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METHODS FOR AUTOMATED AND CONTINUOUS COMMISSIONING OF BUILDING SYSTEMS

Final Report

April 2003

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1. Executive Summary

Background and Goals

Effective commissioning and maintenance of building systems and equipment extends equipment life, improves or maintains occupant comfort, and improves equipment availability. Conversely, poorly maintained systems and equipment will have shorter lives and will experience more frequent failures, leading to lower levels of equipment availability and greater occupant dissatisfaction. Currently, effective commissioning, ongoing manual maintenance, and recommissioning can be expensive.

To address this issue, the Air Conditioning and Refrigeration Technology Institute (ARTI) launched an investigation into methods for automating the continuous commissioning of building systems. The overall goal of this project is to develop methods for improving the commissioning and maintenance of HVAC systems and equipment through automation. To achieve this, the project was broken down into five tasks.

Task 1: Investigate Building Commissioning Processes and Procedures

Using a literature search and interviews with commissioning providers, the project team documented current commissioning processes and procedures. Separate commissioning processes for new construction and existing buildings are presented, but both integrate with the typical phases of the corresponding design and construction processes.

Current efforts to automate commissioning fall into four categories: developing and managing building design information, developing test procedures, managing data, and automating functional testing.

Currently, functional testing methods are either "active" or involve monitoring. Active testing uses hand-held instruments, immediate control system readouts or direct observation to verify performance. Monitoring records the parameters of equipment operation using data loggers or the trending capabilities of the building automation system. Only monitoring methods are currently automated.

The literature search and interviews identified several HVAC systems and system components that are frequently commissioned or are time consuming and challenging to commission. The queries also identified the typical processes executed during the commissioning process for both new and existing buildings. Commissioning providers, when asked to gauge their interest in automated tools, were most interested in automated diagnostic tools and tools that reduced document handling and repetition. Some were concerned, however, that any automated tool might not be versatile enough to accommodate the diverse situations seen in commissioning projects.

Task 2: Identify Systems and Processes for Automated Commissioning

The project team prioritized classes of components, equipment, systems, and commissioning processes according to how amenable they are to, and how much they would benefit from automated or continuous commissioning.

A group of seven engineering and commissioning experts analyzed three matrices (each of which are included in the Appendix). The first matrix listed 139 problems associated with 19 common building systems. The second matrix listed 69 new construction commissioning tasks in all phases of the typical new construction commissioning process. The third matrix listed 39 existing building commissioning tasks.

The system problems most amenable to automated or continuous commissioning include:

- diagnosing faulty economizer operation;
- diagnosing uncalibrated or malfunctioning sensors;
- diagnosing uncalibrated or malfunctioning valves, dampers, or actuators;
- diagnosing faulty or improper ventilation control strategies;
- diagnosing malfunctioning economizers and dampers; and
- identifying improper setpoint settings.

New construction commissioning processes amenable to automation included:

- perform checkout and functional tests;
- collect data used for performance verification; and
- retain completed functional test sheets.

Existing building commissioning processes amenable to automation included:

- perform functional tests;
- collect monitored data; and
- retain functional test and monitoring data results to confirm initial findings.

Task 3: Select the Equipment and Systems and the Commissioning Processes and Procedures to Automate

The project team identified and recommended specific commissioning activities and procedures that are most appropriate for automation. Based on the matrix scores from Task 2, we condensed the list of processes amenable to automation and compiled a short list of seven potential items for further investigation as part of this project. The short list included two categories of activities: data management and functional testing.

Data Management

- Make design information available for commissioning
- Develop a method to record, use, and store building data

Functional Testing

- Assess faulty economizer operation
- Identify improper setpoint settings
- Identify malfunctioning sensors
- Identify malfunctioning valves and dampers
- Identify faulty ventilation control strategies

The team considered each item on the short list in terms of the potential impacts and benefits of demonstrating automation potential for the item, the risks and costs associated with demonstrating each item, the range of applicability of each item, and whether each item could apply to continuous commissioning. The final recommendations proposed to the Project Monitoring Subcommittee are:

- Import recorded building data into a functional test procedure template
- Automatically assess faulty economizer operation
- Automatically identify malfunctioning sensors

(**Note:** By agreement, a fourth item was added later: automatically identify malfunctioning valves and dampers.)

Task 4: Identify Automation Techniques and Methods

The project team reviewed technologies and techniques that may be applicable to automated and continuous commissioning of building systems. The goal was to provide background information for selecting specific commissioning procedures to automate in this project, and to provide information critical for selecting the analytical tools and techniques to be used in the prototype applications that will be developed to automate these procedures. We surveyed available tools and techniques and described the technology context into which automated commissioning applications will be introduced.

Key findings for the major categories of tools are as follows:

Tools and Techniques for Managing Commissioning Data Various new technologies and applications of technologies promise to be useful in streamlining and automating aspects of the commissioning process. Chief among these are the Internet and World Wide Web, wireless communications, lightweight portable and hand-held computers, high capacity data storage devices, and standards for data representation and data sharing between commissioning participants. These technologies and the software applications built on them show considerable promise for speeding, making continuous, and reducing the cost of commissioning processes.

Analytical Techniques A variety of techniques are available, from first principles–based models to classical statistical methods to artificial neural networks. Currently, it appears that methods based on parametric models are likely to best match the analytic modeling and processing needs of commissioning processes. The ability to tune parameters will likely best match the need to accommodate a broad range of equipment and unique characteristics of individual buildings.

Analytical Tools Existing mathematical, statistical, and data processing tools and software toolkits are likely to prove immensely valuable in testing and developing techniques for automating parts of the commissioning process and will be required in this project. Programming languages, such as C++, may prove valuable for prototyping automated commissioning processes in this project and will certainly prove critical in developing tools for commissioning providers in follow-up work to develop and deploy these tools.

Task 5: Develop Methodologies for Automating Selected Procedures and Processes for Continuous Commissioning

Following the recommendations and findings of the previous tasks, we develop and document a generic, automated, continuous commissioning process that involves detecting, diagnosing, and evaluating faults and choosing a course of action. We use that generic process to adapt and develop specific and detailed methods and procedures (upon which automated tools can be built) that continually detect and assess the operation of economizers and outdoor air ventilation. In doing so, we discuss topics such as data requirements, passive versus proactive detection and diagnosis, and balancing analytical sensitivity with false alarms.

We then take a similar approach to faulty sensors. We develop a generic method for detecting faulty sensors, then use that to develop detailed procedures for identifying which sensors are faulty and for diagnosing problems with each type of sensor.

We develop a generalized approach for detecting malfunctioning valves and dampers that can be applied in a variety of HVAC applications.

Finally, we specify and prototype a methodology that formalizes and expedites determining what information is needed for commissioning and then compiling that information into a database.

Conclusions

Summary

This research project identified methodologies that could be used to develop commissioning tools for the four problems and processes that emerged as the top candidates for automation within the commissioning process:

1. Faulty economizer operation;
2. Malfunctioning sensors;
3. Malfunctioning valves and dampers; and
4. Project data management.

The need and desire for automated tools to help reduce the time and cost associated with commissioning is prevalent in the commissioning community. Fault detection and data management techniques can be integrated into proactive fault detection tools which can use measured data, design data, and equipment operating parameters to perform actual functional tests to improve system diagnosis. Methodologies for detecting system operation faults were developed and demonstrated through flow diagrams and simplified mock-up applications. Data management techniques were demonstrated through examples illustrating how prefunctional and functional test forms could be populated with design information and equipment operating parameters.

Future Research

This project focused on developing methodologies for automated tools for two broad commissioning tasks: 1) detecting faults in system operation, and 2) managing commissioning related data. In each of these areas, we have identified future research that is key to advancing the widespread implementation of automated continuous commissioning.

Detecting Faults The methodologies and diagnostic logic recommended in this report should be validated. This validation should include testing the methodologies using mock-up software in the laboratory and in the field, and empirically investigating the effect of tolerances on sensitivity and false alarms. Comprehensive automated fault detection software tools should also be developed. The most effective way of integrating these tools into the continuous commissioning process should be determined.

Managing Data Current efforts to develop data schemata for identifying and classifying building and construction data should be expanded to include information specific to commissioning building systems and equipment. Software tools for gathering, organizing, and managing this information should be developed. That data management software should be integrated with the emerging automated fault detection software.

It is evident that significant additional research and development are necessary to produce automated tools and to develop an implementation framework around an automated continuous commissioning process. The potential for practical application of automated commissioning tools by building operators and commissioning providers is high. However, resistance to new technology and practices exists in every market segment. Therefore, an important element in the implementation strategy will be market transformation initiatives to train building operators and commissioning providers to integrate the new tools into their existing practices.

2. Introduction

Many buildings today use sophisticated building automation systems (BASs) to manage a wide range of building systems. Although the capabilities of the BASs seem to have increased, many buildings still are not properly commissioned, operated, or maintained. A lack of commissioning, improper commissioning, the inability of the building operators to understand and interact with the complex controls, and the lack of proper maintenance all contribute to inefficient operations and reduced lifetime of the equipment.

Poorly maintained equipment will have shorter lives and experience more frequent failures, leading to lower levels of equipment availability and greater occupant dissatisfaction. Conversely, effective maintenance and recommissioning extends equipment life, maintains comfort, improves equipment availability, and results in fewer complaints from building occupants. However, implementing enhanced maintenance or recommissioning practices can be expensive.

To address this issue, the Air Conditioning and Refrigeration Technology Institute (ARTI) launched an investigation into methods for automating the continuous commissioning of building systems. The overall goal of this project is to develop methods for improving the commissioning of HVAC systems through automation.

Automated commissioning and diagnostic technologies address two of the main barriers to commissioning: cost and schedule. Automated continuous commissioning tools can reduce both the costs and time associated with commissioning, as well as enhance the persistence of commissioning fixes. In the long run, automation even offers the potential for automatically correcting problems by reconfiguring controls or changing control algorithms dynamically.

To achieve these objectives, the project was broken down into five tasks:

Task 1: Investigate building commissioning processes and procedures

Compile and categorize information about the commissioning procedures used for both new and existing buildings, current testing methods, and pervasive problems related to equipment performance and the commissioning process.

Task 2: Identify systems and processes for automated commissioning

Prioritize classes of components, equipment, systems, and commissioning processes relative to how amenable they are to, and how much they would benefit from, automated or continuous commissioning.

Task 3: Select the equipment and systems and the commissioning processes and procedures to automate

Identify and recommend specific commissioning activities and procedures that are most appropriate for automation.

Task 4: Identify automation techniques and methods

Review technologies and techniques that may be applicable to automated and continuous commissioning of building systems.

Task 5: Develop methodologies for automating selected procedures and processes for continuous commissioning

> Develop and demonstrate methodologies and tools that continually detect and diagnose faults in the selected equipment and processes. Specify and prototype tools that implement those methodologies.

This reports describes the work performed under each task and presents the findings of each. The *Conclusions* section presents conclusions drawn from the entire project and suggests areas suitable for further research.

3. Task 1: Investigate Building Commissioning Processes and Procedures

3.1. Introduction

This section presents the results of Task 1, in which we compiled and categorized information about the commissioning process for both new and existing buildings, current testing methods, and pervasive problems related to equipment performance and the commissioning process. This information is used in Task 2 to identify equipment and processes that may be amenable to, and will benefit most from, automation.

3.2. Approach

Task 1 of this project was completed in two steps. In step one, PECI conducted a literature search of periodicals, conference proceedings, and research reports. The review identified tasks performed during the commissioning process for both new and existing buildings, current testing methods and functional and performance problems. Current automation efforts were also identified.

In step two, PECI conducted a survey of commissioning providers. The goal of the survey was to identify commissioning processes best suited for automation. Commissioning providers were also asked what they would like to see in an automation tool. The results of the literature search and survey are described below.

3.3. Commissioning Process in New Construction

The following summarizes the basic commissioning process in new construction, including major equipment replacements and renovation. Ideally it is integrated with the phases of construction and begins in the pre-design phase and continues through occupancy and the one year warranty period. The commissioning process involves the development and management of building and commissioning information, forms and test procedures—all of which provide opportunities for automation.

A brief description of each phase and expected commissioning activities are outlined below.

3.3.1. Pre-Design Phase

During pre-design, the commissioning team includes at least the project manager, commissioning provider, and design team. Generally for a new construction project, contractors have not been selected yet, nor have building operators been assigned; however, representatives from both disciplines should be included in the team as soon as possible. The main commissioning tasks during the pre-design phase are listed chronologically below.

Commissioning Provider Selection The project manager sends out requests for proposals (RFPs) or requests for qualifications for commissioning services and selects a commissioning provider.

Develop Owner's Project Requirements The commissioning provider or design team may assist the owner in developing or reviewing the Owner's Project Requirements documentation for the proposed building. The owner's objectives may be developed through a meeting of owner stakeholders with the design team and commissioning provider in attendance. At a minimum, the commissioning provider reviews the Owner's Project Requirements for clarity and completeness.

Commissioning Scoping Meeting The commissioning provider assembles the commissioning team and holds a scoping meeting with the team to communicate the owner's goals, needs and expectations for building operation and function and to identify commissioning responsibilities. Items discussed in this meeting are used to develop the scope and rigor of the commissioning effort.

Design Phase Commissioning Plan The commissioning provider begins to develop a design phase commissioning plan. The plan will be enhanced as the design progresses.

Written Work Products During pre-design, the project manager should receive a written commissioning plan from the commissioning provider, as well as comments on the Owner's Project Requirements document.

3.3.2. Design Phase

The goals of commissioning during the design phase are to ensure that:

- the concepts for building systems developed during pre-design and earlier design phases are included in subsequent design phases;
- the Design Record document is updated;
- commissioning is adequately reflected in contract documents; and,
- no significant deficiencies exist in the contract documents.

If the commissioning process does not begin until the design phase, the project manager should ensure that tasks outlined in the pre-design phase are completed. The main design phase commissioning tasks in chronological order are outlined below.

Design Phase Commissioning Plan The commissioning provider updates the design phase commissioning plan (or develops a commissioning plan if one was not started during pre-design).

Design Narrative and Basis of Design The design team develops formal Design Narrative and Basis of Design documentation. The commissioning provider and owner ensure that these documents are written and updated and reviewed for clarity, completeness and compliance with the owner's objectives and earlier design narratives.

Design Record The commissioning provider compiles and updates the Design Record as design progresses. The design record is a compilation of the owner's requirements, design narrative and basis of design.

Design Review The commissioning provider attends selected design team meetings and formally reviews and comments on the design at various stages of development (ideally at least once during schematic design, design development, and contract document phases). Potential system performance problems, energy efficiency improvements, indoor environmental quality issues, operation and maintenance issues, and other issues may be addressed in these design reviews, depending on the commissioning provider's scope and the needs of the project. The commissioning provider ensures that the design follows and meets the original Owner's Project Requirements. The commissioning provider does not approve the design, but makes recommendations to facilitate commissioning and improve building performance. The project manager evaluates and discusses all findings with the design team and implements those approved.

Construction Phase Commissioning Plan The commissioning provider should begin developing the commissioning plan for construction, which will guide the development of the commissioning specifications.

Commissioning Specifications The commissioning provider develops detailed commissioning specifications to be included by the design team in the final contract document. The specifications comprise commissioning related requirements that will be the contractor's responsibility, including equipment installation and start-up, documentation and functional testing. In addition, the commissioning provider may recommend enhanced language regarding training, documentation, installation, and system checkout for inclusion in non-commissioning sections of the specifications.

Design Phase Issues Log The commissioning provider develops and keeps a record of issues and findings that come up during design that require further attention, tracking, or correction.

Written Work Products During design, the project manager should receive regular commissioning progress reports from the commissioning provider, as well as updated comments and recommendations from design reviews that the project manager must resolve with the design team. The commissioning provider submits updates of the Design Record. The commissioning provider also submits an initial construction phase commissioning plan and commissioning specifications.

3.3.3. Bidding Phase

During the bidding phase, contractors review the contract documents and submit bids for constructing the project. The commissioning provider may be asked to attend the pre-bid conference to answer any questions about commissioning and may review bids, alternates, and addendums to ensure that commissioning, and the Owner's Project Requirements, are not compromised by the changes.

3.3.4. Construction Phase

The main construction phase commissioning tasks are listed chronologically below.

Construction Phase Commissioning Plan The commissioning provider updates the construction phase commissioning plan, which includes a list of all systems and specific equipment and components to be commissioned, the process to be followed, communications, reporting and documentation protocols, and an estimated schedule for the commissioning process.

Construction Phase Commissioning Kickoff Meeting The commissioning provider coordinates a construction phase commissioning kickoff meeting. The meeting should include the project manager, construction manager , design team, commissioning provider, and respective representatives from the general contractor and mechanical, electrical, controls, and testing and balancing (TAB) subcontractors. At this meeting, the commissioning provider outlines the roles and responsibilities of each project team member, specifies procedures for documenting commissioning activities and resolving issues, and reviews the preliminary construction phase commissioning plan and schedule. Team members provide comments on the plan and schedule, and the commissioning provider uses these suggestions to help finalize the commissioning plan and schedule.

Issues Log The commissioning provider develops and keeps a record of issues and findings throughout the construction phase commissioning process that require further attention, tracking, or correction. The log is updated regularly and submitted to the project and construction managers and each contractor for discussion and resolution during construction meetings.

Construction and Commissioning Meetings The commissioning provider attends periodic planning and job site meetings to remain informed on construction progress and to update the parties involved in commissioning. During the initial stages of construction, the commissioning provider may attend regular construction meetings and hold a line item on the agenda. Later in construction, the commissioning provider may coordinate entire meetings devoted to commissioning issues.

Submittal Review The commissioning provider reviews contractor submittals of equipment to be commissioned during the normal submittal review process. The commissioning provider reviews and comments on each submission, and forwards them to the project manager or designer.

Additional information will be requested by the commissioning provider including installation and start-up procedures, operation and maintenance information, equipment performance data, and control drawings prior to formal operations and maintenance (O&M) manual submittals. This data is used by the commissioning provider to become familiar with the systems and to write functional test procedures. Project manager support for obtaining these additional documents from the contractors is critical.

Monitor Coordination Drawing Development The commissioning provider may assist the project manager in monitoring the development of coordination drawings to ensure reasonable interface between trades.

Change Order Review All requests for information (RFIs) and change orders applicable to the commissioned systems should be provided to the commissioning provider for review for impacts on commissioning and Owner’s Project Requirements.

Construction Observation The commissioning provider visits the construction site periodically and notes any conditions that might affect system performance or operation. Construction observation reports are provided to the project manager.

Construction Checklists and Start-up The installation, start-up and initial checkout of the equipment and systems are executed and documented by the contractor on construction checklists provided by the manufacturer shipped with the equipment and any additional checklists provided by the commissioning provider. Many commissioning providers have their own checklists that are modified for specific jobs. These checklists are submitted to the commissioning provider, who makes sure they are complete before functional testing begins. The commissioning provider may witness some of the start-up execution and will spot check selected items on the checklist prior to functional testing.

Functional Testing After developing written test procedures, the commissioning provider manages, witnesses, and documents the functional tests, with the actual hands-on execution of the test procedures typically carried out by subcontractors, particularly the controls contractor. Commissioning providers typically have their own set of functional testing procedures that they modify for specific projects. Acceptable performance is reached when equipment or systems meet specified design parameters under full load and part load conditions during all modes of operation, as described in the commissioning test requirements of the specifications and commissioning plan. Some testing is completed by monitoring system operation over time through the building automation system or data loggers and is not normally completed until a few weeks after occupancy. The commissioning provider may prepare test plans for, assist with execution of, and document tests of commissioned equipment overseen by regulatory authorities and should ensure that such tests meet the testing rigor desired by the owner.

O&M Manuals The commissioning provider reviews the operation and maintenance manuals and verifies that they are complete, clear, explicit, and available for use during the training sessions.

Training Ideally, enhanced training requirements are included in the specifications. The commissioning provider assists the project manager in ensuring that adequate training plans are used by the contractor and that the training is completed per the contract documents. The commissioning provider may provide training agendas to the contractor’s/manufacturer’s trainers to review and use. The agendas should list, among the other things, the areas of particular concern to the owner that should be covered in the training.

Systems Manual The commissioning provider compiles a Systems Manual that consists of the Design Record; space and use descriptions; single line drawings and schematics for major systems; control drawings; sequences of control; table of all setpoints and implications when changing them; time-of-day schedules; instructions for operation of each piece of equipment in emergencies, seasonal adjustment, startup and shutdown; instructions for energy saving operations and descriptions of the energy saving strategies in the facility; recommendations for recommissioning frequency by equipment type; energy tracking recommendations; and recommended standard trend logs with a brief description of what to look for in them.

Commissioning Record Shortly after occupancy, the commissioning provider typically writes a final commissioning report, which summarizes the commissioning effort and gives the commissioning provider's disposition on each piece of commissioned equipment relative to installation and start-up, functional performance, O&M documentation, and training. The Commissioning Record also contains the commissioning plan, functional tests, individual commissioning reports and reviews, issues log and information on commissioning activities that will occur during warranty.

Written Work Products The commissioning process generates a number of written work products during the construction phase of the project. The project manager should receive at least the following products from the commissioning provider.

- Updated construction commissioning plan
- Updated commissioning schedule
- Minutes from commissioning meetings
- Periodic commissioning progress reports
- Reports of submittal reviews
- Updates to the commissioning issues and related memoranda
- Construction checklists and functional test form templates
- Completed construction checklists and functional test forms
- Report of training completion
- Report of O&M manual review
- Systems Manual
- Commissioning Record

3.3.5. Warranty Period

Although the project is essentially considered complete once the facility is occupied, some commissioning tasks from the initial commissioning contract continue throughout the typical one year warranty period. The main commissioning tasks during the warranty period are listed chronologically below.

Seasonal Testing Seasonal testing is conducted, ideally, during winter, summer, and swing-season conditions to verify proper system operation. Presumably, one of the "seasons" was tested before building turnover. The testing should be performed by the appropriate contractor and witnessed by the commissioning provider and building operators. However, the owner may have their operations staff and the commissioning provider execute the tests and bring contractors back only if there are problems.

Near Warranty End Review The commissioning provider may also be tasked with returning a few months prior to the expiration of the contractor's one year warranty to interview facility staff and review system operation. Acting as the owner's technical resource, they assist the facility staff in addressing any performance problems or warranty issues. If there are still any outstanding issues, the owner shall address them with the contractors or design team.

Written Work Products The project manager should receive an "as operated" sequence of operations from the commissioning provider or controls contractor, as well as a finalized issues log outlining all deficiencies identified throughout the entire process and their resolutions. The commissioning provider should also submit a summary report after performing seasonal testing and the pre-warranty expiration review of each system.

3.4. Retrocommissioning Process

Retrocommissioning, or existing building commissioning, is a systematic process applied to existing buildings for identifying and implementing operational and maintenance improvements and for ensuring their continued performance over time. Automated diagnostics that detect and diagnose equipment problems would be very valuable in the retrocommissioning process.

The four phases of the basic retrocommissioning process are as follows:

Planning Phase The owner or manager decides which buildings would likely benefit most from retrocommissioning, develops the scope and objectives for the project, and puts together a team to achieve the goals. Information about the building and current operating conditions is also gathered during this phase.

Investigation Phase The in-house staff and/or Commissioning Provider review all information pertaining to the building to determine how each major piece of equipment and building system is supposed to operate and then test and monitor how the systems actually operate (both independently and interactively). The primary task during the investigation phase is to generate a prioritized list of operating deficiencies and energy saving opportunities for the facility, from which the owner selects the measures for implementation.

Implementation Phase The in-house staff or outside contractor will correct the highest priority O&M deficiencies, implement cost effective energy saving opportunities, and verify proper system operation.

Hand-off Phase The Commissioning Provider presents the owner or manager with a final report that contains, at minimum, the scope of the project, a master list of deficiencies and potential improvements, a detailed description of improvements that were implemented, and a list of recommended capital improvements for further investigation. The Commissioning Provider also shows the building operators how to sustain proper operation of the equipment and system.

The primary tasks within each phase are outlined below.

3.4.1. Planning Phase

Develop Project Scope and Objectives The retrocommissioning process begins when an owner selects a building and outlines the scope and objectives for the project. The scope and objectives, as well as the level of rigor and detail, may vary depending on the current needs of the owner, the budget, and the condition of the equipment. Sample objectives for a retrocommissioning project may include:

- bringing equipment to its proper operational state;
- reducing comfort complaints;
- reducing energy and demand costs;
- increasing equipment life;
- improving indoor environmental quality;
- reducing staff time spent on emergency calls; and
- improving facility operation and maintenance.

Develop Team Typically, a successful retrocommissioning project is a team effort. The team generally consists of facility operators and a Commissioning Provider, and the team is responsible for achieving the goals and objectives of the project. The building personnel should have in-depth knowledge of the building control systems, how and why equipment and systems are operated and maintained in the present manner, and should also have access to historical data. The Commissioning Provider brings troubleshooting, problem solving, as well as diagnostic monitoring, testing, and analysis expertise to the team. Together they will identify obvious problems and potentially uncover hidden problems with building systems that must be solved to meet project goals. The commissioning provider may also question the use of current equipment, practices, or methods that may be causing problems and identify useful and cost effective solutions for the problems.

Collect and Review Facility Documentation Accurate, complete, and updated documentation is not only important to the building staff for future use but also immediately important to the Commissioning Provider. The Commissioning Provider uses the documentation during the investigation phase of the project for conducting the site assessment and developing the appropriate diagnostic and functional test plans that may be required to verify equipment performance.

Typically, the following documentation is gathered and reviewed:

- general building description;
- drawings relevant to the systems scheduled for commissioning, especially control drawings;
- sequences of operation for all or some equipment;
- energy efficient operating strategies for all or some equipment;
- equipment list with nameplate information for all or some equipment;
- O&M manuals for all or some equipment;

- HVAC system test, adjust, and balance (TAB) reports;
- project management (PM) logs for all or some equipment; and
- energy bill (electric and gas) information for at least 12 months along with a rate schedule.

In an ideal situation, the documentation described above would have been collected and stored electronically during the design phase of the original construction project. Automating the documentation management process, either during the original design phase or even at this stage of the retrocommissioning project, would provide accurate and reliable information and reduce the time and cost associated with future projects.

3.4.2. Investigation Phase

The primary tasks for the investigation phase are: understanding how and why building systems are currently operated and maintained; identifying deficiencies and potential improvements; actively testing and monitoring system operation; and recommending the most cost effective "fixes" for implementation.

Assess the Site The goal of the site assessment is to gain an in-depth understanding of how and why the building systems and equipment are currently operated and maintained and what problems building staff and occupants consider the most significant. This task is generally achieved by reviewing all building documentation gathered during the planning phase, conducting interview with building occupants about general space conditions and detailed discussions with facility staff regarding operating strategies, and performing an in-depth site survey of all equipment and noting its current condition. The site assessment typically addresses the following:

- overall building energy and demand consumption;
- current design and operational intent and actual control sequences for each piece of equipment included in the project;
- equipment nameplate information, operating parameters, and equipment condition issues (broken dampers, dirty coils, sensor calibration, etc.);
- current schedules (setpoint, time-of-day, holiday, lighting, etc.);
- the most severe control and operational problems;
- location of the worst comfort problems or trouble spots in the building; and
- current O&M practices.

It is common for many simple problems and obvious corrections to reveal themselves during the site assessment. It is generally a good idea to make minor adjustments and repair these problems as they arise during the site assessment because these problems can mask more subtle ones that could otherwise go unnoticed. These "field fixes" should be summarized and documented on the Master List of Deficiencies and Improvements (the Master List is discussed below).

The overall objective of the site assessment is to uncover the best opportunities for optimizing the energy using systems and improving O&M practices. It also provides a basis for identifying where active testing and/or monitoring may be appropriate.

These diagnostics provide insight on current system operation and help to pinpoint complex system problems.

Develop List of Findings Concurrent with the site assessment, the Commissioning Provider begins to develop a Master List of Deficiencies and Improvements. This Master List ultimately becomes an important decision making tool for the facility manager and building staff and is a primary product (deliverable) of the commissioning effort. Every finding from the investigation phase is summarized on the Master List, including those adjustments and repairs made during the course of the investigation process. At a minimum, the list should include the name of the system or piece of equipment, a description of the deficiency or problem, and a suggested solution.

Active Testing and Monitoring The information gained from the site assessment may indicate that it will be necessary to obtain more complete and exact data on when and how systems are actually operating, since the assessment may only identify suspected areas for improvement. If more information is needed, the Commissioning Provider generally oversees both active testing and monitoring of selected systems. The term “active testing” refers to performing functional tests on systems by using the building automation system (BAS) to manipulate setpoints and control parameters and observe system response. The term “monitoring” refers to long term collection of system performance data under normal operating conditions. Monitoring can be achieved using stand alone data logging equipment and/or BAS trending capabilities. Both diagnostic methods allow the Commissioning Provider to observe temperatures, flows, pressures, and other system characteristics under varied operating conditions and determine if the systems are operating efficiently and effectively. Preparing for active testing or monitoring may include checking and calibrating control points such as sensors and actuators. Any deficiencies or problems identified through active testing and monitoring will be added the Master List.

Prioritize and Select Energy Saving Opportunities Once the site assessment and diagnostic testing and monitoring have been completed, the Commissioning Provider finalizes the Master List, including estimates of energy savings and implementation costs for each finding. The owner then decides which items on the list provide the most benefit and effectively meet the project objectives.

3.4.3. Implementation Phase

During the investigation phase, several of the simple, obvious, and less expensive repairs and improvements are usually completed. During the implementation phase, the more complicated and expensive ones are completed. This section discusses implementing more costly or complex improvements and verifying the results, along with some important issues to consider during these activities.

Implement Improvements A primary goal for most retrocommissioning projects is to actually implement the major cost effective improvements so that results can be realized. Although the investigation phase provides important information and products, unless improvements are actually put in place, the retrocommissioning process remains incomplete. Depending on their availability and expertise, the implementation process may be carried out by in-house O&M staff. However, in some cases, the implementation may require outside help. For example, hiring a controls contractor may be necessary if in-house staff lacks the expertise, access, or time required to make control strategy changes at the program level.

It is often necessary, and highly recommended, that active testing and/or monitoring be performed after implementation to verify correct system operation. Another benefit of retesting is the possibility of finding additional opportunities that were masked by the original problems.

System monitoring can also be used to benchmark the final performance of the improvements. This benchmarking information can then be used to establish criteria or parameters for tracking whether or not the improvements are performing properly throughout the life of the equipment or systems.

3.4.4. Hand-off Phase

Prepare Final Report The commissioning provider prepares a final report. The owner may specify what information the report should include. Ideally, the final report contains the following components.

- Executive summary
- Project background
- The retrocommissioning plan
- The "Master List" of improvements with a description of which improvements were implemented
- A cost/savings analysis for the estimates of savings and the actual improvement costs for each improvement implemented (see methods below)
- List of capital improvements recommended for further investigation
- The filled out initial site operations assessment forms
- The BAS trending plan and logger diagnostic / monitoring plan and annotated results
- All completed functional tests and results
- Recommended frequency for recommissioning by equipment type, with reference to tests conducted during initial commissioning.
- Complete documentation of revised or new strategies adopted to optimize systems operation along with the rationale that lead to selection of these strategies.
- A Systems Manual that includes a brief design narrative of all systems investigated, with corrected and created sequences of operation and a description of and rationale for all energy saving features and strategies with operating instructions and caveats about their function and maintenance relative to energy use. Also included are a list of all user adjustable setpoints and reset schedules and a list of time of day schedules.

3.5. Automating the Commissioning Process

There are several efforts underway to develop automated commissioning tools. These can be grouped into the following four categories:

- Building design information
- Testing procedures development
- Data management
- Functional testing

Current advancements in all four categories focus on commissioning new buildings; however, automated tools for data management and functional testing could also be applied to retrocommissioning or continuous commissioning applications.

3.5.1. Developing and Managing Building Design Information

Two noteworthy tools are being developed to automate the development of building design information. The first is the Design Intent Tool that was developed by Lawrence Berkeley National Labs and Portland Energy Conservation, Inc. (PECI) for the California Institute for Energy Efficiency. The tool's objective is to provide a mechanism for documenting 1) the design intent; 2) the resulting design concepts and design basis the designers are proposing to meet the design intent; and 3) performance metrics for verifying that the design intent has been met (Stum 2000).

The second tool is being developed by PECI and Marinsoft for the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE). The intent of this project is to identify the engineering data required to verify the performance of HVAC&R systems and to develop methods and procedures for identifying, collecting, and transmitting this data. HVAC&R engineering data includes design data, equipment performance characteristics, sequences of operation and building operating data. The hope is that others will then develop software that uses these data to monitor HVAC&R performance over time and/or track this information through the commissioning process.

3.5.2. Developing Test Procedures

Developing test procedures requires a significant amount of time. Since each building is different from every other building, test procedures need to be customized for each building. The Commissioning Information Tool (ComIT) developed in MS Access by Facility Dynamics addresses this problem. ComIT allows the commissioning provider to develop inspection checklists and functional performance tests from a standardized component library of checklists and tests. The appropriate component procedures are automatically added to the test being built up when the commissioning provider indicates various components exist in the system at hand. This saves the commissioning provider time. The stock procedures can then be edited as needed or totally new procedures added. Additionally, ComIT provides many of the same functions as the LBNL and PECI tools described above—it records commissioning issues, equipment nameplate and performance data, balancing data and operations and maintenance data.

3.5.3. Managing Data

During the design and construction of a building, a great deal of information is generated and transferred among all of the parties involved in the process. Since commissioning is a quality assurance process, the commissioning provider manages much of this documentation. Many commissioning providers manage this information via reams of hard copy forms, memos, manuals, etc. If the project is not managed well, the paperwork can take an inordinate fraction of the total commissioning time and less effort remains for improving and verifying system design and performance. Automating aspects of the commissioning process will make the commissioning process more efficient and as a result more cost effective. Automation also allows tracking and reporting to be completed more accurately and consistently (Stum 2000). In addition, an automation tool that tracks building system information would be very helpful over the life of the building.

Essential to an effective commissioning process is effective management of, and expedient access to, the myriad of information required in the design, construction, commissioning and operations and maintenance of a facility (Brightbill 2000). As a result of increased capabilities of computer technology, there has been more and more interest in computer based commissioning tools that facilitate the organization and use of commissioning data. Below is a summary of two such efforts.

In 1996, Lawrence Berkeley National Laboratory initiated a multiyear project entitled the *Building Life-Cycle Information System* to address the loss of information that occurs as a building moves from design to commissioning and operations. The project has been looking at how to construct information libraries that can be updated over the life of the building. For example, a tool could be created that stores design intent and design simulation information and uses them as a starting point to develop functional tests and a commissioning plan. Data collected during commissioning could then be used to update the design simulations to reflect as-built and as operated conditions that could then be used as the basis for ongoing performance evaluation and tracking. Because it is too difficult to develop tools for all building systems at once, LBNL's initial effort was to develop a prototype chiller commissioning tool to assist in the construction, execution and archiving of commissioning plans (Piette 1996).

