RETRO-COMMISSIONING THE ARIA BUILDING USING CITE-AHU: AN ANNEX 40 COLLABORATION

Natascha S. Castro*, Hossein Vaezi-Nejad**
** National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg Maryland, 20899-8631, USA*
*** Centre Scientifique et Technique du Bâtiment, Paris, France.*

Summary. In the summer of 2003 the Centre Scientifique et Technique du Bâtiment (CSTB, French Scientific and Technical Building Center) in Paris, France, and the National Institute of Standards and Technology (NIST) in Gaithersburg, MD USA collaborated to develop a service tool called CITE-AHU, an automated commissioning tool for air-handling units. The work was carried out as part of an IEA Annex 40 research project and included the retro-commissioning of a real building in Paris as a field test of the prototype. This document provides an overview of the retro-commissioning process, discusses how CITE-AHU can be used to facilitate this process, and presents results for two constant air volume air-handling units serving office and laboratory space.

Keywords: automated commissioning, air-handling unit, functional performance tests

INTRODUCTION

Despite advances in building control technology, building operation often does not meet the owner's and operator's requirements and in many cases building control systems do not work as intended. Because of this, people have looked to the commissioning of control systems as a means of improving building operation, increasing occupant comfort and improving energy performance. Numerous case studies have been presented at technical conferences. Haasl [1] and Claridge [2] have documented several examples of retro-commissioned buildings with energy savings of up to 20%. However, many of the benefits of commissioning are not easily quantified, there is no established methodology for determining the benefits and the real/perceived costs of commissioning remains a high obstacle to the acceptance of building commissioning as a standard practice.

IEA ECBCS Annex 40[1] research is aimed at developing, validating, and documenting tools for commissioning buildings and building services and is specifically focused on heating, ventilation and air-conditioning (HVAC) systems and their plant facilities. Recognizing the potential to improve the effectiveness of building commissioning, several Annex 40 researchers have developed automated commissioning tools with the capability of decreasing the cost of providing commissioning, enabling more comprehensive testing and providing a means to demonstrate the benefits obtained through the commissioning process.

Automated commissioning tools can use various methods to analyze system operation. Quantitative models use mathematical relationships to represent physical processes, i.e., a detailed physical model that uses a set of equations derived from mass, momentum, and energy balances, heat transfer, and mass transfer. This type of approach is valued for its ability to make good predictions of system operation, but it requires extensive validation and detailed system data that can be difficult to obtain. In contrast, qualitative models use expert knowledge of the relationships that represent a physical process (i.e., a rule-based model which uses qualitative rules based on the same fundamental engineering principles listed above and quantitative system relationships) to evaluate its operation. This approach is simple to develop and apply with clear reasoning, but is limited by the expertise of the developer and their knowledge of the system.

THE CONCEPT

The collaboration between NIST and CSTB focused on creating a service tool called CITE-AHU, an automated commissioning tool for air-handling units (AHUs). The concept is to enable the testing and analysis of air-handling units by means of commanding the system into its normal modes of operation and then applying expert rules which are capable of detecting improper system operation. Due to the gross nature of the faults that impact comfort and efficiency, it is usually sufficient to use qualitative models to identify faults.

Tools such as CITE-AHU are designed to decrease the amount of time needed to carry out manual commissioning and to reduce the skill level required to carry out the process. These tools enable more thorough testing of building HVAC systems to improve quality and persistence of correct system operation.

The basis for the analysis used in this study is APAR (AHU Performance Assessment Rules), a set of expert rules designed to assess the performance of AHUs using data from existing sensors in the building energy management system (BEMS) to asses the performance. The extent of the assessment is generally limited by the availability of operational data (e.g., occupancy information, setpoint values, sensor measurements, and control signals) and design data (e.g., ventilation requirements and sequencing strategy). However, because the typical commercial grade sensors that are already installed for control purposes have sufficient accuracy, laboratory grade instruments are not required.

APAR uses control signals and occupancy information to identify the mode of operation for the AHU, where,

Mode 1: heating
Mode 2: cooling with outdoor air

[1] The International Energy Agency's (IEA) Energy Conservation in Building and Community Systems (ECBCS) program established Annex 40, a research working group on Commissioning of Building HVAC Systems for Improved Energy Performance.

