Title: Development of an Online Expert Rule based Automated Fault Detection and Diagnostic (AFDD) tool for Air Handling Units: Beta Test Results

Ken Bruton	**Daniel Coakley**	**Peter O Donovan**	**Marcus M. Keane**	**D. T. J. O'Sullivan**
i2e2 Researcher Department of Civil & Environmental Engineering, University College Cork, Ireland	i2e2 Researcher Informatics Research Unit for Sustainable Engineering, National University of Ireland, Galway	i2e2 Researcher Informatics Research Unit for Sustainable Engineering, National University of Ireland, Galway	Lecturer & Principal Investigator Informatics Research Unit for Sustainable Engineering, National University of Ireland, Galway	Lecturer & Principal Investigator Department of Civil & Environmental Engineering, University College Cork, Ireland

Abstract -

Heating Ventilation and Air Conditioning (HVAC) system energy consumption accounts for an average of 40% of an industrial sites energy consumption. Studies have indicated that 20 – 30% energy savings are achievable by recommissioning Air Handling Units (AHU) in HVAC systems to rectify faulty operation. Studies have also demonstrated that continuous commissioning of building systems for optimum efficiency can yield savings of an average of over 20% of total energy cost. Automated Fault Detection and Diagnosis (AFDD) is a process concerned with automating the detection of faults and their causes in physical systems. AFDD can help support multiple stages in the commissioning process. This paper outlines the development of an AFDD tool for AHU's using expert rules then details the results of its beta testing phase on twenty-six AHU's across six large commercial & manufacturing sites. To date, validated energy savings of over €157,000 have been identified by the AFDD tool.

1 INTRODUCTION

The building sector contributes up to 30% of global annual greenhouse gas (GHG) emissions and consumes up to 40% of all primary energy [1], [2]. This figure is expected to rise by an average rate of 1.5% per annum over the next 20 years [3]. Heating Ventilation and Air Conditioning (HVAC), and more specifically the operation of the Air Handling Units (AHU's), accounts for an average of 40% of an industrial sites total energy consumption [4]. This is due primarily to the stringent cleanliness requirements that many of the industrial processes (clean-rooms, pharmaceutical production, etc.) require to comply with international standards [5]. Approximately 50% of a commercial building's energy consumption is associated with HVAC energy consumption [6]. Overall, it is estimated that HVAC energy consumption accounts for 10 – 20% of total energy consumption in developed countries [3] with AHU associated energy use accounting for the majority of this.

Buildings rarely perform as well in practice as anticipated during design due to improper equipment selection or installation, lack of commissioning, or improper maintenance [7] to cite but a few reasons. Studies have indicated that 20 – 30% energy savings are achievable by recommissioning HVAC systems, and more specifically AHU operations, to rectify faulty operation [8]. A major item of concern in commissioning these systems however is the persistence of the savings achieved by the process as degradation of savings results over time [9].

Studies have also demonstrated, using a sample set of over 80 buildings, that on-going commissioning of building systems for peak efficiency can yield savings of an average of over 20% of total energy cost [7]. Further savings are possible by coupling the re-commissioning with on-going commissioning of a HVAC system. In one demonstration study, savings of 44% of electricity consumption and 78% of gas consumption over a ten year period were identified. [10], [11].

AHU operations are typically supervised and maintained by either an onsite facilities team or an offsite third party contractor. Based on information garnered from this project1, the number of AHU's in a typical HVAC system often outnumbers those supervising and maintaining the system by 20 to 1. This means that routine mechanical maintenance is typically carried out only when necessary due to an end user complaint, a machine breakdown or a breached alarm limit. The complexity of modern AHU control philosophies also commonly results in onsite personnel not having the required knowledge to root cause issues without procuring costly external consultancy. Building operators are also typically overwhelmed by AHU data as the overlying monitoring and control systems have had little effort put into consolidating the vast quantities of information into a clear and coherent format [12]. Both top down (system level) approaches employing monitoring & targeting (M&T) systems, energy performance indicators, and performance dashboards to manage site energy consumption and the more commonplace bottom up (component level time based maintenance) are common methods of managing AHU operation in terms of optimising their energy consumption and achieving other operational targets. BMS systems are also used to supervise the performance of AHU's in HVAC systems, raising alarms when upper or lower limits of operation are breached. However, typically, they do not diagnose the root cause of these alarms, with few current BMS systems having fault detection or diagnostic capabilities. Automated Fault Detection and Diagnosis (AFDD) is a process concerned with automating the detection of faults and their causes in physical systems [13].

In order to ensure effective maintenance of an AHU, it must firstly be set up to operate effectively at the commissioning stage. As HVAC systems grow more complex, so too will the commissioning process required to ensure their initial efficient operation. If current trends continue this movement towards more complex systems will result in a more expensive and lengthy commissioning process. Xiao & Wang [6] support this hypothesis stating that commissioning is labour intensive and that the future will be that of an automated lifecycle commissioning process embedded in the operation of the building management system. This study goes on to state that AFDD is a key means of achieving automated commissioning. IEA Annex 47 [10] reviewed the operation of 18 such tools, concluding that automation is still uncommon during the commissioning process, and that future tools should be developed that are easily embedded in existing operational practices.