PECI has developed, and has been using, an Access database management tool for commissioning providers entitled *Commissioning Manager*. PECI's tool is not as sophisticated as the tool described above. It does not automatically transfer information gained in one stage of commissioning to the next stage. It does, however, go a long way toward organizing and documenting the information gained in the commissioning process.

Currently it has five modules: Design Comments Log, Construction Commissioning Progress Record, Construction Issues Log, Construction Submittal Comments Log, and Internal Items to Track Log. The Design Comments Log consists of a database form to enter, modify, track, record responses and report design phase reviews conducted by the commissioning provider. The Commissioning Progress Record module stores the equipment list for the project with installing contractor, scheduling and contact information. It also allows tracking of documentation needed by the commissioning provider as well as any documents and reports that leave the commissioning provider's office. The Issues Manager module documents the commissioning findings during construction. Fields are provided for details of the issue, recommendations by the commissioning provider, actions taken by the design and construction team, when and how the correction was made and when the issue was closed. The *Commissioning Manager* also contains an Items to Track Log that tracks miscellaneous items internally that are not sufficiently developed nor severe enough to require external reporting. The tool also contains a database to record construction submittal review comments (Stum 2000).

Table 1 lists management related activities and tasks that could be automated. It was excerpted from "Commissioning Tools for Managing Design, Construction and Implementation" written by Karl Stum for the National Conference on Building Commissioning.

Table 1: Overview of Commissioning Management Related Tasks That Could Be Automated Electronically

Task		Current Practice
Design Phase		
1	Document programming.	A/E task.
2	Document initial design intent, responses and changes.	A/E task, rarely done at all.
3	Document initial, responses to and changes to design basis and design concepts narrative.	A/E task, rarely done at all.
4	Document and track design reviews and responses.	CA task.
5	Generate commissioning specifications.	CA, A/E task. Particularly testing requirements by equipment type.
Construction Phase		
6	Document and track construction submittal comments.	CA, D task.
7	Track submissions of O&M documents. (Prior to the formal O&M manual submittal)	CA, A/E task. Design narrative, construction submittal, shop drawings, installation guide, O&M booklet and control drawings.
8	Track documents leaving the CA's office.	CA task. Submittal review, construction checklists, blank functional test form, training agenda, completed functional test form, O&M manual review, trend log report, etc.
9	Track reports submitted to CA.	CA task. Completed construction checklists, start-up reports, TAB reports, certifications, training record.

Task	Current Practice
10 Planned and completion dates for each piece of equip.	CA task. Start-up, functional testing, training, seasonal testing.
11 Document, track and report findings and issues.	CA task
12 Generate requests for information tied to a finding	CA, GC task.
13 Printing construction checklists with tag data	CA task. From a library and project equipment list.
14 Development of functional test procedure forms	CA task. From a library. Can be customized.
15 Fill out functional test forms electronically in the field, feeding data directly into database	CA task.
16 Store performance data for reference during testing.	CA task. Cut sheets, performance curves and tables, etc.
17 Manage design and construction commissioning issues on Web-based project site.	CA task. Site with live database of issues, comments and responses.

Note: Items 1, 5 and 13–17 are tasks not accommodated in current PECI tools.

3.5.4. Automating Functional Testing

Many opportunities exist for automating functional testing in both new construction commissioning and retrocommissioning projects. The Functional Testing section and the Functional and Performance Problems sections below provide helpful information for prioritizing these opportunities.

3.6. Functional Testing Methods

The following provides an overview of functional testing methods and tools currently used by commissioning providers. The advantages and disadvantages, limitations and areas of application are discussed for each testing method. Testing procedures that address performance problems for specific pieces of equipment will be provided later in the project for the top candidates for automation. Most methods and tools are applicable to both new construction commissioning and retrocommissioning.

There are two primary testing methods: active and monitoring.

Active testing uses hand-held instruments, immediate control system readouts or direct observation to verify performance. Monitoring is the recording of parameters (flow, current, status, pressure, etc.) of equipment operation using data loggers or the trending capabilities of control systems. Currently, only monitoring methods are being automated, though it is entirely conceivable for manual methods to be automated as well.

3.6.1. Active Testing Procedures

Active testing assures equipment and systems function properly under expected conditions and demonstrates that the systems meet the design intent. It involves checking setpoints and sequences of operation and can be done by simulating a wide range of conditions using the building automation system (BAS).

Active testing involves putting each system or piece of equipment through a series of tests that check its operation under a large range of modes or conditions. Equipment is turned on and various conditions are changed to force a response in the equipment or system, such as verifying the boiler shuts down when the outside air temperature is raised above 55°F, or verifying the standby pump starts when the lead pump fails.

The following are examples of conditions and parameters that can be changed during active testing to observe system response:

- setpoints (increase the supply air temperature setpoint from 55°F to 60°F);
- schedules (change the schedule so the air handler switches to the unoccupied mode); and
- sensor values are over-ridden (overwrite the outside air temperature to be 54°F)

Data is gathered by taking spot measurements using hand-held instruments such as multimeters, anemometers, digital thermometers, and light meters, or by taking readings from the building automation system. (BAS).

3.6.2. Monitoring

Monitoring to verify equipment or system performance is achieved by setting up trend logs in the BAS or in portable data loggers and storing information about temperatures, pressures, status, flow rates, rpm, etc. This information is generally stored during normal operation of the systems and during natural environmental conditions, but could also be done during forced events, like a temporary power outage, etc. The data is typically stored over a one to two week period at sampling intervals of 2 to 15 minutes. Data is gathered electronically in files and put in an electronic spreadsheet or other data analysis tool. The data is displayed in line or point graphs with 1 to 6 data point streams illustrated. Point streams are added and deleted from the graph and different time windows are viewed as the data is analyzed. Correct operation or anomalies are identified and documented.

3.6.3. Comparison of Active and Monitoring Methods

Monitoring is done under natural conditions and involves BAS trend logs (when available) and data loggers (when there is no BAS or the BAS does not monitor the required data points) to gather data about what the equipment is doing over time. In both cases, the data is then used to verify correct operation. Note: the BAS must be commissioned before it is used for trending or the results will be unreliable.

Rigorous active functional testing should uncover most equipment problems but it can become expensive because it is time consuming. Active testing provides immediate results and looks at a wide range of conditions. However, it may miss the nuances of changing conditions, may be unable to investigate multiple parameters at the same time, and will not identify hunting. Monitoring under natural conditions offers greater ease in analyzing multiple parameters simultaneously and provides large data sets. However, testing under natural conditions may miss peak or special conditions, thus making it difficult to test safeties or alarms. Monitoring also requires time for data collection during normal operation and for data analysis (Stum 1999).

If there are large numbers of essentially identical equipment in a system (e.g., multiple VAV terminal boxes), it may be possible to reduce the time required for the functional tests by testing only a representative sample of the equipment (PECI 1998).

Active functional testing has two important disadvantages. First, the cost of functional testing is still relatively high and second, it cannot detect (or remedy) problems that develop after testing is completed.

3.6.4. Semi-Automated Testing and Diagnostic Tools

Semi-automated diagnostic tools rely on data that is collected by the building automation system and portable data loggers, then use internal algorithms to detect and diagnose problems in equipment. Semi-automated testing and diagnostic tools can address the disadvantages of testing by monitoring. For example, it reduces the significant time burden of gathering, downloading, and converting data into a suitable format for analysis and significantly reduces the analysis time as well. Automated testing also lowers the required skill level of the party performing the testing. With standard monitoring techniques, full analysis can only be done by an experienced person, while automated testing generally only requires an experienced person during initial setup of the program. In the long run, as automated tools improve and mature, an experienced engineer shouldn’t even be required for initial setup of programs.

Though these diagnostic tools are still very new to the market and are facing some resistance due to the necessary learning curve, the potential to save time and cost is significant. Semi-automated diagnostic tools could also facilitate standardized testing. If the tools are developed well, less learning should be required for automated tools than for manual procedures. This is partly a tool capability problem and partly a tool interface problem. This problem should be addressed by developers of automated tools to make them acceptable to users.

Examples of semi-automated diagnostic tools include the Whole Building Diagnostician (WBD) developed by Pacific Northwest National Laboratory, the Performance and Continuous Recommissioning Analysis Tool (PACRAT) developed by Facility Dynamics Engineering, the ACRx Palm Pilot™ based tools developed by Field Diagnostic Services and the AEC ENFORMA. Information about these tools was gleaned from the literature search. Few commissioning providers surveyed had actually used these tools.

- The Whole Building Diagnostician has two modules: one that tracks overall energy use and the other that detects and diagnoses problems with outside air control and economizer operation. The overall energy use module “learns” what the total building energy use for the building should be as a function of outside air temperature and other key parameters. Then over time, when the total energy use exceeds a pre-set allowance above the "proper" value, it registers an alarm to the user. The economizer module uses periodically measured conditions (temperature or enthalpy) of air flow streams, outdoor conditions and status information (e.g., fan on/off) to navigate a decision tree and reach conclusions regarding the operating state of the AHU (Pratt et al. 2000). It relies on the existing BAS sensor network to minimize the cost of providing diagnosis. The economizer module uses thermodynamic principles for diagnosis. Both modules detect a range of faulty or misplaced sensors. If set up correctly, systems automatically collect and process data. Both modules also provide estimates of energy and cost impacts for problems or anomalies found. The economizer module goes a step further by identifying probable causes of a problem and recommending actions for each probable cause.

- PACRAT, developed in MS Access, provides four basic tools: automated HVAC fault detection and diagnosis, building performance characterization, measurement and verification, and data visualization. PACRAT currently has an air handler module, a chiller module and a hydronic loop module. Modules to diagnose boiler plants and VAV air terminals are under development (Santos, Brightbill, and Lister 2000). PACRAT analyzes and reports trend data recorded using the BAS or data loggers and compares the results to a baseline. Currently, the tool requires data to be manually downloaded and input into the software analysis module and is not directly linked "hot" to the BAS trend data. Using standard operating and thermodynamic principles, the tool uses a series of rules for comparing data values and determines when there is a malfunction and offers the user some probable causes and energy cost impact estimates.
- The ACRx diagnostic tools are Palm Pilot–based tools with integrated sensors, which allow for field testing of equipment. These tools currently offer the simplest fit into current systems and, as a result, the lowest incremental cost compared to other semi-automated diagnostic tools. There are now three ACRx tools: the Handtool for immediate HVAC problem detection and diagnosis, the Servicetool for short term monitoring of HVAC equipment for difficult to detect problems and the Controller which is permanently installed to provide integrated building control and long term monitoring capability (Rossi 1999). The ACRx tools have historically focused on the vapor compression cycle of direct expansion HVAC&R equipment and have not addressed economizers, outside air ventilation, fan modulation, control sequences, etc. The tool uses thermodynamic principles for diagnosis.
- Data loggers programmed with AEC ENFORMA's software could also be considered semi-automated diagnostic tools. The ENFORMA software programs data loggers to gather and process performance data. They assist in setting up the initial logging plan and in managing the database of data points. They also provide the user with some information on interpreting graphs of data. Software similar to the ENFORMA software could be developed to program data loggers to collect the data required to meet commissioning requirements. This method of

testing would still require some manual trend analysis, but it would facilitate test standardization.

Only two of the tools above are commercially available – the ACRx Handtool; and AEC's ENFORMA and data loggers. PACRAT and the Whole Building Diagnostician may be obtained for limited use. Listed below are representative problems that diagnostic tools detect:

- uncalibrated sensors;
- simultaneous heating and cooling;
- failed sensors;
- failed outputs;
- unoccupied period operation (fan and ventilation);
- inadequate ventilation rates;
- missed free cooling opportunities;
- struggling system capacities and terminal outputs;
- deviations from defined setpoint ranges; and
- unstable control.

3.6.5. Manufacturer-Specific Controllers with Diagnostic Capability

Manufacturer diagnostics can be used to diagnose a number of possible problems and have the potential to save both time and costs. Both the number of manufacturer diagnostics and the capability of these systems are increasing. We expect manufacturer diagnostics to be available soon in most equipment that contains microelectronics. Below we have given some examples of equipment that currently supports or has the potential to support automatic diagnostics.

Programmable thermostats and lighting controls There are no known self diagnostic capabilities but they are likely to be available in the future.

Building Automation Systems (BAS) Software is available that gives the BAS the capability to access and diagnose other equipment such as terminal unit controllers and air handler units. An example is the HVAC PRO software for the Johnson Controls Metasys BAS, which allows limited terminal unit diagnostics if the terminal unit is equipped with a proprietary control module. Terminal unit diagnostics include verifying actuator accumulated run time, average flow and space temperature. Recent advancements with BACnet and other technologies have improved communication between controlled equipment that will in turn allow improved diagnostic capabilities. Automated alarming of out-of-bound conditions has also been a capability available in many BAS systems for over fifteen years.

Chiller Controllers Chiller controllers have long had diagnostic capabilities and their capabilities are increasing. Significant performance optimization opportunities exist utilizing these diagnostic capabilities. An example of a chiller with diagnostic capability is the 130 to 400 ton Trane Air Cooled Series R Rotary Liquid Packaged Chiller. The microprocessor control logic allows human interface via a digital display that shows operating and diagnostic codes, compressor status, setpoints, specified temperatures, specified pressures, and enable/disable features and options. The diagnostic routines indicate a variety of faults and operating conditions, including problems with evaporator and condenser pressure and refrigeration pressure. Percent load and percent kW are also displayed which indicate the loading condition and efficiency of the chiller.

Variable Frequency Drive (VFD) Controllers Most VFD controllers contain a human interface display module for programming and/or troubleshooting and may include diagnostics as well.

Small Package Unit Controllers Most small package units now have microelectronic unitary control modules (UCMs). An example is the Trane Voyager Packaged Gas/Electric 3 to 7½ ton rooftop unit. Jumpering across a terminal strip initiates test steps (that verify fan, economizer, cooling, and heating stages every thirty seconds). Performance is verified by visually inspecting equipment.

Large Package Unit Controllers Large package unit controllers are growing both in programming complexity and diagnostic capability. An example is the 20–130 ton Trane Intellipak rooftop package unit. The *Service Mode* selectively turns individual unit outputs on or off to test them (compressors, fans, dampers, heaters, etc.). The *Diagnostics Mode* automatically reports sensor failures, setpoint failures and communications failures. A comprehensive *Troubleshooting Chart* lists the diagnostic displayed, the reason for diagnostic, the unitary control module's reaction to the failure, and the reset required.

3.7. Functional and Performance Problems

Listed below are high priority functional and performance problems found in typical buildings. Depending on how functional tests are written and the systems defined, areas of overlap may occur. Equipment designated with a (*) were identified by interviewees as frequently commissioned and/or time consuming or challenging to commission. Given the budget constraints of this project, we do not plan to automate diagnostic routines for all performance problems that occur in a specific piece of equipment or system.

Building Automation System* Control sequences can significantly impact energy use in commercial buildings. Control sequences are often quickly programmed in order to meet construction deadlines. Optimum control sequence strategies that reduce energy use or improve performance are often not programmed because design intent and control sequences have not been thoroughly documented. Common system deficiencies include improper sensor and actuator calibration and location, BAS data points wired to incorrect sensors improper setpoint adjustments, improperly applied or nonexistent temperature and pressure resets, hunting, excessive cycling, less than optimum scheduling and temperature settings, simultaneous heating and cooling, and ineffective night time control strategies.

Variable Air Volume System (including VFD, VAV boxes)* Variable speed fans are potential candidates for significant performance improvements. Common deficiencies are uncalibrated sensors, improper sensor location, and poorly functioning actuators and dampers. Other prevalent deficiencies include inadequate low load modulation, improper static pressure control sequences, algorithms or setpoints, improper building pressurization, control defeating overrides and improperly implemented economizer cycle.

Chiller and Cooling Tower System* Commissioning chillers and cooling towers can result in significant performance, operations and maintenance, and energy improvements. Improvements often include ensuring proper communication with the BAS system and optimizing control setpoints, sequences and algorithms. Condenser water temperature, chilled water reset, and condenser water setpoints are often not optimized. Chiller and pump staging, part load operation, and imbalanced cooling towers also lead to many problems and inefficiencies. Other areas for improvement include head pressure reductions, pump selections and installations, piping and valve arrangements, and sensor and actuator calibrations.

Large Package unit (20 ton or larger) Large package units represent significant energy saving opportunities. Large package units can be operated with built-in unitary controls and/or the Building Automation System (BAS). Communication between these two systems is usually poorly coordinated. Common deficiencies are improper static pressure setpoints, uncalibrated sensors, simultaneous heating and cooling, improper static pressure control sequences and algorithms, improper outside air flow, improper building pressurization.

Economizer (air or waterside) Several studies have found economizer failure rates of 50% or higher. When economizers fail, they often consume considerably more energy than if they were in proper working order. The level of effort involved in diagnosing and correcting their operation varies considerably. Common deficiencies include malfunctioning sensors, malfunctioning dampers, improper high limit temperature settings, incorrect lockout temperature settings, and improper control of building pressure.

Variable Water Volume (VFD pumping, bypass, etc.)* Variable speed pumping systems are potential candidates for significant performance improvements. Common deficiencies are uncalibrated sensors, inadequate low load modulation, poorly installed and poorly sized pumps, and inadequately sized secondary by-pass piping or valve arrangements. Control issues, such as improper static pressure control sequences, algorithms or setpoints, also often lead to performance problems.

Small Packaged Unit (3–20 ton) Common deficiencies are faulty economizer operation, improper static pressure setpoints, uncalibrated sensors, simultaneous heating and cooling, improper static pressure control sequences and algorithms, and improper outside air control. Energy savings can be also be found by optimizing the vapor compression refrigeration cycle and matching the size to the load. For example, equipment short cycling can be caused by over sizing or low refrigeration charge.

Ground or Water Loop DX Cooling/Heating System Systems that fall into this category include water source heat pump systems, geothermal heat pump systems, ground water condenser loop systems, and ground or water cooling refrigerant systems. These system types should become more common due to the relatively high equipment efficiencies that can be achieved. Their complex design and installation often lead to performance problems. Common deficiencies include inadequate ground water circulation or temperature, inadequate pump circulation, inadequate heat rejection, and improper loop temperature control – all of which can prevent high efficiencies from being realized.

Additional Occupancy, Zoning, and Part Load Reduction Opportunities Using automatic controls for intermittently occupied areas is often overlooked in the design process. Currently most of the better occupancy sensors are available with HVAC auxiliary contacts. They could easily be used to reduce terminal unit minimum ventilation for conference rooms for example. Other examples include Lightstat thermostats that setback when lights are turned off and Hotelstats that modulate typical hotel room supply fan units. Scheduling air handlers and lighting off can result in significant energy savings. This measure also covers the common construction of yet-to-be built-out zones still receiving part or full HVAC unnecessarily. These additional opportunities that have been overlooked during the design process can in some cases have a significant impact on the building's energy use.

Programmable Thermostat and HVAC Time Control Programmable package unit thermostats and time controllers are becoming increasingly complex in their capabilities. In many cases, they offer occupancy based input, optimized start routines, and other features. When these units are installed, their programmed setpoints need to be inspected and optimized. Fan switch settings are quite often set to "auto" rather than "on." This setting may be more energy efficient but it may force the building into non-compliance with ventilation codes and may lead to dangerous air quality.

Air Handler Unit* Air handlers, especially large built-up units, can offer significant opportunities for energy and maintenance savings. Energy saving opportunities include poor damper operation, uncalibrated actuators, temperature stratification in the mixed air plenum, improperly piped or sized heating and cooling coils, improper fan operation, incorrect air flow and inadequate outdoor air flow.

Split DX Systems Since refrigerant lines for split systems are not integral to the system as they are in packaged units, proper refrigerant charges should be verified. This becomes particularly important when long suction/discharge lengths are employed. Another common deficiency is the substitution of lesser efficiency units.

Ductwork (leakage, dampers, duct heaters, static pressure considerations, etc.) Ductwork is custom–fabricated and, as a result, there are many opportunities for deficiencies. Leakage tests to verify minimal duct leakage are recommended wherever possible. Proper use of duct sealing mastics and fasteners ensures that this leakage rate can be maintained at an acceptable level for years to come. Also pressure loss can be minimized by good duct system design.

Ventilation, Pressurization, Air Balance and Quality The above examples analyze problems at the equipment level. The interaction of these systems on a building wide level also needs to be verified to ensure optimum building performance. The following areas should be addressed: building pressurization, economizer pressurization relief, infiltration/exfiltration rates, proper ventilation rates and carbon dioxide (CO_2) levels, and parking garage ventilation rates for proper carbon monoxide (CO) control.

Heating Hot Water and Domestic Hot Water* Commissioning should be done on the following: the flue damper, the boiler controls, by-pass piping arrangements, mixing valves, package controls calibration, and pumps. Common problems include incorrect boiler staging, boiler lockout temperature not set for seasonal shutoff, poor efficiency and emission levels, piping and control sequences that do not protect the boiler and poor low load operation.

Commercial Refrigeration Defrost cycles, floating head pressure controls, compressor sequencing, and door closure controls are examples of components to be performance verified in commercial refrigeration systems.

Miscellaneous Energy Conservation Measures Examples of specialized energy conservation equipment are heat recovery units and desiccant units. These systems are often complex and therefore their operation needs to be verified. Areas that could be verified are sequence of operations, calibrations, capacity and efficiencies where applicable.

Non-Energy Systems (Fire alarm, etc.) Some systems such as fire alarm systems, sprinkler piping, fire/smoke dampers, and emergency power systems that have little or no energy impact, but are integrated with each system and must be tested for proper operation. Sequence of operations, interlocks, alarms and emergency responses are examples of areas that should be verified on all equipment and systems that fall within the commissioning scope.

3.8. Interest in Automated Tools

Most of the commissioning providers that we spoke with as part of our survey were very interested in using automated commissioning tools. Commissioning providers were particularly interested in diagnostic tools and tools that reduced document handling and repetition. The following commissioning tasks were identified as being very time consuming:

- implementing or observing functional tests;
- compiling a systems manual;
- documenting or tracking submittal comments;
- tracking commissioning communications;
- developing a commissioning plan;
- developing an issues log or deficiencies list;
- developing functional tests and checklists; and
- analyzing test results and data.

However, a few experienced commissioning providers were wary of automated tools because they did not feel they could be versatile enough to effectively respond to the diverse inputs seen in commissioning projects. In fact, they saw a danger in oversimplifying the commissioning process. One interviewee thought automating test procedures could easily oversimplify a process. Commissioning providers interviewed felt that price, ease of use, and setup time would be important criteria in determining if they would use an automated tool. One respondent thought that it would be very valuable if manufacturer start-up tests were more thorough and tested all modes of operation—including normal operation, failure, safety and restart modes.

Very few commissioning providers had used automated tools, which is not surprising since few are available to the public. Tools commissioning providers were familiar with include PECI's Commissioning Manager; Facility Dynamics' ComIT, PACRAT, and the Design Intent tool; and PNNL's Whole Building Diagnostician and Outside Air Diagnostician.

Interviewees considered the following tasks to be good candidates for automation:

- tracking commissioning communications;
- tracking submittal comments;
- tracking status of deficiencies (Web-based if possible);
- managing information (data is input once and carried through the project);
- standardizing commissioning forms;
- design intent development; and
- standardization of commissioning RFPs.

Functional tests suggested for automation by the interviewees include:

- verification of air handling system temperatures and pressure drops;
- verification of the BAS system;
- verification of air and water flow readings (possibly by taking readings with pressure differential switches that are built into dampers and valves);
- verification of rooftop economizer controls; and
- verification of variable frequency drives.

4. Task 2: Identify Systems and Processes for Automated Commissioning

4.1. Introduction

In Task 2 we prioritized classes of components, equipment, systems and commissioning processes according to how amenable they are to, and how much they would benefit from automated or continuous commissioning.

This section focuses on the analyses of three matrices by a group of seven engineering and commissioning experts. The first matrix reviewed 139 problems associated with 19 common building systems. The second matrix reviewed 69 new construction commissioning tasks that occur from pre-design to warranty in a typical new construction commissioning process. The third matrix reviewed 39 existing building commissioning tasks that occur during the planning, investigation and implementation phases of a retrocommissioning project.

4.2. Systems Matrix Analysis

4.2.1. Overview

PECI developed a matrix to evaluate problems with systems and equipment based on the likelihood that the problems would benefit from automated commissioning. The research encompassed 139 problems associated with 19 common systems. Each problem was scored by engineers using their expert judgment based on the following criteria:

- prevalence of the equipment and associated problem;
- propensity for the problem to reoccur;
- magnitude of the impact of each problem;
- the cost associated with fixing each problem;
- potential for reducing commissioning costs;
- potential for improved data quality; and
- the likelihood that a problem would not be detected without commissioning.

Each criteria was weighted based on its relative importance to the other criteria and the weighted scores were then aggregated into an overall score for each problem. Out of 164 possible points, the scores ranged from 58 to 122 points. The following discussion looks at the most significant problems overall and the most significant problems within each system type.

4.2.2. Most Significant Problems

This section describes the top seven problems that are likely to benefit most from automated or continuous commissioning. These problems show great potential for further research. They are listed in descending order of significance.

Small Packaged Units and Split Systems

- Faulty economizer operation (122 points) emerged as the top candidate for automated commissioning.

Economizer Air System

- Uncalibrated or malfunctioning sensors in Economizer Air systems were the next most “popular” problem (118 points).
- Uncalibrated or malfunctioning valves or dampers and actuators in Economizer Air systems scored almost as high (117 points).

Air Handler System

- Faulty or improper ventilation control strategies (117 points)
- Uncalibrated or malfunctioning sensors or actuators (115 points)
- Malfunctioning economizers and dampers (114 points)

Building Automation System

- Improper setpoint settings, e.g., space, discharge temperature, static pressure, etc. (115 points)

4.2.3. Problems by System

This section discusses each of the 19 systems evaluated and highlights the top problems within each system. For systems with more that six problems identified, the top three scores, in addition to the problems mentioned above, have been evaluated. For systems with six or less problems, only the top score is evaluated.

Building Automation System

The highest scoring problem within this system type has already been accounted for as one of the top seven: improper setpoint settings (115 points). The next three highest scores are: faulty control sequences (111 points), uncalibrated sensors and actuators (111 points), and inefficient control sequences (111 points). The average, median, and mode scores for this system are 100, 103, and 111, respectively.

Chiller & Cooling Tower and Primary Loop

The top three problems within this system type are: faulty, inefficient, or non-existent chilled water reset (106 points); uncalibrated or malfunctioning sensors and actuators

(105 points); and faulty, inefficient, or non-existent condenser water reset (102 points). The average, median, and mode scores for this system are 88, 89, and 74, respectively.

Heating Hot Water Plant

The top three problems within this system type are: improper setpoints (112 points), uncalibrated or malfunctioning sensors (104 points), and improper boiler staging (94 points). The average and median scores for this system are 91 and 88, respectively.

Air Handler

The significance of this system type is demonstrated by the fact that the top three problems are among the top seven problems overall: faulty or improper ventilation control strategies (117), uncalibrated or malfunctioning sensors or actuators (115), and malfunctioning economizers and dampers (114 points). The next three highest scores are: simultaneous heating/cooling from poor sequencing (110 points), improper duct static pressure control sequences or setpoints (109 points), and heating or cooling coil valve leak-by (108 points). The average, median, and mode scores for this system are 98, 100, and 98, respectively.

Large Packaged Unit (20 tons or larger)

The top three problems within this system type are: malfunctioning economizer and dampers (111 points), faulty or improper ventilation control strategy (110 points), and uncalibrated or malfunctioning sensors or actuators (108 points). The average, median, and mode scores for this system are 92, 91, and 100, respectively.

Small Packaged Unit (3–20 tons) and Split System

The highest scoring problem within this system type has already been accounted for as one of the top seven: Faulty economizer operation (122 points). The next three highest scores are: uncalibrated or malfunctioning sensors (111 points); improper outside air control (110 points); and improperly programmed controls (105 points). The average and median scores for this system are 101 and 100, respectively.

Air Terminal Units

The top three problems within this system type are: uncalibrated or malfunctioning sensors (110 points); inconsistent flow readings from bad flow station or inlet conditions (103 points); and heating coil valve leak-by (102 points). The average, median, and mode scores for this system are 98, 100, and 92, respectively.

Economizer Air

The top two problems within this system type have already been accounted for in the top seven problems: Uncalibrated or malfunctioning sensors (118 points) and uncalibrated or malfunctioning valves or dampers and actuators (117 points). The next two highest scores are: improper enthalpy control settings (113 points); and improper change over temperature settings (111 points). The average and median scores for this system are both 115. This system has the highest median score for all systems evaluated and two of the seven highest ranking problems overall.

Variable Volume Water System (Secondary Loop Pumps and Piping)

The top three problems within this system type are: malfunctioning or uncalibrated sensors or actuators (103 points); faulty or inefficient differential pressure control sequences or setpoints (99 points); and inadequate low load modulation of VFDs (95 points). The average, median, and mode scores for this system are 90, 85, and 85, respectively.

Programmable Thermostat

The top problem within this system type is: improper fan switch settings—auto/manual/off (102 points). The average and median scores for this system are both 101.

Domestic Hot Water Heating

The top problem within this system type is: improper temperature setpoints (95 points). The average and median scores for this system are both 86.

Heat Recovery Units (run around, heat wheels, etc.)

The top problem within this system type is: faulty or unoptimized sequence of operations (100 points). The average and median scores for this system are 96 and 97, respectively.

Exhaust Fan System

The top problem within this system type is: improper room pressurization (111 points). The average and median scores for this system are 104 and 109, respectively.

Parking Garage Ventilation

The top problem within this system type is: inefficient control strategies (90 points). The average and median scores for this system are both 84.

Commercial Refrigeration

The top problem within this system type is: unoptimized defrost cycles/schedules (96 points). The average and median scores for this system are 87 and 88, respectively.

Lighting Controls

The top three problems within this system type are: schedules are not optimized by zone (100 points); expected sequences don’t work (92 points); and poorly located or calibrated photocell sensors (86 points). The average, median, and mode scores for this system are 85, 86, and 86, respectively.

Fire Alarm

The top three problems within this system type are: fire/smoke damper malfunction (83 points); miscellaneous devices that don't alarm (79 points); and specified alarms and communications offsite don not all work (78 points). The average and median scores for this system are 76 and 77, respectively.

Emergency Power

The top problem within this system type is: specified circuits or equipment not energized to generator or uninterruptible power source (66 points). The average and median scores for this system are both 62.

Envelope & Insulation

The top problem within this system type is: improper pressure relationships and moisture intrusion (84 points). The average, median, and mode scores for this system are 71, 69, and 70, respectively.

4.2.4. Systems Summary and Observations

Within each system, we calculated the average, median, and mode score for all the problems, which presents an alternate picture of the systems that may best benefit from automated or continuous commissioning. The top seven systems, as ranked by median score are outlined in Table 2.

Table 2 Top Median and Average Scores

System Type	Median Score	Average Score
Economizer Air	115	115
Exhaust Fan System	109	104
Building Automation System	103	100
Programmable Thermostats	101	101
Small Packaged Unit	100	101
Air Terminal Units	100	98
Air Handler	100	98

A reoccurring theme among all systems is uncalibrated or malfunctioning sensors and actuators and improper or non-existent control sequences and setpoints. Sensor actuator calibration issues showed up as one of the highest ranked problems 11 times (for an average score of 108 points), and sequence/setpoint issues occurred as one of the highest ranked problems 22 times (with an average score of 105 points). Both of these general problem categories may benefit greatly from automated commissioning. A complete list of all system problems and their related score can be found in Appendix A.

4.3. Analysis of the New Construction Commissioning Process

4.3.1. Overview

PECI evaluated the new construction commissioning process for potential automation opportunities. The research encompassed 69 new construction commissioning tasks that typically occur from the pre-design phase through the warranty period of a new construction project. The potential for automation of each task was scored by engineers and commissioning professionals using their expert judgment on the following four criteria: potential for reducing the cost of commissioning; potential for improved archiving or sharing of data; potential for improved data collection; and potential to reduce change orders. Each criteria was weighted based on its relative importance to the other criteria and the weighted scores were then aggregated into an overall score for each task. Out of 104 points possible, the scores ranged between 74 and 34 points. The following discusses the tasks that scored highest overall, as well as the highest scoring tasks within each general procedure category. A general theme that emerges from the highest scoring tasks is that the collecting and distributing data, as well as developing and performing functional tests, could benefit greatly from automation.

4.3.2. Highest Scoring Processes

The following four processes scored the highest in our investigation of potential for automation. Two of the four processes involve performing tests according to procedures outlined on the test sheets. (Note: Rich Sydlowski at the Center for Energy and the Environment has already automated this task, using a pen-based computer). The four top scoring tasks are listed below in the general procedure category in which they occur. A complete list of all new construction commissioning processes and their related score can be found in Appendix B.

Seasonal Testing

- Perform functional tests according to procedures outlined on the test sheets (74 points)
- Retain completed functional test sheets for future reference and inclusion in the Commissioning Record (70 points)

Design Review

- Fill in data collection sheets with performance criteria (needed to verify that Owner’s Project Requirements are met) and data necessary to perform verification (72 points)

Construction Checklists Execution

- Perform checkout tests according to procedures outlined on the test sheets (70 points)

4.3.3. Top Candidates for Automation by Project Phase

The following discussion looks at the top scores by project phase (60 points and higher). The task description is followed by the name of the general procedure category to which it belongs, if applicable.

