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Market Barriers and Drivers for the Next Generation Fault Detection and Diagnostic Tools

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ABSTRACT

Commercial buildings in the U.S. consume as much as 30% excess energy compared to buildings that operate fault free and efficiently. Fault detection and diagnostic (FDD) platforms help to continually identify operational inefficiencies and maintain low-carbon performance. However, the recommendations generated by FDD tools need to be implemented by technicians, resulting in delays or lost savings opportunities. Recent research advances showed fault AUTO-correction integrating with commercial FDD offerings filled this gap. Seven innovative AUTO-correction algorithms were integrated into two FDD platforms and deployed across four buildings. The enhanced tools successfully correct faults focusing on incorrectly programmed schedules, override not released, control hunting, rogue zone, and suboptimal setpoints. Although its technical efficacy has been proven in the field, fault AUTO-correction is still early in the deployment cycle and opportunities and barriers need to be understood to reach its full potential in market transformation.

This paper broadly introduces the new technology that automatically corrects HVAC faults. The authors describe in detail technology potential, market barriers, and enablers for scalability based on field testing results and interviews with the FDD providers and facility managers. The interviewees agreed that AUTO-correction can reduce the extent to which savings are dependent upon human intervention, scale building operators' ability to act on FDD findings (especially for facilities with small operation teams), and achieve significant savings. To enable scalable deployment, future efforts are needed to overcome the barriers such as cybersecurity and accountability concerns from building operators and standardization of control parameters used in building automation systems.

Introduction

Research in the last 20 years has shown that commercial buildings in the U.S. waste up to 30% of energy due to inefficient operations and faults (Roth et al. 2005; Fernandez et al. 2017; Deshmukh, Glicksman et al. 2018; Fernandes et al. 2018). To address this issue, in the last decade, several fault detection and diagnostic (FDD) platforms have entered the market. A recent review identified more than 30 products being offered in the US (Kramer et al. 2020). These tools continually and automatically identify operational inefficiencies and provide information to building operators to achieve enhanced performance. Some benefits of these platforms include energy savings and improved operational efficiency, utility cost savings, persistence in savings over time, streamlining operations and maintenance processes, and supporting continuous energy management practices such as monitoring-based commissioning (Pritoni et al. 2022). On the high end, building operators using FDD enable median whole-building portfolio savings of 9% (Kramer et al. 2020). However, to harvest these benefits, building operators and technicians must act upon these recommendations, since these platforms do not fix these faults automatically. This often causes delay or inaction, resulting in additional operations and maintenance (O&M) costs or lost savings opportunities (Lin et al. 2020a).

Recent research advances showed that automatic correction of faults has the potential to fill this gap. Fernandez et al. (2009) and Brambley et al. (2011) developed passive and proactive fault auto-correction algorithms for an air-handler unit (AHU) and a variable air volume (VAV) terminal unit addressing faults on temperature sensors, humidity sensors, and dampers. The authors evaluated these routines in a laboratory environment using research-grade scripts and not commercial FDD products. More recently, Lin et al. (2020b) complemented and extended this work, by developing fault auto-correction algorithms designed to be integrated with commercial FDD tools. The new auto-correction algorithms provide the FDD technology a certain control capability, as the autonomous correction of faults are enabled by opening 2-way interfaces between the Building Automation System (BAS) and the FDD tool. The algorithms developed target incorrectly programmed schedules, override not released, sensor bias, control hunting, rogue zone, and suboptimal setpoints in HVAC systems. In Pritoni et al (2022) these algorithms were further tested across four buildings and three different building automation systems. The next section summarizes this work to provide some background on the capabilities of the auto-correction technology.