Mode 3: mechanical cooling with 100 % outdoor air
Mode 4: mechanical cooling with minimum outdoor air
Mode 5: unknown

Once the mode of operation has been determined, the rules based on conservation of mass and energy are applied to the operational data in order to assess the system operation. House et al. [3] provide a detailed description of 28 APAR rules developed for Variable Air Volume (VAV) AHUs and the reasoning behind them. While many of the more general rules can apply to various systems, the rule set must be customized using expert knowledge of the design data and sensor availability of the system(s) to be tested. Furthermore, the research collaboration includes enhancements to enable a commissioning authority or a building operator to run test scripts for the purpose of exercising particular components and documenting test results.

THE BUILDING DESCRIPTION

The demonstration building is CSTB's Aria building in Paris, France. Built in 1999 with a total gross area 2000 m^2, it is a combined laboratory and office building equipped with a BEMS with remote control/monitoring capabilities. The Aria building has a combination of HVAC equipment, including three constant air volume (CAV) air-handling units. AHU 1 serves laboratory space which contains biological experiments and therefore prohibits active testing. AHU 2 serves laboratory space and AHU 3 serves office space as well as a small area that has been converted into laboratory space and conditioned using three fan-coil units.

AHU 3, shown in the left side of Figure 1, has a constant speed supply fan which draws 6575 m^3/hr (100 %) of outdoor air through a plate heat exchanger with exhaust air crossflow. A manual damper controls the bypass. Preconditioned air is then filtered and passed over a hydronic heating coil before being supplied to the zone. The control of the heating coil valve is based on maintaining the supply air temperature setpoint. A constant speed fan exhausts 7020 m^3/hr of air.

AHU 2, shown in the right side of Figure 1, has a constant speed supply fan which draws 250 m^3/hr of outdoor air and 3600 m^3/hr of return air from the zones. The air is conditioned via a staged hydronic heating coil, hydronic cooling coil, and steam humidifier before being supplied to the zone. The supply temperature setpoint is regulated within a band of 14 to 30 ºC to achieve the desired return air temperature setpoint. The return air humidity setpoint of 60% is achieved by regulating the supply air humidity between 50% and 70% though there is no capability to dehumidify or to modulate the amount of supply air. There is no exhaust fan.

AHU 1 (not pictured) is similar to AHU 2 in design but supplies 6500 m^3/h of air which has been conditioned to meet the 20 ºC supply air temperature setpoint by means of a staged hydronic heating coil and hydronic cooling coil. As a safety precaution, a portion of the supply air is drawn out via AHU 3's exhaust duct to maintain a negative pressurization in the laboratory.

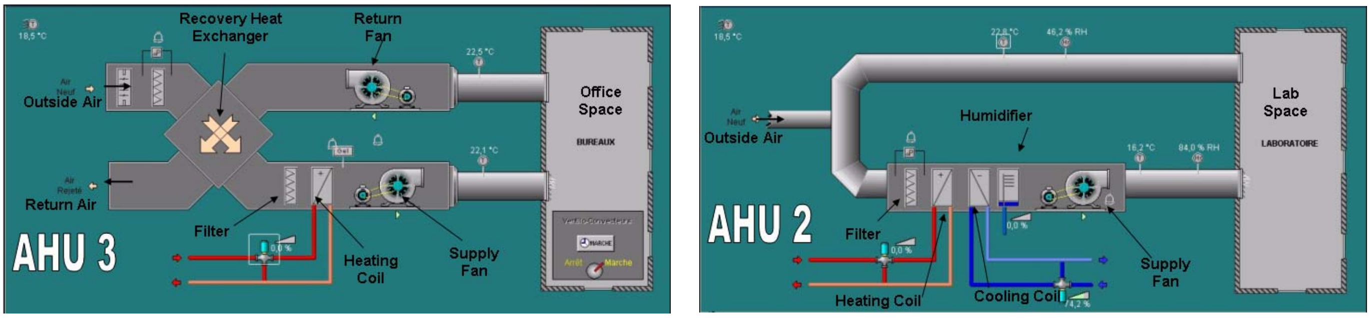

Figure 1: Schematic diagrams of AHU 2 and AHU 3

The following occupancy information, setpoint values, sensor measurements, and control signals for tests of CAV AHUs are used:

Table 1: Available sensor data for the Aria building

Sensor, Setpoint, Control Signal	AHU 3	AHU 2	AHU 1
Occupancy status	✓	✓	✓
Supply air temperature setpoint	✓	✓	✓
Return air temperature	✓	✓	✓
Return air setpoint	-	✓	✓
Relative humidity	-	-	✓
Outdoor air temperature	✓	✓	✓
Cooling coil valve control signal	-	✓	✓
Heating coil valve control signal	✓	✓	✓

COMMISSIONING PROCEDURE

The methodology implemented in retro-commissioning the ARIA building was adapted from several sources including Annex 40 interactions and the Commissioning Test Protocol Library [4]. It involves the seven steps described below that were applied to the ARIA building.

Step 1: Design Review
❖ check control logic, sensor placement
Step 2: Installation Review and Verification
❖ field-inspection to determine installed characteristics of the equipment including condition and sensor availability **and sensor accuracy**.
Step 3: Operator Interview
❖ capture the knowledge of the equipment, operation history, and general assessment of its operation
Step 4: Measurement Verification Using the BEMS
❖ this includes defining which measurements to log with BEMS, evaluating the data for compliance and compare data.
Step 5: Configuration of CITE-AHU
❖ APAR rules are robust and applicable to various systems. However, a review of the rule set must be carried out and re-configured if needed, prior to their implementation in a new system due to differences in equipment configuration and sequence of operations.
Step 6: Forced Response Testing and Analysis with BEMS
❖ direct manipulation of the system through manual override, setpoint change, and sensor input tests (e.g., subjecting freezestat to low temperatures using a compressed air can.
Step 7: Documenting Results
❖ includes a record of tests and evaluation of cost-benefit of commissioning

COMMISSIONING TOOL CITE-AHU DESCRIPTION

The CITE-AHU tool is software to assist the Cx authority and/or the building operator to evaluate the performance of different types of AHUs in buildings. It could help the user in the different aspects of the commissioning process:

- Manual verification (Step 2) or verification using BEMS (Step 4),
- Functional testing during the handover phase or for seasonal testing (Step 6),
- On-going commissioning during regular operation (weekly or monthly),
- Document and archive the results of verifications and tests (Step 7).

Manual Verification and Checklist

During the manual verification step, the CITE-AHU tool advises the user on which points are essential to check, suggests a method to use and aids the user to save the results of the test activity in a formatted document.

For example, to test the “Return Air Temperature Sensor” the user must answer the following questions:

1. Is the sensor really available?
2. Is the sensor placement optimal for measuring the physical phenomena?
3. Is the sensor correctly connected to the control equipment (wiring)?
4. Is the sensor measurement consistent with reference values?

Figure 2 presents the user interface designed to assist the user in manually test the AHU sensors.