Based on the sample of companies involved in the i2e2[2] project, most commissioning activities are currently performed manually, as labour-intensive, once-off undefined processes upon completion of an installation. For commissioning to be truly successful, it must be embedded in the overall project process, and must follow a defined procedure in order to ensure it is effective and repeatable. Studies have indicated that a savings persistence degradation of 25% can be expected every four years after initial commissioning [14]. By firstly re/retro commissioning the AHU's in a HVAC system, their performance can be set to optimum levels. This would serve to return the AHU's in the HVAC system to optimal "fault free" operation. This could be achieved using an AFDD tool, which identifies a number of areas which are not performing as intended. Once these items have been remedied, the AFDD tool could be used as part of an on-going commissioning process to ensure that any new faults in the system are detected effectively.

[2] The Innovation for Ireland's Energy Efficiency (i2e2) Technology Centre is an Irish government sponsored initiative. The I2E2 research focus is on energy efficiency improvements in manufacturing processes and supporting systems. The current research agenda focuses on a number of areas of common interest to group members, one of which is HVAC systems. The original scoping of the HVAC project started in January 2009 and the project currently involves 2 research providers and 6 industry partners. The main objective of this research is to provide an automated FDD tool that has been extensively tested on a range of different AHU's across a number of disparate industrial sites

2 AFDD TOOL DEVELOPMENT

Based on extensive literature review carried out at the inception of the project, the experience base of the research team as well as industry garnered feedback on the technical domain, a number of key requirements were elicited, which in the opinion of the research team if adhered to, would lead to the successful development of a commercially viable AFDD tool. A number of frameworks and tools were then developed and alpha tested in order to address each requirement. Table 1 lists each of these requirements alongside the framework/tool component developed to address it while Figure 1 details the architecture of the AFDD tool developed as part of this project.

The AFDD analysis carried out in the business layer of this tool utilises a rule based expert system methodology. This business layer uses actual data from instrumentation as well as implied virtualised information to determine fault instances in order of priority. False positives/negatives are minimised utilising bespoke heuristic error thresholds which are calculated for each combination of instrumentation involved in each detection path. It has been developed as a cloud based application (GUI shown in Figure 2), with the business layer residing on the cloud rather than being deployed locally on each participant site.

Rationale	Requirement(s)	Framework/Tool Developed
Data Access Layer Flexibility	Compatibility with any BMS type or age Ability to process BMS data into a generic form for post processing	A generic data access tool was developed which could upload BMS data from the client server irrespective of the type of BMS software being utilised or the mechanism of data storage A standard naming convention for each recorded value within both the database and the AFDD tool so that different AHU's can easily be compared at a glance.
Business Layer Flexibility	Compatible with various combinations of sensors and components found in typical AHUs.	A client side application performs mode checks, calculates virtual values, applies business layer logical algorithms, and stores consequent results in a MySQL database. The business layer has been designed so that it can be broken down into individual rule libraries utilised for different purposes.
Reliability	Low number of false positives/negatives in order to build confidence in the tool.	A single, heuristically defined error threshold value that was applied to each individual rule based on a specific number and type of instrument involved in the processing.
Usability	User friendly graphical user interface (GUI) which allowed the evaluation of on-going performance of AHUs without in depth domain expertise	A browser based GUI was developed to allow secure cloud based access of each pilot sites information from remote locations using unique user identification.
Fault Priority	The quantification and prioritisation of the diagnosed faults to ensure maximum return on investment.	Each fault is prioritised in terms of cost and frequency of occurrence to allow the user to make informed decisions as to which to repair first to maximise return on investment
Scalability	Rapid setup time per AHU to facilitate quick set up and maximum scalability across an organisation	A web based site configuration tool was developed to allow an AHU to be set up in less than five minutes remotely once key information is available.
Low Cost	Ability to use existing measurements without the need to install additional instrumentation in order to limit associated installation costs	The business layer has been developed to work with minimal instrumentation. It utilises first principal techniques and engineering computation to calculate readings where non are present based on existing instrumentation