Fault Auto-Correction Technology Overview

The objective of the fault auto-correction technology is to perform automatic corrections of a subset of operational faults which can be identified by FDD tools. In commercial buildings, fault auto-correction solutions can be integrated with existing FDD solutions to enable a seamless connection between the passive diagnostics and active control in the HVAC system. Consequently, the technology can improve the HVAC system's operating performance, increasing energy and cost saving potentials generated by FDD tools, without heavily relying on building operators' intervention (Lin et al. 2020b). The innovative aspects of our research on auto-correction consist of: 1) a collection of platform-independent auto-correction algorithms that can be integrated into commercial FDD tools (Lin et al. 2020b) 2) a FDD-BAS architecture which allows two-way communication between the FDD tool and the BAS (Lin et al. 2020a) 3) the implementation of these algorithms in two FDD platforms 4) the field implementation and test of these algorithms using a rigorous testing procedure (Pritoni et al. 2022).

Auto-correction Algorithms

To date, we have developed ten fault auto-correction algorithms (Lin et al. 2020a) and conducted field evaluation of seven of them in three BAS across four buildings (Pritoni et al. 2022). These include: 1) HVAC schedules are incorrectly programmed; 2) manual overrides not released; 3) improve zone temperature setpoint setback; 4) control hunting; 5) rogue zone; 6) improve AHU static pressure setpoint reset; and 7) improve AHU supply air temperature setpoint reset. Table 1 summarizes them.

Table 1. Summary of the auto-correction algorithms tested (Pritoni et al. 2022)

No.	Fault/Opportunity Name	Fault/Opportunity Description	Type of Correction	Variables Corrected
1	HVAC schedules are incorrectly programmed	HVAC equipment doesn't turn on/off according to intended schedule due to error in control programming	One-time correction	Schedule
2	Override not released	Operator unintentionally neglects to release what was intended to be a short-term override of setpoints or other control commands (e.g. fan VFD speed, valve control command).	One-time correction	Override property of setpoint or command
3	Improve zone temperature setpoint setback	The zone temperature cooling setpoint is lower than needed or the heating setpoint is higher than needed while the space is scheduled occupied or unoccupied.	One-time correction	Zone temperature setpoint
4	Control hunting	The actuator operates under oscillation due to improper PID parameter setting	Active testing + one-time correction	PID parameters
5	Rogue zone	A zone continuously sends cooling/heating requests, due to zone-level equipment problems like a leaky reheat valve, a dysfunctional supply air damper, or unachievable zone temperature setpoints.	Continuous Optimization	Number of ignored requests from zones
6	Improve AHU static pressure setpoint reset	Non optimized AHU static air pressure setpoint	Continuous Optimization	Supply static pressure setpoint
7	Improve AHU supply air temperature setpoint reset	Non optimized AHU supply air temperature setpoint	Continuous Optimization	Supply air temperature setpoint

These algorithms can be categorized into three groups 1) one-time correction; 2) active testing + one-time correction; and 3) continuous optimization. The first category includes faults that are corrected once and they do not require further action until the FDD tool detects a new fault. Algorithms #1- #3 in Table 1 belong to this group. The second group includes algorithms that require active perturbation of the system to define the correction parameters. The algorithm #4 in Table 1 belongs to this category. The third group includes algorithms that run continuously, similarly to BAS control sequences. In this case the BAS variables are overwritten continuously without the direct approval of an operator. Algorithms #5-#7 in Table 1 belong to this group.

New FDD-BAS architecture

In order for the FDD tool to control and override the BAS, the communication between the two has to be bi-directional, unlike in most traditional FDD integrations. To enable this secure two-way communication, we developed alternative architectures for on-premise and cloud-based FDD platforms, as illustrated in Figure 1 and described in Lin et al. (2020a, 2020b) and Pritoni et al. 2022. The left side of Figure 1 shows an architecture in which all FDD auto-correction routines and applications reside on an on-premise server. This architecture was designed for cases in which access to the server is restricted to the administrators due to cybersecurity requirements. The right side of Figure 1 shows another architecture in which a local device is added to the control network to systematically poll the networked devices to retrieve configuration and operational data, continuously delivering these data sets to the cloud servers for storage and analysis. The local device performs the corrections with local logic and periodically pushes back the updates to the cloud FDD platform.