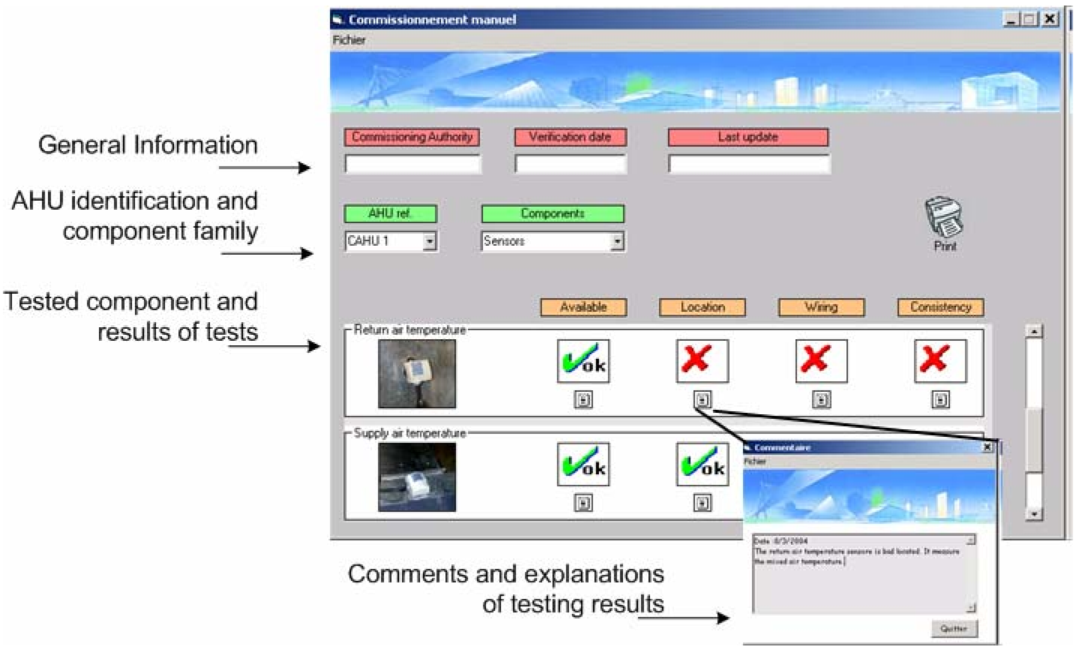

Figure 2: User interface for manual testing

Functional Testing

During the functional testing phase,active testing scenarios are applied to verify the performance of the AHU. The active tests are usually automatically executed during unoccupied period so as not to disturb normal building operation. The different scenarios of active testing are saved in the CITE-AHU library and can be applied periodically (each year or each season).

Two main types of active tests are open-loop and closed-loop:

- With open-loop tests, the performance of different components of the AHU is evaluated while exercising the component over its full range of operation. Here, the system is operated in manual override and the performance of the component is evaluated over the operating range (i.e., the cooling coil valve is opened to 0%, 30%, 60% and 100%). A diagram depicting this process using CITE-AHU is shown in Figure 3.
- With closed-loop tests, the performance of the overall equipment is evaluated while operating in different functional modes (heating, free-cooling, mechanical cooling, etc.) To perform the tests, the setpoints are changed to operate the system in the chosen mode (example: the setpoint of the supply air temperature is changed from 20°C to 16°C to test the cooling mode and from 20°C to 25°C to test the heating mode).

CITE-AHU automatically executes the different scenarios as shown in the first screen capture of Figure 3 where the actions are highlighted in green as they are completed. Using the BEMS, CITE-AHU, helps the user to analyze the results and automatically saves the results in a formatted document.