Table 1: AFDD tool requirements and tools developed to meet them

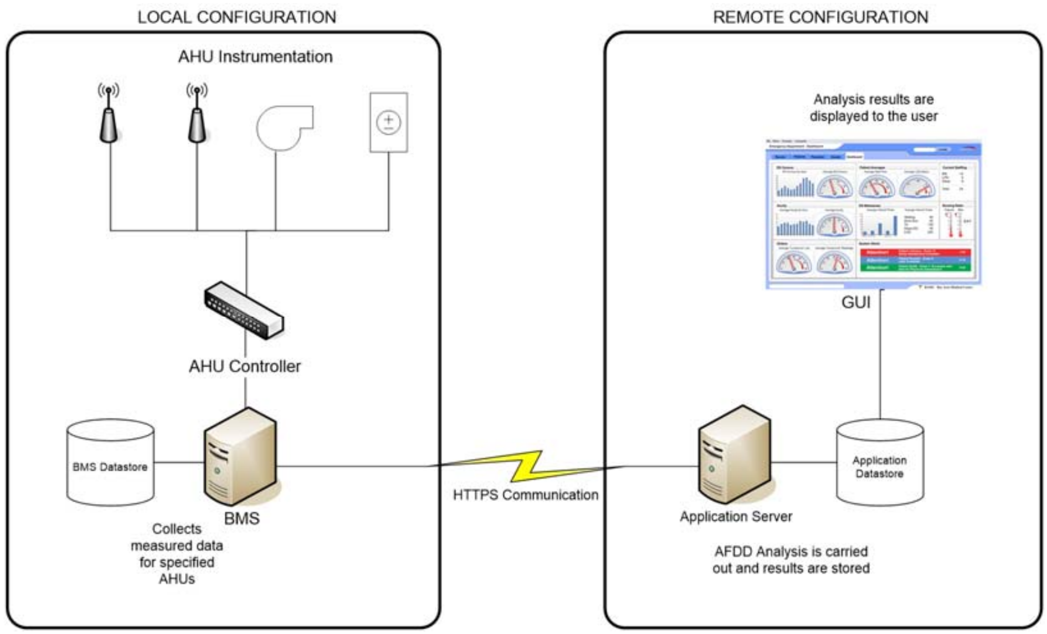

Figure 1: AFDD tool Architecture

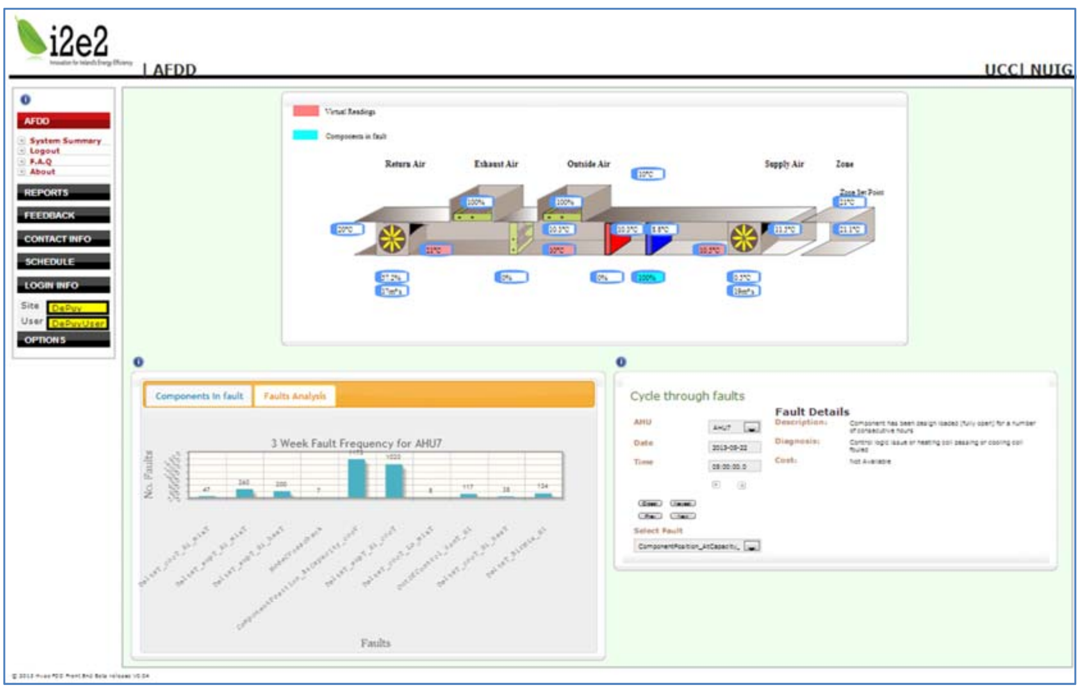

Figure 2: i2e2 AFDD tool Web Based GUI

3 AFDD TOOL FIELD TESTING

3.1 Design of Test Study

Several hundred AHU's were available for selection as part of this project due to the scale of the industrial sites involved in this collaborative project. A number of characteristics were taken into consideration in order to select a number of representative units for the purpose of developing and validating the tool. As such, AHU's were selected with the following characteristics:

- Different component and sensor layouts in order to ensure that the AFDD tool can be applied effectively and comprehensively;
- Varying levels of instrumentation in order to demonstrate effectiveness of AFDD

tool on AHU's with varying levels of instrumentation;

- Typical/characteristic units, thereby maximising the potential for duplication across multiple sites, thus ensuring scalability and increasing return on investment.

Table 2, in which the industry partners are anonymous, describes the major characteristics of each pilot AHU, which were selected to offer varying component and sensory distributions.

Site	Number of Identical AHUs in pilot	AHU Type	AHU Operation	Design Air Flow (m^3/s)	Type of zone(s) supplied	Operating hours per annum	BMS/Data logging Platform	Frequency of logged data
1	2	Recirculation	Constant volume	10	Office & canteen	8760	Trend	15 minutes
2	4	Recirculation	Constant volume	20	Manufacturing Floor	8760	Tridium	15 minutes
3	9	Recirculation	Variable Volume	10	Manufacturing Floor	6240	Cylon	15 minutes
4	4	Recirculation	Constant Volume	12	Commercial office space	6240	Cylon	7.5 minutes
5	3	Full Fresh Air	Variable Volume	8	Commercial office space	6240	Schneider	15 minutes
6	2	Recirculation	Constant Volume	22	Manufacturing Floor	8760	Qlikview	15 minutes

Table 2: Major characteristics of the pilot AHUs

3.2 <u>AFDD Tool Test Path</u>

After an initial, very successful period of alpha testing in early 2012 using a lab developed and supported AFDD tool running the business layer, it was decided to move to a beta test phase in October 2012 in order to test the effectiveness and robustness of the AFDD tool developed as part of this project. Beta licences were issued to each project participant in order to protect the integrity of the software as well as to ensure all parties were in agreement as to the defined risks and outcomes of the initial 6 month period of testing which was due to end at the end of March 2013.