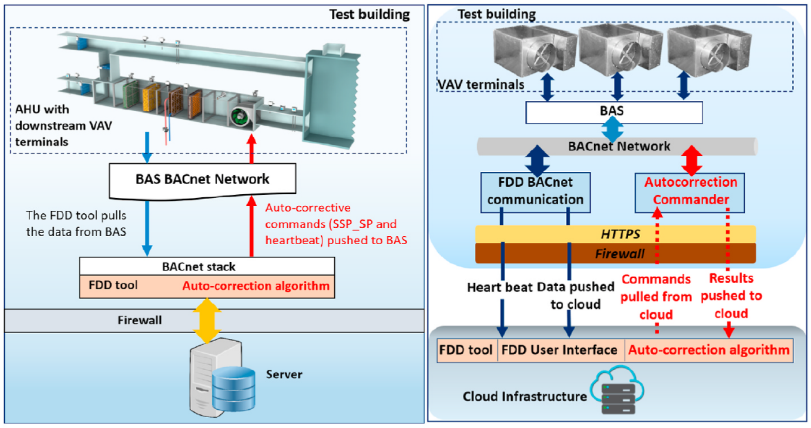

Figure 1. Updated FDD-BAS architectures (Pritoni et al., 2022)

FDD platform-specific implementation

The algorithms were converted from pseudo-code into platform-specific auto-correction algorithms by three technology partners. This was achieved by using the native scripting language of each FDD platform. To facilitate interaction with users, the FDD providers also customized their user interfaces. The integration with underlying BAS required creating new points and sometimes modifying the BAS control logic. The control logic had to be modified for the third category of routines (continuous optimization) to create a “fall back” control logic, in case of loss of connection with the FDD tool.

Field Testing

To evaluate the technology we performed field testing in collaboration with two FDD technology partners. The tests were conducted for an extensive period of time (2020-2022) in four buildings in the U.S. and Canada. The technology was tested on a variety of HVAC equipment, such as fan coil unit (FCU), AHU, heating recovery ventilation (HRV) unit and VAV box. During the testing, faults were artificially introduced into the system when they were not naturally occurring. The testing results demonstrated that all seven auto-correction algorithms can correct the faults in the system without negatively impacting the system operation and building occupants. Table 2 illustrates the field testing results.

Table 2 Field testing results in four buildings (Pritoni et al. 2022)

No	Algorithm tested	Building	Equipment type (number)	Artificially imposed fault	Successful Correction
1	HVAC schedules are incorrectly programmed	Site C	FCU(1)	Y	Y
		Site D	AHU(1)	Y	Y
2	Override not released	Site C	FCU(3) and HRV(1)	Y	Y
		Site D	VAV(3)	Y	Y
3	Improve zone temperature setpoint setback	Site C	FCU(3)	Y	Y
		Site D	VAV(6)	Y	Y
4	Control hunting	Site A	VAV(1)	Y	Y
5	Rogue zone	Site A	AHU(2) and VAV(48)	N	Y
		Site B	AHU(2) and VAV(163)	N	Y
6	Improve AHU static pressure setpoint reset	Site B	AHU(2) and VAV(163)	N	Y
7	Improve AHU air temperature setpoint reset	Site B	AHU(2) and VAV(163)	N	Y

Market Drivers and Barriers

The research team conducted a series of interviews with a cross section of professionals having familiarity with FDD, including eight different FDD providers, three control providers, one control and FDD provider, and two facility managers. The researchers asked questions about the perceived benefits of auto-correction, as well as market barriers and potential drivers of adoption of this technology. A portion of the professionals were primarily engaged in FDD and/or control in large buildings, and the remainder worked primarily in small and medium-sized buildings. Before discussing market insights from the interviews, it is beneficial to highlight some of the characteristics that influence the prospects for fault auto-correction in these two segments of the building market.