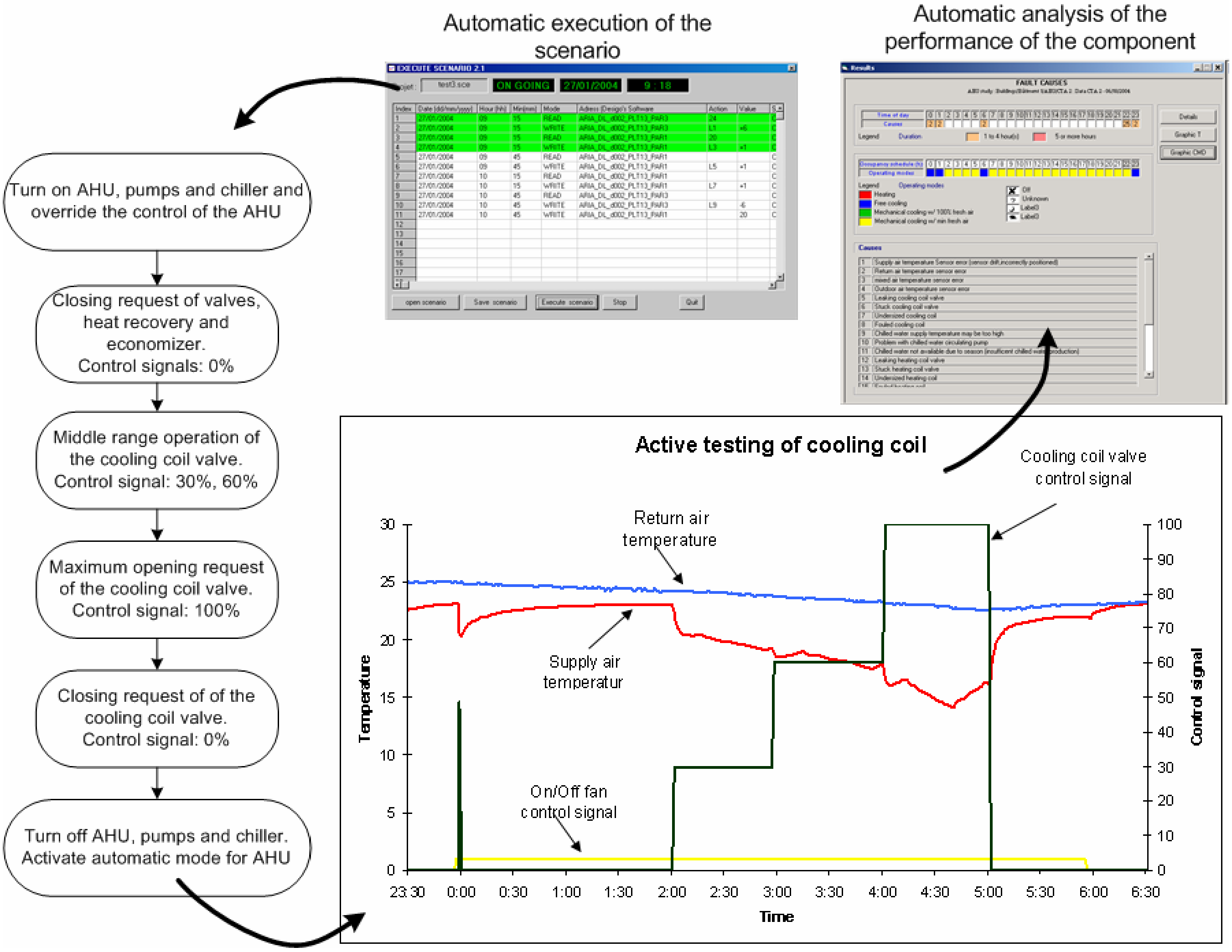

Figure 3: Diagram of an open-loop test of a cooling coil using CITE-AHU

On-going Commissioning

Under normal building operation, the data collected by the BEMS can be analyzed regularly (daily, weekly, or monthly) using CITE-AHU. CITE-AHU helps the user to detect and diagnose AHU faults and presents the results in a hierarchical way to provide the user with access to several levels of diagnostic detail.

In Figure 4, the first screen shot presents the results in table format. Here the user can select the week and year to view the automatic fault detection summary for one or more specified AHU(s). In this table, the darker color red indicates the importance of the fault detected for an AHU, based on fault duration and threshold levels. The repetition of the faulty days in the table is also an indication that the system is in need of maintenance.

By clicking on a specific cell on the table, the user can access more detailed diagnosis results stating which fault was detected and under which operating mode. The user can also validate the diagnosis by using graphs (temperature plots and control signals plots) accessible at this level.

CITE-AHU is self-documented. It can be used with different AHUs (constant and variable air volume) and can be reconfigured for specific cases.