Pre-Design Phase

63 Points

- Develop, distribute and track owner’s project requirements

Design Phase

72 Points

- Fill in data collection sheets with performance criteria (needed to verify that Owner’s Project Requirements are met) and data necessary to perform verification (Design review)

67 Points

- Review all design documents including Owner’s Project Requirements, Design Basis, Design Narrative, and specifications (Design review)

66 Points

- Develop, distribute and track Design Narrative, Design Basis, and Design Record documentation
- Input all findings into an Issues Log (Design review)

64 Points

- Review or assist in developing specifications (Develop commissioning specifications)

62 Points

- Use design information to modify specifications (Develop Commissioning specifications)

Construction Phase

70 Points

- Perform checkout tests according to procedures outlined on the test sheets (Construction Checklists Execution)

69 Points

- Update data collection sheets with pertinent information needed to verify Owners Requirements and perform functional tests (Submittal review)
- Update data collection sheets with pertinent information needed to verify Owners Requirements and perform functional tests (Change order and RFI review)

67 Points

- Retain complete functional test sheets for future reference and inclusion in the Commissioning Record (Functional testing)

66 Points

- Retain complete checklist sheets for future reference and inclusion in the Commissioning Record (Construction checklists execution)

65 Points

- Perform functional tests (Functional testing)

63 Points

- Select generic boiler plate functional tests (Functional test form development)

61 Points

- Develop, maintain and distribute issues log
- Revise issues log as individual findings are discussed, reviewed, and resolved (Submittal review)

Warranty Period

74 Points

- Perform functional tests according to procedures outlined on the test sheets (Seasonal testing)

70 Points

- Retain completed functional test sheets for future reference and inclusion in the Commissioning Record (Seasonal testing)

4.4. Analysis of the Existing Building Commissioning Process

4.4.1. Overview

PECI evaluated the existing building commissioning process (retrocommissioning) for potential automation opportunities. The research encompassed 39 tasks that typically occur throughout the planning, investigation, and implementation phases of a retrocommissioning project. The prospect for automation of each task was scored by engineers and commissioning professionals using their expert judgment on the following criteria: potential for reduced commissioning cost; potential for improved data collection; and potential for improved archiving or sharing of data. Each of the criteria was weighted based on its relative importance to the other criteria and the weighted scores were then aggregated into an overall score for each task. Out of 84 points possible, the scores ranged between 71 and 28 points. The following discusses the individual tasks that scored highest overall, as well as the highest scoring tasks that occur within each project phase. A general theme that emerges from the highest scoring tasks is that the collection and distribution of data could benefit greatly from automation.

4.4.2. Highest Scoring Processes

The following specific tasks scored the highest and may represent the greatest potential for automation. Note that three of the top four tasks occur within the same general process category—"Implement diagnostic monitoring and test plan." A complete list of all existing building retrocommissioning processes and their related score can be found in Appendix C.

Implement Diagnostic Monitoring and Test Plan

- Collect monitored data using BAS and/or data loggers (71 points)
- Perform general and specific functional tests (64 points)
- Use functional test and monitoring data results to confirm initial findings and identify additional findings (63 points)

Retest and Monitor

- Perform functional tests and monitor systems and compare results with previous values to determine if deficiency has been resolved (66 points)

Due to the narrow range of scores, many other findings scored relatively high and will be identified in the next section.

4.4.3. Top Candidates for Automation by Project Phase

The following discussion looks at the top scores in each project phase. The task description is followed by the name of the general procedure category to which it belongs.

Planning Phase

In general, retrocommissioning tasks in the planning phase do not lend themselves to automation because they are conceptual and require actual face-to-face meetings for planning, goal setting and hiring of a commissioning provider. They lay the groundwork for later tasks that could be automated. The task with the highest score was: collect and review facility documentation (44 points).

Investigation Phase

71 Points

- Collect monitored data using BAS and/or data loggers (Implement diagnostic monitoring plan)

64 Points

- Perform general and specific functional tests (Implement diagnostic monitoring plan)

63 Points

- Use functional test and monitoring data results to confirm initial findings and identify additional findings (Implement diagnostic monitoring and test plan)

61 Points

- Update findings log as necessary (Implement diagnostic monitoring plan)
- Retain copies of the functional test and monitoring results for future reference and inclusion in the final report (Implement diagnostic monitoring plan)
- Input all findings into Findings Log (Findings log)

59 Points

- Estimate implementation cost for each finding (Develop initial findings and energy calculations)
- Select generic boiler plate functional tests and monitoring points (Develop diagnostic monitoring and test plan)
- Update findings log as individual findings are discussed, reviewed, and resolved (Findings log)

58 Points

- Use data gathered during the site assessment to identify deficiencies and opportunities (Develop initial findings and energy calculations)
- Input findings into Findings Log (Develop initial findings and energy calculations)
- Use data gathered during the site assessment to estimate savings for each finding (Develop initial findings and energy calculations)

56 Points

- Use data gathered during the site assessment as parameters for system operation in functional tests (Develop diagnostic monitoring and test plan)
- Retain copies of the findings log for future reference and inclusion in final report (Findings log)
- Perform simple payback calculations on findings with energy savings (Select cost effective opportunities for implementation)

55 Points

- Physically inventory all energy consuming equipment and fill in data sheets (Perform site assessment)

Implementation Phase

60 Points

- Assess functional test and monitoring results performed prior to implementation of changes (Retest and monitor)

56 Points

- Use information from finding calculations as parameters for proposed system operation (Retest and monitor)
- Identify additional findings as necessary (Retest and monitor)

55 Points

- Update findings log as individual findings are discussed, reviewed, and resolved (Retest and monitor)

53 Points

- Assist and/or manage improvement implementation (Retest and monitor)
- Retain copies of the new functional test and monitoring results for future reference and inclusion in the final report (Retest and monitor)
- Update all changes made to system control sequences, proposed O&M modifications, functional test and monitoring results which can be used as system benchmarks for future operation (Update building documentation).

52 Points

- Include fabrication drawings, equipment submittals, O&M manuals, start-up and shutdown procedures (Update building documentation).

4.5. Summary of Findings

The system problems most amenable to automation or continuous commissioning include:

- faulty economizer operation;
- uncalibrated or malfunctioning sensors;
- uncalibrated or malfunctioning valves, dampers, or actuators;
- faulty or improper ventilation control strategies;
- malfunctioning economizers and dampers; and
- improper setpoint settings.

New construction commissioning processes amenable to automation included:

- perform checkout and functional tests;
- collect data used for performance verification; and
- retain completed functional test sheets.

Existing building commissioning processes amenable to automation included:

- perform functional tests;
- collect monitored data; and
- retain functional test and monitoring data results to confirm initial findings.

5. Task 3: Select the Equipment and Systems and the Commissioning Processes and Procedures to Automate

5.1. Introduction

In Task 3 the project team identifies and recommends specific commissioning activities and procedures that are most appropriate for automation. This section of the report describes how the team developed its recommendations for further investigation. Based on the matrix scores from Task 2, we condensed the list of processes amenable to automation and compiled a short list of seven potential items for further investigation as part of this project.

5.2. Review of Matrix Results

Our review of the matrices began with a conversation on breadth versus depth. Working within the project budget, we can address a broad range of problems and processes in preliminary fashion, or, as specified in the Scope of Work, focus on a few problems/processes in depth. The decision was made to focus in depth in a few areas, on the assumption that this would produce a result with greater chances of actually leading to the production of an automated tool.

The team used the Matrices as a basis for identifying top candidates for automation. We wanted to select items from each matrix, to ensure that we offered a candidate from both Commissioning Process arenas—new construction and existing facilities (largely a data management process) and the Equipment Problems arena (largely a technical diagnosis process).

First, we looked at the matrix of most significant problems with equipment. Reviewers rated each problem on the following criteria:

- prevalence of the equipment and associated problem;
- propensity for the problem to reoccur;
- magnitude of the impact of the problem (in terms of energy use, indoor air quality, comfort and O&M);
- cost associated with fixing each problem;
- potential for reducing commissioning costs;
- potential for improved data quality; and
- likelihood that a problem would not be detected without commissioning.

Based on these criteria, faulty economizer operation emerged as a top candidate for automation. Faulty economizer operation in small packaged units and split systems scored highest overall and was deemed the most prevalent of the 139 problems evaluated. In addition, the Economizer Air system problems with uncalibrated or malfunctioning sensors, valves and dampers scored second and third highest overall. In general, economizers were deemed a prime candidate because of their widespread prevalence, their large negative impact on energy use, and the high likelihood that problems would go undetected without commissioning.

The matrix of problems with systems and equipment indicated that in addition to economizer problems, the following were top problems:

- faulty ventilation control strategies;
- improper setpoint settings; and
- uncalibrated or malfunctioning sensors or actuators.

Next, we reviewed the Matrices of Commissioning Processes in New Construction and Existing Buildings. The processes were rated on the following criteria:

- potential for reduced commissioning costs;
- potential for improved data collection;
- potential for improved data archiving and sharing; and
- potential to reduce change orders (new construction only).

We wanted to select processes that applied to each construction type (new and existing), and ideally, to both. These matrices revealed that for both new construction and existing buildings, the commissioning tasks most amenable to automation are:

- perform checkout and functional tests;
- collect data used for performance verification; and
- retain completed functional test sheets or tests monitoring and data results.

As we discussed the matrices, it became apparent that the core of the Commissioning Process is the management of data (recording, storing, and retrieving data in the most universally accessible format, and in the most convenient and timely fashion.) The problems with systems and equipment revolved around functional testing. We decided to recommend addressing both areas: data management and functional testing. Based on our original criteria, we developed the following short list of candidates for automation.

5.3. Short List of Items to Target for Automation

Data Management

1. Make design information available for commissioning activities (and operation activities), possibly drawing data from IFC sources.
2. Create/demonstrate a method that records, utilizes, and stores project data.

Functional Testing

3 Assess faulty economizer operation.

4 Identify improper setpoint settings for air handler static pressure control and reset.

5 Identify malfunctioning sensors to target recalibration/replacement efforts.

6 Identify malfunctioning valves and dampers in a generic way, and then apply that method to outside air and economizers.

7 Identify faulty/improper ventilation control strategies for air handlers.

We held a team meeting to discuss the short list, in terms of the following criteria:

Impact/benefits Consider the direct benefits of automating this activity, the likelihood that automation in this domain would be used, the potential business opportunity created for ARI members, whether automating this activity would promote commissioning.

Risk/cost Consider whether we can deliver something useful and significant within the allowable time and budget, and the likelihood of successful validation of the methodology.

Range of applicability Does the opportunity presented by this activity have the depth and breadth necessary to appeal to the client and to potential users? Can the work performed to automate this activity be modified and applied elsewhere?

Applies to continuous commissioning Can the automated activity be used to facilitate ongoing, repetitive commissioning efforts? Can the automated activity be used to monitor and assess certain building performance criteria over time?

5.4. Final Recommendations

We narrowed the candidate list to the following three candidates:

Data Management

1.a. Assess management of commissioning data utilizing the Industry Foundation Classes (IFC) protocol.

OR

1.b. Import recorded building data into a functional test procedure template.

Functional Testing

2. Automatically assess faulty economizer operation.

3. Automatically identify malfunctioning sensors.

The following discusses each of the final recommendations in terms of the selection criteria.

1.a. **Assess management of commissioning data utilizing the Industry Foundation Classes (IFC) protocol.** Since data management is such a large part of the commissioning process, methods to streamline any part of the process could greatly impact commissioning costs. This approach is widely applicable and useful for continuous commissioning, however is recommended only if there is an interface that allows implementation. At this time, there is not an IFC model developed specifically for HVAC equipment and related information. Although this area has enormous potential for future research and application, we recommend our alternative Data Management candidate be implemented:

1.b. Import recorded building data into a functional test procedure template. Again, data management is so time consuming that any opportunity to reduce time spent collecting and importing data could greatly reduce commissioning costs. If a method were developed to import building data into a functional test procedure template, the tool would presumably be useful for performing both commissioning and continuous commissioning.

2. Automatically assess faulty economizer operation. This includes assessing faulty outdoor air ventilation strategies. Economizers are prevalent in a wide range of buildings, both large and small, and problems with economizers are so pervasive that any tool to assess operation would have a high impact on commissioning. Economizer operation is not only a pervasive problem, it is especially amenable to continuous commissioning and re-commissioning. Without continual monitoring, problems tend to reoccur. Battelle has already looked at the problem with the Whole Building Diagnostician. We would borrow the logic (not the tool) and describe its use in a commissioning context. We would then extend the methodology to include automating proactive tests often done manually as part of the commissioning process. Building on work already completed would allow us to investigate and extend automated and continuous commissioning for economizers more deeply than possible for any other application area, and proceed further within the existing budget.

3. Automatically identify malfunctioning sensors. As with economizers, malfunctioning sensors are so pervasive that any method to detect and isolate them would have a large impact on commissioning (as well as routine operation). Detecting and diagnosing malfunctioning sensors is critical to continuously ensuring proper operation of all equipment and is fundamental to automated and continuous commissioning. In addition, the methodology would be generic enough to be useful for other applications (such as identifying malfunctioning dampers and valves.)

The final three candidates offer a range of methodologies on which future tools could be built: methodologies for data management in the commissioning process; and methodologies for automatically and continuously testing and evaluating the performance of specific equipment and systems. These methodologies meet our criteria: high impact; low risk; relevance to many system types; and applicability to continuous commissioning.

6. Task 4: Identify Automation Techniques and Methods

6.1. Introduction

In Task 4, the project team reviews technologies and techniques that may be applicable to automated and continuous commissioning of building systems. The goal is to provide background information for the selection of specific commissioning procedures to automate in this project, and to provide information critical for selecting the analytical tools and techniques to be used in the prototype applications that will be developed to automate these procedures. This section provides a survey of available tools and techniques and also describes the technology context into which automated commissioning applications will be introduced.

The body of this section is divided into three main parts which address:

- technologies and techniques that may be applicable to various general data management steps in the commissioning process;
- analytical techniques that may be useful in automating fault detection and diagnostic procedures; and
- analytical tools that may be applicable in the development and deployment of automated and continuous commissioning tools.

6.2. Summary of Automation Methods

This section describes automation techniques applicable to building commissioning and software tools that can be used in implementing these automation techniques. This summary of automation techniques is divided into three major sections:

- Section 6.2.1 (*Technologies and Techniques for Managing Commissioning Data*) addresses procedures and technologies that could be applied to the acquisition, entry, verification, validation, communication, processing, storage, and archiving of commissioning data.
- Section 6.2.2 (*Analytical Techniques*) contains a review of a range of available techniques that may be applicable to automating functional testing and diagnostics procedures used in commissioning or continuous commissioning. This section focuses on the analytical and computational aspects of automating commissioning, as opposed to the logistical, data handling aspects of the problem.
- Section 6.2.3 (*Analytical Tools*) describes the major types of analytical tools (i.e., software) that are relevant to automating (or partially automating) the analytical techniques described in Section 6.2.2.

The intent throughout this task section is to provide a useful overview of these tools and techniques rather than in-depth or encyclopedic descriptions of them. The goal of the report is to familiarize the reader with the range of available techniques and to convey sufficient understanding of their nature and suitability to guide further investigation. Section 6.4 (*Suggested Reading*) provides references that may be helpful to readers seeking additional information on specific techniques.

6.2.1. Technologies and Techniques for Managing Commissioning Data

This section describes technologies and techniques that are potentially applicable to the general process of building commissioning. The more complex and analytical engineering based procedures (such as fault detection) and tools (such as pattern recognition software) are covered in Sections 6.2.2 and 6.2.3, respectively.

This section attempts to characterize the technology context into which automated and continuous commissioning solutions may be deployed following completion of this work. Many pertinent technologies are developing rapidly. Some technology applications that have not yet been commercialized or gained widespread acceptance are included in an attempt to prevent this review from prematurely becoming obsolescent. The review is organized around data management steps in the commissioning process and the technologies and techniques that may be applicable to those steps. The term *data management* is used here in a very general sense and includes any handling, storage, transmission, or transformation of data that may occur as part of, or in support of, the commissioning process.

Entering Setup Data

By *setup data*, we mean static information about the project, the building design, and its constituent systems and equipment. An automated or continuous commissioning application would need this setup data before it could become operational. Examples of setup data might include building location, rated efficiency of a chiller, or a design flow rate in a chilled water piping loop.

Currently, setup data are most often manually extracted from plans and specifications or discovered through on-site observation as part of site assessments or functional testing. In the future, we expect it will be possible to acquire much of these data from electronic contract documents. The principal impediment to file sharing currently is the lack of standards for representing this information electronically. Two efforts currently underway to address this need for information and data communications standards are the International Alliance for Interoperability's (IAI) development of Industry Foundation Classes (IFCs) and the American Society of Heating, Refrigerating and Air Conditioning Engineers' (ASHRAE) guideline project 20P, *XML Definitions for HVAC&R*.

Efforts to define standards for sharing building data have been ongoing for many years. New impetus has been given to these efforts by vendors of computer aided design (CAD) and related design support software responding to meet demands for Internet based software to support collaborative design by geographically disbursed teams. While automated commissioning is not dependent on the capability to acquire setup data electronically, such a capability could streamline the setup process and make it feasible and advantageous to use more extensive setup data, thereby reducing data transcription errors and improving accuracy.

Acquiring Performance Data

By *performance data* we mean instantaneous and short time step readings collected from the building, its equipment, or immediate environment as the building operates. In the past, most performance data used in commissioning was derived from gauges and sensors on building equipment, at electrical panels, or placed outside the building to monitor ambient conditions. Data were read (often manually) from meters or gauges, from short term data logging equipment, or in some cases from a building's automation system (sometimes called an energy management system).

In the future, we anticipate the deployment of specific technologies that will lower the cost of automated metering, making it feasible and cost effective to monitor a larger set of conditions and parameters. Developments expected to help bring about these changes are continued miniaturization and improved economies of mass production for data loggers and sensors and the increased use of wireless communications for data collection within buildings. A large part of the cost of automated metering involves installation of wiring between sensors and data acquisition systems. Developments that promise to lower the costs of data acquisition include use of wireless communications for sensors, rapid growth in wireless local area networks (on which building data can potentially piggyback and be made accessible via the Internet), and self powered sensors (i.e., sensors that do not require wiring to obtain power to operate).

These developments will lower the cost barriers to permanently deploying building sensors and the capabilities to read them, as opposed to using the sensors only for one-time commissioning of new buildings. Even for buildings with building automation systems (BAS), these technologies are likely to make it cost effective to add additional sensors in situations where previously they were considered cost prohibitive.

Verification and Validation

An important aspect of commissioning involves verifying through site inspection that materials and equipment have been installed in accordance with plans and specifications. This process can involve walk-throughs where such items as equipment nameplates are inspected and components are spot checked against plans and specifications. It can involve a more structured and rigorous process in which checklists of features requiring inspection are prepared in advance, used in on-site inspections, and later transcribed and included in reports. Regardless of the formality of the commissioning process, portable computing devices can potentially be used to improve the on-site verification process. Small personal computers or personal digital assistants (PDA)—small hand-held computers—can be used to record findings in the field and expedite their inclusion into reports and documentation of site conditions. Voice synthesis and voice recognition are complementary technologies that may facilitate this process by enabling the person conducting the inspection to capture findings and observations using oral commands with auditory confirmation of entries from the computing device.

Most PDA are currently used as mobile substitutes for a personal computer and are used intermittently and then synchronized with an office or home personal desktop computer. Within a year or two, widespread use is expected from more advanced devices. The emerging Bluetooth wireless technology provides a protocol and vision for continuous and effortless mobile connection of computing devices, enabling them to function in real time as networked devices (Motorola 2001; Bluetooth Special Interest Group 2001). These advanced portable devices, using Bluetooth or other similar competing technologies (such as wireless Ethernet, IEEE 802.11 (IEEE 1997))[1] will support concurrent field verification and operation of automated commissioning applications plus convenient access to information and assistance via email and phone. An engineer performing on-site verification would no longer be working with a notepad that requires later transcription, but rather could be documenting and sharing findings on faults and defects with contractors and equipment vendors in real time.

Communications, Data Sharing, and Reporting

Under a conventional commissioning process, communications and reporting is done primarily by telephone supplemented with paper based memos and reports. Commissioning requires information about the building and equipment as input to the process. Outputs from the commissioning process involve data documenting observed performance and conclusions regarded the status of tested systems. These outputs are ultimately compiled and summarized in a report to the client.

The need for communications and data sharing becomes greatest when the operation of systems or equipment is found to not meet specifications. In the case of new building commissioning, the contractor responsible for the work must be contacted, and the system must be retested once the fault is corrected. In some cases, correction may involve the equipment manufacturer and that company’s service personnel or technical troubleshooters. In the case of continuous commissioning, reporting might involve an on-screen message or an alarm from the BAS. The building operator would likely be the first person called upon to determine the appropriate response.

A technology assisted commissioning process is likely to rely on cell phones, email, and direct access to monitored data by those called upon to diagnose and fix problems uncovered through the commissioning process. Placing data in a single location that is accessible to everyone who needs access to the data holds great potential for streamlining the commissioning process and lowering costs.

Key technologies for facilitating these data sharing improvements are data acquisition systems that are Internet enabled and wireless, roving access of on-site commissioning agents to Web based applications supporting two-way communications with contractors, manufacturers, owners, and owners’ agents. Such

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[1] IEEE 802.11-1997. Standard for Information Technology, Telecommunications and Information Exchange Between Systems, Local and Metropolitan Area Networks, Specific Requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher Speed Physical Layer Extension in the 2.4 GHz Band, Institute of Electrical and Electronic Engineers.

steps as integrating inspection and reporting in a Web-based application could further streamline the process by enabling various parties to simultaneously view current information and to eliminate effort involved in transcribing information gathered on site. Such technologies as digital still and mini video cameras could also be used where visual information is necessary for determining appropriate corrective action. An additional advantage of such processes is that they become nearly self documenting once a system is in place to ensure proper archiving of electronic documents. Faced with the recurrence of a problem, an appropriately designed database and query function could provide service personnel ready access to this history and documentation of previous remedial actions.

Data Processing

The *data processing* step discussed here pertains to the fault detection and diagnostic analyses addressed under Sections 6.2.2 and 6.2.3. While some data processing may be involved in any step of the commissioning process that involves a computer (aside from the above analyses), computational needs are trivial.

Depending on the form in which an automated commissioning capability is deployed, data processing would be performed by different systems. In a building with a building automation system, data processing would be performed by the BAS software or a separate continuous commissioning module running on the computer that hosts the BAS software. For a commissioning process that employs short term metering, data processing might occur on a remote computer that receives data from a data logger via phone lines. Data processing can also be performed on portable computers operated by engineers performing testing in the field.

The Internet and small hand-held computers may offer additional alternatives for data processing for commissioning. The Pacific Northwest National Laboratory (PNNL) has developed data logging modules that function as Internet devices and can stream metered data to any computer on the Internet for use with Web browser–based applications. When such devices are used, data processing can be performed almost anywhere—on the Intel Pentium processor in the data logger, on a networked computer somewhere in the building being commissioned, on a host Web server, or on the workstation of a continuous commissioning contractor anywhere in the world. Depending on computational requirements, the data processing might even be performed on the PDA of an on-site commissioning engineering using real time data streams via wireless data links—although this scenario would require greater data processing power and higher data transfer rates than are available in current PDA products.

Storage and Archiving

For almost any automated commissioning application, some kind of database will be required to provide persistent data storage. Various types of databases are available, and these databases can be structured in different ways. For example, databases can be categorized as *flat*, *relational*, and *object oriented*. Various, often incompatible, database software products are available for developing and querying databases. Database selection and design decisions affect the flexibility that is available for sorting and extracting data, the speed with which database operations can be performed, the flexibility for adding new types of information to the database, the quantity of data that can be handled effectively, and the feasibility of having various different applications and users access the database. Very large databases have been created in many fields. These large databases and the need to access the data they contain have given birth two new terms and categories of software—*data warehousing* and *data mining*. *Data warehousing* is the storage of large amounts of disparate data types in a way that facilitates their later retrieval for purposes of analysis. *Data mining* is the complementary capability that enables information such as patterns and relationships to be efficiently extracted from large quantities of warehoused data.

As with data processing, available technologies offer numerous options for performing the necessary data storage and archiving functions needed for building commissioning. For continuous commissioning, data storage requirements are likely to be far more demanding than those for one-time commissioning of new buildings. Continuous monitoring of building operation creates the opportunity to build historical records of past performance, which can provide a benchmark representing normal operation. Records of past performance may also be helpful in correctly diagnosing equipment problems that become progressively worse over time. Where short time step data are collected, databases can grow very large over time. Procedures may be needed to compress, archive, and summarize these data in order to avoid data overload and the need to discard the data entirely.

6.2.2. Analytical Techniques

The analytical techniques described in this section are potentially applicable to the functional testing, fault detection, and diagnostic aspects of automated commissioning. A table entitled *Problems with Systems and Equipment*, developed under Task 1 and presented in the Appendices, lists more than 100 system and equipment problems for which some kind of functional test or diagnostic is available. Some of these tests are best performed through direct observation of physical systems or equipment. For example, detecting missing fire alarm components that are required by code or confirming that lighting controls have been zoned in accordance with specifications would best be done through direct visual inspection. Other problems, such as improper economizer operation or building pressurization, are promising targets for automation.

An essential capability of any automated commissioning process is to be able to distinguish correct or, at least, normal operation from incorrect or abnormal operation. Key objectives for this review of techniques are to describe how each technique would distinguish between acceptable and unacceptable performance, to identify any constraints that would limit the application of the technique, and to assess strengths and weaknesses of each technique for application to automated commissioning.

This discussion of analytical techniques has been divided into two general categories, *first principles–based methods*, which build primarily on the theory of how building systems perform, and *data driven methods*, which build primarily on experience with how the systems perform. While most techniques contain elements of both of these general approaches, the distinction between approaches that are primarily theoretical versus primarily empirical is worth emphasizing. The underlying nature of the analytical techniques, which the distinction reveals, has major implications for which aspects of commissioning they are applicable to and the conditions under which they are likely to prove effective.

First Principles–Based Methods

The first category of analytical techniques we call *first principles–based methods*, because they are rooted in physics and a fundamental understanding of the scientific principles governing the behavior of energy related systems in buildings. However, very few, if any, of the calculation methods or computer models that fall in this category are based strictly on physics; virtually all use empirically derived assumptions and approximations. Nonetheless, there is a class of methods for understanding and analyzing building thermal and energy use behavior that are primarily based on a well established body of theory and practical engineering procedures and belong in this category.

Certain characteristics can be ascribed to these first principles–based approaches in general. Strengths, weaknesses, and key attributes affecting suitability for use in addressing automated commissioning problems are presented here in a general way. Differences among the various first principles–based methods are addressed in more detail under an individual subsection for each method.

Strengths First principles–based approaches are well suited for use with problems that are well understood and for which tools are available for analyzing performance. For instance, wherever there is accepted theory and analytical tools available to implement the theory, first principles–based methods have the ability to define how the system or equipment *should* perform—which is crucial for commissioning new buildings. Recognized industry test standards, product ratings, and standard design specifications reinforce and complement first principles–based approaches. Together they offer the most direct method for confirming that design intent and contractual obligations have been met. In addition, these methods inherently provide a benchmark of correct behavior, which can be useful in assessing the likely consequences of faulty behavior and, hence, the urgency for corrective action.

Weaknesses An inherent weakness of first principles–based methods lies in the difficulty of relating theoretical performance expectations to the often messy and poorly controlled operating conditions that occur in actual buildings. Systems and equipment perform differently when bench tested in a laboratory than when they are placed in an actual building. In actual buildings, systems are subject to environmental, loading, and installation conditions that differ from those assumed for design and used for laboratory testing.

The primary purpose for which most first principles–based models were developed was for modeling buildings and systems "as designed." As a result, most models are limited, or at least underdeveloped, in their ability to model faulty performance. Anyone needing to simulate faulty, broken, or aberrant modes of operation will likely find little help in current program manuals or the published literature. First principles–based methods are still clearly useful in detecting faults, although significant development and enhancements are necessary

Suitable Applications First principles-based methods are applicable to most aspects of functional testing and fault detection for new and existing buildings. However, development of new tools based on first principles will be required in many cases for these applications.

Engineering Calculation–Based Methods

Description Most traditional commissioning procedures that require calculations (as opposed to simple observation) are based on procedures in this category of straightforward engineering approaches. These use mostly steady-state methods similar to the calculations performed by design engineers in the design of new systems. For example, a continuous commissioning (software) agent for economizers would likely use engineering calculations along with air stream temperatures and flow rates to verify correct operation of outside air dampers.

Many commissioning procedures could be readily adapted for automated commissioning processes by simply defining an acceptable tolerance by which measured results are permitted to vary from predicted results based on engineering calculations. However, such a simple static approach would be unlikely to meet reliability and other performance expectations for an automated commissioning application suitable for widespread deployment.

Strengths These methods are well developed and have been tested using manual commissioning procedures. The methods are familiar and credible to prospective system users. They are straightforward to implement in almost any type of software development environment, as they require only simple, procedural processing using conventional functions.

Weaknesses Most use static methods geared towards design. Performance adjustments for actual off-design conditions can add considerable complexity.

Suitable Applications These methods would likely serve as the foundation for any automated commissioning system. They are likely to prove most effective when combined with other approaches discussed below.

Simulation Based Methods

Description Computer simulations have been used for more than 30 years to analyze and predict the thermal performance and energy use characteristics of commercial buildings. A few of the better known simulation tools used for commercial buildings are DOE2, BLAST, and Trace. The computational methods employed in simulation tools vary from simplified temperature bin–based methods to sophisticated dynamic models that can use analysis time steps measured in seconds. Energy simulations are most often used to estimate cumulative energy use, but can also be used to estimate various operating parameters, such as: peak and instantaneous power use; space temperatures; air flow rates and temperatures; and other detailed aspects of system performance.

Strengths Simulation programs offer an accurate method for estimating how a system should perform when operating properly.

Weaknesses Many simulation programs (especially those for whole buildings and complex systems) are complex, computationally intensive, and require extensive inputs to realize major accuracy advantages over simpler methods. The necessity for extensive user input creates opportunities for poor judgment or input errors to impact results. At this time, simulation programs would represent overkill if applied to most commissioning problems. Simulations of specific equipment and systems may be more accurate and useful for commissioning purposes than simulations of whole buildings or major systems in cases where actual fault detection and diagnosis is the objective. Simulations of complex systems typically found in large commercial buildings rarely represent actual system performance accurately because of differences between modeled and actual system configurations and control strategies. Differences between modeled results and actual performance also result from differences between inputs for operating conditions (e.g., occupancy, occupant behavior, functions taking place in the building) and actual conditions. In addition, few simulation programs for buildings exist that extend beyond thermal and fluid flow analysis into the mechanical behavior of actual equipment. Because many failures result form mechanical failure or incorrect mechanical installation, simulation models do not enable extension of diagnoses into this important domain.

Suitability Simulation based methods are unlikely to emerge as the method of choice to define acceptable performance for commissioning, particularly if applied to equipment or components, as opposed to complex systems or entire buildings. Simpler approaches, such as engineering methods and heuristic rules will normally be adequate.

At least in theory, however, simulation tools could in the future play an important role in applications that perform automated or continuous commissioning. A brief discussion of this potential is provided here primarily for consideration in future work. For continuous commissioning applications that monitor complex systems or even entire buildings, simple engineering based methods are unlikely to provide a sufficiently accurate benchmark of acceptable performance (although simple data driven empirical models discussed later in this report, may very well provide suitable accuracy for evaluating changes in whole building and complex system performance, as may calibrated engineering based simulations). We anticipate in the future the emergence of software that enables simulation program inputs to be acquired automatically from computer aided design (CAD) systems, other design tools, and even physical installations themselves. Those developments will improve accuracy and ease of use of simulation tools and may even make simulation models a routine part of building design documentation in the future. To be valuable in continuous commissioning, simulation models would also need to be automatically *calibrated* to (or perhaps driven by) metered data from the operating building, in order to account for such dynamic factors as occupant behavior and weather. Such a simulation could offer excellent capabilities to both detect and diagnose energy related building faults. However, such a capability is likely years away.

Heuristic Rule–Based Methods

Description This category encompasses use of a range of different types of information. By *heuristic rules*, we mean simple, practically derived rules or approximations that have been tested and proven to be operationally useful. Rules of thumb for design are examples of heuristic rules. It is possible to derive heuristic rules from first principles or to develop them empirically through observation of system performance. We have included this discussion of heuristic methods under first principles–based approaches because heuristics are usually developed by individuals who understand the engineering domain within which the heuristic will operate. In our view, it is primarily the conceptual understanding of the system that enables the development of successful heuristics. Too often technicians and operating staff without strong backgrounds in the fundamental underlying principles develop and use their own heuristics that are incorrect, or correct only over very limited ranges of conditions. We do not include these heuristics in our discussion here.

Strengths Heuristics are simple to understand and implement in software, and they are amenable to testing and incremental refinement.

Weaknesses Heuristics generally do not work well outside of the restricted domains for which they were developed. A heuristic for an isolated system or piece of equipment might work well. A heuristic developed for a large or complex system (e.g., a whole building) would likely appear simplistic and perform unreliably. In addition, unlike methods more directly rooted in physics, heuristics do not work everywhere. It may not be obvious how best to restrict the domain of application of a heuristic or even that it is necessary to restrict its domain. Heuristic rules may be useful but will need to be used with caution in automated commissioning systems.

Suitable Applications Heuristics methods provide shortcuts and may offer the most expedient way to meet analytical needs where more rigorous approaches are time or cost prohibitive.

Expert Systems

Description Expert systems are computer based applications used to deploy the insights, knowledge, and/or guidance of individuals with recognized expertise in a given field. In developing expert systems, the knowledge of domain experts is usually elicited through interviews administered by a knowledge engineer, who later enters the collected information into a database (often referred to as a knowledge base) in the form of if-then statements. Some expert systems enable users to enter confidence levels along with the information on which the user is uncertain.

Expert systems are usually deployed using software packages referred to as expert system shells, and within an expert system shell is a software component called an inference engine. The inference engine is capable of inferring from the information the user has entered any additional information it needs to reach a conclusion or diagnosis; and then, given that additional data, it infers a conclusion. Expert systems have been developed to diagnose and analyze problems in many fields. Systems for medical diagnosis are among the most widely recognized. Prototype systems have been developed to perform diagnoses for operational problems in commercial buildings (Andelman, Curtiss, and Kreider 1995), although to our knowledge, none have been commercialized or have achieved widespread acceptance.

Strengths Expert systems are effective for solving well understood but poorly structured fault detection problems for which symptoms, failure mechanisms, and heuristics are available or could be developed. Though there are several manufacturing and processing plant monitoring systems using expert systems, their use in the building industry for fault detection and diagnostics has, to date, been exploratory, and existing knowledge bases have been used only for demonstration purposes.

Weaknesses The existing expert systems with which we are familiar have been designed to emulate the interaction of a building manager with a human expert. It is unclear how readily such work could be adapted to applications that (at least in the case of continuous commissioning) are expected to operate autonomously rather than highly interactively.

Expert systems can only be as knowledgeable and insightful as the experts who create them. Diligence is required from both knowledge engineer and expert in appropriately qualifying statements and clarifying the boundaries within which the knowledge applies. Based on the experience of one of this report's authors, it is likely to be very difficult to create an expert system capable of achieving the high levels of reliability (and in particular the low incidence of false positives) that would be required for use in a continuous commissioning application. It is also unlikely that available knowledge bases will prove well matched to the commissioning processes selected for use in this project. Knowledge base availability is likely a major impediment to use of this technique in this project. In addition, validation of expert systems from fundamental principles is not possible because they rely on heuristics.

Suitable Applications None, except possibly as a source of heuristic rules for commissioning or for use in interpreting results from other methods.

