market because the incremental costs are a smaller fraction of the overall unit costs and the customer base is more aware of the benefits and opportunities for energy savings.

The importance of early detection and diagnosis of RTU cycle and ventilation faults is well understood. After fault detection and diagnosis is performed, the subsequent step in the general FDD methodology is to determine a recommended action to deal with the fault. Fault impact evaluation and recommended actions is an area of AFDD that has had limited focus.

For fault impact evaluation and recommended actions to be successful, past and potential future impact needs to be estimated.

Fault impact evaluation is an important component for AFDD, since the benefit to fixing some faults may be less than the cost to perform the necessary service.

Research Finding: AFDD Impact Evaluation and Optimal Service Scheduling

RTUs serve 60% of commercial floor space and account for about 150 Terawatt hours of annual electrical usage (~1.56 Quads of primary energy) and about $15B in electric bills in the US.

The key to a successful AFDD system is to provide the user with actionable information. Actionable information historically has been that a fault has been detected and identified. This is often inadequate information to trigger a repair in the small and medium-sized commercial building market. The missing element is the financial information to determine a return on investment for the particular maintenance task. This is especially true if the particular fault does not impact the comfort of the building occupants.

By choosing to perform service on an air-conditioner when it makes the most economic sense, it is possible to reduce utility and equipment cost impacts by incurring some additional service costs instead.

CBEI results, to date, support the concept of using fault detection, diagnostics, and fault impact isolation to determine total energy and runtime impacts and costing to deliver automated service recommendations.

Overall AFDD Systems Approach

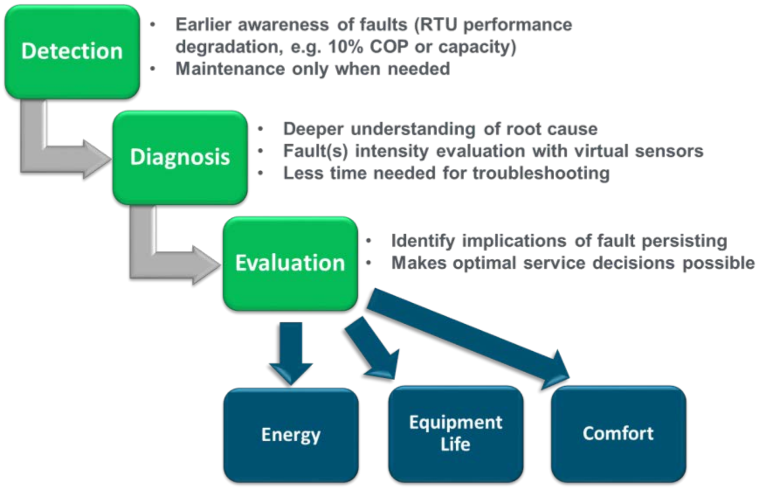
Much attention has been placed on fault detection and diagnostics and most of this work focuses on identifying the root cause of systems faults.

Step 1: Detection of performance degradation. Performance degradation of an RTU is expressed in terms of capacity and coefficient of performance (COP) reductions due to the presence of operational faults. It is important to select the right threshold at which the owner or service provider will be notified about the degradation. Using a target of 90% accuracy in fault detection with a 1% false alarm rate, a 10% degradation threshold for either capacity or COP was selected which provides a reasonable approach.

Step 2: Diagnosis of root cause. This step involves the identification of specific faults and fault intensities using virtual sensors that are uniquely dependent on individual faults.

Step 3: Impact evaluation. The impacts include increased energy usage due to efficiency degradation and decreased RTU life due to reduced capacity and increased runtime. The direct effects of faults in increasing the probability of mechanical/electrical failures and decreasing the runtime life of equipment are not considered.

Step 4: Optimal service scheduling. Fault impacts are inputs to an optimal service / maintenance scheduling algorithm that is based on economic analysis. The decision to perform service is based on a tradeoff between extra costs associated with these impacts and costs of performing service.