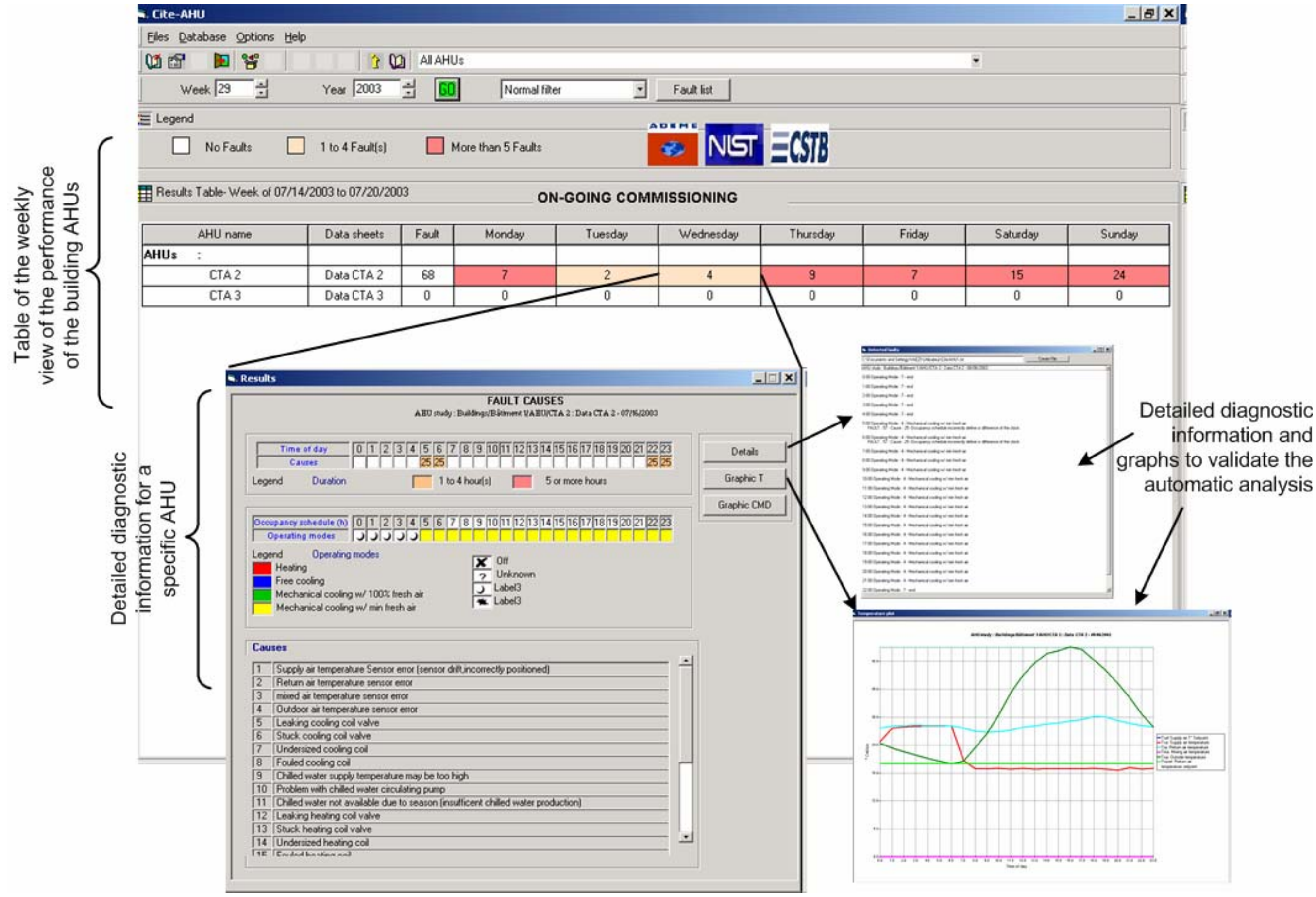

Figure 4: Screen images of hierarchical analysis with CITE-AHU

COMMISSIONING RESULTS AND DISCUSSION

For the Aria building, system design information was taken from the design documents prepared by the architect and designer while control logic was taken from the functional analysis documents. Expert knowledge of the system was required as neither document matched the as built operational state.

A manual verification of sensor locations and system temperatures was carried out before the BEMS data was available. The faults identified in the course of the manual verification have been incorporated into the summary in Table 2. The initial analysis was based on two laboratory-grade thermocouples with data logging capabilities that recorded the room ambient temperatures (T_{amb1} and T_{amb2}) in the office and an outdoor air temperature sensor (T_{OA}) located on the roof of the Aria building. However, for systems where a BEMS can be used to assist in the commissioning process, the system sensors are the only ones used for the analysis. Overlay sensors can be useful to determine the source of sensor measurement discrepancies identified by CITE-AHU.