Fuzzy Logic

Description Fuzzy logic is a computer science formalism (or theory) that enables programs to draw appropriate inferences based on conditions that are fuzzy; e.g., neither true nor false but something in between. Fuzzy logic has been most widely employed within expert systems, where it provides a theoretical basis and the necessary algorithms for systems that address types of problems that cannot be handled adequately using classical (or Boolean) logic.

While many find the distinction confusing, fuzzy logic is not primarily a solution to the problem of making logical inferences from evidence on which there is uncertainty. Reasoning under uncertainty as to whether the evidence is true or false is a problem amenable to probabilistic solution. Fuzzy logic is useful in drawing inferences when the evidence indicates a condition that is (figuratively) sort of black and sort of white, and not just when there is uncertainty as to whether the condition is black or white. Fuzzy logic offers a systematic approach to decision making during diagnostic problem solving under conditions in which evidence is "fuzzy."

Building related examples that might benefit from fuzzy logic could include diagnostics that respond to evidence of *partially* fouled condenser tubes in a chiller or increased static pressure in an air handling unit due to a *somewhat* dirty air filter.

Strengths/Weaknesses/Suitability While fuzzy logic has generated considerable interest and controversy, for purposes of this project it is best considered as either a variation on, or an embedded capability of, expert systems. As such, most of our assessment of expert systems applies equally to systems employing fuzzy logic. In particular, the desirability of avoiding false positive detections of fault conditions would probably argue for avoidance of any automated commissioning problems for this project for which fuzzy logic is needed.

Data Driven Methods

We use the term *data driven methods* for the second major category of analytical techniques addressed in this report. This category includes methods that are predominantly empirical (or data driven), although elements of first principles–based approaches are also included. Other terms such as *pattern recognition* are also used to describe methods in this family of techniques. Many of these pattern recognition and data mining techniques have been developed to address problems of filtering and interpreting large data sets. These problems have major similarities with the problem of analyzing and interpreting the continuous streams of data anticipated from continuous commissioning applications.

A key characteristic of data driven methods is their reliance on training data. Training data sets comprise data in which both system inputs and the corresponding system outputs are known and used to train models. After training, the models are tested against other data sets known as *test data sets*, which contain input data and corresponding output data. The analytical methods reviewed in this section use a variety of methods to "learn" or characterize the relationships between inputs and outputs, such that input conditions can later be inferred by observing outputs.

A non-buildings related example where these methods have been successfully used is in character recognition. Using training data that maps alphanumeric characters to corresponding hand written characters from a sample of different individuals, applications have been developed that accept hand written characters as input and return the corresponding alphanumeric characters as output. These applications are empirically developed in the sense that no conceptual knowledge about the shape or structure of the characters was used in developing the analytical capability.

A buildings related continuous commissioning example might involve mapping an index or flag representing correct vs. faulty economizer operation to outdoor and mixed air temperatures in an HVAC system. A pattern or signature of faulty operation could be captured using a variety of data driven methods. The resulting commissioning application could then monitor temperature data looking for matches with the recorded pattern for faulty economizer operation.

Such patterns can be developed using methods that are purely empirical, or they can be developed using methods that also exploit available first principles–based knowledge about the nature and behavior of the system. Methods that exploit knowledge about principles underlying the problem are called parametric methods.

Methods that are free of any knowledge of underlying principles are referred to as nonparametric methods. If training data are sparse or incomplete, the system developed using data driven approaches is likely to perform unreliably in cases where the missing data ranges are encountered. If training data are completely unavailable, data driven approaches are infeasible. In general, it is advantageous to exploit whatever first principles–based knowledge is available, because parametric methods tend to be simpler, easier to use, and permit faster development of automated procedures than nonparametric methods.

Acquiring suitable training data for use in building commissioning may be problematic. Commercial buildings are different enough from one another in terms of design, operating patterns, and the environmental conditions under which they operate that training data from a different building may not be useful, at least for most commissioning purposes. Another potential source of training data is the building itself. Over time, if data are captured from normal building operations, these data can be used to develop patterns representing normal building operation. In addition, a commissioning agent could, at least in theory, perturb a building's operation in ways that mimic specific building faults. However, it seems unlikely that in practice a building commissioning agent would have sufficient opportunities to operate the building this way to generate adequate training data; particularly if data acquired in this way was to serve as the primary method for identifying building faults for continuous commissioning.

A potentially useful alternative to capturing training data from the building itself would be to capture it from a simulation of the building. In concept at least, this approach could enable sufficient quantities of training data to be generated and pertinent fault conditions to be simulated. However, as discussed in the previous section on simulation-based methods, there are a number of challenges related to simulating faults and comparing simulated and metered data.

Strengths Data driven methods are well suited to problems for which theoretical models of behavior are poorly developed or inadequate to explain observed performance. Some problems are simply too complex or intractable to be addressed using approaches based on engineering principles, even if the underlying science is well understood. Empirically based approaches are well suited to situations in which training data is plentiful or inexpensive to create or collect.

Empirically based methods can be trained to recognize normal patterns of behavior and detect when those patterns—even quite complex patterns—have changed. Such methods may prove useful in capturing patterns from fully commissioned new buildings and in using them to detect changed behavior, such as would be needed in a continuous commissioning mode of operation (after initial commissioning).

Weaknesses Data driven methods alone are unlikely to prove useful in determining whether a new system is performing according to specification. These methods, by themselves, offer no direct way of relating building performance to design specifications, and any training data for new buildings will likely need to come from other buildings and would need to be reviewed for relevance and possibly adjusted.

Suitable Applications Detection of changes in performance for systems with recorded operating histories. Commissioning of new and existing packaged components, for which training data can be derived from other units, such as by a manufacturer.

Statistical Methods

Description Various statistical methods can be used to capture patterns in the relationships between system inputs and outputs. These include linear regression, logistic regression, cluster analysis, decision trees, as well as a host of other statistical methods. Statistical methods can be subdivided into parametric and nonparametric categories. Linear and logistic regression techniques are parametric methods; cluster analysis, decision trees, and most other methods are considered nonparametric. Conceptual understanding of the problem can be exploited using parametric methods. These approaches all require training data and enable the resulting application to infer system inputs from system outputs.

Selection of the most appropriate statistical method depends on a number of attributes of the problem being addressed, including whether the objective of the commissioning task will be classification (e.g., determining if the systems is within spec or out of spec) or estimation (e.g., determining that the furnace is operating at *x*% efficiency). The strengths and weaknesses of various statistical algorithms is a topic far beyond the scope of this review. A good review of suitability considerations can be found in Kennedy et al. (1998), Chapter 10, *Selecting Architectures and Training Parameters*.

Strengths Development methods are conventional and well documented. Needed software is widely available and capable of being used with large data sets. Computational requirements vary, but are generally manageable.

Weaknesses Development of applications using many of the recommended statistical methods require considerable statistical expertise.

Suitable Applications Within this broad category of data driven statistical approaches, some methods are applicable for virtually any kind of pattern recognition problem, including those considered in this project.

Parametric Statistical Methods

Description Parametric methods are a subset of statistical methods, but are discussed here separately to highlight specific differences. Parametric methods are so called because they rely on parametric models in which model outputs are expressed as known functions of model input parameters. In contrast, nonparametric methods rely on models that have arbitrary structures that are defined by the data used to train them. Commonly used parametric methods include linear regression, logistic regression, and unimodal Gaussian.

A buildings related example of a parametric model would be using first principles knowledge of how a cooling tower operates to develop a model that predicts cooling tower range and approach temperatures based on design information about the cooling tower and monitored flow rates and temperatures (e.g., cooling water, ambient dry bulb and ambient wet bulb temperatures). A continuous commissioning application could then use actual deviations from predicted range and approach temperatures to infer the presence of a fault in the cooling tower, such as fouling of the tower, faulty control settings, or physical failure of a drive motor. It is often necessary or advantageous to tune parametric models using training data, similar to the way in which nonparametric models are trained. For example, once the structure of a parametric model (i.e., the relationships among independent variables including any exponents, cross products, or transformations) has been defined, linear regression can be used to define a set of coefficients that provide the best fit to the training data.

Strengths Parametric models are usually simpler and easier to develop than nonparametric models and tend to perform better when used in situations not represented in the training data. Parametric methods offer some of the simplest approaches to pattern recognition problems and are often used early in a project to establish a benchmark for assessing the performance of more complex alternative methods. Parametric methods represent a classical statistical approach; hence, they are well understood, statistical tools that use them are widely available, as is the statistical expertise needed to use them effectively.

Weaknesses Parametric models are not suitable for use in situations where the underlying phenomena being modeled are not well understood or where attempts to model them for the intended purpose have shown them to be unreliable. Some problems may be so complex that it is infeasible to fully describe their structure and the relationships among parameters.

Suitable Applications Parametric methods appear well suited to use with many of the envisioned automated or continuous commissioning tasks. The principles underlying most building operation problems (at least when viewed in a steady-state) are well understood, and the ability to tune parametric models to empirical data from the building make these methods a promising approach for a range of building commissioning applications.

Artificial Neural Networks

Description Artificial neural networks are so named because they were first proposed as a model of neurobiological processes. Neural networks can be viewed as sets of interconnected nodes usually arranged in multiple layers. The nodes of the network serve as the computational elements and pass data to the other nodes to which they are connected. Neural networks can be thought of as a subset of statistical methods.

Strengths Most neural network algorithms are suitable for both classification and estimation problems. They use nonparametric algorithms, hence they are applicable to problems for which no prior first principles–based knowledge is available.

Weaknesses Neural networks are among the more complex algorithms that are used to solve pattern recognition problems. They are slower to train than alternative conventional statistical algorithms and, because they are a relatively new approach, the required expertise to use them effectively may be less widely available.

Suitable Applications Pattern recognition problems that are very complex or poorly understood and for which relevant training data are available.

Data Preprocessing

Data preprocessing is an important step in the process for developing pattern recognition solutions. Data preprocessing is done to make various types of solutions work better and be more efficient to develop. As such, data preprocessing is really a crosscutting technique that is applicable with both parametric and nonparametric methods.

The purpose of data preprocessing is to simplify the data inputs to the system and to increase the strength and clarity of the signal in the data relative to noise in the data. Data preprocessing can involve the use of a variety of different techniques to manipulate the input data. The usefulness of the various approaches is highly problem dependent. While data preprocessing can be a highly complex topic, it is an important step that can often mean the difference between a system that performs well and a system that performs poorly. The objective of this discussion will be to provide the reader only a general description of the nature of the preprocessing step and an overview of the types of techniques that are most frequently employed.

Techniques that are commonly employed in data preprocessing are averaging data values, thresholding data, reducing input space through statistical techniques such as principal component analysis, combining non-correlated variables, normalizing data, and feature extraction. Each of these techniques is described briefly below.

Averaging data values With time series data, moving averages are frequently used rather than raw instantaneous data from sensors or data loggers to smooth out fluctuations that are not meaningful; for example, when monitoring temperatures in ducts or piping loops.

Thresholding data This technique can be used to discount or ignore inputs that are below a threshold and to remove noise from a signal due to transient phenomena (e.g., equipment startup).

Reducing input space In some situations, there may be so much input data that identifying the signature of a problem is like looking for the proverbial needle in a haystack. In these cases, such statistical techniques as principal component analysis may enable the most meaningful data to be identified and the remaining data discarded, resulting in dramatic reductions in the quantity of data that needs to be processed as well as a clearer signal from the data that remains.

Combining non-correlated variables Knowledge of the relationships underlying the problem can often be used to translate input data into a more concise and meaningful form before pattern recognition algorithms are applied. For example, it might be easier to identify operational problems with a rooftop direct expansion (DX) unit by monitoring the unit’s efficiency versus ambient temperature, rather than from the measured values, such as input current, supply air flow rate, and ambient, mixed, and supply air temperatures.

Normalizing data Normalizing (or scaling) data is often necessary to keep numerically large inputs from overwhelming numerically smaller ones. The problem addressed by normalization is similar to the problem of scaling the axes on a graph to effectively display trends in the data. Sometimes nonlinear transformations are necessary (like using a logarithmic scale) to enable the pattern recognition algorithms to perform most effectively.

Feature extraction Feature extraction involves exploiting knowledge about the underlying problem to improve the performance of pattern recognition algorithms. An example would be recognizing vertical and horizontal lines as distinct features in an alphanumeric character recognition problem, as opposed to recognizing characters from raw bitmaps of the characters. In commissioning, feature extraction might involve filtering data so that only certain predefined data are used when conducting a test; for example, focusing on data from a warm-up period in confirming proper outside air damper operation.

6.2.3. Analytical Tools

This section describes a range of software tools that may be relevant or useful to the development of automated commissioning software applications.

Spreadsheets

Description Most readers will be very familiar with computer spreadsheets. Programs such as Microsoft Excel provide a relatively easy-to-use environment for recording, analyzing, and graphing data. Most spreadsheets offer an array of basic mathematical, statistical, and database functions. In addition, nonprogrammers can easily create spreadsheet macros that can automate moderately complex data analysis and data manipulation tasks.

Strengths Spreadsheets are flexible and relatively easy to use. They are well suited for use in prototyping and proof-of-concept testing.

Weaknesses Spreadsheets are not well suited to serve as the platform for implementing automated commissioning functions. They generally lack capabilities for automating data acquisition and continuous processing functions and are not well suited for managing large data sets. In addition, they lack the specialized statistical and advanced pattern recognition algorithms, such as neural networks, that could prove effective in continuous commissioning applications.

Suitable Applications Spreadsheets are suitable for method development and early prototyping.

General Purpose Statistical Packages

Description There are a number of powerful and versatile general purpose statistical analysis programs available. SASS, SPSS, and S are three such programs that were originally developed for use on large, multi-user computers but have since been migrated to personal workstations including Windows based personal computers. S, a statistical program with which the author is familiar due to its extensive use at PNNL, offers powerful graphics capabilities, as do other similar statistical programs. Statistica (StatSoft, *Background*, 2001) is an example of newer general purpose statistical packages originally developed for personal computer systems.

These programs are capable of handling large data sets and performing complex statistical analyses, but are primarily designed for interactive and batch processing. To our knowledge, most are not suitable for creating components that can be embedded within a continuous commissioning application. Some of these programs (SAS and Statistica are two examples) are promoted as enterprise wide data warehousing and data mining solutions. In addition to containing the traditional statistical algorithms used in pattern recognition, such as regression and cluster analysis, programs such as Statistica also contain support for a variety of neural network architectures. If performance data were stored in a format compatible with this type of program, a general purpose statistical package might well be an appropriate environment for development of a fault detection and diagnostic capability. These programs tend to be quite expensive, and assuming purchase of the software would be required of each end user, software license costs could be a significant barrier to use of such software in the ultimate deployment of fault detection, diagnostic, and commissioning software.

Strengths General purpose statistical packages offer rich and powerful assortments of statistical analysis capabilities. Some packages also offer strong data warehousing and data mining features, such as those we have described in our discussion of pattern recognition techniques.

Weaknesses To our knowledge, most are not suited to continuous data acquisition or monitoring functions or suitable for us in the creation of linkable or embeddable software components. If end users must purchase statistical software before being able to use automated commissioning capabilities from this work, the cost of software purchases could present a significant barrier to use.

Suitable Applications General purpose statistical packages are suitable for performing statistical and pattern recognition analyses, at least for purposes of methodology development.

Pattern Recognition Workbench

Description Pattern Recognition Workbench (PRW) is a software program designed for solving pattern recognition and data mining problems. It also can be used in developing program code that can be compiled and linked into other software applications. There may be other programs on the market that serve similar functions, although PRW is the only such program with which the author is personally familiar.

PRW can be thought of as a specialized spreadsheet program capable of performing many of the analytical procedures described in the previous section on data driven techniques. For example, PRW contains the algorithms necessary for implementing a variety of different statistical analyses useful in addressing pattern recognition problems including neural networks.

Strengths PRW provides a convenient environment for development and testing of automated commissioning techniques using a rich set of data-driven approaches. In addition, the capability to compile code that can be linked to other computer applications may make it possible to use PRW as an environment for both procedure development and software implementation.

Weaknesses PRW is more difficult to use than a spreadsheet program. The program has no facilities for continuous data acquisition, and is not suited for use in continuous monitoring, so prototype code would need to be linked with another software development environment. Significant uncertainties surround support and licensing issues for the PRW software.

Suitable Applications PRW appears suitable for development and testing of analysis components for automated commissioning applications and possibly also for the development of modules that be linked into final applications.

ENFORMA

Description ENFORMA is a program developed and marketed by Architectural Energy Corporation (AEC) in Boulder, Colorado, for analyzing short-term building energy use data. ENFORMA was designed as a companion product to the *MicroDataLoggers* offered by AEC. Both products are intended for use in short-term (e.g., several days or weeks) monitoring, such as for building commissioning, recommissioning, or troubleshooting.

ENFORMA provides facilities for developing metering plans, uploading metered data from data loggers, and analyzing metered data. ENFORMA's capabilities focus on data visualization, rather than on computational analyses using the data. The program offers considerable power and flexibility in data visualization, allowing the user to display and filter that data in a variety of different ways. In addition, the program contains a library of graphs representing hypothetical faulty operation for comparison with the metered data from the building being studied.

Strengths Very good data acquisition and visualization capabilities within an application specifically designed for the commissioning and recommissioning of HVAC systems.

Weaknesses The program is designed for manipulation and visualization of building data by a human user performing fault detection and diagnostic functions. The program has no facilities for automating these functions or for generating modules or code that can be used outside of the ENFORMA program.

Suitable Applications ENFORMA currently is suitable for manual testing and diagnostics. ENFORMA metered data sets and fault library may provide useful examples of problems seen in commissioning.

Programming Languages

Description There are a wide variety of computer programming languages that have developed over the past several decades. Most early computer languages were *procedural*; that is, designed for implementing procedures that execute as a set of sequential steps. FORTRAN, BASIC, and Pascal are examples of older procedural languages. Currently, the most popular programming languages are *object oriented*. Object oriented means that the language is designed to facilitate the handling of "objects," which consist of both data and functions (or behaviors) of the objects. Object oriented languages encourage the creation of modular code, code libraries, and objects that can inherit attributes from other objects, all of which serve to facilitate reuse of object oriented code. Popular object oriented languages include C^{++} and Java. In addition to languages that have enjoyed widespread use as general purpose programming languages, there are many special purpose languages that excel in certain types of applications or in solving certain types of problems. For example, Prolog is a language that was developed to efficiently perform the kind of logical operations needed for expert systems.

Programming languages can be classified into compiled and interpreted languages. Most popular languages for large applications, such as FORTRAN and C^{++}, are compiled languages. Applications written in these languages can be installed on a new computer by installing an executable version of the program along with any necessary supporting files. Interpreted languages such as BASIC, FORTH, and Java can be run without compiling your program's source code into a separate executable form, an advantage that can speed development and debugging. However, in order for programs written in these languages to run on a new computer, the computer must have the necessary interpreter installed. In the case of Java, a World Wide Web–oriented language, the interpreter is called the *Java virtual machine*.

Strengths The largest advantages that programming languages offer over other tools discussed here is versatility and power. Virtually any process for manipulating or analyzing data that can be defined could be automated using many of these languages. In addition, the license agreements that come with most programming languages enable code developed using them to be disseminated without royalty payment to the language vendor. In contrast, solutions developed using almost all of the other tools discussed here would require users to have or acquire software in order to use the procedure or application.

Many of the tools discussed here require specialized expertise for effective use. Most programming languages require a high level of expertise for effective use. However, the needed expertise in programming is likely to be easier to obtain than the specialized expertise needed to work with some of these other tools, because of the broad application of general purpose programming skills.

Weaknesses The largest disadvantage of using programming languages are that development tends to be slower and more expensive, because many of the needed functions or procedures need to be developed rather than simply used, as in the case of the specialized tools. Programming languages are best suited for applications for which the software requirements can be fully defined before development begins. Where substantial experimentation, prototyping, and exploratory development is needed, use of programming languages is likely to result in high cost development.

Suitable Applications Use of programming languages is appropriate where detailed requirements for the desired software can be fully defined, where high levels of refinement are desirable for the program's user interface, where performance (e.g., execution speed) of the application is important, and where the software must be disseminated in the form of compiled executable code.

6.3. Conclusions

In this section we reviewed methods and technologies that may pertain to automated and continuous commissioning of building systems. The review has been structured into three major sections dealing with

1. technologies and techniques applicable to streamlining the general steps in the commissioning process,
2. analytical techniques that may be applicable to the problem of automating fault detection and diagnostics for building systems, and
3. analytical tools that may applicable in developing and deploying tools that automate building commissioning.

A summary of the methods and characteristics of them is provided in Table 3. Major conclusions are presented separately for each of the three major sections of this report below.

Table 3: Summary of the Evaluation of Analytical Techniques

Technique	Strengths	Weaknesses	Suitable Applications
Analytical Techniques—First Principles–Based Methods			
Engineering Calculation–Based Methods	• Well developed • Tested using manual commissioning procedures • Familiar and credible with prospective users • Straightforward to implement	• Most use static methods • Performance adjustments required for off-design conditions	• Foundation for any automated commissioning system. • Combine with other approaches
Simulation Based Methods	• Accurate method for determining proper performance	• Complex • Computationally intensive • Require extensive inputs • Potential for input errors significantly affecting results • “Overkill” for many commissioning applications • Current versions for buildings limited mostly to thermal/ fluid flow	• Unlikely choice for commissioning
Heuristic Rule–Based Methods	• Simple to understand • Easily implemented in software • Amenable to testing and incremental refinement	• Generally do not work well outside of the restricted domains • Might work well for isolated systems or equipment • Likely simplistic and unreliable for large or complex systems	• Could provide shortcuts • May offer the most expedient analysis • Caution required to avoid limitations

Technique	Strengths	Weaknesses	Suitable Applications
Expert Systems	• Effective for solving well understood but poorly structured problems	• Unclear if useful for autonomously applications • Only as knowledgeable, insightful, and correct as the experts • Diligence required of knowledge engineer and expert • Likely difficult to achieve high levels of reliability • Available knowledge bases unlikely to match commissioning needs • Knowledge base development required	• Possible source of heuristic rules for commissioning
Fuzzy Logic	• Useful for well understood but poorly structured problems • Useful where input information is “fuzzy”	• Poor match with avoiding false positives	• Applications where inputs are “fuzzy” • Potential for use with other methods
Analytical Techniques—Data Driven Methods			
Statistical Methods	• Underlying principles and methods are broadly understood and well documented • Develop tools are widely available • Useful with large data sets • Computational requirements vary but are generally manageable	• Considerable statistical expertise required for application development	• Applicable to a broad range of pattern recognition problems
Parametric Statistical Methods	• Simpler to develop than nonparametric models • Perform better than nonparametric models in regions with little data • Statistical tools and expertise that use them are widely available	• Not as simple as fixed engineering models • Require more data than fixed engineering models • Underlying phenomena must be well understood (compared to nonparametric)	• Promising for automated and continuous commissioning • Building operations problems are mostly well understood • Tunable uniquely to buildings and equipment
Artificial Neural Networks	• Algorithms are suitable for both classification and estimation problems • Applicable to problems for which no prior first principles–based knowledge is available	•Complex algorithms •Slower to train than conventional statistical algorithms •Require less widely available expertise •Require significant training data	• Complex or poorly understood problems • Problems with significant data available

Technique	Strengths	Weaknesses	Suitable Applications
Analytical Tools			
Spreadsheets	• Flexible • Easy to use • Well suited for preliminary implementations and conceptual testing	• Not well suited for final implementations • Lack automated data acquisition capability • Lack continuous processing functions • Not well suited for large data sets • Lack specialized statistical and pattern recognition algorithms	• Suitable for method development and early prototyping • Suitable for preliminary implementations and conceptual testing
General Purpose Statistical Packages	• Rich and powerful assortments of statistical analysis capabilities • Sometimes strong data warehousing and data mining features	• Most are not suited to continuous data acquisition or monitoring functions • Not suitable for creation of linkable or embeddable software components • Potentially add considerable cost to users if made part of final implementations	• Valuable for performing statistical and pattern recognition analyses and methodological testing during development
ENFORMA	Very good data acquisition and visualization capabilities within an application specifically designed for the commissioning and recommissioning of HVAC systems.	The program is designed for manipulation and visualization of building data by a user performing fault detection and diagnostic functions. The program has no facilities for automating these functions or for generating modules or code that can be used outside of the ENFORMA program.	ENFORMA currently is suitable for manual testing and diagnostics. ENFORMA metered data sets and fault library may provide useful examples of problems seen in commissioning.
Programming Languages	• Versatility—can implement any process for manipulating or analyzing data • License agreements generally permit distribution of code without royalties • Programming language expertise is widely available	• Development tends to be slower and more expensive than using pre packaged tools • Best suited for applications for which the software requirements can be fully defined before development begins • Not as compatible with concept testing, proof of principles, or investigating methods as prepackaged toolkits	• Appropriate for development of final commissioning tools • Valuable where user and application specific interfaces are needed • Useful where application execution speed is important • Valuable where software must be disseminated in the form of compiled executable code

6.3.1. Tools and Techniques for Managing Commissioning Data

Various new technologies and applications of technologies promise to be useful in streamlining and automating aspects of the commissioning process. Chief among these are the Internet, wireless communications, lightweight portable and hand-held computers, high capacity data storage devices, and standards for data representation and data sharing between commissioning participants. Effective application of these technologies to commissioning could enable building commissioning to be done more effectively, more quickly, and at lower cost.

6.3.2. Analytical Techniques

A variety of techniques would likely prove suitable for use with our problem. Relative to other pattern recognition problems, ours is not particularly challenging. A range of approaches are available from use of first principles–based models to classical statistical methods to artificial neural networks. The decision as to the best approach to use is highly problem specific. An advantageous attribute of our problem is that the underlying theory and engineering algorithms to describe system behavior are well developed and widely available. In general, it is advantageous to exploit this knowledge if it is available, rather than rely on strictly data-driven approaches, such as artificial neural networks. Differences between measured results and results from first principles–based models suggest that some tuning of parametric models using training data will be necessary to achieve the desired performance and reliability.

6.3.3. Analytical Tools

There are a range of tools that may be useful in prototyping and deploying tools for automated commissioning. The expected need for powerful statistical functions and for dealing with potentially large data sets suggests that ordinary spreadsheet programs (such as Microsoft Excel) are unlikely to offer the needed capabilities. Programming languages, such as C^{++}, while providing adequate capabilities are labor intensive to use and hence ill-suited for methodology and prototype development work. The most promising types of tools for near-term use appear to be Pattern Recognition Workbench, a spreadsheet-like program developed specially for use with pattern recognition problems, and general purpose statistical package such as S or Statistica.

6.4. Suggested Reading

This section contains several good sources of information that may help the reader find additional information on key topics that has been only summarized in this report. See the *References* section, starting on page 175, for full citations.

Solving Data Mining Problems through Pattern Recognition by Ruby L. Kennedy, R. L., Yuchun Lee, Benjamin Van Roy, Christopher D. Reed, and Dr. Richard P. Lippman.

This book provides an excellent summary of the data mining and pattern recognition techniques that may be pertinent to automated building commissioning. The book addresses a broad range of possible approaches, and while it contains technical detail in appendices, most of the book is written so as to be accessible to most readers. A copy of the *Pattern Recognition Workbench* software (with temporary software license) is included in the back of the book. This book is *highly recommended* as an introduction to pattern recognition and was a valuable resource used in preparing this report.

Wireless PDA Communications, by Brown, Bruce and Marge.

This brief, somewhat dated (June 2000) on-line article summarizes recent and emerging trends in wireless communications for small communications devices. Technological developments, product introductions, and the technical standards and protocols that emerge as winners in the market place are all extremely fluid. Web based articles, such as this, and industry reports may be the best available means for tracking such developments, which may key to successfully deploying technology enhanced commissioning solutions. ZD Net and PC Magazine, in particular, are excellent sources for information on these types of emerging developments.

Electronic Statistics Textbook, StatSoft, Inc.

This is a Web site hosted by the vendor of the Statistica software package. This “electronic textbook” contains a technical glossary of terms and general sections that explain various analytical techniques related to statistics, database functions, and pattern recognition. Although, much of the material is geared to StatSoft’s own software products, the site offers convenient access to much explanatory information that may be relevant to methods applicable to automated commissioning that is not included in traditional statistical text books.

7. Task 5: Develop Methodologies for Automating Selected Procedures and Processes for Continuous Commissioning

7.1. Introduction

Automated commissioning and diagnostic technologies address two of the main barriers to building commissioning: cost and schedules. Automated continuous commissioning tools can reduce both the costs and time associated with commissioning, as well as enhancing the persistence of commissioning fixes. In the long run, automation even offers the potential for automatically correcting problems by reconfiguring controls or changing control algorithms dynamically.

The objectives of this task are:

- to adapt and develop methods upon which automated tools can be built that continually detect and assess the operation of economizers and outdoor air ventilation,
- to develop and demonstrate automated methods for identifying faulty and malfunctioning sensors used (or potentially used) on HVAC equipment and systems,
- to develop a generalized approach for detecting malfunctioning valves and dampers that can be applied in a variety of HVAC applications in which valves and dampers are used, and
- to specify and prototype a methodology that will formalize and expedite the process for determining what information is needed for commissioning and then compiling that information into a database.

In this section of the report, we describe the development of the methodologies and prototype software that demonstrates the automated continuous commissioning process. The approach used for this investigation is described in Section 7.2. The distinction between continuous commissioning and automated continuous commissioning is described in Section 7.3. In Section 7.4, we provide a brief description of how automated fault detection and diagnostics can be used in the commissioning process. Section 7.5 contains definitions and a comparison of passive and proactive diagnostics. A generic automated continuous commissioning process is described in Section 7.6, followed by the details of implementing an automated continuous commissioning process for AHUs in Section 7.7. The proactive diagnostic process with examples is described in Section 7.8, and in Section 7.9, a generic method to identify faulty and malfunctioning sensors is described. A generalized approach for detection of faults in dampers and valves is provided in Section 7.10. Guidelines for the selection of tolerances and thresholds for detection, diagnosis, and proactive diagnostics are described in Section 7.11.

7.2. Approach

As a result of Task 3, the project team selected three candidates for automation:

- extracting building data from existing sources to feed into a functional test
- assessing faulty economizer and ventilation operations of an AHU
- identifying malfunctioning sensors

Pursuant to discussions with ARTI's project monitoring subcommittee, a fourth topic was added to this list:

- identifying malfunctioning valves and dampers

Once these candidates were selected, the team began developing methods for automation and validating the use of these methods for automating the selected processes. This section of the report describes the results of this work. The approach made use of earlier work in automated fault detection and diagnostics for the air side of air handling units, and extended the depth of the resulting diagnoses through the use of automated proactive diagnosis. In addition, a generalized approach for detecting malfunctioning sensors, valves and dampers in a variety of HVAC subsystems was developed.

Task 4 concluded that a variety of techniques would likely prove suitable for use for automated continuous commissioning. A range of approaches is available extending from use of first principles–based models to classical statistical methods and artificial neural networks. The best approach to use is highly problem specific. For HVAC systems, the underlying theory and engineering algorithms for describing system behavior are well understood and developed. In general, it is advantageous to exploit this knowledge when it is available, rather than rely on strictly data-driven approaches, such as artificial neural networks. As a result, we selected a rule based approach in which the rules are derived from engineering principles and from knowledge of the behavior of HVAC systems and components.

7.3. Continuous Commissioning vs. Automated Continuous Commissioning

Commissioning is a systematic process by which proper installation and operation of building systems and equipment are checked and adjusted when necessary to improve performance. A good commissioning process begins during design and continues throughout the construction process. The process also helps develop a preventative maintenance program to ensure that the benefits of commissioning persist over the life of the building. (PECI 1997; US DOE and PECI 1998).

The six generic steps for commissioning each system, sub-system, or piece of equipment as described in the work statement are:

1. **Review the design criteria.** Find the loads, specified capacities, flow rates, temperatures, etc. on which the design was based. Verify their accuracy and appropriateness.
2. **Review the sequence of operations.** Find the specifications for the operating modes of the system or equipment. Check them for consistency and completeness. Clarify inconsistencies, report omissions, and complete as necessary for commissioning.
3. **Develop a commissioning plan.** Determine the procedures to be executed, the criteria for passing the procedure, the conditions required of the system or equipment for the procedure to be valid, and the data required and how it will be obtained. Define who will conduct and witness the procedure, and when in the construction process it will be conducted. Also, identify any other commissioning procedures or functional tests that must be successfully completed as a prerequisite for the test to be feasible, valid or relevant.
4. **Conduct verification procedures.** Ensure the conditions are appropriate to evaluate each procedure as it is executed. Collect the measured data needed for the procedures from manual measurements, the building automation system, and installed data loggers. Interpret the results of each procedure to identify problems (detection). Draw conclusions about the status of the system or equipment (diagnosis) and develop any needed corrective actions.
5. **Issue corrective actions and retest when complete.** Communicate corrective actions to the responsible parties; track all outstanding actions and recommissioning.
6. **Document commissioning procedures and results.** Document the design criteria, the sequence of operations, and the procedures used along with the commissioning results for delivery to the owner and for the operators to utilize for future recommissioning activities.

Continuous commissioning involves the same planning elements and investigation procedures as commissioning. Like commissioning, it is a systematic process to identify and correct building system problems and optimize system performance in existing buildings.

The performance of well commissioned systems can and will deteriorate over time. Therefore, to ensure optimal operation, building systems must be continuously (or at least periodically) monitored and recommissioned. Ensuring persistence is the key difference between continuous commissioning and initial system start-up and performance testing. In addition, some operational problems may only occur when the equipment is operating under normal atmospheric conditions, compared to simulated conditions that may have be used during initial performance testing.

Ideally, system performance tests should be performed during all seasons to ensure overall system performance. For example, a complete check of an AHU would require testing under both occupied and unoccupied mode for each of the following operating conditions:

- peak heating;
- economizer cooling with throttling [outdoor air temperature (or enthalpy) lower than supply air temperature (or enthalpy)];
- economizer cooling with the outdoor air damper fully open (outdoor conditions lower than return air condition but higher than the desired supply air conditions); and
- peak mechanical cooling with the economizer locked out (i.e., outdoor air intake closed to the minimum required ventilation position) because outdoor conditions are too warm and/or humid to provide beneficial cooling.

In a continuous commissioning process, performance is monitored continuously and compared to the expected performance; therefore, all operating modes get tested. By constantly testing and diagnosing automatically during routine building operation, commissioning is more complete (covers all operating conditions) and provides continuous feedback to help ensure that the benefits obtained from initial commissioning continue to accrue into the future.

“Continuous commissioning,” as practiced today, involves periodic review of monitored results and manual diagnosis of anomalous behavior, which requires frequent monitoring, significant labor, and high costs. Making “continuous commissioning” truly continuous and practical requires that monitoring, detecting, and diagnosing abnormal operation be highly automated. Continuous commissioning might involve continuous, automated, but passive detection of problems. Then, when certain conditions are found, the system would trigger a fully automated proactive procedure to complete the diagnosis.