Stuck Damper Fault Ventilation Impact Example

A typical fault that occurs in RTU economizers is a stuck outdoor-air damper. When the damper becomes stuck at its minimum position, mechanical cooling or heating is not affected significantly. However, opportunities to provide ``free-cooling'' are diminished. Conversely, if the damper becomes stuck in an open position, cooling and heating are affected significantly due to the larger ventilation load. A stuck damper has a direct impact on the ventilation load since it controls the amount of fresh, outdoor-air that enters the RTU mixing box. When the damper is stuck open under warm and/or humid conditions, the ventilation load increases.

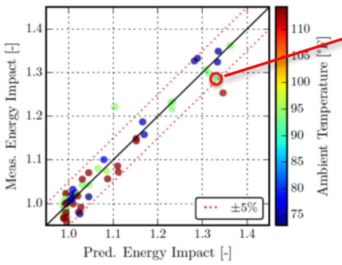
The impact of a stuck damper fault on capacity, efficiency, and ventilation load are important, but they do not provide a measure of the economic impact of the fault when taken by themselves. In order to estimate the economic penalty of the fault, the impact on energy consumption provides a more direct evaluation. Neglecting the indoor and outdoor fan power, the energy consumption required to meet a space load is equal to the product of the compressor power and the runtime required conditioning the space.

A methodology to determine the energy impact of a stuck outdoor-air damper fault on the cooling and ventilation performance of a rooftop air-conditioner (RTU) has been demonstrated. The methodology combines the impacts of the fault on cooling capacity, cycle efficiency, ventilation load, and equipment run-time to yield a physical model for the relative increase in energy consumption of the faulty equipment over a normally operating system.

The methodology can be extended to determine the economic penalty of the fault on operating costs and equipment costs using existing methodologies.

Energy Impact of Multiple Faults

Multiple detected faults need to be assessed and their respective energy impacts evaluated based on actual versus normal component performance. Energy impact of each fault then must be determined with the understanding of the other faults that are present. The laboratory test example below shows detection of two simultaneous faults and determination of their combined energy impact.



Multi-Fault Scenario
~25% Condenser Airflow Reduction
~12% Compressor Ref. Leakage
0% Liquid Line Restriction

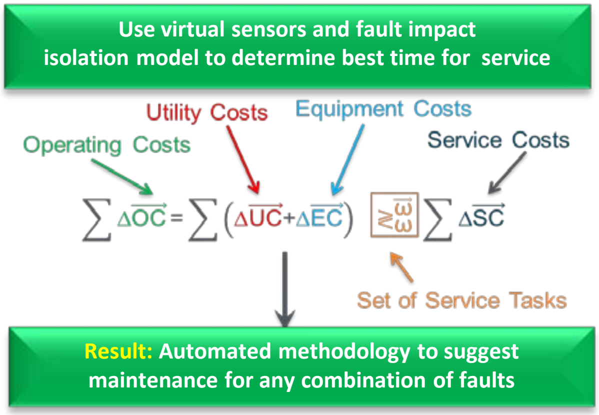
Energy Impact Isolation Results:

Total Energy Impact:	**+30.7%**
Condenser Fouling:	+20.5%
Compressor Leakage:	+10.2%
Liquid Line Restriction:	0.0%

Delivering Optimal Service

By choosing to perform service on an air-conditioner when it makes the most economical sense, it is possible to reduce utility and equipment cost impacts by incurring some additional service costs instead. In essence, a trade-off between running a system when it is less efficient or performing service to make the system more efficient is determined.

The figure below depicts the overarching concept of using fault detection, diagnostics, fault impact isolation, runtime and costing to deliver automated service recommendations.



Use virtual sensors and fault impact isolation model to determine best time for service

$$\sum \Delta\overrightarrow{OC} = \sum\left(\Delta\overrightarrow{UC}+\Delta\overrightarrow{EC}\right) \boxed{\gtreqless} \sum \Delta\overrightarrow{SC}$$

Result: **Automated methodology to suggest maintenance for any combination of faults**

Tested Evaluation and Optimal Service Scheduling Approach[1]

The following overview depicts the logic structure of the algorithms developed and tested.