Market Segments

Building size is correlated to numerous characteristics that impact the opportunities for, and barriers to, auto-correction. Among these are HVAC equipment and system types, the level of sophistication of the controls, and the extent to which there is onsite facilities staff. These characteristics are highlighted below for two segments of the buildings market, namely: 1) large commercial buildings (i.e., above 100k sf); and 2) small and medium-sized commercial buildings (i.e., below 100k sf). Also described are the auto-correction algorithms that are seen to have the greatest potential in each segment.

Large commercial buildings

Large commercial buildings commonly have built-up HVAC systems with chillers and boilers, variable-air-volume (VAV) air-handling units, and VAV boxes for zone conditioning. These systems are typically controlled by a building automation system (BAS). Though still small, the fraction of buildings with FDD systems interfaced to the BAS to monitor building performance is growing steadily in this market segment. Typically these buildings will have an onsite facility staff responsible for operations and maintenance. Although an FDD tool may alert them to a fault soon after it occurs, their ability to respond and correct the fault in a timely manner will be dictated not only by the severity of the fault and its prioritization by the FDD tool, but also by other responsibilities they may have.

Previous research in the area of HVAC auto-correction has primarily been focused on large commercial buildings (Pritoni et al., 2022). The algorithms listed in Table 1 have all undergone successful field demonstrations in large buildings. A description of the main challenges experienced with these algorithms is provided in the section titled “Market Barriers and Achieving Scale”.

Small and medium-sized commercial buildings

Small and medium-sized commercial buildings are predominantly served by self-contained (“packaged”) rooftop equipment (so-called rooftop units or RTUs) utilizing direct expansion cooling and gas-fired heating. Buildings in this market segment generally do not have a BAS, and control of RTUs is commonly provided by onboard controllers and individual thermostats. In some cases multiple RTUs, each controlled by a separate thermostat, serve large open spaces. In schools, a classroom may have a dedicated RTU and thermostat, or several classrooms may be served by a single larger RTU and thermostat. One interviewee estimated that less than 10% of buildings in this market segment use systems serving multiple zones where VAV box dampers facilitate the control of cooling and heating at the zones. The remaining 90% use RTUs or other HVAC system types such as variable refrigerant flow (VRF) systems, coupled with dedicated ventilation systems (i.e., DOAS).

Smart thermostats are becoming more prevalent in this market and help facilitate cloud-based control and FDD capabilities. Most buildings will not have onsite technical staff unless the building happens to be on a campus. Thus, routine maintenance and urgent repairs are generally contracted to a service company and the amount of time required to respond to a service request could be highly variable.

Automated FDD is not common in the small and medium-sized building market today. Typically what is implemented is single-point alarms, such as equipment safeties (e.g., high and low pressure cutout) and sensors exceeding thresholds. These alarms come from onboard equipment controllers and are reported on the controller LED display. They may also be reported to a BAS (if one exists) using BACnet (ASHRAE, 2020) or a proprietary communication protocol. To the extent that FDD is utilized in this market segment, it is most commonly found in buildings having platforms with combined control and FDD capabilities that are part of a large national account with 100 or more buildings. These national accounts will typically have a central command center where alarms are received. Smaller portfolios of buildings often lack the resources (financial and technical) needed for state-of-the-art FDD capabilities.

Faults are typically identified after an occupant complaint occurs or during periodic inspections of equipment. The most common symptoms of faults in this market segment are supply air and zone air temperature issues, which are frequently linked to a compressor or a fan that is not running. Economizer problems and compressor short-cycling were also cited as common issues. Several of these issues are among a list of faults identified by interviewees as the most promising opportunities for auto-correction in this market segment. That list consists of thermostat setpoint overrides, economizer faults, ventilation faults, failure of units to start and compressor trips, and compressor short-cycling. Developing and demonstrating algorithms to address these issues remains as future work, as it was not the focus of our previous projects.

Technology Benefits

Auto-correction algorithms enhance the capabilities of FDD tools, augmenting existing passive diagnostics with the ability to correct faults and perform active control. This fundamentally changes the workflow associated with implementing corrective actions. In a traditional workflow, after a fault has been detected and diagnosed, a member of the facilities staff (or technician from a service provider) is assigned to perform the required corrections. When the corrections are completed, the individual who performed the work may enter a record of the correction in a computerized maintenance management system, although these systems are primarily found in campus or national account settings.