Beta testing was thus expanded to six pilot sites from the initial four sites engaged in the alpha test phase of the project [15]. Each of these sites would monitor their own specific front end, but would be supported by project researchers where required.

This period of testing focused on end user interaction with the system with a view to garnering feedback on its use in practice by people not inherently involved in its development. Each beta site was given a unique user ID and password to access the AFDD tool cloud based GUI (Figure 2) with only the project research team having access to all beta sites for data integrity rationale. A maintenance and interaction flowchart (Figure 3) was distributed to all beta participants. This outlined how feedback would be garnered and beta installations expanded and bug fixed where required. This interaction was facilitated utilising a cloud based tool called Trello [16] to centralise bug notification and user feedback.

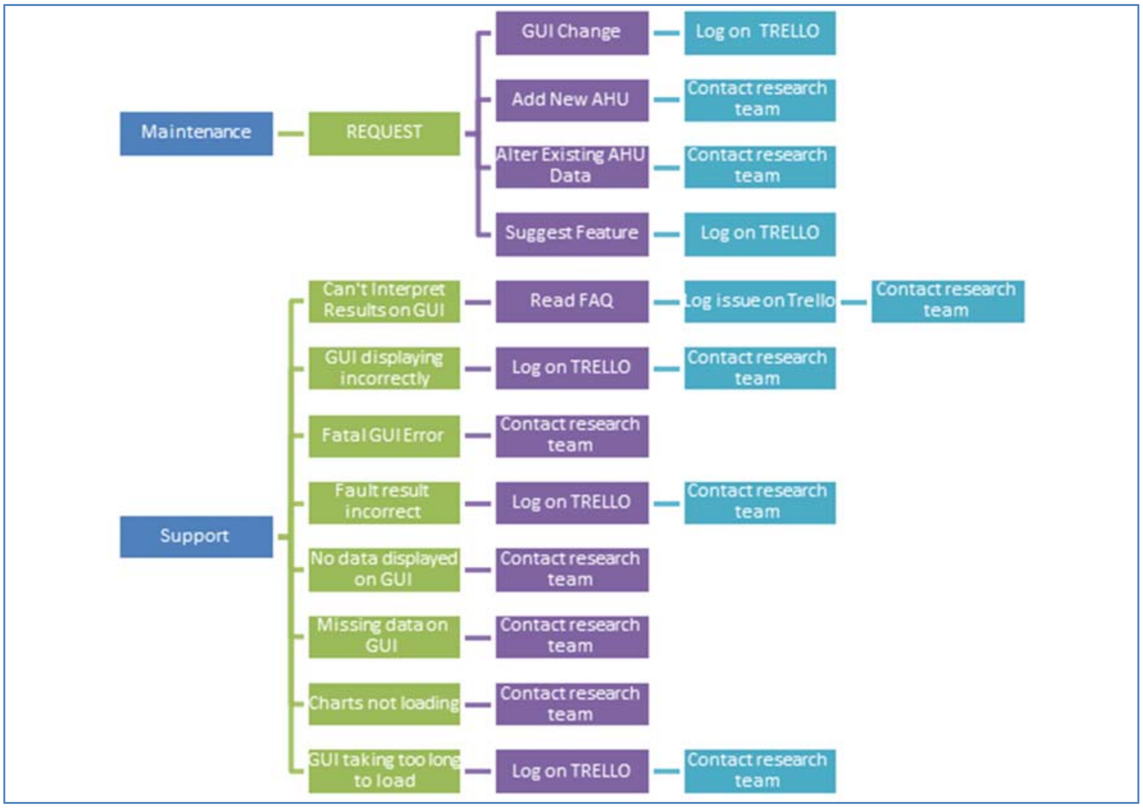

Figure 3: Beta Phase Maintenance Support and Feedback flowchart

3.3 Beta Tool Deployment & Development

The alpha test phase, undertaken between early to mid-2012, involved the use of a VBA/excel based GUI. This user interface was heavily dependent on researcher support due to its complexity and engineering specific outputs. A number of development improvements were undertaken based on both the findings of the alpha test phase and the initial deployment of the AFDD tool for use on the Beta test sites, each of which is outlined in Table 3.

During the first deployment of the AFDD VBA/Excel based GUI at the first beta test site, difficulties with external communication to the project's cloud based server from within industrial firewalls became apparent. This coupled with the need to maintain each local installation of the GUI expedited the requirement to develop a web based GUI. This would not need to be deployed on each site individually but could exist on the cloud and hence be centrally supported and developed.