The operator interview conducted in the summer of 2003 was an iterative process. The Aria building operator was involved in the maintenance and operation of the buildings HVAC systems since 2001 and provided valuable information not available in system documentation. Information about which systems were problematic, occupant comfort complaints, and historical information proved valuable. For example, a zone was partitioned for office spaces without any modifications to the HVAC design which resulted in large temperature gradients across the room. In addition, a cooling coil was added to AHU 1 without an independent loop to the chiller. When it was discovered that the the desired room conditions were not maintained, the cause was traced to improper scheduling of the of the chilled water circulation pump.

The original local AHU control panel could only display instantaneous values for a single data point, hence, comparisons were not feasible. Once the BEMS was installed and validated, the trending capabilities greatly facilitated the evaluation of the system sensor readings and uncovered numerous errors, listed in Table 2. Scheduling errors were immediately apparent due to a test program that forced the AHUs in to continuous operation (Table 2, Ref. F) and the use of temperature profiles confirmed that the outdoor air temperature sensor was poorly shaded from direct solar radiation (Table 2, Ref. E).

Armed with expert knowledge of the system, additional rules were added. The APAR rules, originally developed for a variable air volume system with economizer, were enhanced for application to the constant air volume systems and to provide a means to test operation during unoccupied periods. These rules were applied in batch format to data collected from the forced response tests.

The forced response tests were carried out using Execute Scenario software which enabled the creation of a library of test scripts to evaluate various components and operating modes. In all cases, tests were scheduled such that discomfort to occupants was minimized with tests conducted primarily during unoccupied periods.

Forced response tests were carried out on AHU 3 and AHU 2 while AHU 1 was only tested passively. In total, sixteen faults were discovered by means of manual and BEMS assisted commissioning. A representative subset of the types of HVAC faults are classified in Table 2 according to categories identified in the Public Interest Energy Research (PIER) funded Commissioning Cost Benefit Study [5]. In this table, the implementation costs are calculated based on equipment costs (i.e., new sensor) and includes any outside labor (i.e., BEMS installer). This excludes the building operator's time (i.e., correcting schedule via BEMS interface). Faults in Table 2 that have been corrected have a check mark.

Table 2: Commissioning results for Aria Building

Ref.	Problem Type	Description	Strategy	Cost € (estimate)	Status
A	Design	N/A			
B	Installation	AHU 2- Return air temperature sensor is faulty. The sensor was found with plastic covering	Remove packing material	0	✓
C	Retrofit	AHU 1 - Cooling coil added without independent loop to chiller		(8000)	
D	Operations & Control	Control of boiler valves is reversed	Re-wire	0	✓
E	Start/stop	Outdoor air temperature not properly shaded	Reposition	0	✓
		AHU 2-Return air temperature sensor is located downstream of the mixing box	Add new sensor	(2000)	
F	Scheduling (occupancy)	Forced continual operation of AHUs due to a test program that was initiated to test the AHU during the initiation in 2000	Remove program	0	✓
G	Setpoints	Recovery Air damper set to heat recovery in summer	Change damper position	0	✓
		Supply air temperature setpoint is constant (21°C) even in summer when the setpoint results in nightime heating	Program summer setpoints	0	✓
		The open period of the boiler isolation valves (3 min) is too long for the on/off period of the boilers (2min),	Reduce time constant	0	✓
H	Equipment Staging	AHU 3 circulation pump cycles with the boiler. The heating coils are not supplied with hot water when the boilers cycle off, Hence boilers were put in manual override even in summer	Remove link to pump control	0	✓
I	Maintenance	Chiller condenser fins 50% fouled, AHU 3 filters fouled	Clean fins	0	✓

Energy Impacts

The two most significant improvements were 1) correcting the boiler control logic, and 2) removing the test program from the AHUs. It was discovered that the boiler plant was running continuously by manual override to avoid occupant discomfort. This is attributed to a lack of system transparency. This transparency is essential because if a system does not work or is not understood, the operators will bring the operation to their level of understanding which in some cases may be manual operation. The manual override and the root cause of the problem, a control logic error listed in Ref. H of Table 2, were corrected in January 2004 and resulted in a decrease in gas consumption while still meeting occupant comfort requirements. The winter season estimate was a 10% gas savings or approximately 700€ for the season. The second improvement, removal of the test program (Ref. F of Table 2), enabled the AHUs to follow their scheduling programs. Hence, the excessive run time for the AHUs was eliminated and resulted in an estimated 47% reduction in annual electrical energy consumption or 4141€.