In contrast, with the auto-correction algorithms in Table 1, tested in our project, the facilities staff is alerted to the diagnosed fault and provided with a suggested software correction. For some fault correction algorithms, they need only authorize a one-time correction through the interface in the FDD tool to enable the update to be made and logged. For other algorithms, the workflow might also include one or more active tests following the diagnosis of a fault and prior to the FDD tool providing a suggestion of a one-time correction. Finally, for continuous optimization algorithms, once the opportunity for improved control is identified by the FDD tool, the facilities staff provides only initial approval of an algorithm and periodic evaluations of its performance. Detailed descriptions of the traditional FDD workflow as well as the modified workflows associated with automated fault correction are provided by Pritoni et al. (2022).

The new workflows and auto-correction algorithms enable a number of benefits to be realized. The interviewees identified the following benefits that these enhancements provide:

- Faster Corrections - Corrections of certain faults can be performed as soon as they are identified, thus reducing the extent to which savings achievable through FDD are dependent on human intervention.
- Energy Savings - Significant energy savings can be achieved by correcting faults and capturing opportunities related to optimal controls.
- Consistent Repairs - Automation can help ensure corrections of common faults are done consistently.
- Reliable Documentation - Changes that are implemented are logged automatically for future reference.
- Improves FDD Scalability - The benefits of FDD can be realized in buildings that have a lean operations and maintenance staff.

Market Drivers

The interviewees viewed the market drivers of automated fault correction and FDD to be largely the same and described a broad range of factors that they believed would influence building owners and operators to value auto-correction algorithms. The ability of the algorithms to improve building energy efficiency and help achieve conservation goals was one clear driver. Interviewees also cited shortages of facilities staff stemming from an aging workforce as an important driver. Automated fault correction was seen as a means of increasing staff productivity, reducing the time to correct certain faults and enabling staff to focus on more challenging tasks. There was even the thought that automated fault corrections such as cycling the power to a tripped compressor might be adequate to restart a unit, thereby reducing the urgency of dispatching a truck to the site. This could be particularly valuable in small and medium-sized buildings with limited or no technical staff.

The value of continuous optimization algorithms that adapt to changing building conditions and occupancy patterns was cited by interviewees, particularly in the wake of the COVID-19 pandemic and the new work arrangements that it precipitated. Knowing that your building will adjust to existing conditions without the need for intervention reduces the risk of waste during low occupancy periods and reduces the risk of poor indoor environmental conditions when occupancy returns to normal. This could be achieved by dynamically changing ventilation rates and, in some cases, will require adding sensors to detect occupancy more accurately.

Interviewees also viewed innovative features like automated fault correction as having particular appeal to facilities staff whose expectations regarding the user experience with FDD tools and control systems may be influenced by their experiences with consumer electronics. And from a purely practical standpoint, there was a belief that as FDD itself continues to gain a foothold in the market, there will be a larger base of users desiring additional features to help maximize the return on their investment.

Finally, interviewees noted the value of having intelligence embedded in the control system or FDD tool that can help facilities staff or technicians understand the corrections that are proposed. The knowledge conveyed with the proposed correction was viewed as having significant value, particularly for technicians servicing equipment in small and medium-sized buildings where guidance on the selection of controller parameter values is frequently missing.

Market Barriers and Achieving Scale

Despite clear technology benefits and market drivers that characterize automated fault correction, there are barriers that must be overcome if these benefits are to be realized. Barriers identified by the interviewees that are considered common to most buildings are presented in the next section. This is followed by a description of specific scalability challenges, and prospects and pathways for broad market adoption, of the auto-correction algorithms in Table 1.