During the fifth beta deployment on a test site at a large commercial building, a company that did not take part in alpha testing, data integrity procedures meant that port 80, which had previously been utilised to access site specific HVAC information, was not accessible due to in house data security procedures. A decision was therefore taken to purchase a secure socket layer (SSL) certificate to allow the secure passage of data via its encrypted transfer (via port 443) over the internet. This decision was to prove beneficial when the tool was put through an internal information technology audit on the sixth beta test site at a large manufacturing company.

During the beta test period, the number of AHU's was also expanded from eighteen to twenty-six. In order to expedite this work, and with a view to further expanding the number of units monitored by the tool in future, a web based configuration tool was developed which allowed each AHU to be set up from an input value and instrumentation perspective remotely. This tool will also facilitate the remote setup of future test sites.

Alpha Stage	Bate Stage	Reason(s)
VBA/Excel based GUI	Browser based GUI	Removed site specific installation requirement Centrally supported GUI allowed single point of support and update
Communication via unsecured port 80	Communication via secured port 443 utilised SSL authentication	Data Security
Local configuration of AHU's	Web based AHU configuration tool	Allowed remote set up of tool Expedited the set up process Allowed research team to alter key parameters from one central point for all beta sites

Table 3: Alpha to Beta Development Improvements

3.4 High Level Results

During the Beta tool installation phase, it became clear that the need for automated tools in the building energy management space exists due in part to the volume of data present and the lack of the knowledge or time to interrogate it for "insights", these being the identification of periods of underperformance.

On site six for example, post installation, the research team contacted the energy manager at the site to query why no data was being collected for some instruments though they had apparently been set to archive. The energy manager reacted with alarm, querying whether the team's data extraction tool had somehow deleted content from the database. On further inspection using the research team's data analysis engine, it was discovered that no data had ever been logged for a large number of instruments though the onsite facilities team thought otherwise. This database was considered a critical component of the system, and was backed up manually by site six personnel monthly with a view to holding a repository of information should a critical failure result. It however was seldom quality checked in terms of the data it housed and as such had fallen into data disrepair in that the data that it archived was no longer as expected. The AFDD tool, by virtue of the fact that it now utilised this information to create insights, had identified data gaps in the system which were remediated immediately.

On site four, the AFDD tool identified that half of the instrumentation on the four AHU's was logged at 15 minute intervals on the hour, while the other half was logged at 15 minute intervals from 7.5 minutes past the hour. This rendered the information useless from a comparative analysis perspective as the data was not aligned sufficient to make parallel analysis possible. As this data had not been interrogated previously, this issue had gone unnoticed for over two years, with the BMS logging information wastefully.

3.5 Energy Saving "Insights" identified by the AFDD tool

The AHUs on several of the test sites have been analysed in detail using the AFDD tool and a number of faults have been detected. Table 4 provides an overview of the major confirmed faults identified to date across the 26 pilot AHU's and their associated energy consumption savings which totalled over €157,000 per annum. These faults have in the majority of cases been verified by physical inspection and subsequent calculation using airside measurements. The cost savings associated with these faults were calculated assuming conservative annualised unit costs of associated energy and surveyed air flow rates through each AHU.

Site	No. of AHUs in Pilot	Faults identified by the FDD tool	Annual Verified Cost savings	Verification method
1	2	Passing heating coil, stuck damper actuator	€74,000	Physical (airside) survey by the authors
2	4	Damaged dampers, low supply temperature, passing cooling coil	€53,000	Physical (airside) survey by the authors
3	9	Damaged dampers	€4,000	Physical (airside) survey by the authors
4	4	Inefficient modes of operation, design issues	Not yet quantified	Not yet verified
5	3	Passing heating coil, design issues	€26,000	Physical (airside) survey by the authors
6	4	Inefficient modes of operation, design issues	Not yet quantified	Not yet verified
Totals	**26**		**€157,000**	

Table 4: Savings identified by AFDD tool

3.5.1 Site 1 Fault Example: Passing Heating Coil Actuation Valve

Fault Rationale: A 5.1C temperature rise was picked up by the AFDD tool across both the heating and cooling coils though the cooling coil was recorded to be 23.5% open as shown in the screenshot from the GUI in Figure 4

Additional Info: There is no mix temp sensor in the pilot AHU under analysis, so a virtual mix temp was utilized. Hence there was a chance that the virtual mix temp could have been calculated too low in error if the return damper was stuck in position or leaking. The only way to validate the accuracy of the tool in the identification of this fault was by physical site survey.

Root Cause analysis: An airside temperature profile analysis was undertaken on the AHU by the research team. A temperature could not be obtained between the heating and cooling coils due to space limitations in the unit. The cooling coil was thus manually isolated and the temperature difference across the coils observed for a period of 15 minutes thereafter. A 10 C rise across the "closed" heating coil was recorded over this period.

Savings Calculation Methodology: Energy savings were calculated on each of the pilot sites using air side measurements taken by the research team across the component in fault state using in the following equation

$$Q = m_a x\ CP_a\ x\ \Delta T$$

Where

Q = *Energy in kW*

$\dot{m}_a$ = *Mass flow rate of air*

CP_a = *Specific heat capacity of air*

ΔT = *Temperature difference across the component in fault sate*

A number of assumptions were then made on a case by case basis to quantify the annual energy saving associated with each fault.