Fully automated continuous commissioning would entail commissioning essentially at the push of a button (or automatically without even pushing a button). Semi-automated continuous commissioning would be slightly less automated, involving automation of parts of the commissioning process while still requiring human expertise for some activities such as input of data or intervention (manually setting control modes, for example). Figure 1 compares the manual commissioning and the automated continuous commissioning processes.

While fully automated continuous commissioning is desirable, such a goal may not be feasible. Proactive diagnostic procedures may be disruptive to normal operation of building systems if performed continually. On the other hand, this may not be true if such proactive tests can be conducted quickly enough so that acceptable control of building systems is maintained. This needs to be assessed as automated commissioning tools become available. Even if automated commissioning procedures are found somewhat disruptive at times, the time periods for enacting them could be carefully selected to avoid disrupting operation. Proactive processes might also be scheduled to occur during unoccupied hours to minimize disruption.

Although automated continuous commissioning could ensure that optimal operation is maintained over the life of the equipment, it is not a substitute for some of the start-up commissioning activities that should be performed during the installation of building systems. Examples include activities that require visual inspection. On the other hand, many functional tests that are routinely performed as part of start-up commissioning can be automated and performed frequently to maintain optimal operation. Some examples include ensuring proper sequences of operations, checking energy saving control strategies, maintaining proper setpoints, ensuring that heating and cooling do not occur simultaneously, ensuring proper ventilation is provided at all occupied times, and ensuring that sensors are providing valid readings.

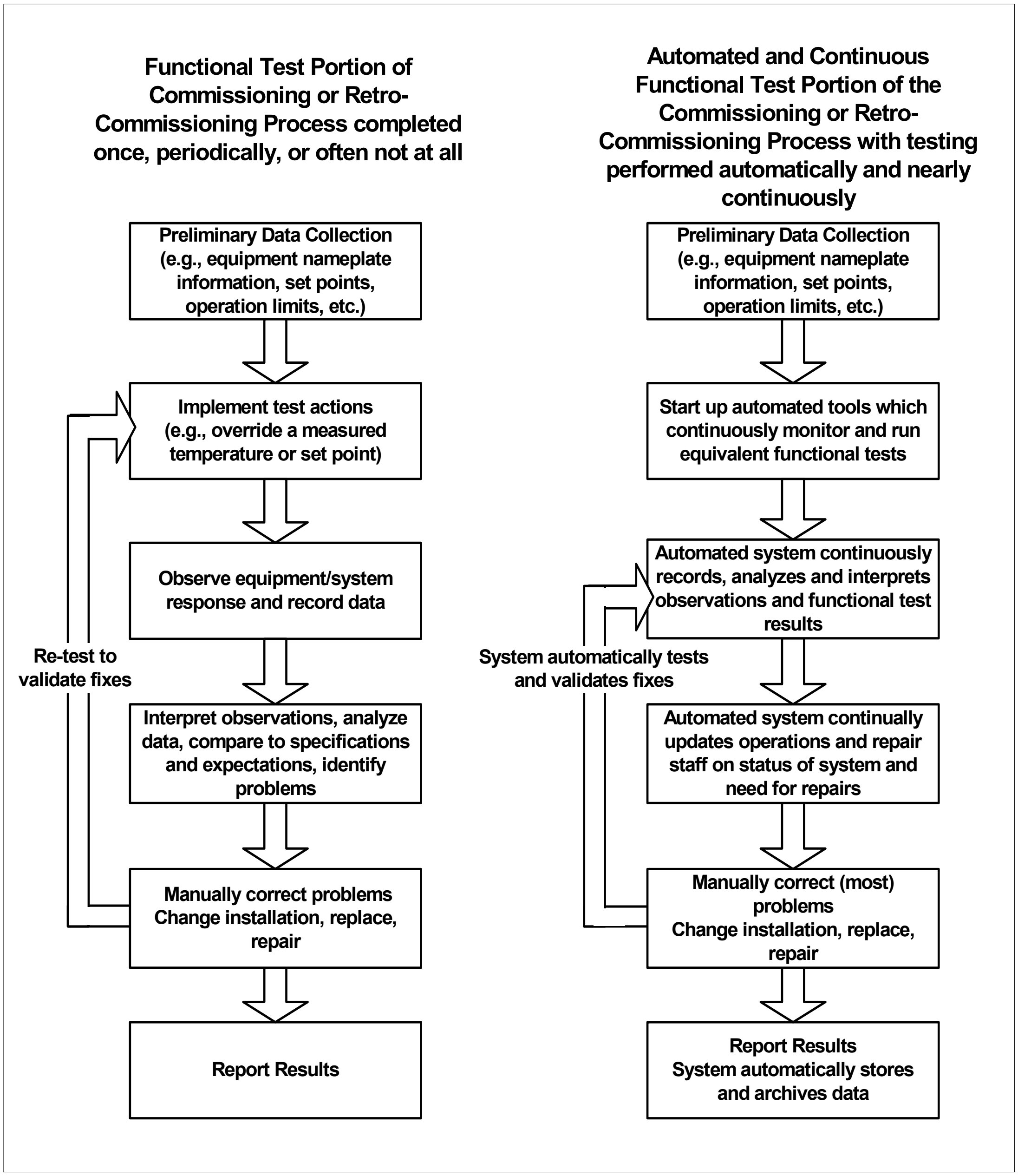

Figure 1: Comparison of manual and automated continuous commissioning processes

7.4. AFDD as an Enabler for Automated Continuous Commissioning

Automated fault detection and diagnosis (AFDD) is an automatic process by which faulty operation, degraded performance, and broken components in a physical system are detected and understood. For example, the temperature of the supply air provided by an air handling unit might be observed to be too high chronically during hot weather. This conclusion can be drawn by visually inspecting a time series plot of the supply air temperature. Alternatively, a computer algorithm could process this data continuously, reach this same conclusion, and report the condition via an alarm to the operator. Automated diagnostics generally go a step further than alarming at this level. In this example, an AFDD system that constantly monitors the temperature and humidity of the outside air, return air, mixed air, and supply air, as well as the status of the supply fan, hot water valve, and chilled water valve of an air handler, might conclude that the outside air damper is stuck fully open. As a result, during hot weather, too much hot and humid outdoor air is being brought in, increasing the mechanical cooling required and at many times exceeding the capacity of the mechanical system for cooling; thus the chronically high supply air temperature. This is an example of how AFDD might work, but we have yet to integrate it into a commissioning process.

Commissioning (new buildings) and retrocommissioning (existing buildings) generally involve functional tests conducted to determine whether a piece of equipment or system is operating properly. So, during commissioning, a test would likely reveal that the outdoor air damper in the example was stuck fully open. Generally, these tests are only performed during the discrete activity of commissioning—at the start-up of a new building or during retrocommissioning of an existing building. To pass the commissioning process, the stuck damper (and other problems) must be corrected and its proper operation verified by observation or by repeating the functional test. This process, however, does not ensure that the equipment continues to function properly. Only by continuously monitoring the status of equipment and its performance can proper operation be ensured continuously. An AFDD system monitoring the damper in our example would detect a new operation problem when it occurs and report that failure and its cause to the building operation team.

As with discrete commissioning, repair usually requires human intervention. So, in response to the information from the AFDD system, a repair person inspects the damper, finds the actual cause of the problem, and fixes it. The AFDD system can then automatically verify that the problem was fixed without an operator or service technician manually performing a test. The AFDD system is central to this continuous commissioning process by constantly, minute by minute, 24 hours per day, 7 days per week, 365 days per year, watching the equipment and identifying if, when, and how it degrades in performance or fails. The human operator or repair person is still critical to completing the commissioning cycle, but without the automated system monitoring continuously these sorts of problems can go undetected for days, weeks, months, or even years (maybe until the next or first manual commissioning is done).

7.5. Passive versus Proactive Fault Detection and Diagnosis

Functional tests performed during commissioning are generally proactive procedures performed to determine whether equipment and systems are installed and operating properly (US DOE and PECI 1998). These tests generally involve observing changes in equipment as it operates, or collecting data after instigating changes in some parameters or conditions in control code (e.g., artificially overriding a temperature measurement with one designed to instigate a behavior to be tested) and then analyzing the resulting data to determine whether equipment performance meets specifications and expectations.

Most AFDD applications developed to date use data collected during passive monitoring of operation. They do not initiate tests automatically to cause operation excursions. As a result, the system must wait weeks, months, or even for changes in season, before the diagnostic system experiences a full range of operating conditions. Proactive diagnostics would involve automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months otherwise. Such tests could be automated to cover a more complete range of conditions or to deepen the diagnosis beyond what might be possible without this capability. Automated proactive diagnostics as a method for providing greater depth and resolution in automated diagnosis are presented later in the report.

7.6. Generic Automated Continuous Commissioning Process

In this section, we describe a generic automated continuous commissioning process that not only can detect and diagnose problems automatically, but can also be used to proactively correct problems that are detected by reconfiguring controls when possible. This process is referred to as an automated continuous commissioning (ACC) process in this report.

Over the past decade, fault detection and diagnostics (FDD) has been an active area of research among the buildings and the heating, ventilation, air conditioning, and refrigeration (HVAC&R) research communities (Katipamula, Pratt, and Braun 2000). As mentioned before, there are many similarities between the methods for automated FDD, predictive maintenance and automated continuous commissioning because they all require monitoring of building systems to detect abnormal conditions.

Because of the similarities between the two methods, FDD systems can be used to build automated continuous commissioning tools. The primary objective of an FDD system is early detection of faults and diagnosis of their causes (and correction of them) before a catastrophic failure of the entire system occurs. Fault detection is accomplished by continuously monitoring the operation of a system or a process to detect and diagnose abnormal conditions. This process is essentially step 4 of the commissioning process described in Section 7.3. In addition to fault detection and diagnosis, an automated continuous commissioning system requires a process to evaluate the severity of the fault and a process to respond to the faults associated with abnormal conditions. This process is essentially step 5 of the commissioning process.

With a couple of exceptions, most existing FDD systems lack the evaluation process (Katipamula, Pratt, and Braun 2000) and none implement the last process of responding automatically to faults.

Based on the six commissioning steps described on page 75, a typical automated continuous commissioning process can be viewed as having four distinct functional processes, as shown in Figure 2. The procedures used within each of the four functional processes are based on the first three steps of commissioning (review the design criteria, review the sequence of operations, and develop a commissioning plan).

The first of the functional steps is to monitor the building system(s) or sub-system(s), and detect any abnormal (fault or problem) conditions. This step is generally referred to as the fault detection phase. If an abnormal condition is detected, then the fault diagnosis process evaluates the fault and diagnoses the cause of the abnormal condition. Following diagnosis, fault evaluation assesses the magnitude of the impact (energy, cost, and availability of the plant) on system performance. Finally, a decision is made on how to react to the fault. In most cases, detection of faults is relatively easier than diagnosing the cause of the fault or evaluating the impact arising from the fault.

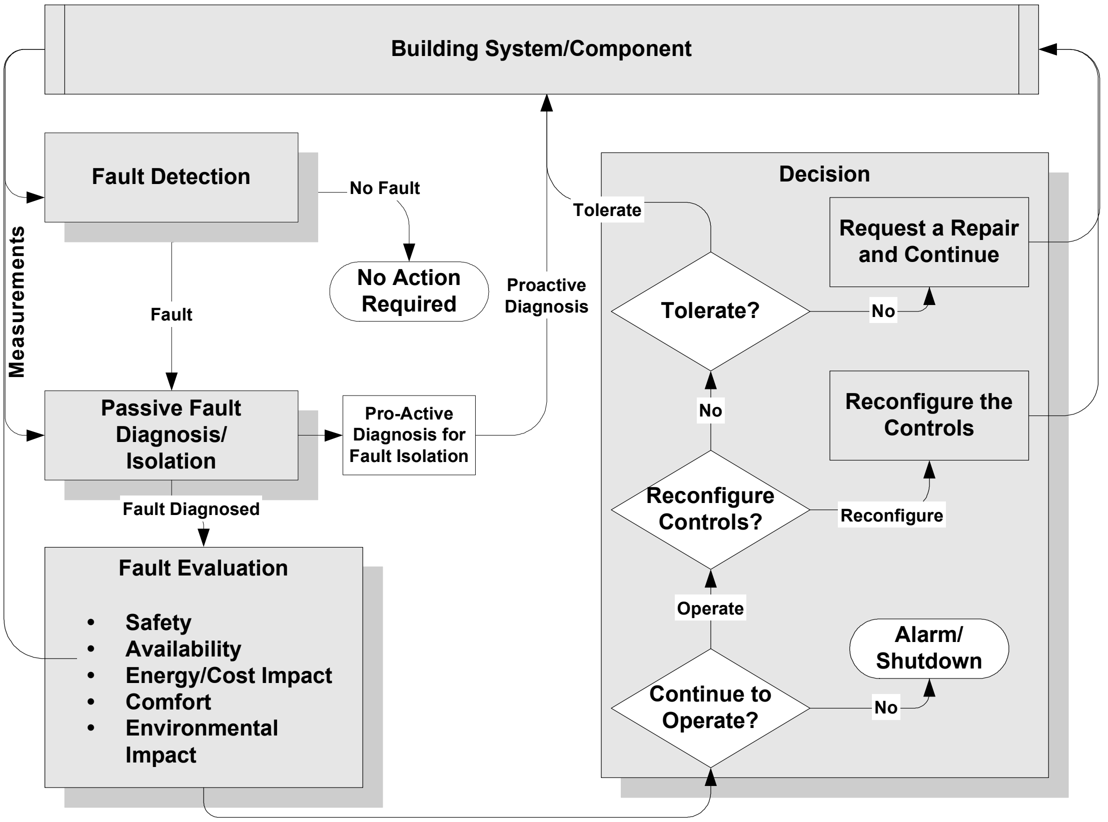

Figure 2: Generic automated continuous commissioning process

7.6.1. Detecting Faults

In the fault detection stage, the building system or component is continuously monitored and abnormal conditions are detected. This process partially addresses step 3 of the commissioning process.

There are several techniques (for example, first principles models, empirical, statistical, direct comparison) by which faults can be detected, including comparing the raw outputs that are directly measured from the components or estimated characteristic quantities based on the available measurements with the expected values. A fault would be indicated if the comparison residual (actual value – expected value) exceeds a predefined threshold. The characteristic quantities are features that cannot be directly measured but can be computed from other measured quantities, for example, the outdoor air fraction for the air handling unit or the coefficient of performance of an air conditioner. In addition to using the raw measured data and characteristic quantities, detailed mathematical models are also widely used in estimating the expected values (Gertler 1988, Issermann 1984) for comparison with the measured values.

In most cases, a model of some kind is essential to detect a fault because most building systems are dynamic in nature. For example, a characteristic quantity such as efficiency can be used to detect a fault in an air conditioner. In the absence of a model, the efficiency calculated from the measured values is compared to a fixed threshold. However, because the efficiency varies with the indoor and the outdoor conditions, the threshold value must be set at the minimum efficiency associated with normal operation in order to prevent a fault from being indicated falsely under those conditions. With a model based approach, the efficiency threshold can be dynamically calculated based on the other measured inputs. This model could be as simple as a specification of the threshold as a function of other conditions or as complicated as a real time simulation of the system.

Several different types of models are used for detection including detailed physical models, empirical models based on first principles, and black box models. These models can be steady-state, linear dynamic, or non-linear dynamic.

7.6.2. Diagnosing Faults

At the fault diagnosis stage, the residuals and other data are analyzed, and the cause of the fault is determined. Unlike fault detection, fault diagnosis is not a binary outcome (fault, no-fault). This addresses the other half of step 4 of the commissioning process.

As shown in Figure 2, fault diagnosis can be passive or proactive. Passive diagnostic procedures use measured data, fault detection from the previous step, and derived quantities to deduce the probable cause of the abnormal or faulty behavior. A range of conditions (i.e., over a span of time) may be required before a problem that is detected can be diagnosed.

Proactive diagnostic procedures, in contrast, use active manipulation of the system or equipment in order to deduce the probable cause of the abnormal or faulty operation.

Passive and proactive diagnostic procedures can work together; a passive procedure can create a list of probable causes, while a proactive procedure can be used to narrow the possible causes or deepen the diagnosis.

For example, if the automated continuous commissioning system detects a sensor failure but is unable to pinpoint the failed sensor from among three sensors (e.g., return , outdoor and mixed air temperatures) of an air handling unit, the proactive supervisory control system can perform additional non-intrusive tests during the unoccupied hours of the day and refine the diagnosis. For example, the air handling unit (AHU) can be operated at 100% outdoor air and the outdoor air and mixed air temperature signals compared. Then, while operating the AHU at 100% return air, the return air and mixed air temperature signals can be compared. The relationships between three temperature measurements, under these two operating conditions, can be used to discern which sensor has failed (the details for doing this are described later in this report).

In some cases, a fault is diagnosed as soon as it is detected at the sub-system or the component level, provided there is adequate measured data. Therefore, top-down fault diagnosis generally applies to applications that are implemented at the system level (with multiple components in the system, for example, air conditioner, chiller, and air handler) or at the component level with multiple sub-components. For example, if a fault is detected with the air filter of the air handler because the pressure drop across the filter is excessive, the cause of the fault is a dirty or clogged filter (provided a sensor fault is ruled out). Therefore, additional diagnosis is not necessary in this case. However, if a deviation of the efficiency of the air conditioner from its expected efficiency is detected, further fault diagnosis is essential to isolate the actual cause for the deviation in efficiency. In this case, the fault diagnosis yielded more than one possible cause for a fault, thus requiring further diagnosis to isolate the cause of the observed fault. Because most building systems have sensors for a very limited number of conditions, the fault diagnosis step is inevitable. Most methods used for detection can also be used for diagnosis, but the criteria used are different.

7.6.3. Evaluating Faults

After detecting and diagnosing a fault, we must evaluate the effect of the fault. Figure 2 identifies five types of impacts that might need to be evaluated. Impacts need to be evaluated to make operation decisions to stop, continue, or reconfigure the controls. For most hidden faults (faults that don’t cause comfort or safety issues), only three areas need to be considered for evaluation. Depending on the system affected, in some cases, only one of the areas may require evaluation. The evaluation criteria depend on the application and severity of the fault. For critical processes, safety is the primary evaluation criterion. For most building systems, however, comfort conditioning and the cost of operations are the primary criteria, although the productivity and health impacts from lack of proper ventilation should not be neglected. Safety and environmental issues can also play important roles for some building systems.

Fault evaluation is particularly important when the performance of a component is degrading slowly over time, such as a heat exchanger fouling (Rossi and Braun

1996). In this case, it is possible to detect and diagnose a fault well before it is severe enough to justify the expense of servicing it.

7.6.4. Choosing a Course of Action

Finally, after the fault has been detected, diagnosed, and evaluated, a course of remedial action must be chosen. The first step in the decision making process concerns whether to stop the system or send an alarm to shutdown the system if the fault is severe and the controls cannot be reconfigured to accommodate the fault. In some FDD applications, such as aeronautics and nuclear power plants where safety is critical, there is redundancy in controllers, actuators, and sensors. In such situations, corrective action can be taken to ensure continued safe operations using redundant fault free components. For example, if a failure of one of the sensors of a redundant pair of sensors is detected, then the supervisory system can reconfigure the controls such that the failed sensor is not used in making control decisions until it is replaced or repaired. This type of FDD system, which can enable corrective action to counteract the fault or make recommendations for altering the system operation, is referred to as a fault tolerant control system or an FDD supervisory system. In most cases, fault tolerant control applications reconfigure the programmable parts of the control loop such that the system operates in a fault free environment. In some cases, reconfiguration in the control loop may slightly degrade the reliability or the performance of the system. Operating the system in a degraded state, in some cases, is better than shutting down the system. However, in other cases, the system can operate without any degradation in performance. For example, if the FDD system detects a sensor bias, it can reconfigure the controls to compensate for the bias.

If the fault is not severe (i.e., it does not create a safety issue and will not damage the system or equipment) and the system controls cannot be reconfigured to accommodate the fault, the fault must be tolerated or a request for repair needs to be made. Unlike critical systems, most building systems do not pose immediate safety problems when operated with a fault; therefore, they are not designed with redundancy and extensive instrumentation. For building systems, if the cost impact is small compared to the cost of correcting the fault and occupants are unlikely to complain, the fault can be tolerated. However, if the cost impact is large, the FDD system should provide information encouraging correction of the problem along with information on the impact it has on the operations. Unfortunately, many faults in building systems are not corrected, even when costs are high, because building operators do not recognize them and occupants do not complain. Automated FDD systems can help remedy these problems.

7.7. Identifying Faulty Economizer Operation

As previously described, an automated continuous commissioning process involves four steps:

1 continuous monitoring and detection of abnormal operations, including detection of faults and degradation of performance;

2 confirmation of the presence of the fault and diagnosis of its cause;

3. evaluation of the impact of the abnormal operation; and
4. proactive reconfiguration of controls.

Identifying faulty economizer operation and demonstrating how the detection methodology could be integrated into an automated continuous commissioning procedure is presented in this section. The procedure also covers continuous commissioning of the overall ventilation for an air handling unit, including detection of simultaneous heating and cooling.

The procedure described in this section is based on an outdoor air economizer (OAE) diagnostic tool that detects and diagnoses faults with AHU and economizer operations. The OAE diagnostic tool is part of a larger tool developed by Pacific Northwest National Laboratory (Brambley et al. 1998; Katipamula et al. 1999) as part of the commercial buildings research program of the U.S. Department of Energy's Office of Building Technology, State and Community Programs. This tool detects and diagnoses faults, but does not perform proactive diagnostics. Therefore, a proactive diagnostic process has been developed and demonstrated in a prototype form as part of this project. In addition, a few new fault detection elements have been added.

The OAE tool works on constant volume and variable air volume systems that do not use volume compensation (i.e., outside air intake is a constant fraction of the supply air flow rate) and AHUs with or without economizer control. For systems with economizers, it detects problems with ventilation and economizer operations and latent faults such as simultaneous heating and cooling. For systems without economizers, the diagnostician detects only simultaneous heating and cooling.

7.7.1. OAE Capabilities

This section provides a brief overview of the OAE diagnostic tool. The OAE continuously monitors the performance of AHUs and can detect over 20 different basic operation problems or faults with outside air control and economizer operation. It, however, does not detect problems with the water-side or the refrigerant side of the AHU; it only detects problems on the air side, i.e., economizer operation and ventilation. As part of his project, the capabilities of the OAE were extended to detect additional faults including some water-side faults.

Supported Economizer Controls

The economizer control strategies that are supported by the OAE tool include: differential dry bulb temperature based, differential enthalpy based, high limit dry bulb temperature based, and high limit enthalpy based.

With differential control strategies, the outside air condition is compared with the return air condition. As long as the outside air condition is more favorable (for example, with dry bulb temperature control, the outside air dry bulb temperature is less than the return air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

With high limit control strategies, the outside air condition is compared to a single or fixed setpoint (usually referred to as a high limit). If the outside air condition is below the setpoint, then outside air is used to meet all or part of the cooling demand; any remaining unmet cooling load is provided by mechanical cooling.

In addition to these economizer control strategies, the OAE supports fault detection with both integrated and nonintegrated economizers. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building's cooling requirements if outdoor conditions allow, or it can supplement the mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor air intake rates between minimum and maximum levels.

Conversely a non-integrated economizer does not operate when the mechanical cooling system is operating. If outdoor conditions are not sufficiently favorable to allow 100% economizing, no economizing is used. A two-stage thermostat often controls a non-integrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

Supported Systems

The OAE tool supports the following types of air handlers:

1. Constant air volume systems.
2. Variable air volume (VAV) systems with no volume compensation (i.e., outside air intake is a constant fraction of the supply air flow rate).[2]

The OAE is not able to detect problems reliably with VAV systems that meter outdoor air flow rate.

Problems Identifiable by the OAE

As with any mechanical system, faults can occur that diminish or eliminate an economizer's usefulness. However, unlike the primary (mechanical) cooling system, a failure of the economizer may go completely unnoticed. Any failure, for example, that prevents outdoor air from being used for cooling when outdoor conditions are favorable, may go unnoticed because the mechanical cooling system will pick up the load and the occupants do not experience any discomfort. Similarly, a failure that results in too much outdoor air may not be apparent in a reheat system since the air supplied to the space is tempered before it is discharged into the space. In both of these examples, however, the system would be using more energy (and costing more to operate) than necessary.

The OAE is designed to monitor conditions of the system not normally experienced by occupants. The common types of outdoor air ventilation and economizer problems handled by the module include stuck outdoor air dampers, failures of temperature and humidity sensors, economizer and ventilation controller failures, supply air controller problems, and air flow restrictions that cause unanticipated

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[2] This is not the most desirable use of VAV, but it is commonly found in the field as an intended operation mode.

changes in overall system circulation. The diagnostician also performs some self diagnosis to identify errors introduced by users in setup and configuration of the software.

At a high level, the faults that can be identified by the OAE module can be grouped into four categories: 1) inadequate ventilation; 2) energy waste; 3) temperature sensor and other miscellaneous problems; and, 4) missing or out of range inputs. These four categories can be further expanded as follows:

1. Outdoor air ventilation problems
    a. no ventilation is being supplied
    b. ventilation is inadequate
2. Energy use is high
    a. too much ventilation during cooling mode
    b. too much ventilation during heating mode
    c. economizer should not be operating
    d. economizer should not be at full flow
    e. economizer operation may be detrimental
    f. economizer should not be off
    g. economizer should not be at part flow
    h. economizer is not throttling to maintain supply air temperature
    i. mechanical cooling should not be off
    j. simultaneous heating and cooling
3. Temperature sensor and other problems
    a. mechanical cooling should not be on
    b. ventilation air flow is less than the minimum required
    c. ventilation air flow is greater than maximum needed
    d. temperature sensor problem

OAE Data Requirements

The OAE algorithm presented in this report is capable of detecting and diagnosing faults with most commonly found AHUs using almost all economizer control strategies. The set-up data required for all AHU systems with economizers includes:

- description of the basic air handling system;
- minimum, maximum, and design (fully occupied) outdoor air fractions;
- operating and occupancy schedule to identify when peak outdoor air must be supplied; and,
- data needed to estimate energy and cost impacts of problems.

In addition to the set-up data, the OAE only requires seven periodically measured data points (shown in Figure 3 with bold labels). In addition to the seven variables, damper position is also required for AHUs with damper position control, i.e., if the damper position is controlled to maintain the indoor ventilation or to control supply or mixed air temperature when the AHU is economizing. For economizers with enthalpy based control, outside and return air (only for differential enthalpy control) relative humidity or dew point temperatures are required. If the supply or mixed air temperature setpoint is reset, then the reset value at each hour is also needed. The methodology has been developed to maximize detection and diagnosis of faults with a minimum number of measured data points. The sensors required to collect all the measured data points are generally installed for controlling the operations of the AHU, the only exception being the mixed air temperature.

7.7.2. OAE Diagnostic Methodology

The OAE uses a logic tree to discern the operational "state" of outdoor air ventilation and economizer systems at each point in time for which measured data are available. The logic is based on the engineering principles that drive the basic operating sequence of the AHU as described below.

Basic Operating Sequence of an AHU

An AHU typically has two main controllers: 1) to control the outdoor air intake, and 2) to control the supply air temperature (in some case mixed air temperature is controlled rather than supply air temperature). The basic operation of the AHU is to draw in outdoor air and mix it with return air from the zones and, when necessary, condition it before supplying the air back to the zone as shown in Figure 3.

An AHU typically has four primary modes of operation during occupied periods for maintaining ventilation (fresh air intake) and comfort (the supply air temperature at the setpoint) as shown in Figure 4. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

When the indoor conditions call for heating, the heating coil valve is modulated (i.e., controlled) to maintain the supply air temperature at its setpoint (heating mode in Figure 4). When the AHU is in the heating mode, the cooling coil valve is fully closed and the outdoor air damper is positioned to provide the minimum outdoor air that would satisfy the ventilation requirements. As heat gains increase on the zone and the zone calls for cooling, the AHU transitions from heating to cooling. Before mechanical cooling is provided, the outdoor air dampers are opened fully to use the favorable outdoor conditions to provide 100% cooling (Economizing mode in Figure 4). In this mode, the heating and cooling coil valves are fully closed and the outdoor air dampers are modulated to meet all the cooling requirements.

As the heat gains on the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the AHU changes modes by initiating mechanical cooling (Cooling and Economizing mode in Figure 4) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating coil valve is fully closed, and the cooling coil valve is modulated to maintain the supply air temperature. As the outdoor conditions become unfavorable for economizing, the AHU changes mode again. This time the outdoor air dampers are modulated to the minimum position to provide the minimum amount of outdoor air necessary to satisfy the outdoor air ventilation requirements. The heating coil valve continues to be fully closed, and the cooling coil valve is modulated to maintain the supply air temperature at its setpoint.

If an AHU does not have an economizer, then there are two basic modes of operation (Heating and Mechanical Cooling). If the economizer is not integrated with the mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), then there are three basic modes of operation (Heating, Economizing, and Mechanical Cooling).

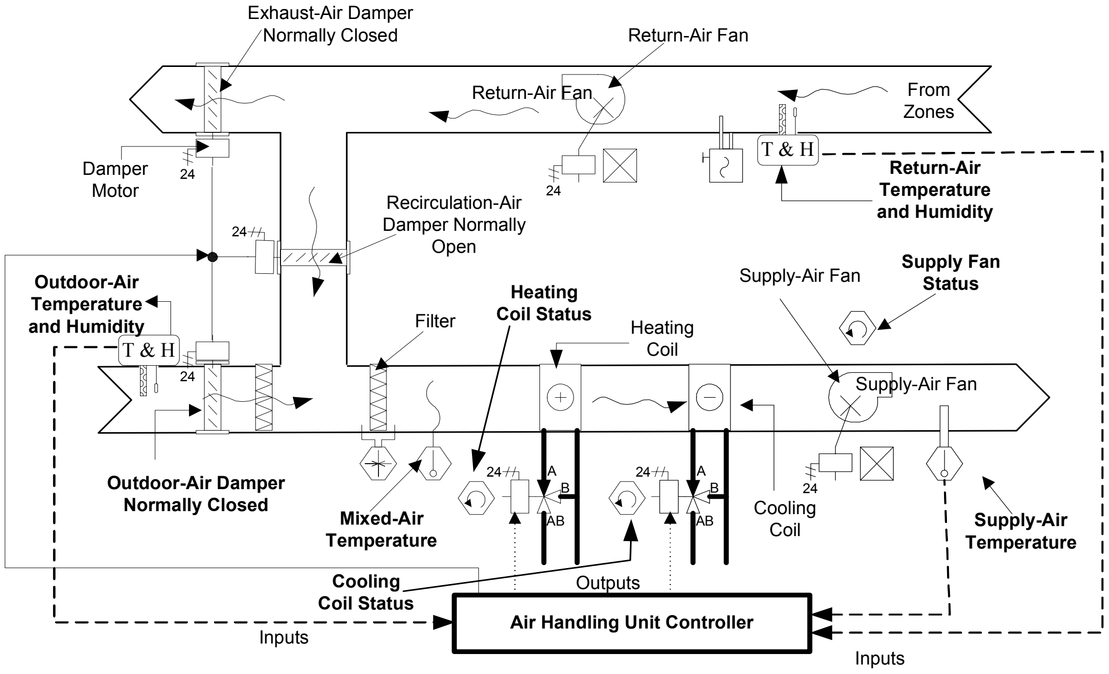

Figure 3: Schematic of a typical air handling unit with sensors and controllers

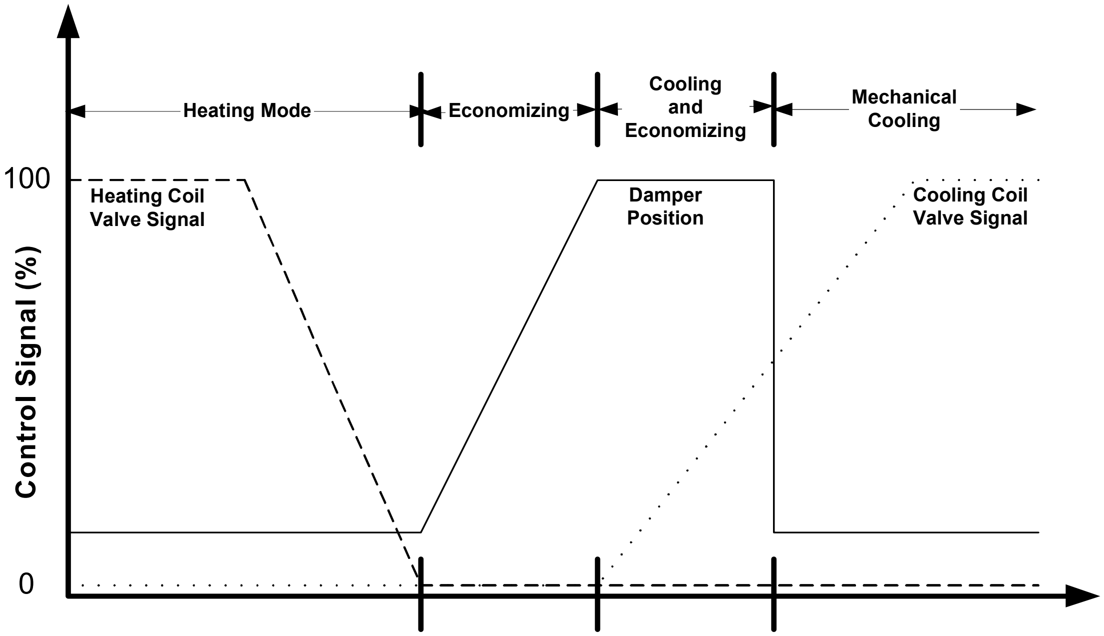

Figure 4: Basic operating sequence of an air handling unit

Implementing the Methodology

The methodology uses basic rules derived from the basic operating sequences described in the previous section. The rules are implemented in a decision tree structure. The OAE uses periodically measured conditions (temperature or enthalpy) of the various airflow streams, measured outdoor conditions, and equipment status information to navigate the decision tree and reach conclusions regarding the operating state of the AHU. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the operational state of the AHU when the end of a branch is reached.

Many of the states correspond to normal operation and are dubbed “OK states.” For example, one OK state is described as “ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate.” Other states correspond to something operationally wrong with the system and are referred to as “problem states.” An example problem state might be described as “economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate.” Other states (both OK and problem) may be tagged as incomplete diagnoses, if sufficient measured information is not available; this can sometimes occur if a sensor measurement is somehow lost temporarily.

Each problem state known to the OAE has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor air damper, an economizer controller failure, or perhaps a misconfigured setup could cause the economizer to be disabled when it should be enabled. Thus, at each metered time period, a list of possible causes is generated.