Common challenges

The first common challenge to market adoption of auto-correction technology is the need for secure two-way communications that enable corrections to be written into the control system. This capability is necessary whether the correction is: 1) coming from an on-premises FDD tool and being written into a control system, in which case an Internet connection is not needed and the main challenge is providing the two-way communication; or 2) coming from a cloud-based control and/or FDD platform and being written in control devices in the building (e.g., BAS, smart thermostat), in which case additional cybersecurity concerns must also be addressed. Secure two-way communications are a necessity for cloud-based control systems, an emerging solution for small and medium-sized buildings, so this solution pathway has an advantage over other solutions in the small and medium-sized building sector. To date, successful two-way communications have been established in field demonstrations involving the connection of both on-premises and cloud-based FDD tools to BAS (Pritoni et al., 2022).

Another common challenge cited by interviewees was an inherent hesitancy among building owners and operators to have a third-party application overriding their control system. This creates concerns about cybersecurity and accountability. These concerns are believed to be particularly acute in the military and healthcare segments, two areas of the building market that were not considered good opportunities for fault auto-correction. Transparency and clear communications were viewed as important to overcoming security and accountabilty concerns. The fault correction interface that requires a human to authorize certain corrections and that captures key information about the correction is one way in which transparency is being introduced to the process. Communicating the changes made to the control system by the auto-correction algorithm to all facilities staff was also seen as important. Finally, it was suggested that owners with well-established FDD programs who are looking for additional features to enhance their return on investment may be less risk averse to third-party overrides and could pave the way for demonstrating the benefits of this technology.

There were also concerns about testing and what it would take to ensure the reliability and robustness of the technology. One interviewee noted that if a technician or facilities staff does not trust the technology, they might disable it or otherwise reduce it to their level of understanding. This is a further indication of the need for clear communications regarding the changes to the control system that are proposed, and the benefit of allowing facilities staff to be the final decision maker as to whether a correction is made.

Finally, one interviewee indicated that making changes to equipment settings could carry liability concerns. Even if the correction was appropriate and led to improved performance, there was concern based on experience that making the change could void a warranty or open a person to litigation. Although this is a major barrier, it should be noted that the algorithms developed in this research involve changes to control settings in the BAS and not in the onboard equipment controls.

Assessing scalability from implementation experience

In addition to identifying common challenges to scalability as described in the previous section, the research team also assessed the scalability of the algorithm types in Table 1 (i.e., one-time correction, one-time correction + active test, and continuous optimization) in terms of the effort required to implement the algorithms and their generalizability. This assessment was based on their experience implementing the algorithms in large buildings. This experience is also used to gauge the potential of the different algorithm types in small and medium-sized buildings.

The one-time correction algorithms were assessed to require low effort to implement and were viewed as highly generalizable. These algorithms were straightforward to implement and for the most part involved modifications of standard BACnet objects. Because of this, there is also a belief that these algorithms can be widely deployed across different buildings and BAS without the need for significant customization. Challenges can and did arise, however, stemming from differences in BACnet objects owing to the use of different versions of the protocol and/or custom objects. Nonetheless, these algorithms appear to have the potential for widespread adoption by FDD tool providers. These algorithms also seem well suited to deployment in small and medium-sized buildings. Some control vendors already have the capability to return overridden setpoint temperatures to their previous or default values after an override timer has expired.

The one-time correction + active test algorithm required significant effort to implement and was assessed to have low to medium generalizability. The prevalence of the control hunting problem makes it an attractive target and from this perspective this algorithm holds great potential. However, implementation was hindered by the fact that neither the FDD tool nor the BAS had the built-in capabilities needed to manage the active tests. As a result, it was necessary to develop several new modules for this purpose. The algorithm was assessed to have low to medium generalizability in large part because there is no single standard form for the PID algorithm. As a result, an FDD tool will need to be customized to the form implemented by the BAS vendor in a particular building. In addition, not all BAS expose the PID controller parameters via BACnet and the effort required to do so can be extensive. And, while a successful auto-correction of the PID parameters for one process was performed, it is important to ensure that the algorithm is robust and can be applied to different types of processes. The applicability of this type of algorithm is thought to be low in small and medium-sized buildings in large part because there are far fewer PID control loops in the equipment in these buildings. In addition, technicians in these buildings are less likely to have the expertise needed to oversee the tests. Commissioning providers offering monitoring-based commissioning (MBCx) services and campus facility groups with in-house expertise are candidates to adopt proven solutions to this problem because of their familiarity with the problem and their understanding of the benefit the solution could provide them.