- The boiler efficiency was assumed at 80%,
- The coefficient of performance of the chiller supplying chilled water to the cooling coil was assumed to be 2.5,
- An 11c cost of electricity per kWh and a 3c cost of gas per kWh were assumed across all pilot sites though variations existed based on contract type and duration
- The annual hours that the fault resulted in energy waste was quantified based on a fault by fault basis taking seasonal variations into account.

Savings Projections: Based on the survey results and the data recorded by the AFDD tool, savings of approximately €29,800 per annum (thermal and electrical) were identified as achievable by replacing the heating coil actuation valve and repairing the mixing box damper/actuator.

Fault Repair Follow Up: The research team recommended the replacement of the heating coil actuation valve based on the findings of the AFDD tool, and their subsequent validation by site survey. This repair was undertaken in late 2012. The

AFDD tool was then utilised to track the effectiveness of the repair. It was found that the repair had not been undertaken effectively by the off site contract team as the temperature rise persisted across the closed heating coil post retrofit (Figure 5 & Figure 6). The contract team were thus called back to site to commission the new valve effectively. The AFDD tool was then utilised to verify the effectiveness of this process thereafter (Figure 7).

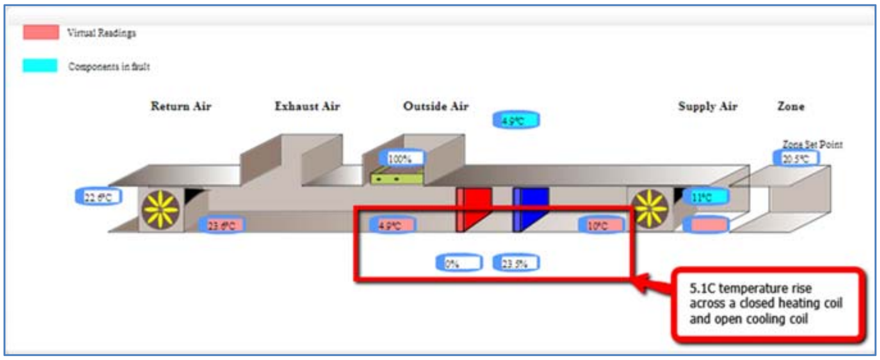

Figure 4: Site 1 AFDD tool Fault Identification

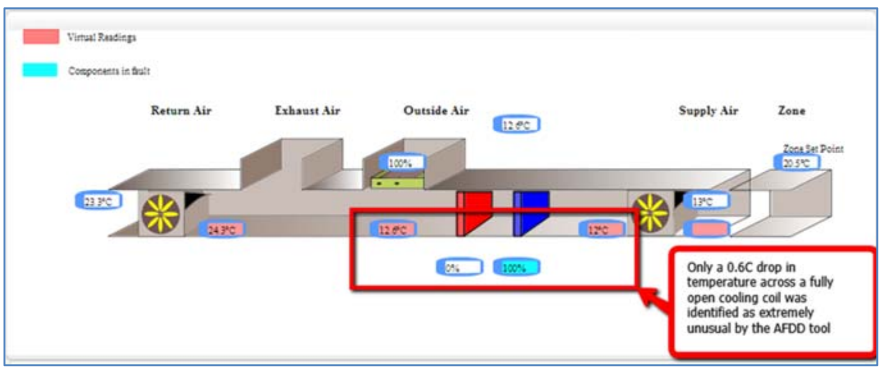

Figure 5: AFDD tool repair effectiveness check (1)

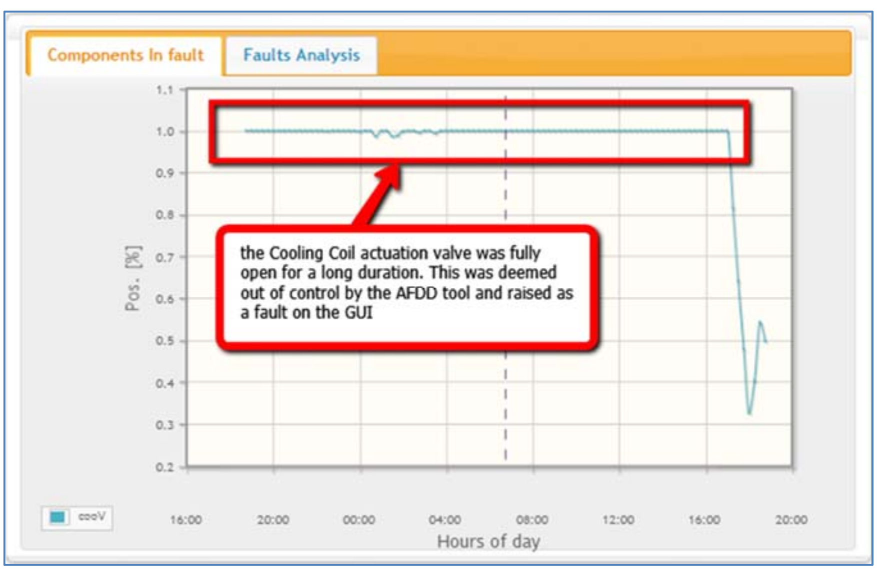

Figure 6: Site 1 AFDD tool repair effectiveness check (2)