7.7.3. Diagnostic Process

The process of detecting and diagnosing faults (i.e., problems) with the AHU is divided into two sub-processes. A single state or instantaneous diagnosis is performed by analyzing the operating state of the system using measured data from a single time period. The single state diagnosis uses diagnostic reasoning to: determine the state of the ventilation air and economizer system; identify possible failures that could have caused the state if it is a problem; identify impossible failures given the state; provide a list of conditions that led to the diagnosis; and estimate the energy and cost impacts of any problems detected.

The second process performs diagnostics using data and single state diagnostic results for multiple time periods. In addition to these two sub-processes, we developed an enhanced methodology to further isolate the cause of certain faults by exercising proactive diagnostic procedures.

7.7.4. Single State Diagnostic Process

The first level diagnostics for an AHU system are performed by using data from a single measurement period to:

1. identify the state the system is in and determine whether that is a problem or not;
2. list possible failures that could cause the state if it is a problem;
3. list impossible failures that could not exist given the state of the system; and
4. provide an explanation of the diagnostic reasoning used to infer the state.

An overview of the process that the OAE uses to conduct the single state diagnosis is provided in Figure 5. The full details of the algorithm, or the decision tree, are provided in Figure 7 through Figure 17, which augment each process (box) or test (diamond) in Figure 5.

After analyzing the data from a measurement period, a state is identified by the single state diagnosis process. A state is a description of the operating condition of the AHU. Every state includes (at least) whether the outdoor air being supplied is adequate for the current occupancy level and whether the economizer operation (or lack thereof) is correct for the current conditions. It also includes the operational status of the system (e.g., "the outdoor airflow indicates that the economizer system is fully open"). The diagnostic process is complete when the state of the system is as fully defined as possible, and processing then continues with data from the next time step when it becomes available.

States are classified as either problems or OK states. OK states are states of operation in which the single state diagnostic module finds no operational problems, given the current conditions. For example: "the system is supplying the required outdoor air and the economizer is (correctly) not operating." Problem states are states in which some function of the system appears to be operating incorrectly, given the current conditions. Problem states include a description of the problem. For example: "the system is not supplying the required outdoor air."

The single state diagnostic process is sequential. It terminates when it determines that the AHU is properly operating or when it finds the first problem. Although the process can be modified to track multiple problems simultaneously, the computational overhead to implement such a process is certainly higher than a sequential process. The flow charts and the discussion presented in this report assume that there is a single predominant fault, unless otherwise mentioned. While it is likely that in reality the AHU could have multiple simultaneous faults, the process that is outlined does not fail. If the AHU has multiple problems, the process only identifies the first predominant problem encountered. However, if the first problem is corrected and new data are then analyzed, the process will identify the next predominant problem encountered. Identifying faults sequentially may take slightly longer time, but is still better than letting the AHU operate inefficiently or in faulty condition.

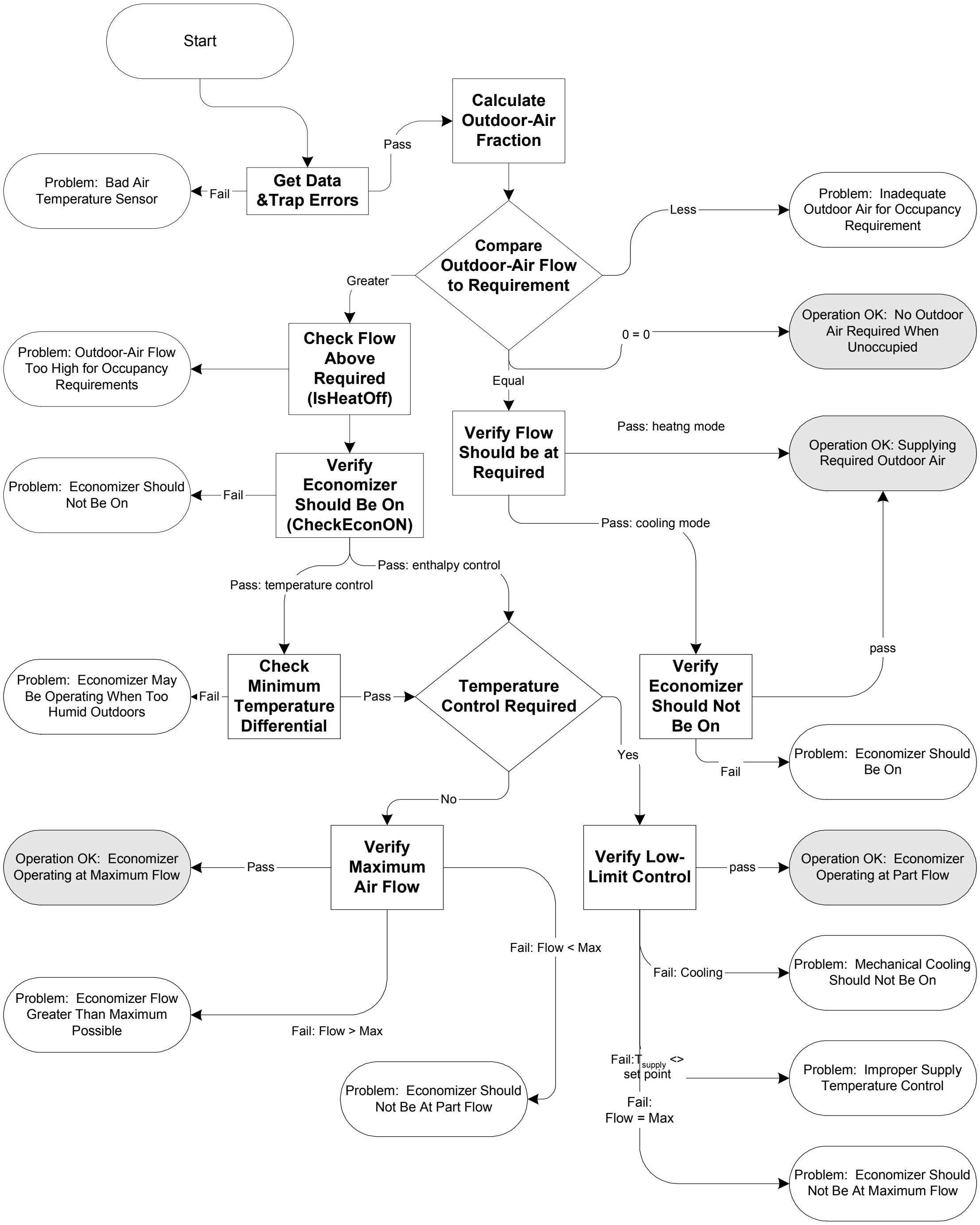

Figure 5: Overview of the continuous commissioning process for an AHU (including economizer and ventilation operations)

7.7.5. Sensitivity versus False Alarm

The rule based methodology relies on comparisons between the values of variables to traverse the decision tree. These comparisons must account for both random noise and measurement uncertainty. In addition, the measured data may also have systematic bias (i.e., be consistently high or low relative to the true value of the variable). The comparison methodology must account for these uncertainties to ensure reasonable levels of confidence in the decisions.

This is accomplished in the OAE software by using specified tolerances for each measured and static input variable. These tolerances are used in all calculations and tests.

The uncertainty of the difference between two measured variables is equal to the sum of the tolerances for each of the two variables. For example, to test whether the outdoor air temperature (T_{out}) is equal to the return air temperature (T_{ret}), assuming that tolerances of ± 0.5°F have been assigned to both variables, ($T_{out}=T_{ret}$) should be considered true only if $|(T_{out} - T_{ret})| \leq (0.5+0.5)$. Similarly, ($T_{out} > T_{ret}$) should be considered true only if T_{out} is greater than T_{ret} by more than (0.5+0.5).

The tolerances assigned to each variable should, at a minimum, account for the measurement uncertainty (or inaccuracy) specified by the sensor manufacturer. For example, a typical commercial grade temperature sensor is accurate to about ±0.5°F to ±1°F.

Similarly, the uncertainty associated with other algebraic combinations of measured variables and tests can be evaluated using standard formulas for propagating errors in calculations (see, for example, Croarken and Tobias (2002)).

By specifying tolerances and propagating them through the comparisons in the decision tree, the level of sensitivity for fault detection and the occurrence of false alarms can be controlled. However, there will always be a trade off between increased detection sensitivity and increased occurrence of false alarms.

Although in this report the comparison tests in the decision tree are shown as simple comparisons, actual implementation requires inclusion of tolerances in each comparison. (In Section 7.10 we discuss selection of tolerances, uncertainty thresholds, and criteria for proactive diagnostics.)

7.7.6. Details of the OAE Decision Tree

In this section we discuss and illustrate the rules derived from engineering models of proper and improper AHU operations. The discussion is limited to the AHU operations and does not include the range and the limit checks for the measured variables and the static inputs (such as setpoints). These checks are essential in any analysis, but the techniques used to implement these options are well known and understood and, therefore, will not be discussed in this report. Also, although data acquisition is a critical element in automated continuous commissioning, we do not discuss it in this section, but rather in Section 7.13.3, *Data Requirements*.

The key symbols used in describing the details of the logic tree are shown in Figure 6. An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 5. The boxes represent major sub-processes necessary to determine the operating state of the air handler. Diamonds represent tests (decisions). Ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview.

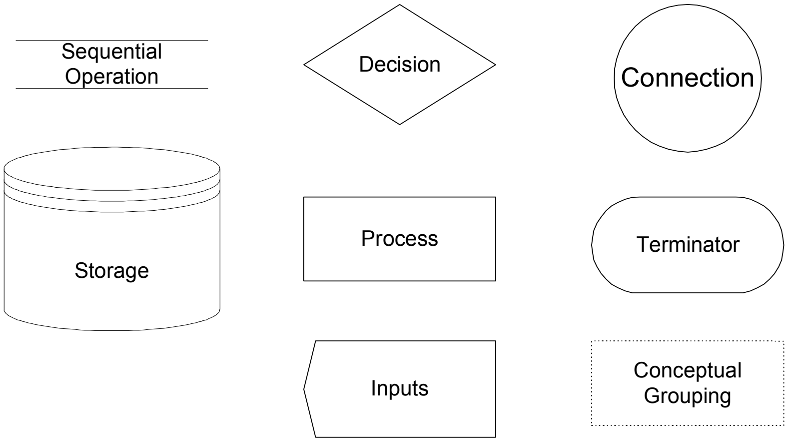

Figure 6: Key to the flowchart symbols

The first step in an automated continuous commissioning process is to make sure that the data are valid. This process is shown in Figure 7 as "Get Data & Trap Errors." The details of checking the critical control temperature sensors (outdoor , return and mixed air) are shown in Figure 7. The mixed air is, as the name implies, a mixture of the outdoor and return air streams; therefore, the value of the mixed air temperature can never be higher or lower than both the outdoor and return air temperatures (within the tolerances of the sensors).

If a temperature problem is detected and the outdoor air fraction is used to control the outdoor air dampers then no further diagnostics of the AHU operation are possible. Diagnoses based on faulty temperature measurements would be faulty themselves. However, if the damper position is directly controlled to maintain the outdoor air flow, then the diagnostics can be continued further, although on a limited basis. The process outlined in Figure 7 is passive and, because it lacks physical redundancy, is incapable of pinpointing which of the three sensors is faulty. A proactive diagnostic method has been developed to extend the passive diagnostic methodology presented in Figure 7. This process is described in Section 7.8, *Proactive Diagnostic Process*.

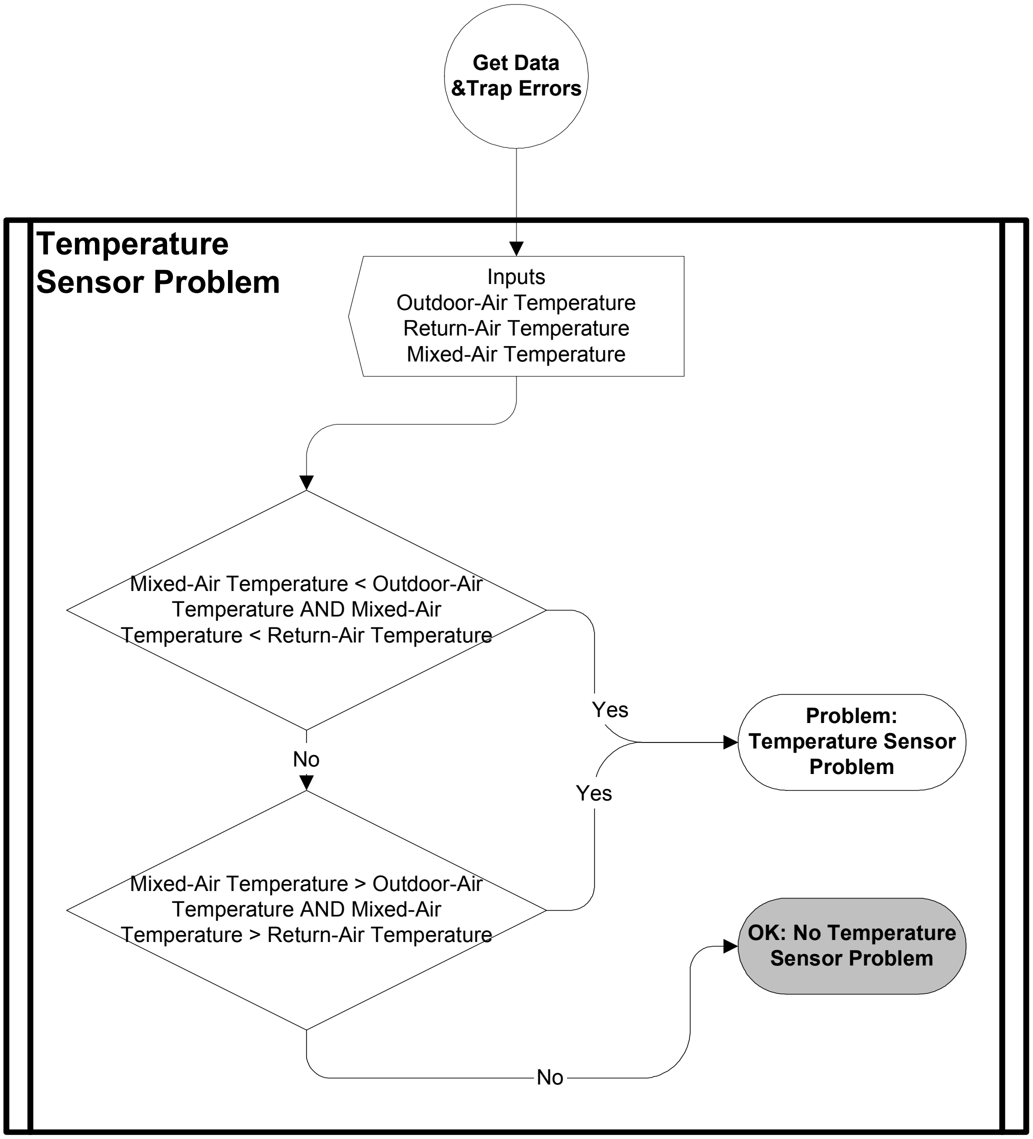

Figure 7: Decision tree to identify temperature sensor problems associated with the measurement of outdoor , return , and mixed air temperatures

The next step in the diagnostic process is to identify the state of the AHU and verify that it is as expected (Figure 4) by comparing the actual outdoor air flow rate to the required and the minimum rates as shown in Figure 8. The comparison variable, outdoor air, can be either the damper position (which is the case in the vast majority of AHUs in the field) or the outdoor air flow rate (OAF). The required outdoor air is the damper setting, or the OAF, that would satisfy the ventilation requirements for the current occupancy. Because the occupancy can change from hour-to-hour, the required outdoor air can also be different for each hour. The minimum outdoor air is either the minimum position to which the outdoor air damper can modulate or the OAF at the minimum outdoor air damper position.

The five possible outcomes for the series of tests shown in Figure 8 are:

1. the supply fan is OFF and no ventilation is required;
2. the supply fan is OFF but ventilation is less than required;
3. the supply fan is ON but ventilation is less than required;
4. the supply fan in ON and ventilation is greater than required; and
5. the supply fan in ON and ventilation is equal to that required.

The first three of these outcomes are problems and the diagnostic processing stops for this record (time step), and then the next record (i.e., the next set of inputs) is processed. The other outcomes are discussed in sections entitled *Outdoor Air is Greater Than Required* and *Outdoor Air is Equal To Required*.

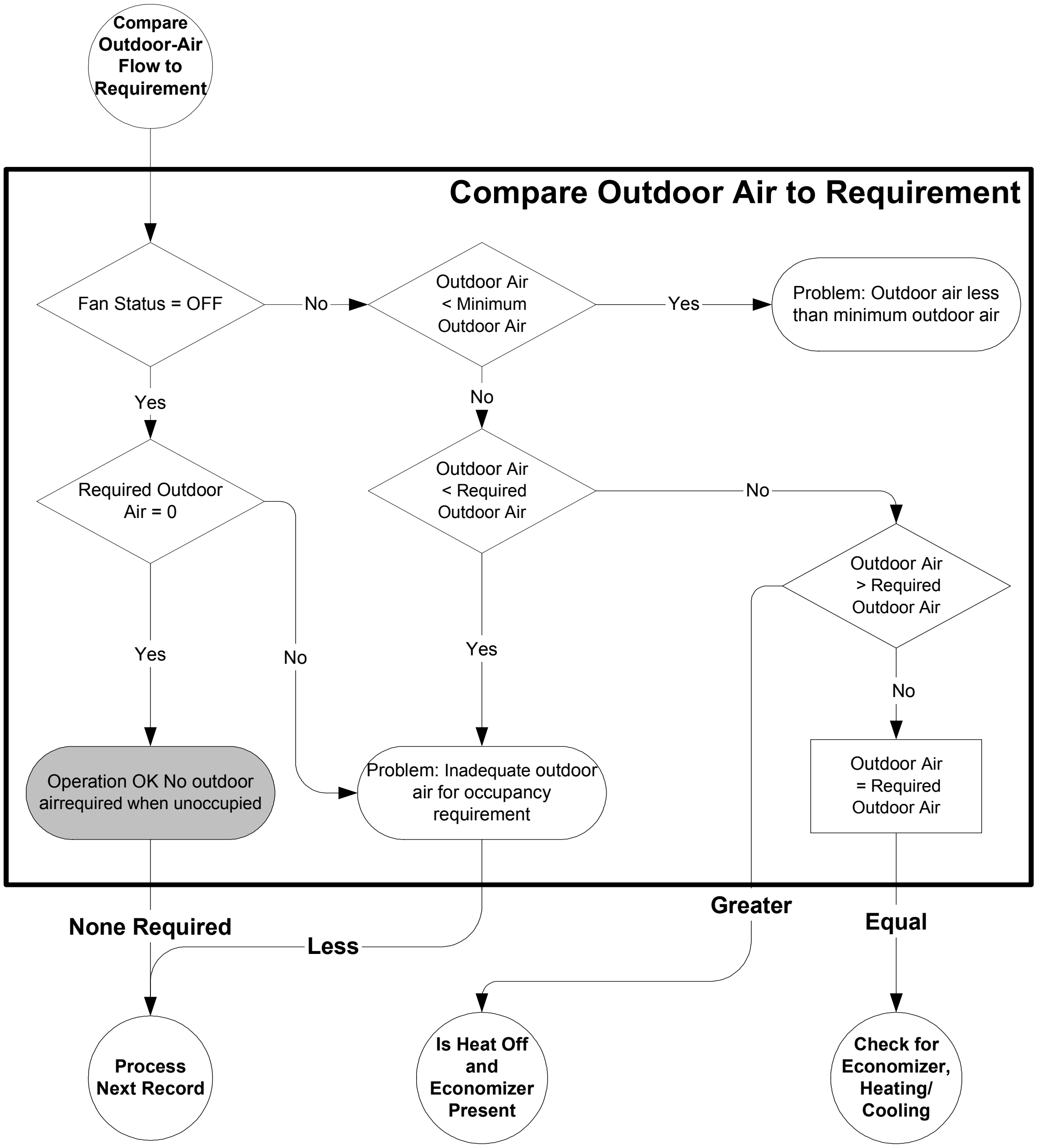

Figure 8: Decision tree to compare the actual outdoor air to the required outdoor air

Outdoor Air is Greater Than Required

If the supply fan is ON and the ventilation is greater than required, the proper states for the AHU are: 1) economizer mode, or 2) economizer with mechanical cooling, as shown in Figure 4. When the AHU is in these states, heating cannot be ON, but cooling can be ON depending on the indoor and outdoor conditions.

The rules governing these states are shown in Figure 9. There are five possible outcomes for the series of tests:

1. the damper position is greater than required, but the OAF is less than required;
2. simultaneous heating and cooling are occurring;

3. there is no economizer, cooling is ON, and the outdoor air is greater than that required;
4. heating is ON and the outdoor air is greater than required; and
5. heating is OFF and outdoor air is greater than required.

Outcomes 1 through 4 are problems. Outcome 5 requires a test of the economizer operation as shown in Figure 10.

There are three outcomes of the series of tests in Figure 10:

1. the outdoor conditions are not favorable for economizing;
2. the outdoor and indoor conditions are nearly equal (within the dead band of economizer operation); and
3. the outdoor conditions are favorable for economizing.

Clearly, outcome “1” is a problem and outcome “3” requires further diagnosis, which is provided in Figure 11.

At this stage, we have verified that the outdoor air intake is greater than the required level, heating is OFF, and the economizer should be ON. The decision tree shown in Figure 11 compares the expected mixed air temperature when the outdoor air damper is fully open to the supply air setpoint temperature. If the expected mixed air temperature is less than the setpoint, then the outdoor air damper position should be throttled to part flow; if not, it should be wide open.

The next step is to verify that the economizer is at the maximum flow (Figure 12) or the outdoor air dampers are fully open. The outcomes of this test are:

1. the economizer flow rate is greater than the maximum flow rate (this condition should not occur unless there is sensor problem or configuration problem);
2. the economizer should not be at part flow;
3. the outdoor air damper position appears to be OK, but the outdoor air fraction is greater than its maximum;
4. the outdoor air damper position appears to be OK, but the OAF shows that the flow is less than its maximum;
5. the damper position is OK; and
6. the OAF is OK.

These outcomes correspond to one of the two end points of the “greater than” tree structure. Outcomes “1” through “4” are problem states.

The next step is to verify that the outdoor air intake is not at the maximum flow and the cooling is not ON (Figure 13). The possible outcomes of this test are:

1. outdoor air intake is greater than its maximum (this condition will only occur if there is a sensor problem or configuration problem);
2. outdoor air intake is equal to the maximum flow;

3 cooling is ON when the outdoor conditions are sufficient to maintain the supply air temperature setpoint; and

4 cooling is OFF, check if the economizer can maintain the supply air setpoint.

Clearly, outcomes "1" through "3" are problem states and outcome "4" needs further testing.

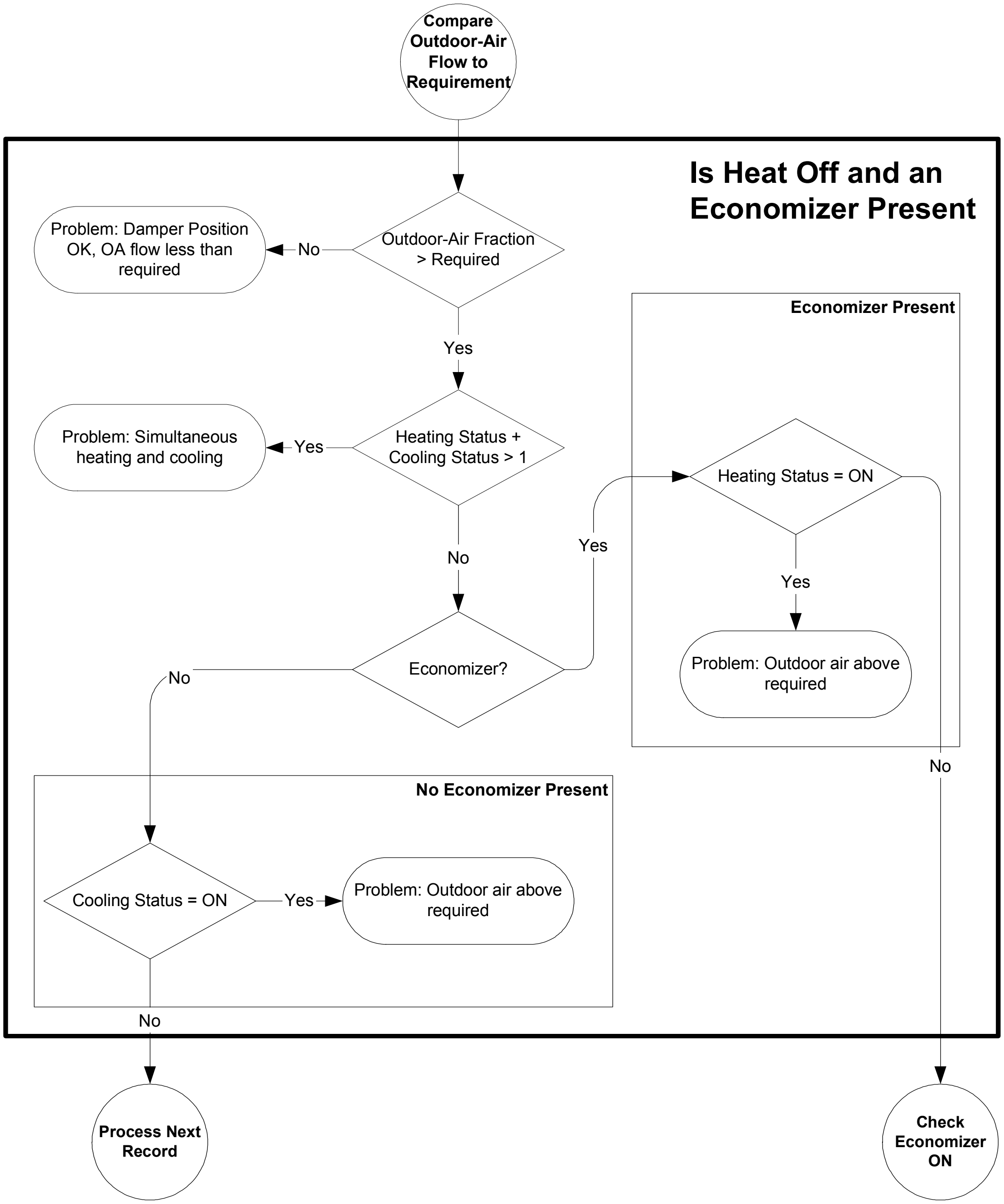

Figure 9: Decision tree to check if heating is OFF and an economizer is present

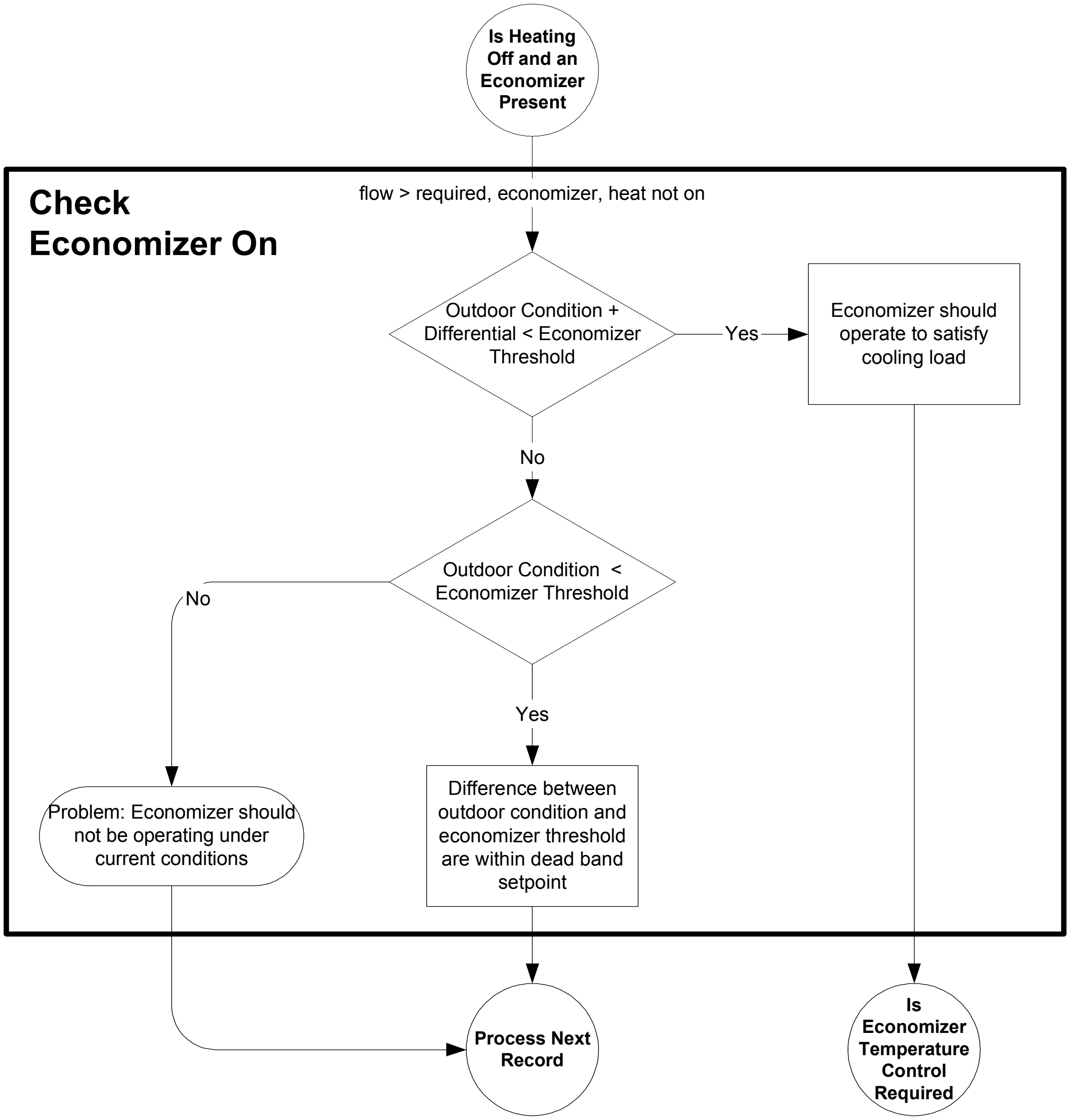

Figure 10: Decision tree to check if the economizer should be ON

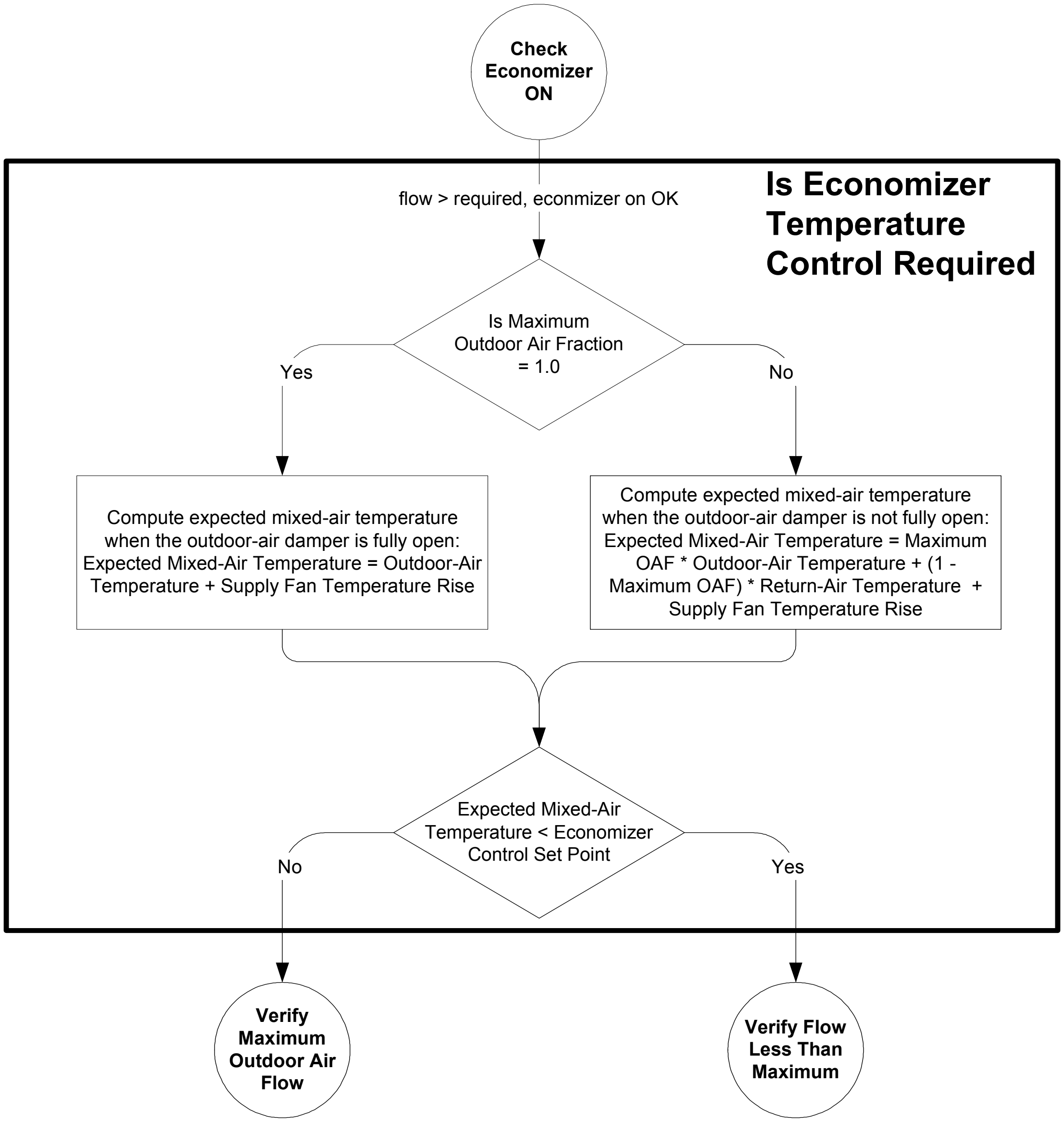

Figure 11: Decision tree to verify whether the economizer should be at part flow or maximum flow