One of the most important impacts of faults commonly affecting packaged air conditioners is a reduction in total cooling capacity. This impact can be quantified using a cooling capacity degradation ratio, where $Q_{\text{cool,actual}}$ is the actual cooling capacity of the system and $Q_{\text{cool,normal}}$ is the normal cooling capacity of the system without faults.

$$r_{cool} = \frac{\dot{Q}_{cool,actual}}{\dot{Q}_{cool,normal}}$$

The total cooling capacity that an air conditioning system delivers is made up of sensible and latent components. The sensible component of the total capacity is especially important for packaged air conditioners since they are generally controlled based only on the dry-bulb temperature of the conditioned space. The change in sensible heat ratio (SHR) caused by a fault can also be measured using an impact ratio.

$$r_{SHR} = \frac{SHR_{virtual}}{SHR_{normal}}$$

The change in COP caused by a fault can also be measured using an impact ratio.

$$r_{COP} = \frac{COP_{virtual}}{COP_{normal}}$$

A runtime impact ratio can be defined where $\Delta t_{\text{run,actual}}$ is the actual runtime required by the air conditioning system and $\Delta t_{\text{run,normal}}$ is the runtime requirement for a normal system without faults.

$$r_{run} = \frac{\Delta t_{run,actual}}{\Delta t_{run,normal}}$$

Runtime impact (r_{run}) can then be calculated by:

$$r_{run} = \frac{1}{r_{SHR} r_{cool}}$$

Energy impact (r_W) can then be calculated by:

$$r_W = \frac{r_{cool}}{COP} r_{run}$$

Equipment cost impact (r_{EC}) can then be calculated by:

$$r_{EC} = Cost_{equipment} r_{run}$$

Utility Cost impact (r_{UC}) can then be calculated by:

$$r_{UC} = Cost_{utility} r_W$$

[1] Project 2.2 – Fault Detection and Diagnostics (FDD) BP4 M2.2.d Progress report describing diagnostic and optimal maintenance scheduling algorithms for Advanced RTU.

Lessons Learned RTU AFDD Impact Evaluation and Optimal Service Scheduling

Major customers of HVAC equipment and systems for commercial buildings are interested in HVAC equipment with advanced diagnostics that minimize energy and maintenance costs and extend equipment life. Advanced RTU fault detection and diagnostics is critical to building energy savings and extending equipment lifespan[2]. CBEI Accomplishments:

- Developed the overall virtual sensor package based AFDD system for RTUs
- Developed and validated fault impact estimation and isolation methodologies
- Developed optimal service recommendation methodology for simultaneous fault scenarios
- Implemented the performance degradation method under lab conditions on an advanced RTU
- Obtained lab test results for single and multiple faults conditions
- Performed performance degradation analysis of single injected faults conditions including, condenser blockage, liquid line constraint, and compressor leakage on an advanced RTU with some dual fault scenarios.

Moving Forward

CBEI has engaged an industry OEM and a National Account Customer to review technical approach and market requirements.

In collaboration with OEM and National Account, customer field demonstration sites need to be selected and testing undertaken to prove out the complete RTU AFDD Impact evaluation and optimal service scheduling system leading to an overall evaluation of field FDD performance and economic assessment.

Additional work needs to be performed to prove out the following key elements:

Performance degradation assessment
Fault impact and isolation evaluation
Maintenance decision making

Improvements to the fault impact and isolation methodology include work on fault impact models that can be applied generically to different systems to reduce training costs. Maintenance decision-making improvements will require considerations of service budgets and concurrent system maintenance.

In the coming year, the RTU AFDD algorithms will be integrated within the VOLTTRON platform to demonstrate the capabilities of distributed performance monitoring.

Consortium for Building Energy Innovation
4960 South 12th Street Philadelphia, PA 19112
p: 215-218-7590
e: info@cbei.psu.edu

CBEI is a research and demonstration center that works in close partnership with DOE's Building Technologies Office.

Acknowledgment:
"This material is based upon work supported by the Consortium for Building Energy Innovation (CBEI) sponsored by the U.S. Department of Energy under Award Number DE-EE0004261."