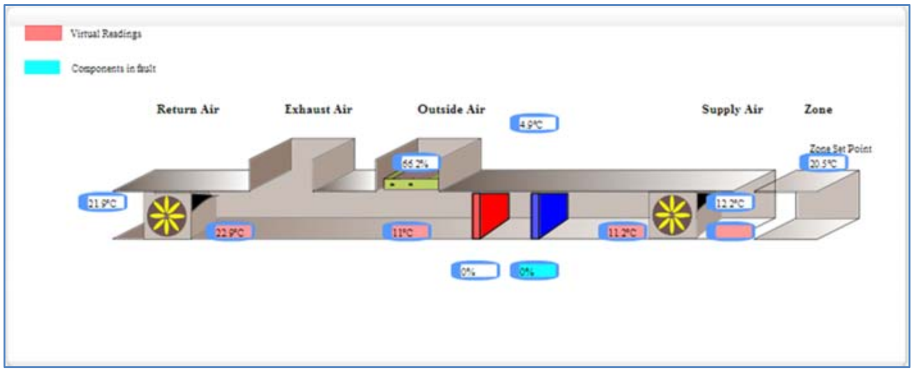

Figure 7: Site 3 AFDD tool repair verification

3.5.2 Site 2 Fault Example: Cooling Coil at Capacity

Fault Rationale: The cooling coil has been open to 100% for a number of consecutive hours (over 70% of the analysis period). A 2.1 C temperature drop across a fully open cooling coil control valve was also identified by the AFDD tool (Figure 8 & Figure 9) as unexpected based on normal operation.

Root Cause analysis The cooling coil control valve should be inspected to ascertain if it is operating through its full range of motion. The cooling coil should also be inspected to determine if it is fouled internally reducing its heat transfer potential.

Savings Projections: €11,500 based on airside calculations.

Next Steps: As this fault has just been identified by the Beta test site, its root cause work has not yet been undertaken. This same fault has also been identified by the AFDD tool on three other similar AHU's on the same test site. It is thus likely than any root cause work undertaken on this AHU will result in similar findings on the other three AHU's thus amplifying the savings proportionally once a resolution is determined and implemented. The AFDD tool will subsequently be utilised to verify the savings once repair work is undertaken.

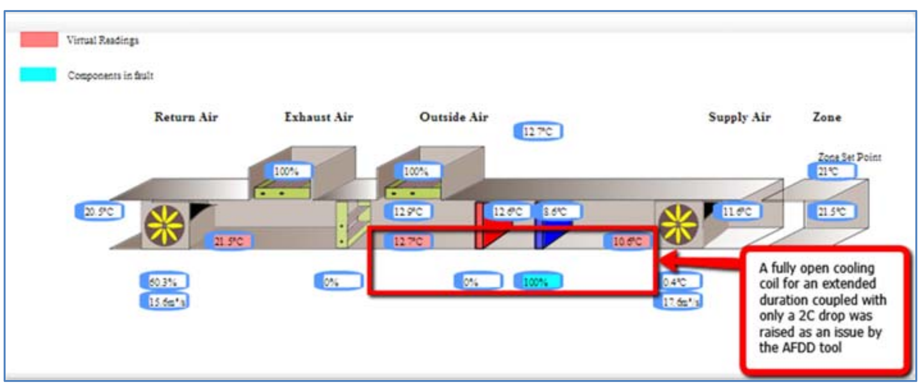

Figure 8: Site 2 AFDD tool Fault Identification

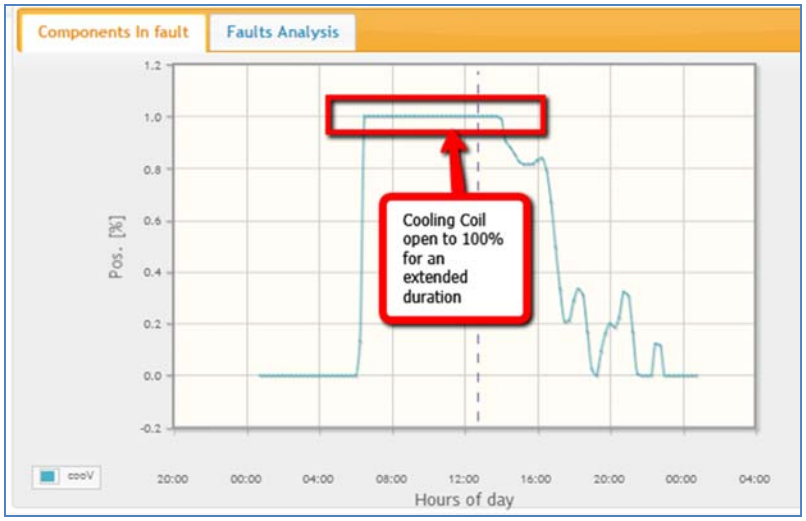

Figure 9: Site 2 AFDD tool Fault Identification

4 CONCLUSIONS AND FUTURE WORK

The results from both the Alpha and Beta testing phase of this project are very encouraging. A data access and processing application has been designed and installed on each of the six beta test sites. This application accesses and uploads data from each of the 26 AHU's on the six test sites to a central database each morning automatically. It integrates successfully with four different types of BMS system with very different data archiving methods. A business layer calculates virtual data points and detects faults in each of the 26 test AHU's across the six pilot sites on a daily basis automatically. A web based GUI has been developed which displays the faults detected a day behind real time on each of the beta test units at AHU level by fault frequency.