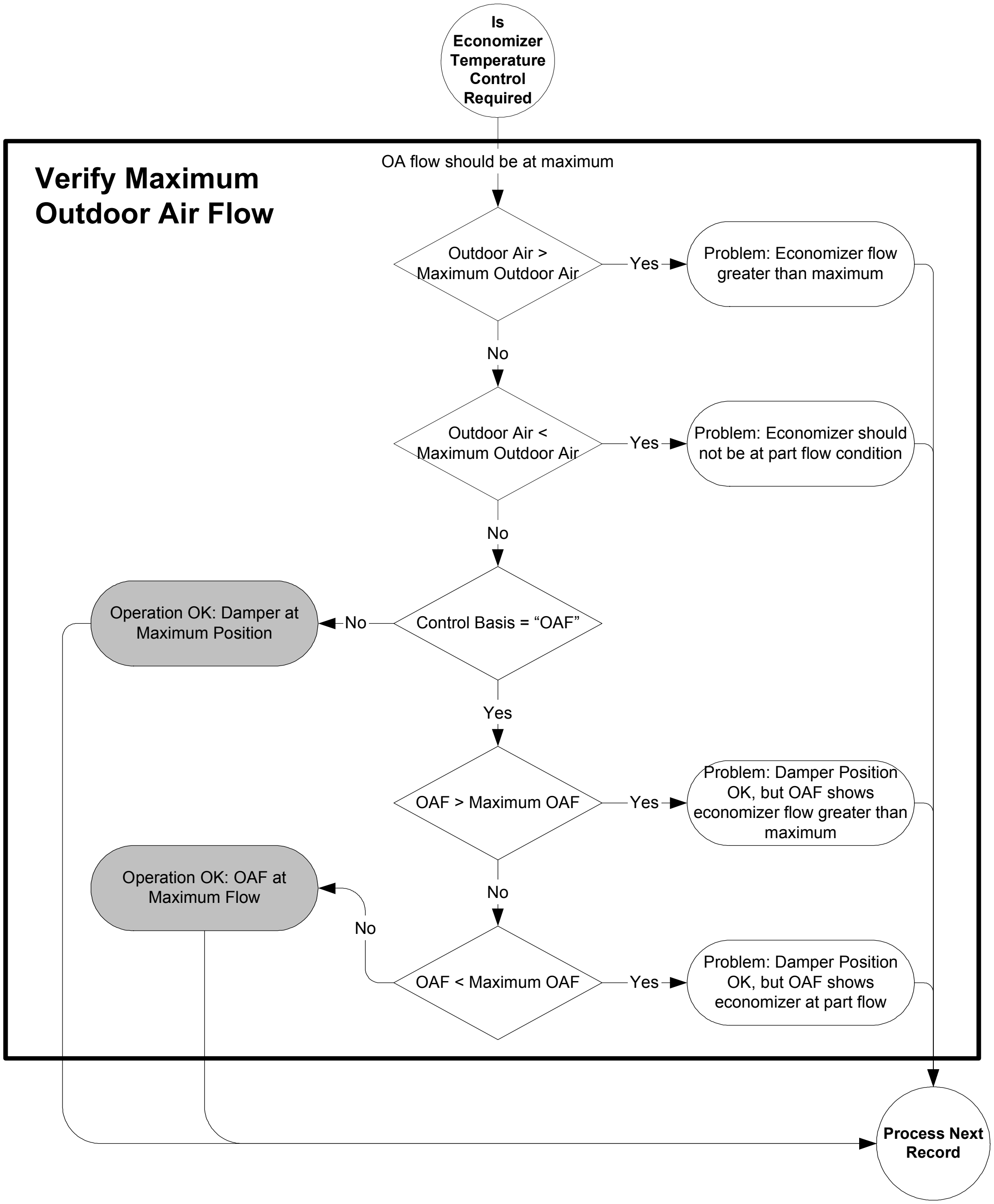

Figure 12: Decision tree to verify that the economizer should be at maximum flow (outdoor air dampers fully open)

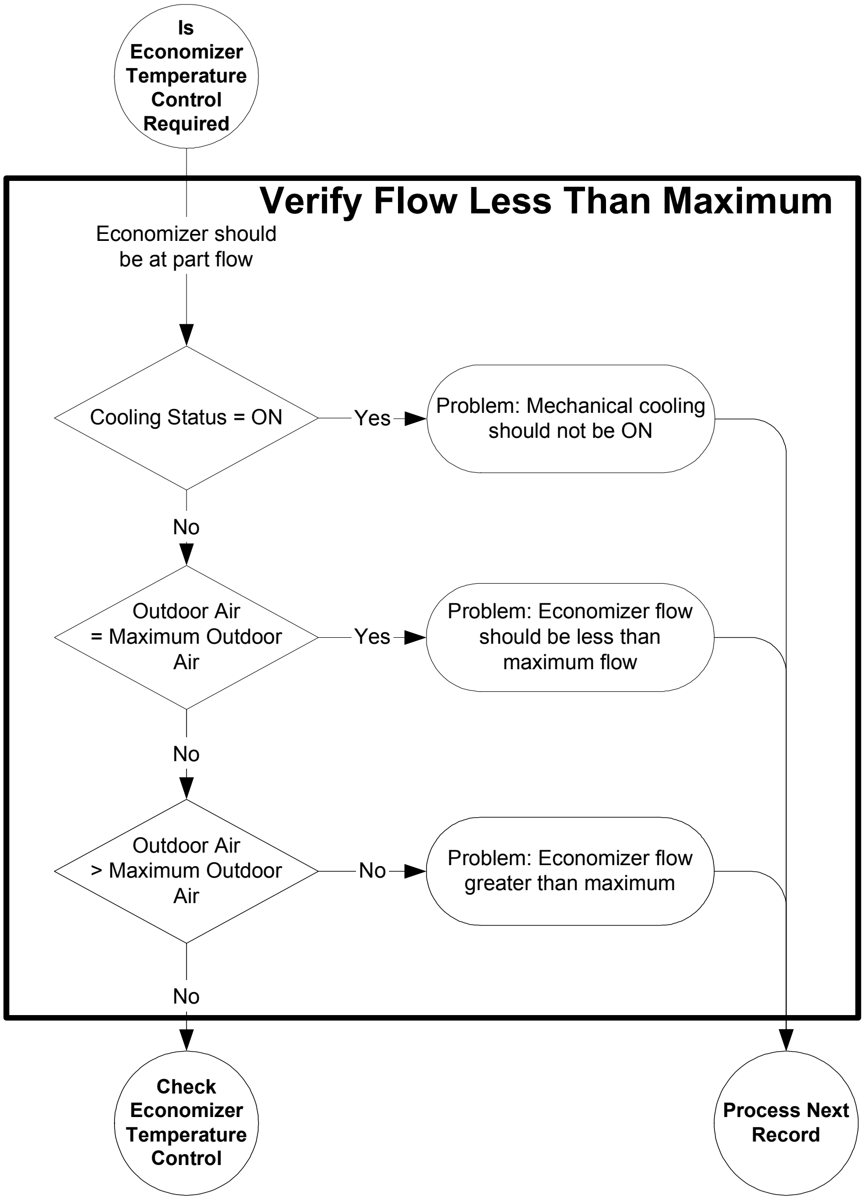

Figure 13: Decision tree to verify that the economizer should be at part flow

The last step is to verify that the economizer can maintain the supply air temperature setpoint (or the difference between the supply air and supply air setpoint is within the dead band) as shown in Figure 14. The outcomes of this test are:

1. mechanical cooling should be ON;
2. the temperature controller is not working properly; and
3. the outdoor air dampers are properly throttled to maintain the required supply air setpoint temperature.

Outcomes 1 and 2 are problem states. This is the second end point of the "greater than" tree structure (see Figure 8).

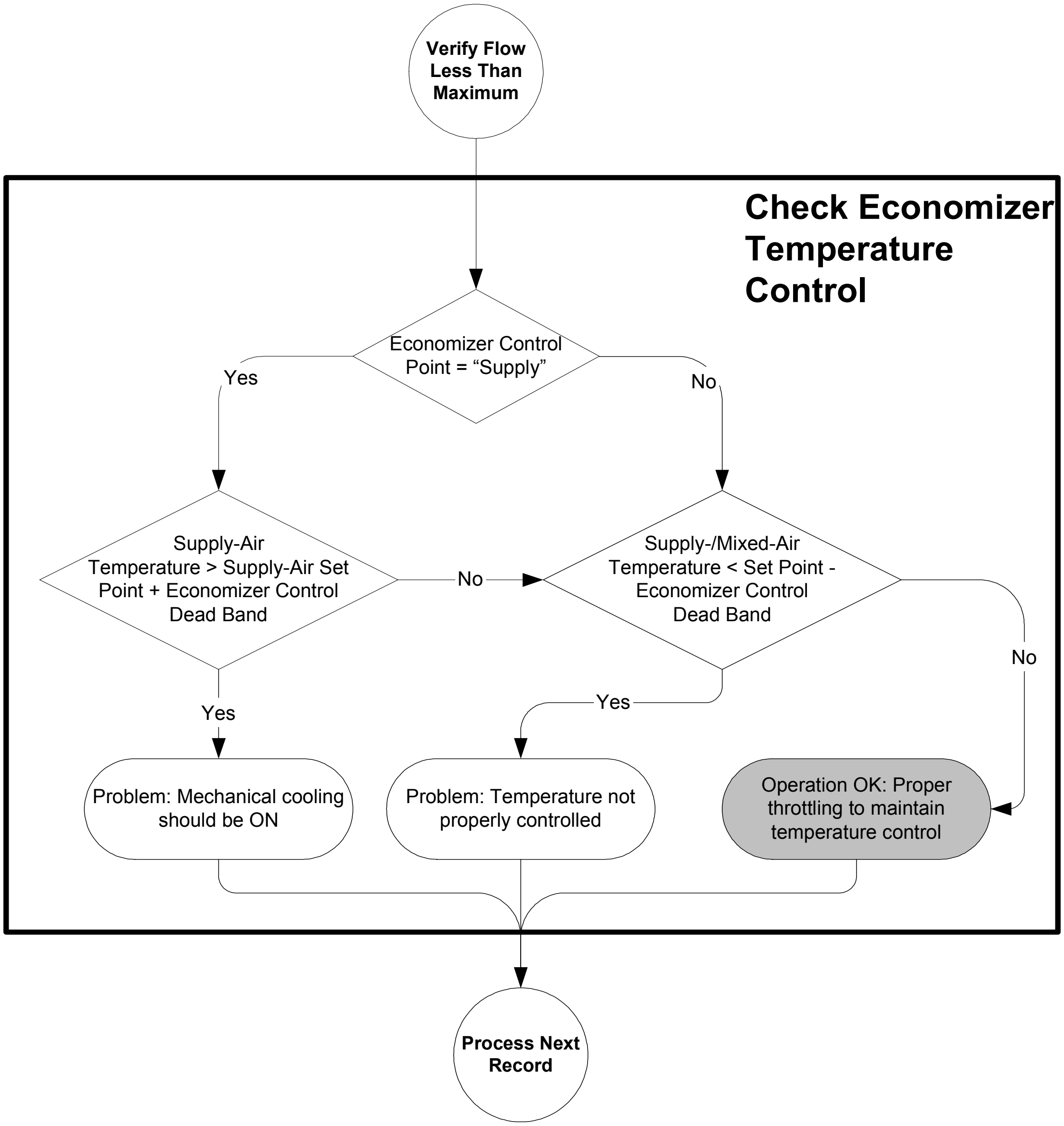

Figure 14: Decision tree to check whether the economizer temperature controls are properly functioning

Outdoor Air is Equal To Required

If the supply fan in ON and the damper is positioned to provided the minimum required ventilation, the proper states of the AHU are "Heating Mode" or "Mechanical Cooling Mode" as shown in Figure 4. If the AHU is in any other state, it is considered to be operating improperly. So, the first step in this part of the decision tree is to verify that no simultaneous heating and cooling is occurring and only heating is ON or cooling is ON (Figure 15).

The possible outcomes of this test are:

1. the damper is positioned properly, but the OAF is less than that required;
2. simultaneous heating and cooling is occurring; and
3. either heating or cooling are ON.

Outcomes "1" and "2" are problem states, while outcome "3" requires additional tests as shown in Figure 16.

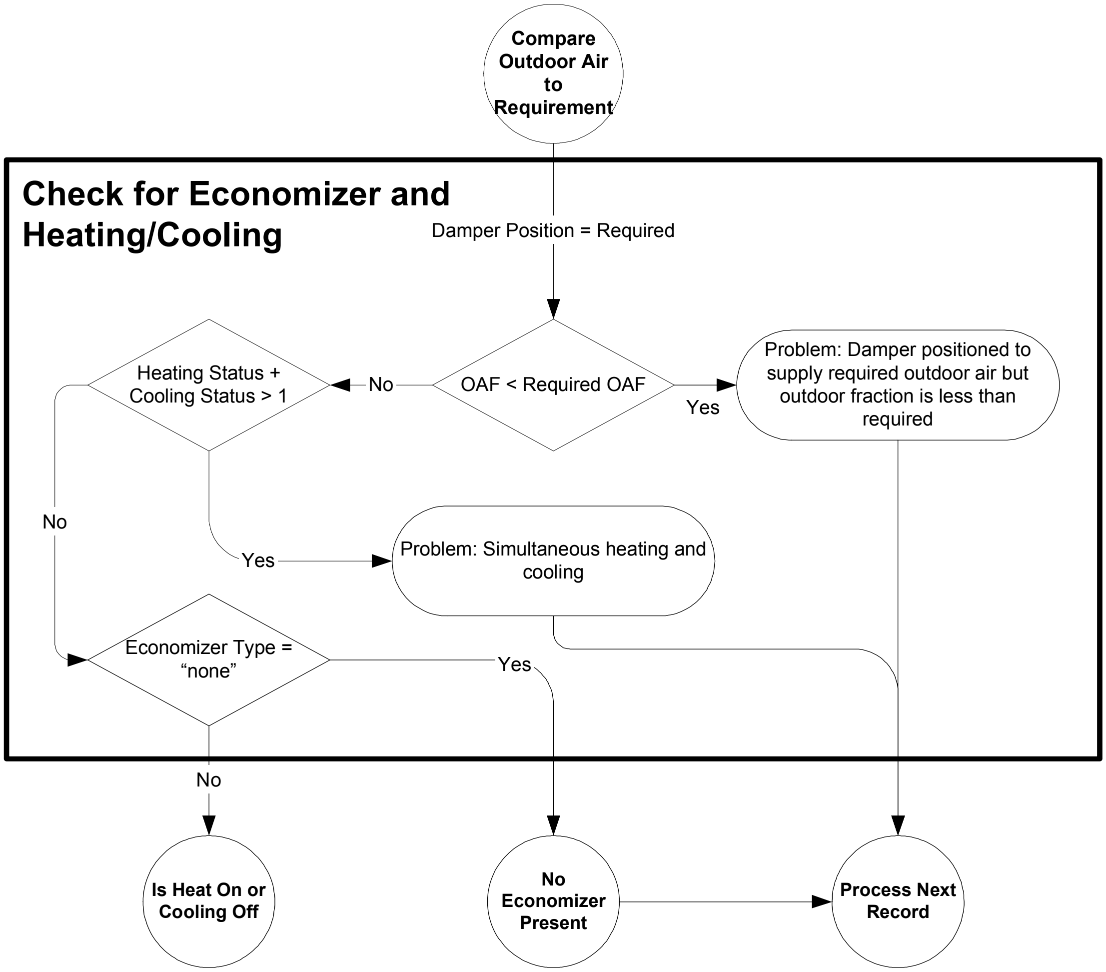

Figure 15: Decision tree to check economizer and heating and cooling operations

The next step is to check that heating is ON and cooling is OFF (Figure 16). The possible outcomes of this test are:

1. heating is ON and ventilation is at the required level;
2. the damper position is at the required position, but the OAF is greater than required; and
3. cooling is ON.

Outcome 2 is a problem, and outcome 3 will need additional tests as shown in Figure 17.

If cooling is ON and the damper position is at the minimum position required to satisfy the ventilation requirement, the outdoor conditions should be unfavorable for economizing (Figure 17). The possible outcomes of this test are:

1. the outdoor conditions are favorable for economizing, so outdoor air should be used to satisfy the cooling load;
2. the difference between the outdoor and the indoor conditions is within the economizer dead band;
3. the damper position is OK, but the OAF is greater than required; and
4. the economizer is OFF correctly, because the outdoor conditions are not favorable for economizing.

The outcome "1" and "3" are problem states. This is the end point of the "equal to" tree structure.

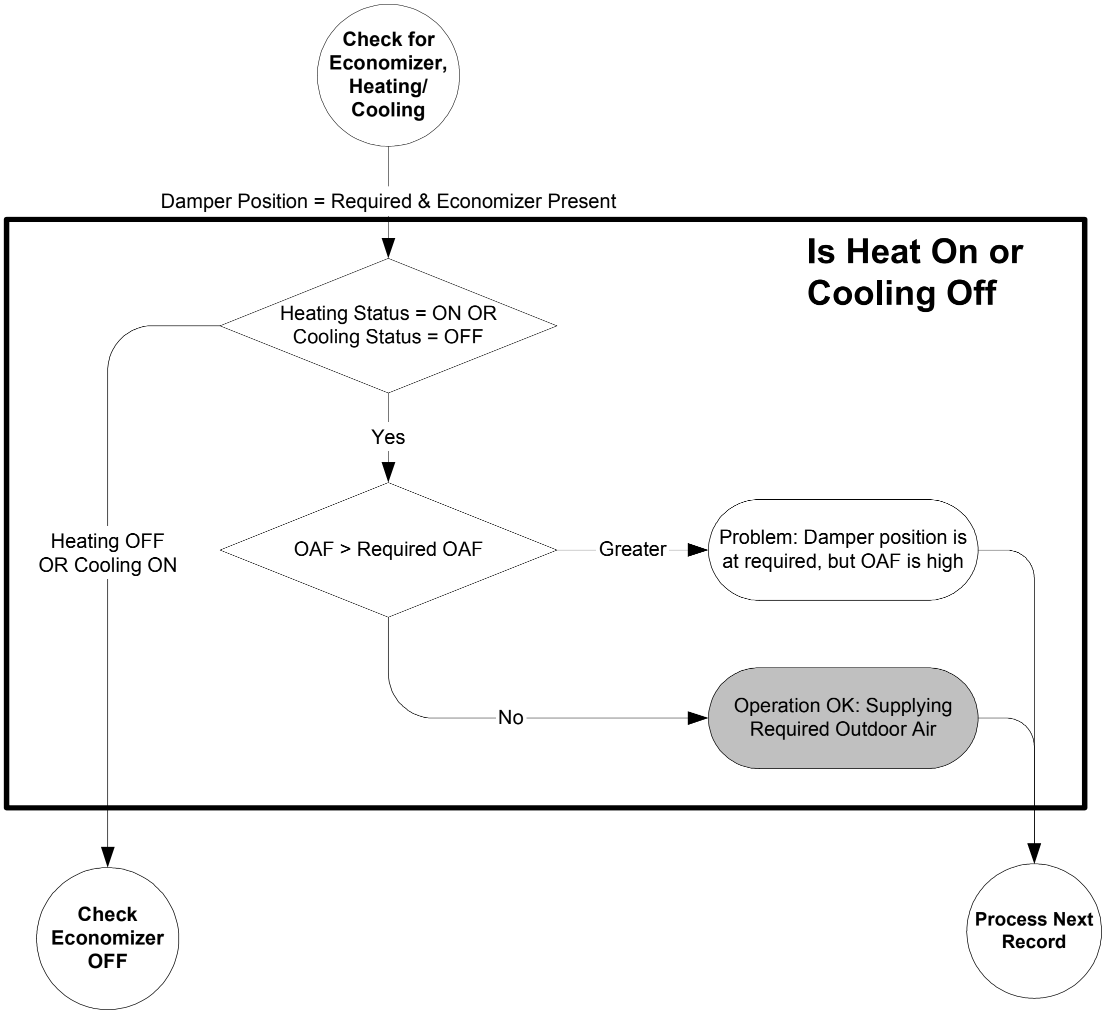

Figure 16: Decision Tree to Check Whether Heating is ON and Cooling is OFF

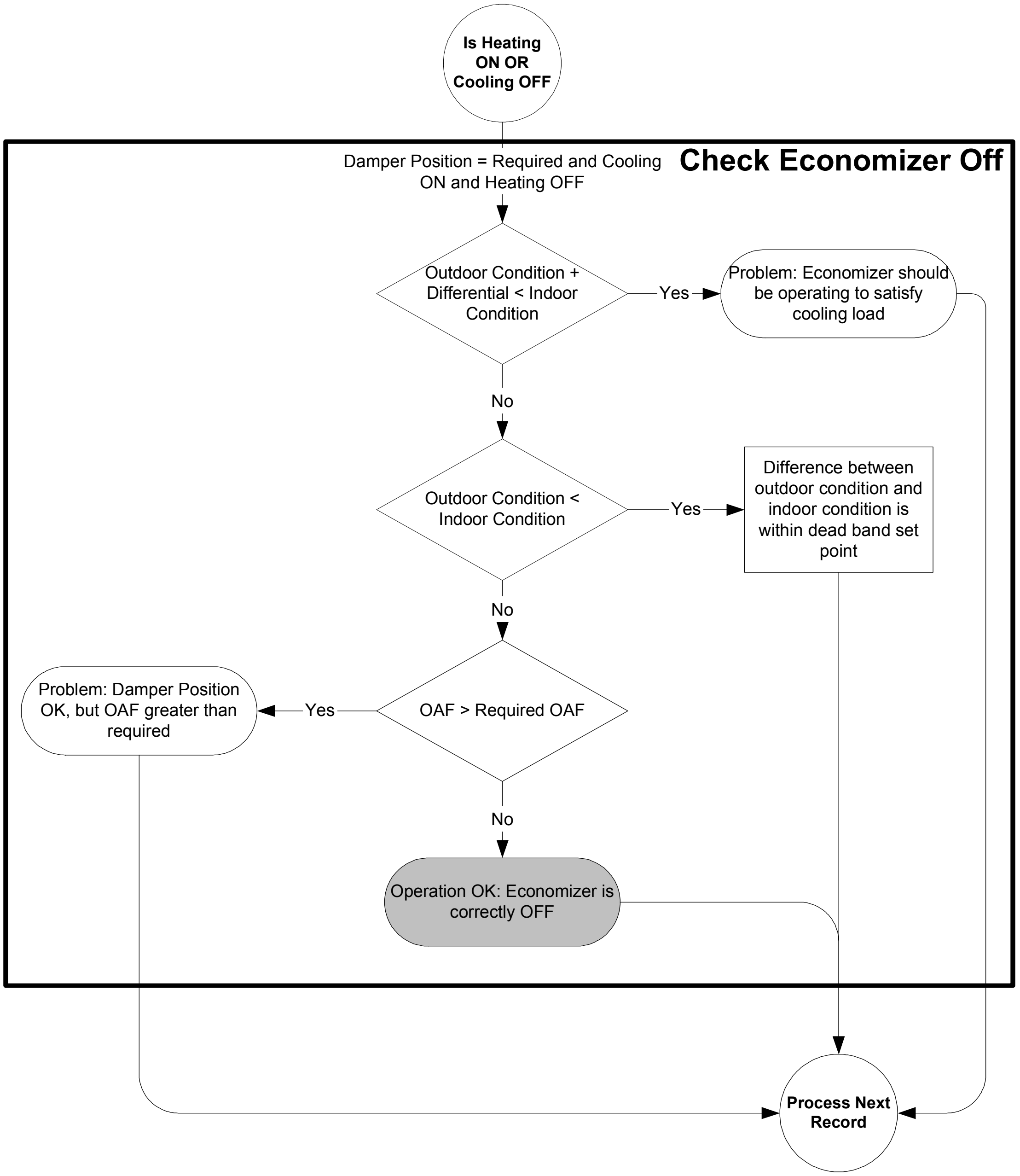

Figure 17: Decision tree to verify that the economizer should be OFF

7.8. Proactive Diagnostic Process

Automated fault detection and diagnosis (AFDD) processes generally rely on analytical or physical redundancies to isolate faults during diagnosis. Most HVAC systems in commercial buildings lack physical redundancy because HVAC systems in the commercial buildings are considered non-critical. An AFDD process can use proactive diagnostic processes to create analytical redundancy to help isolate the cause of a fault. The proactive diagnostic process is similar to functional testing that is performed during manual commissioning of systems.

Therefore, proactive diagnostics would involve automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months otherwise. Such tests could be automated to cover a more complete range of conditions or to deepen diagnosis beyond what might be possible without this capability.

The proactive diagnostic process can help diagnose and isolate faulty operations to a much greater extent than passive diagnostics, but it is intrusive. Some building owners and operators may consider this to be disruptive to the normal operation of their building systems. They may not, however, if such proactive tests can be conducted quickly enough to maintain acceptable control of the building systems. Alternatively, entirely proactive commissioning procedures could provide "continuous" commissioning if they are frequently triggered (e.g., once a day, week, or perhaps month). These procedures might be scheduled to occur during unoccupied hours to further reduce their intrusiveness.

Because proactive tests are potentially disruptive, the criteria and thresholds to activate them should be thoroughly analyzed before implementation. If the criteria and thresholds are loosely defined and the proactive tests are initiated too often during occupied periods, they could potentially disrupt normal operation. Sections 7.9 and 7.10 discuss selecting thresholds and criteria for initiating proactive diagnostics.

7.9. Identifying Faulty Sensors

Accurate and reliable sensors are essential to automate the continuous commissioning process, because automated methods depend on sensor measurements to verify proper operation or identify improper operations. In reality, however, sensors measurements are corrupted by random noise and degradation over time. To overcome these shortcomings, sensor data must be validated to assess the integrity of the information. Although the effects of faulty sensors on energy consumption (Kao and Pierce 1983), monitoring and control optimization (Usoro et al. 1985), and FDD applications (Katipamula, Pratt, and Braun 2000) are well known in the HVAC industry, the quality of sensors in HVAC systems is not comparable to that of sensors in critical applications such as aeronautics, nuclear power, and chemical processing. A primary concern of building owners and operators is first cost. Therefore, fewer sensors (usually the minimum required) and inexpensive sensors are usually used.

The aerospace, nuclear, and process industries have been concerned about the accuracy and reliability of sensors for many years because of the critical role of sensors in system control, monitoring, and supervision. These processes require high reliability and operational safety, so they tend to have reliable and redundant sensors. If an application has redundant sensors, an automated diagnostic process can easily detect and isolate a faulty sensor and still continue to detect and diagnose other faults with the system. However, if there is no physical redundancy, the automated process must rely on other methods to detect and isolate faults (and to verify proper operation). Since it is not common to have redundant sensors in HVAC applications, methods that do not rely on physical redundancy to isolate faults must be used. In this section, we present a generic approach to detecting sensor faults.

7.9.1. Types of Sensor Faults

In general, sensor faults fall into two broad categories: 1) complete failure (hard faults) and 2) partial failure (soft faults). Sensors with hard faults are relatively easy to detect and diagnose, while soft faults are difficult. The most common soft faults are sensor bias and gradual drift. Unlike hard faults, soft faults can go undetected and adversely affect the health of occupants (through inadequate ventilation) and increase energy consumption.

7.9.2. Available Methods

Most FDD methods rely on two basic approaches to detect and diagnose faulty sensors: 1) physical redundancy and 2) analytical redundancy.

Physical redundancy, employs multiple sensors to measure key variables. In a system with physical redundancy, the fault detection and diagnostic process can continuously monitor and poll all redundant information and then discard the sensor information that does not correspond to the other sensors. This approach often requires additional capital cost, space, and physical complexity, so it is only used in monitoring critical processes. Unless the cost of the sensors drops significantly, this approach is not attractive for HVAC systems.

Analytical redundancy uses data that is estimated from physical (mathematical) models or analytical relationships between the variable of interest and other measured variables and other known characteristics of the process or system to isolate the faulty sensor. There are two disadvantages to this approach: 1) it may be difficult to develop analytical relationships for all monitored variables; and 2) since the measurements have noise in them, the corresponding estimates from the physical model are likely to be sensitive to noise as well. In spite of these disadvantages, it is the only attractive method available for most HVAC applications.

All procedures developed as part of this research effort use analytical redundancy to isolate faulty sensors.

7.9.3. Generic Sensor Fault Detection

Figure 18 shows a generic process for isolating sensor faults. Although the process appears to be an independent process, it should be implemented as an integral part of the automated continuous commissioning process.

A number of sensor faults, especially hard faults, can be detected by performing simple limit checks, so the first step is to verify the range of the measured sensor data. For some sensors, tight limits can be specified so the sensor deviations can be easily detected. However, for some other sensors, such as outdoor air temperature, there is a large range of valid values. In such cases, the high and the low limits must be seasonally adjusted, reset using a condition (day of year, for example), or sufficiently wide so that adjustment is not necessary (although this decreases the value of the limits).

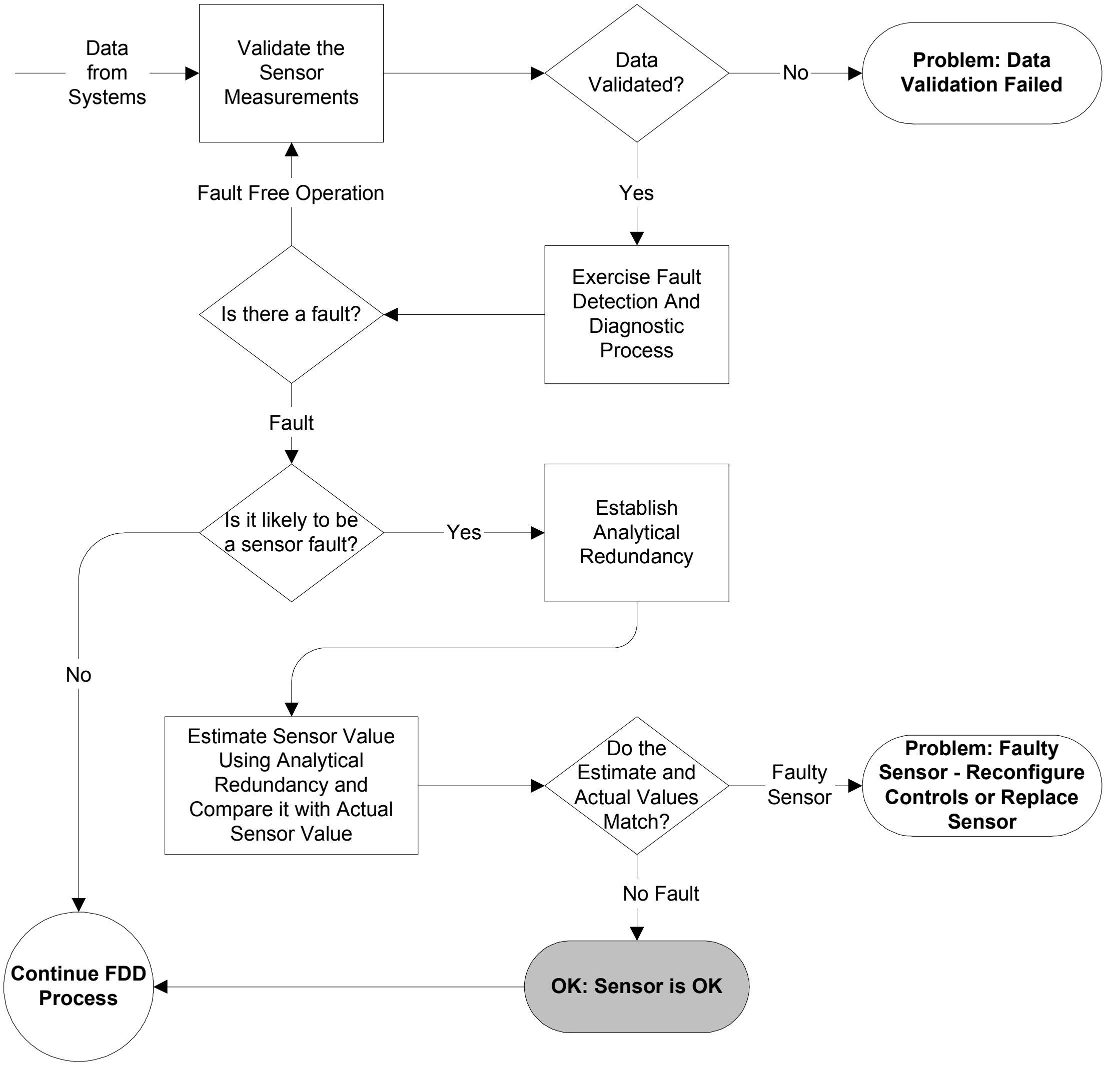

Figure 18: Generic process for isolating sensor faults

If the data is verified, then the FDD process is exercised. If the FDD process detects a fault and the fault is likely to be related to the sensor, then the sensor value must be estimated using available analytical redundancy. Analytical redundancy can be based on first principle, empirical, or analytical models as described previously. Proactive diagnostics may be needed to establish the analytical redundancy.

If the estimated sensor value does not match the actual sensor value within the limits of uncertainty, it can be concluded that the sensor is faulty. The next step is to reconfigure the controls to account for the failed sensor or to replace the faulty sensor. If the estimated sensor value matches the actual sensor value within the limits of uncertainty, the FDD process continues to isolate the cause of the fault.

In the following sections, we present automated proactive diagnostic methods to isolate faulty temperature and humidity sensors. Several examples are provided: 1) isolating a faulty outdoor , return or mixed air temperature sensor, 2) isolating a faulty supply air temperature sensor, and 3) isolating a faulty outdoor , return or mixed air humidity sensor.

7.9.4. Isolating a Problem with a Temperature Sensor

Before the proactive diagnostic process is initiated, the presence of a fault must be identified. This step can be conducted using passive diagnostic procedures outlined in Figure 7. In our example, the series of tests in Figure 7 concluded that one of the three temperature sensors (outdoor , return , or mixed air) was faulty. The passive diagnostic process was unable to identify which of these sensors was faulty because of lack of physical redundancy in the measurements. Although not shown in Figure 7, the passive diagnostic method included limit checking of all three sensors, which could have identified a sensor far out of range, but this was not found in our example. Analytical redundancy techniques can help isolate the faulty sensor, as explained in the next section.

Isolating a Problem with the Outdoor , Return , or Mixed Air Temperature Sensor

In an AHU, the return and outdoor air streams are mixed and the resulting air stream is called the mixed air stream (see Figure 3). Therefore, the fundamental equations for sensible energy balance along with positioning of the return air and the outdoor air dampers can be used to isolate the fault. Positioning of the dampers at specific positions in this case provides the analytical redundancy, which provides sufficient additional information to close the problem.

As shown in Figure 19, the first step in the proactive diagnostic process is to close the outdoor air damper completely and wait for the conditions to reach steady state. Unfortunately, a steady-state detection filter for the temperatures cannot be used, because at this time we do not know which of the three sensors is faulty. The air-side conditions reach steady state rapidly, usually within a few minutes. While keeping the outdoor air damper fully closed, the return air and mixed air temperatures are sampled for a few minutes and compared. If the average mixed air and average return air temperatures measured during the sampling period are approximately equal, this indicates that the return air and mixed air temperature sensors are consistent with one another and the outdoor air temperature sensor is faulty.