The continuous optimization algorithms also required a large effort to implement and were assessed to have low to medium generalizability. To implement the algorithms it was necessary to encode the logic in the FDD tool and to modify the control logic in the BAS. Both were time consuming, and it is important to realize that proprietary tools from the BAS vendor are often needed to access and modify the logic implemented there. Furthermore, a thorough understanding of the custom algorithms implemented by different BAS vendors is necessary to ensure modifications have the intended effect. As control sequences such as those in ASHRAE Guideline 36 (ASHRAE, 2018) become more prevalent, these sorts of challenges will wane. A research effort aimed at digitizing the control delivery process (Wetter et al., 2022) could further improve transparency around control sequences; however, standardized sequences and workflows that may result from this work are still on the horizon. Another implementation point that must be considered is the importance of synchronizing the FDD tool with the BAS. This is particularly important for cloud-based FDD tools, where a loss of connectivity could disrupt updates to the optimization algorithms and jeopardize occupant comfort. Demand controlled ventilation, while not implemented in this study, appears to have good potential for adoption in the small and medium-sized buildings market; however, for the algorithms investigated in this study, continuous optimization is more scalable in large buildings because the HVAC equipment in small and medium-sized buildings severely limits what can be implemented. Potential early adopters of continuous optimization algorithms include MBCx providers, who could implement these routines in their commercial offerings for use in buildings where the existing BAS does not have comparable routines, and FDD providers who want to expand their suite of offerings to include automated system optimization tools (Kramer et al. 2020).

Conclusions and Future Work

A FDD tool is a type of energy management and information system that is designed to continuously identify the presence of faults and efficiency improvement opportunities through a 1-way interface to the building automation system and application of automated analytics. It is estimated that 5-30% energy saving can be achieved by employing FDD tools and implementing efficiency measures based on FDD findings. Although the potential of this technology is high, actual savings are only realized when an operator takes an action to fix the problem. Automated fault correction can close the loop between the passive diagnostics and active control, increase the savings enabled by FDD tools, and reduce the reliance on human intervention.

This paper broadly introduces automated fault-correction technology that could be integrated with commercial FDD and BAS products to enhance their capability of quickly fixing the identified problem and improving system operational performance, and summarizes the successful testing results. Further, the paper describes technology benefits, market drivers, and barriers for scalability in small to large buildings based on field testing results and interviews with the FDD providers and facility managers. The key benefits reported from the interviewees include consistent and faster repairs, energy savings, reliable documentation of changes, and improving FDD scalability. The developed fault auto-correction technology can be deployed in the commercial FDD tools currently serving large commercial buildings and in the emerging cloud-based controls and FDD platforms for small and medium-sized buildings.

To enable scalable deployment, future efforts are needed to overcome the barriers such as cybersecurity and accountability concerns from building operators and standardization of control parameters used in building automation systems. For these reasons, future work should:

- Support of additional commercial fault diagnostic providers in modifying their product architectures to enable secure, operator-approved two-way BAS integrations. This will enable larger adoption of this technology in the market by addressing one of the main technology market barriers.
- Work with industry organizations such as ASHRAE to discuss standardization of BACnet objects, such as the ones identified in the challenge section above (i.e., algorithm #5).
- Develop an open-source library of reference algorithms, in particular new algorithms for small commercial buildings. Targeting this market segment is particularly important for equity reasons, since owners and tenants in these buildings typically have less access to capital and maintenance staff than larger building or campus owners.
- Field test the technology in additional sites, in particular in small commercial buildings to increase confidence in its reliability and robustness, addressing another important barrier identified in the interviews.
- Engage more broadly with industry and building owners to disseminate this work.

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