Consequently, over €157,000 per annum of energy savings have been identified and verified by site survey across the six beta test sites. These faults would most likely either not have been identified using the traditional maintenance practices of the companies in question or they would not have been identified unless an energy audit or a review of the system were undertaken. Invariably this would have led to considerable energy waste. A commercial case therefore exists for the further development of this software. Based on the work undertaken in the beta testing phase of this project, it is clear that a number of areas require further research and development in order to ensure the widespread application of a robust AFDD tool namely;

- The expansion of the business layer to incorporate humidity control fault diagnostics is imperative for the widespread application of the AFDD tool. A number of the Beta test sites house environmentally sensitive HVAC controlled environments and thus would benefit greatly from the addition of this functionality to these energy intensive processes.
- The addition of automated costing and prioritisation of the identified faults is imperative to the success of this project. The end user feedback garnered during the Beta phase of development showed that the users were having some difficulty consuming the results of the analysis of the AFDD tool. In order for the tool to be a success, it is key that the user can comfortably interact with and interpret the results generated by it.
- The improved diagnostic performance of the tool would aid root causing of fault instances. The tool currently outputs a number of potential "root causes" for a fault instance. Feedback from end users to date has supported the development decision to improve the functionality of the tool first before focusing on improving the accuracy of diagnostics as in most causes the technician root causing the fault will have to visit the AHU in any case. This can negate the need for

improved accuracy as they will identify the root cause in the majority of cases on first sight. However, there is merit in adding some improved diagnostic capabilities to the AFDD tool, where conflicting departments/personnel may be tasked with the final repair. For example, the decision to contract a control specialist to modify a control logic issue or the use of an in house maintenance technician to recalibrate a faulty sensor could be resolved by a more effective diagnosis.

Each of these items have been added to a project technical development roadmap, which will be undertaken by the research team in collaboration with its industrial and commercial partner sites over the next 12 month period.

Acknowledgements

This research was funded by Enterprise Ireland. The authors would also like to thank the Innovation for Irelands Energy Efficiency (I2E2) Technology Centre.

References

[1] UNEP Sustainable Buildings and Climate Initiative (SBCI), “Buildings and Climate Change: Summary for Decision-Makers,” 2009.

[2] National Energy Technology Laboratory, “Building Energy Data Book,” Nov. 2008.

[3] L. Pérez-Lombard, J. Ortiz, and C. Pout, “A review on buildings energy consumption information,” *Energy and Buildings*, vol. 40, no. 3, pp. 394–398, 2008.

[4] “HVAC SWG - Spin I, 2007.” [Online]. Available: http://www.seai.ie/Your_Business/Large_Energy_Users/Special_Initiatives/Special_Working_Groups/HVAC_SWG_07/. [Accessed: 13-Sep-2011].

[5] ISO - International Organization for Standardization and ISO - International Organization for Standardization, “ISO - International Organization for Standardization.” [Online]. Available: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=25052. [Accessed: 13-Sep-2011].

[6] F. Xiao and S. Wang, “Progress and methodologies of lifecycle commissioning of HVAC systems to enhance building sustainability,” *Renewable and Sustainable Energy Reviews*, vol. 13, no. 5, pp. 1144–1149, Jun. 2009.

[7] M. A. Piette, S. K. Kinney, and P. Haves, “Analysis of an information monitoring and diagnostic system to improve building operations,” *Energy and Buildings*, vol. 33, no. 8, pp. 783–791, Oct. 2001.

[8] International Energy Agency, “Computer Aided Evaluation of HVAC system Performance,” 34, 2002.

[9] J. D. Bynum, D. E. Claridge, and J. M. Curtin, “Development and testing of an Automated Building Commissioning Analysis Tool (ABCAT),” *Energy and Buildings*, vol. 55, no. 0, pp. 607–617, Dec. 2012.

[10] International Energy Agency, “Cost Effective Commissioning of Existing and Low Energy Buildings,” 47, 2010.

[11] Daniel Choinière and Maria Corsi, “A BEMS assisted commissioning tool to improve the energy performance of HVAC systems,” in *ICEBO*, 2003.

[12] H. Wang, Y. Chen, C. W. H. Chan, and J. Qin, “An online fault diagnosis tool of VAV terminals for building management and control systems,” *Automation in Construction*, vol. 22, pp. 203–211, Mar. 2012.

[13] S Katipamula and M Brambley, “Methods for Fault Detection, diagnosis and Prognostics for building Systems Parts I & II,” 2005.

[14] Toole C and D.E. Claridge S, “Review on Persistence of Commissioning Benefits in New and Existing Buildings,” presented at the ICEBO, China, 2006.

[15] Bruton, Ken, Raftery, Paul, Aughney, Niall, Keane, Marcus M., and O’Sullivan, Dominic T.J., “Development of an Automated Fault Detection and Diagnosis tool for AHU’s,” in *ICEBO*, Manchestor, 2012.

[16] “Trello,” *Trello*. [Online]. Available: www.trello.com.