Non-Energy Impacts

Non-energy impacts are evident, but difficult to quantify. For example, the presence of the test program meant that the AHUs were running day and night. This meant that the maintenance schedule did not keep up with the operating schedule. Filters were not replaced frequently enough which could reduce system efficiency and affect indoor air quality. The following non-energy impacts are a result of the measures already implemented:

- Improved comfort for occupants
- Increased protection of the boiler plant equipment.
- Improved indoor air quality
- Improved productivity
- Extended equipment life
- Improved documentation

Table 3 present the labor estimates for re-commissioning the AHUs in the ARIA building with the help of CITE-AHU.

This estimation does not take into account some of the task iterations that were due to the lack of experience in applying the commissioning procedure. The estimation of the labor tasks was carried with the collaboration of the operator expert and the technicians involved in the project. After the re-commissioning task was performed, the operator must continue to use the on-going commissioning functions of CITE-AHU in order to detect operating faults.

Table 3: Labor Estimates for CITE-AHU Application

Phase	N°	Step	Comment	Days
Manual	1	Design Review	Check control logic, sensor placement and sensor accuracy with design documents	3
	2	Installation Review and Verification	Conduct a field inspection to determine installed characteristics of the equipment including condition and sensor availability (real location)	1
	3	Operator Interview	Ask building operator about the performance of the system and about unclear points detected during design and installation reviews	1
BEMS assisted	4	Installation Review and Verification with BEMS	Verify mismatch between BEMS control logic and design documents	1
	5	Measurement Verification with BEMS	Define measurements to log with BEMS, evaluate data for compliance	4
	6	Configuration of CITE-AHU	Configure CITE-AHU	0,5
	7	Forced Response Testing and Analysis	Analyse performance of the system with CITE-AHU. Document the results.	4
			Total	**14,5**

SUMMARY

As a part of the IEA ECBCS Annex 40 research, several automated commissioning tools have been developed and tested in real buildings. CITE-AHU is a service tool designed to evaluate air-handling units. The major benefit of this software is that it reduces the effort required to carry out manual and/or BEMS assisted commissioning while ensuring that there is a thorough check of the system operation. This tool simplifies the work for the operator by automating the execution of test scripts and the documentation of test results. Automated commissioning tools such as CITE-AHU enable more comprehensive testing of building HVAC systems because once the expert rules are developed, the operator involvement is shifted from tedious and repetitive sensor checks to the review of the fault analysis and fault remedy.

CITE-AHU has a rule base to test both constant air volume and variable air volume AHUs. The results presented in this field test of the prototype show eleven of the fifteen faults that were successfully identified in the constant air volume systems of the Aria building. The rules are robust, but due to the variety in AHU system designs a review of the rule configuration is required when beginning a new application.

Future work includes the application of CITE-AHU to new systems.

REFERENCES

1. **Haasl, T. et al.** *Retrocommissioning's Greatest Hits*, Portland Energy Conservation, Inc, http://www.peci.org/papers/rcxhits.pdf, PECI project, 1999.
2. **Claridge, D. et al.** *Commissioning of Existing Buildings-State of Technology and It's Implementation* , International Symposium on HVAC Commissioning, Kyoto, 2003.
3. **House, J.M., Vaezi-Nejad, H., and Whitcomb, J.M**., *An Expert Rule Set for Fault Detection in Air-Handling Units,* ASHRAE Transactions, Vol. 107, Pt. 1., 2001.
4. **Gillespie, K., and Misti Bruceri.**, 2001, *Library of Commissioning Test Protocols* in Proceedings of the 9th National Conference on Building Commissioning, Cherry Hill, N.J., May 2001.
5. **Public Interest Energy Research** (PIER) *Commissioning Cost and Benefits Study* [LBNL].