If the return air and the mixed air temperatures are not approximately equal, command the outdoor air dampers to open fully and wait until steady-state conditions are achieved. When the outdoor air damper is fully open, the average mixed air temperature should nearly equal the average outdoor air temperature during the sampling period. If they are equal, then the outdoor air and mixed air temperature sensors are consistent with one another and the return air temperature sensor is faulty. If they are not, then the mixed air temperature sensor is faulty (because earlier the return air temperature sensor was ruled OK).

After isolating the faulty sensor, further diagnosis is possible to identify the underlying cause or nature of the problem. Unlike relative humidity, air flow, fluid flow, and pressure sensors, temperature sensors are more reliable, but they do exhibit erratic behavior occasionally. In addition to random noise, common problems are biased measurement and drift over time. Detecting and estimating the bias in a temperature measurement is described below in the sections entitled *Diagnosing the*

Bias in the Outdoor Air Temperature Sensor, *Diagnosing the Bias in the Return Air Temperature Sensor*, and *Diagnosing the Bias in the Mixed Air Temperature Sensor*. Detecting drift over time does not require a proactive diagnostic process. Passive methods, as described in Section 7.7, can help do that.

All dampers have some type of seal to prevent leakage when they are fully closed. However, some leakage occurs around the seals. As the AHU ages, the seals deteriorate, increasing air leakage. Under these conditions, the mixed air temperature may not approximately equal the outdoor air temperature when the return air dampers are fully closed. Therefore, in addition to the measurement accuracies of the sensors, the equality tests in Figure 19 should also account for leaky dampers. This can be accomplished by relaxing (increasing) the tolerances. This may sometimes lead to an incorrect diagnosis of the mixed air sensor being a problem even if the outdoor air or the return air temperature sensor is slightly biased (because it is the least resistive path on the flow chart). The tradeoffs between sensitivity of diagnosis to detect problems and the potential for false alarms or false diagnoses should be clearly understood before implementing any automated commissioning processes. Although there are some general rules-of-thumb for selection of thresholds, field tests are necessary to fully understand the effects of tolerances and select values for them.

Another potential source of error is the measurement of the mixed air temperature caused by stratification of air across the duct. The mixed air temperature measured at a single point may not accurately represent the true average mixed air temperature and could lead to misleading diagnoses. Therefore, the mixed air temperature should always be measured across the duct and averaged using an averaging sensor.

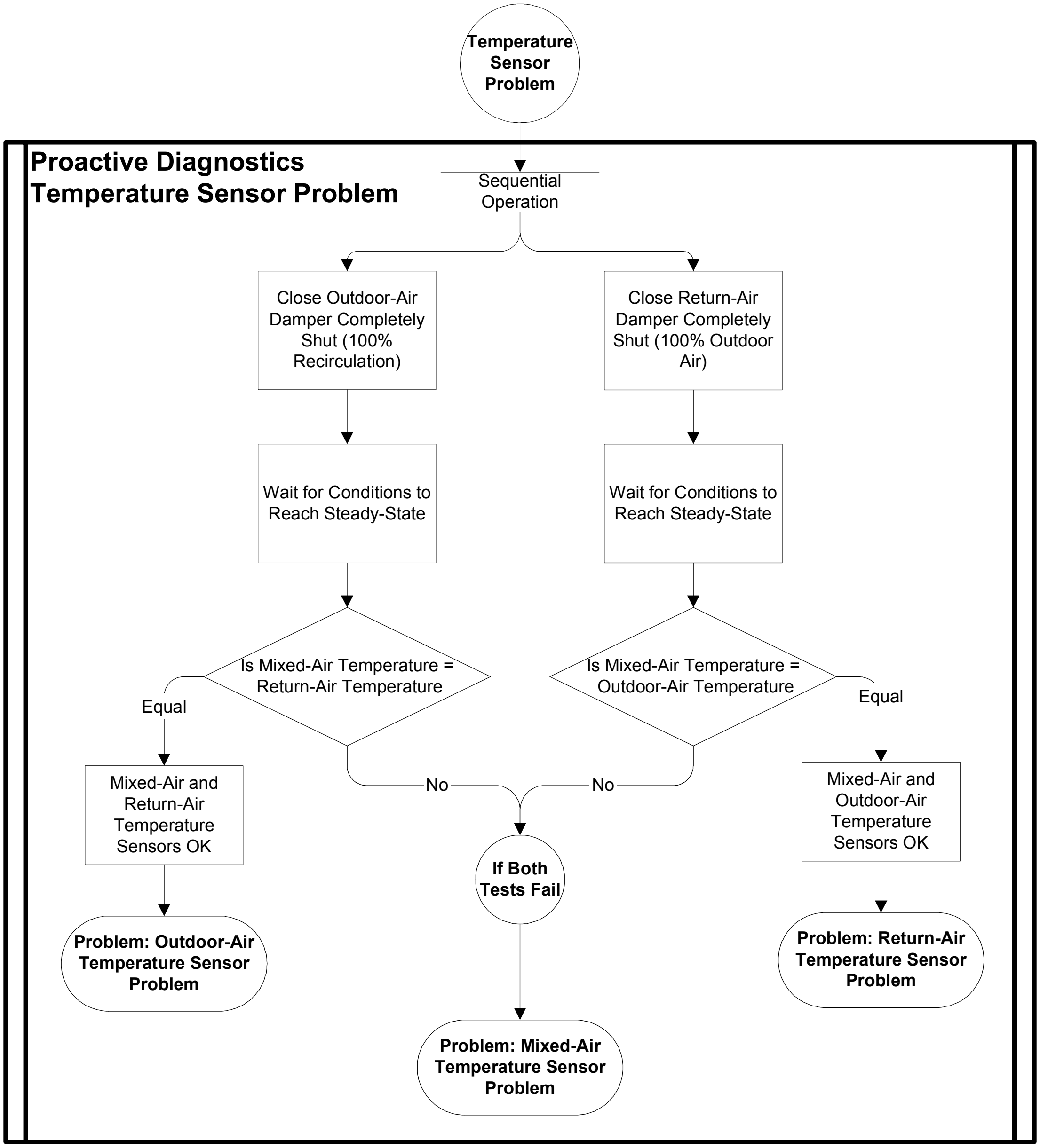

Figure 19: Decision tree to isolate the faulty temperature sensor

Diagnosing the Bias in the Outdoor Air Temperature Sensor

When the outdoor air temperature sensor is identified as the faulty sensor using the process described in Section 7.9.4, further diagnosis of the cause is possible. If the outdoor air temperature sensor is biased, the process to estimate the bias and reconfigure the controls is described in this section.

The first step in this proactive diagnostic process (see Figure 20)is to fully open the outdoor air damper and wait for conditions to reach steady state. In this case, the mixed air temperature values can be used to identify when steady-state conditions are attained, because at this point in the diagnostic process, we know that the mixed air temperature sensor is good. One form of steady-state filter is based on the rate of change of the mixed air temperature. If the rate of change is zero or below a certain predefined threshold, it indicates that steady-state conditions have been achieved. After steady-state conditions are achieved, compute the difference between the outdoor air and the mixed air temperatures and store it for further analysis.

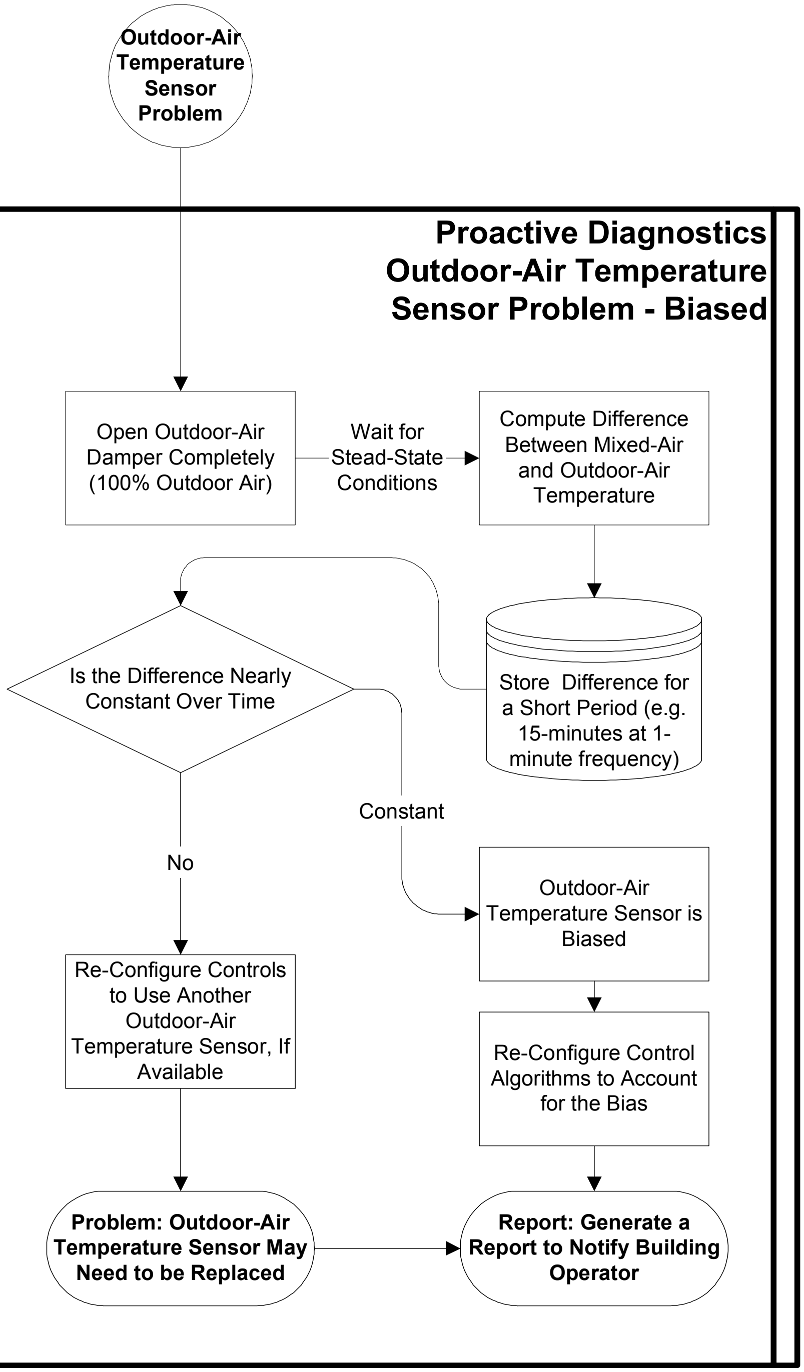

Figure 20: Decision tree to check if the outdoor air temperature sensor is biased and implement a temporary correction

The frequency of the sampling and the duration of the proactive test depend on the field conditions. A sampling rate of one minute or less and a total duration of test of

15 minutes should be sufficient in most cases. In some cases, the test may have to be performed at different times of the day to ensure that the bias is consistent at all hours of the day. For example, an improperly positioned outdoor air temperature sensor may read a few degrees high or low for a few hours in a day, the amount depending on the angle of incidence of the sunlight, but may otherwise be reading normal. This type of a bias or problem is difficult to detect, unless the proactive test is repeated several times at different hours of the day. The need to do this may be indicated by an outdoor air temperature sensor bias being detected during the same hours of the day for several days in a row (but not at other hours). Again as mentioned earlier, field tests are required to better understand these issues.

After the difference between the outdoor air and the mixed air temperatures are computed for the duration of the test at a desired sampling rate, the next step is the analysis of the stored data to confirm whether or not the difference is nearly constant over the entire test period. Commonly used statistical tests such as the mean and the standard deviation of the sample are recommended. The mean provides the central tendency of the sampled data (the estimate of the bias) while the standard deviation provides the dispersion (how tightly the data are clustered around the mean).

In order for the test to be true (i.e., the difference nearly equal over the test period), the mean must be greater than the tolerance or the accuracy of the temperature sensors and the standard deviation should be reasonable. A third statistical test called the coefficient of variation can be used to check whether the standard deviation is reasonable compared to the sample mean and the sensor tolerance. The coefficient of variation measures the relative scatter in data with respect to the mean; it is computed as the ratio of the standard deviation to the mean. A threshold for the coefficient of variation must be selected. Below this threshold, the standard deviation would be acceptable and the bias considered constant. A coefficient of variation of about 15% should be reasonable.

The next step is to reconfigure the control algorithms such that they account for the bias in the outdoor air temperature sensor. If it is concluded that the temperature difference is not constant, then the controls can be reconfigured to use another properly functioning outdoor air temperature sensor. Most often a commercial building has several outdoor air temperature sensors (sometimes one for each air handling unit), so another sensor should be available to substitute for the failed one. Any time a proactive test has been conducted and controls reconfigured, a report should be generated to notify the building manager or the building operator of this change. Then, when the sensor is repaired or replaced, the outdoor air sensor used for control can be reconfigured.

Diagnosing the Bias in the Return Air Temperature Sensor

When the return air temperature sensor is identified as the faulty sensor using the process described in Figure 19, further diagnosis of the cause is possible as described in this section.

The proactive test for diagnosing bias, as shown in Figure 21, is similar to the test for diagnosing the bias for the outdoor air temperature sensor described in the previous section. If the sensor is biased, the control algorithms can be reconfigured to account for the bias. If found to be faulty but not with a constant bias, the controls can be reconfigured to use the average zone air temperature in place of the faulty return air temperature. Again, all proactive tests, control reconfigurations and problems are reported to the building manger or the building operator.

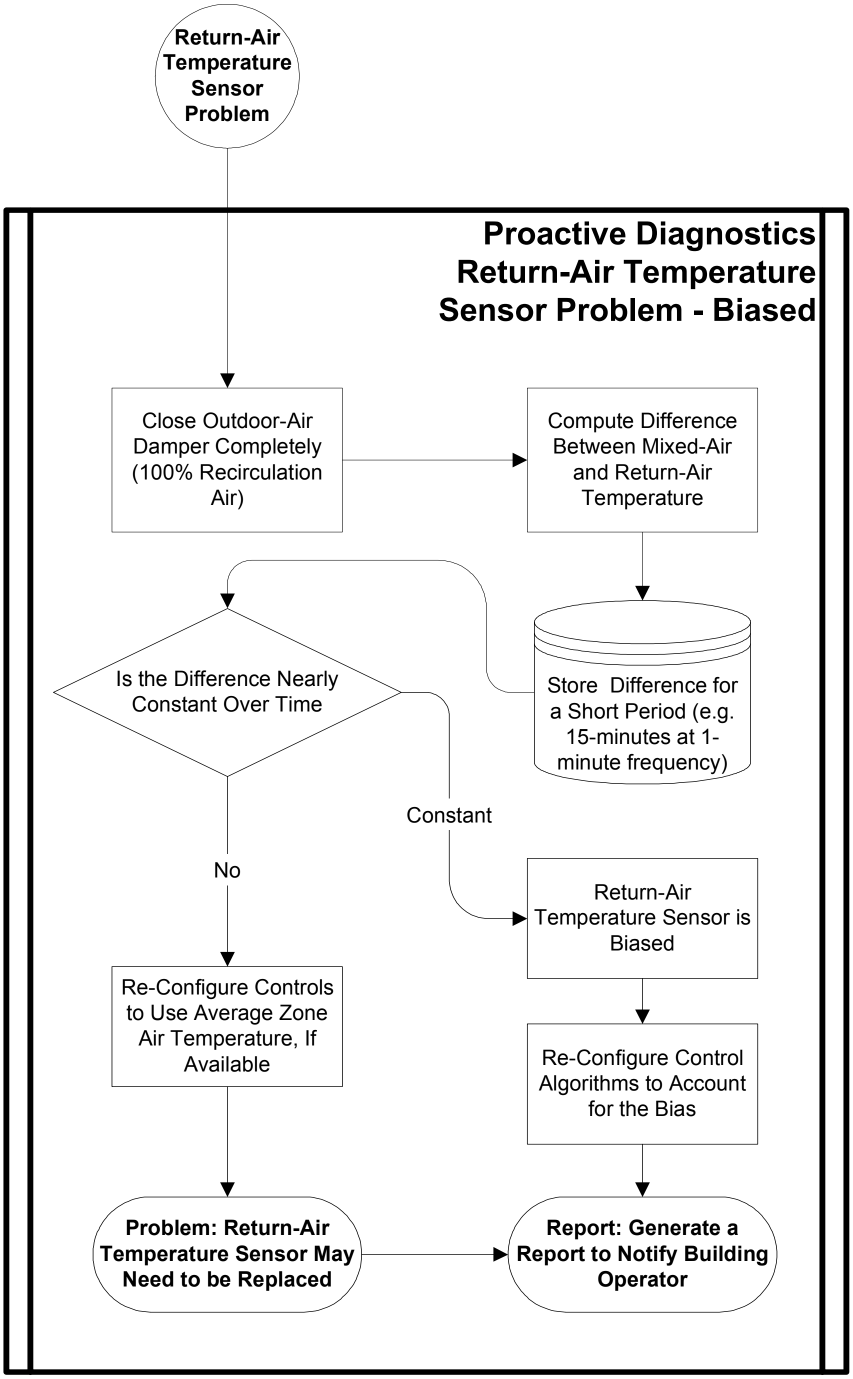

Figure 21: Decision tree to check if the return air temperature sensor is biased and implement a temporary correction

Diagnosing the Bias in the Mixed Air Temperature Sensor

When the mixed air temperature sensor is identified as the faulty sensor using the process described in Figure 19, further diagnosis of the cause is possible as described in this section.

To estimate the bias in the mixed air temperature sensor, two proactive tests are necessary, as shown in Figure 22. Each of the tests is similar to the ones described in the previous sections. However, both tests must conclude that the difference is constant in order to conclude that the mixed air temperature sensor is biased. The mixed air temperature is not generally used to control the operation of an AHU; therefore, if the sensor is biased or faulty it may not affect the operations of the AHU, but it must be replaced if it is to be used to detect and diagnosis other faults in the AHU’s operations.

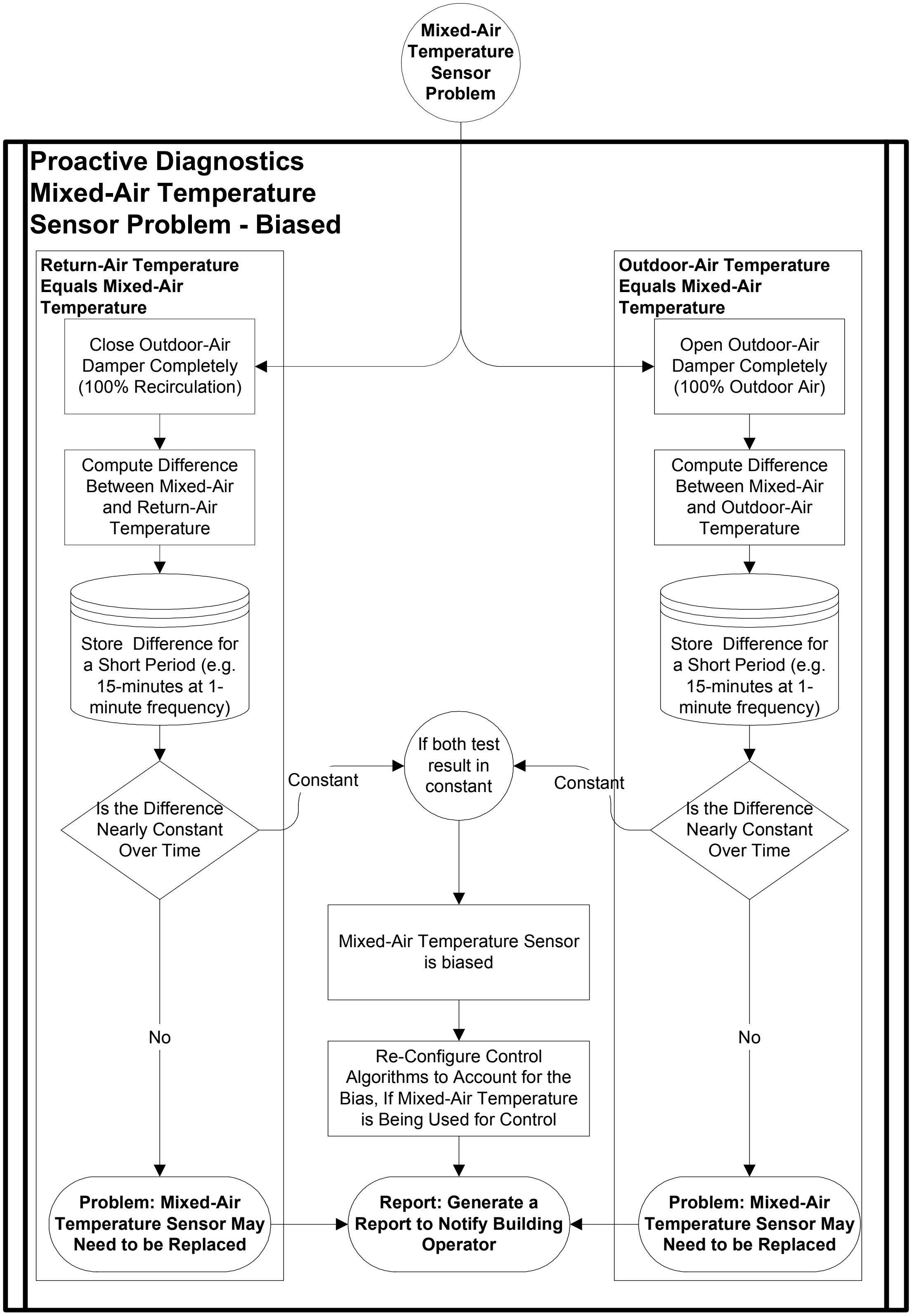

Figure 22: Decision tree to check if the mixed air temperature sensor is biased

7.9.5. Isolating a Faulty Relative Humidity Sensor

Most humidity sensors commonly used in HVAC applications measure either the relative humidity or the dew point temperature of the air stream. To identify a faulty dew point temperature, the methodology presented in Section 7.9.4 can be used. When the dew point temperature increases, it is an indication that the amount of moisture has increased. Unlike dew point, the change in relative humidity can be caused by temperature changes, moisture changes, or both. Therefore, to isolate a faulty relative humidity sensor, a property derived from relative humidity and dry bulb temperature must be used (enthalpy, for example). A proactive methodology to isolate a faulty or malfunctioning relative humidity sensor using this approach is presented in this section.

Before the proactive diagnostic process is initiated, the presence of a fault must be identified. This step can be conducted using the passive diagnostic procedures outlined in Figure 23. When a fault exists, the series of tests in Figure 23 concludes that one of the three (outdoor , return , or mixed air) humidity or temperature sensors is faulty. The passive diagnostic process is unable to identify which of these sensors is faulty because of lack of physical redundancy in the measurements. Although not shown in Figure 23, the passive diagnostic method includes limit checking of all six sensors, which could identify a sensor far out of range, but we assume this is not found in our example.

To isolate the faulty sensor, the first step is to exercise the proactive diagnostic process to isolate the temperature sensor problem as described in the Section 7.9.4. If the conclusion of the series of proactive tests is negative, then the problem is with one of the three relative humidity sensors. The process to isolate the faulty relative humidity sensor is described in the next section.

Isolation of Outdoor , Return and Mixed Air Relative Humidity Sensor Problems

In an AHU, the return and outdoor air streams are mixed and the resulting air stream is called the mixed air stream (as shown in Figure 3). Therefore, the fundamental equations for energy balance, along with positioning of the return air and the outdoor air dampers, can be used to isolate the faulty sensor. Positioning of the dampers at specific positions in this case provides the analytical redundancy, which provides additional information to close the problem.

As shown in Figure 24, the first step in the proactive diagnostic process is to close the outdoor air damper completely and wait for conditions to reach steady state. Since we know that all three temperature sensors are good, the mixed air temperature values can be used to identify when steady-state conditions are attained. One form of steady-state filter is based on the rate of change of the mixed air temperature. If the rate of change is zero (within the resolution of measurement) or below a predefined threshold, it indicates that steady-state conditions have been sufficiently achieved.

The next step is to keep the outdoor air damper fully closed and sample the return air and mixed air temperatures and relative humidities for a few minutes (e.g., five minutes). Then determine the return air and mixed air enthalpies from the sampled measurements. If the average mixed air and return air enthalpies measured during the sampling period are approximately equal, this indicates that the return air and mixed air enthalpy sensors are consistent with one another and the outdoor air enthalpy sensor is faulty.

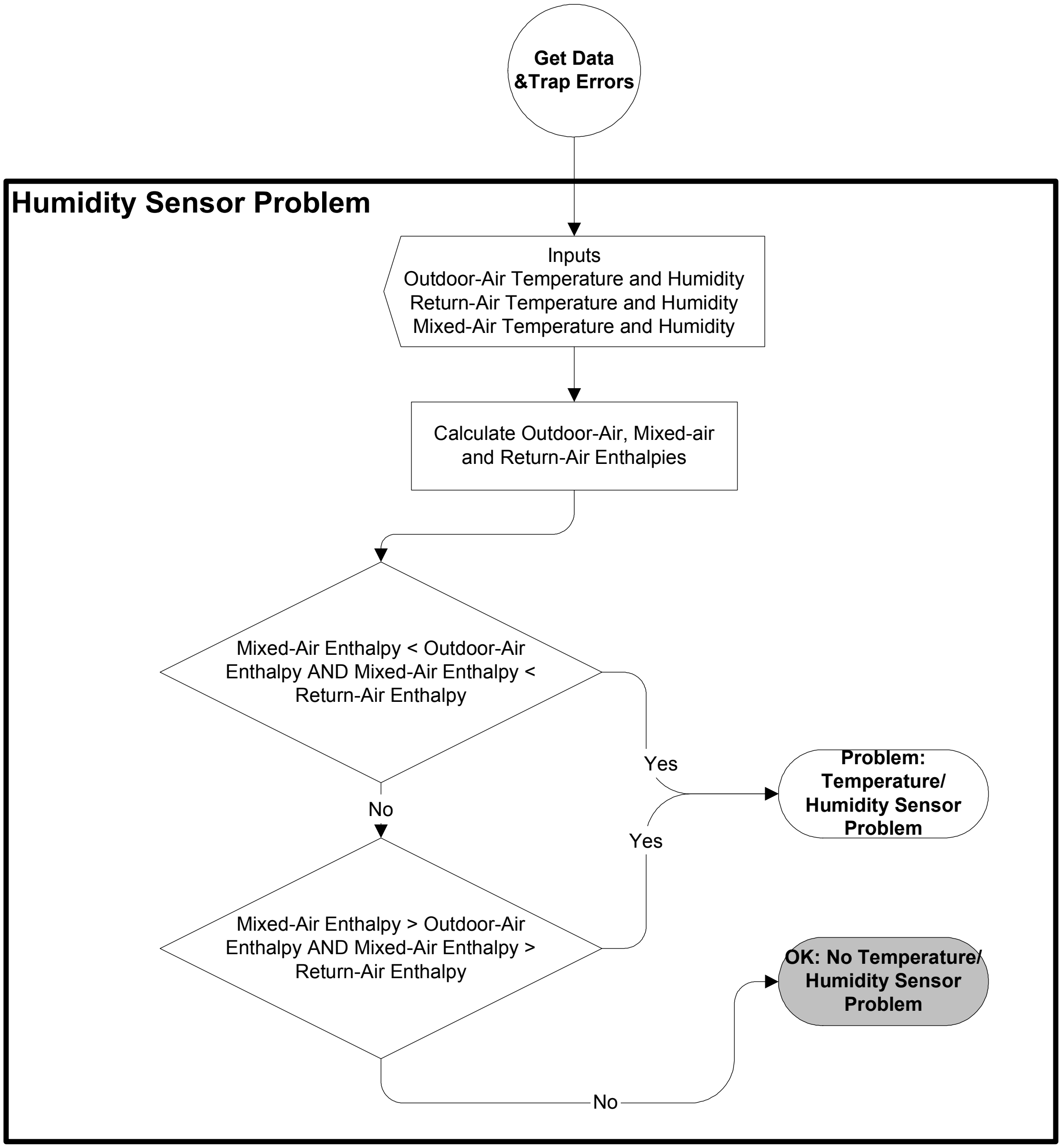

Figure 23: Decision tree to identify humidity sensor problems associated with the measurement of outdoor , return , and mixed air humidity

If the average return air and mixed air enthalpies over the sample period are **not** approximately equal, command the outdoor air dampers to open fully and wait until steady-state conditions are achieved. When the outdoor air damper is fully opened and steady-state conditions reached, the average mixed air enthalpy should nearly equal the average outdoor air enthalpy during the sampling period. If they are equal, then the outdoor air and mixed air relative humidity sensors are consistent with one another and the return air relative humidity sensor is faulty. If they are not, then the mixed air relative humidity sensor is faulty (because earlier the return air relative humidity sensor was ruled OK).

After isolating the faulty sensor, further diagnosis to identify the underlying cause or nature of the problem is difficult because the relationship between relative humidity and enthalpy is non-linear in nature.

As mentioned earlier in this report, the effect of leakage around the damper seals must be taken into account when isolating a faulty humidity sensor. Leakage will prevent achieving 100% recirculated air or 100% outdoor air and, as a result, the condition (temperature or humidity) of the mixed air may never exactly equal the condition in the supplying air stream. This difference may be accounted for by carefully selecting tolerances for the comparison of values (discussed elsewhere in this report). In addition, if measurements for mixed air are made at a single point, this will introduce errors. We recommend use of averaging sensors for temperature to somewhat compensate for stratification in the mixing box, but this option may not be available for humidity measurements. Tolerances again need to be selected carefully for use with this diagnostic process to ensure useful results.

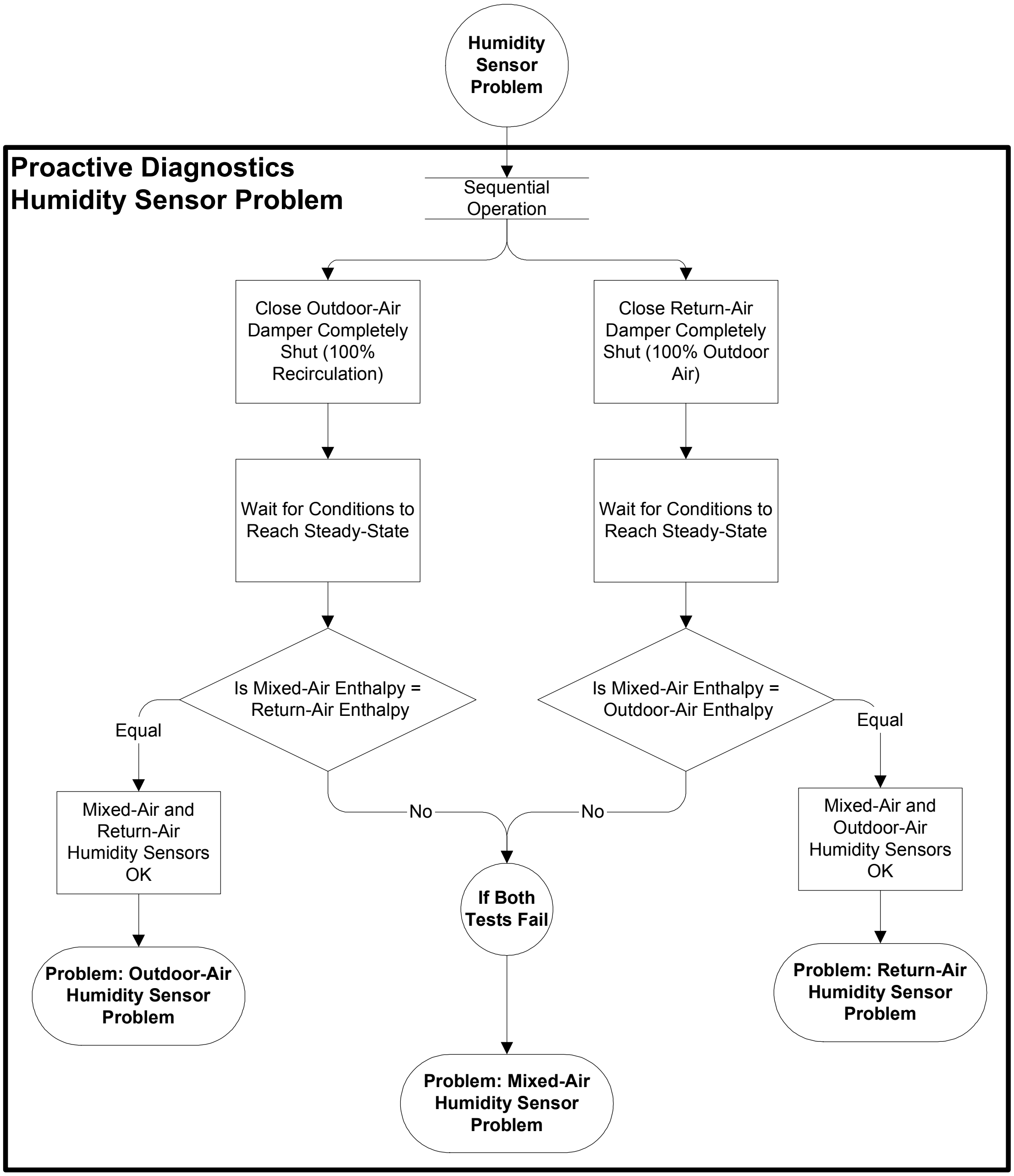

Figure 24: Decision tree to isolate the faulty relative humidity sensor

7.10. Identifying Malfunctioning Valves and Dampers

Identification of malfunctioning or faulty valves and dampers within an AHU is difficult, especially when based on occupant's complaints about comfort, unless the fault is severe. This is true because a moderately malfunctioning valve or damper does not affect the occupants' comfort and can go undetected for a long period of time. For example, a leaky hot water valve in the cooling mode increases both the heating and cooling energy consumption. Although the faulty behavior of the hot water valve increases the temperature of air entering the cooling coil in the cooling mode, it does not affect the comfort of occupants because mechanical cooling compensates. Similarly, faults with damper systems have little or no impact on comfort because the heating or the cooling systems generally compensate for the faulty behavior.

Depending on the severity of the fault, passive and even proactive diagnostic methods may fail to detect faulty operation. In this section, a generalized approach for detecting malfunctioning valves and dampers that can be applied in a variety of HVAC applications is presented. Although valves and dampers can fail due to broken linkages, failed actuators, improper control sequences, and broken motors, it is difficult to distinguish among the causes with limited monitored data. As a result, in this report unless otherwise noted, all causes that lead to valve or damper malfunctions are reported as faulty valves or dampers.

7.10.1. Background Damper Information

In HVAC applications, dampers are widely used to control the flows of outdoor air, return air and exhaust air within an AHU, as shown in Figure 3. The relationships among the outdoor air, return air and exhaust air damper positions during normal operation are illustrated in Figure 25. As described in Section 7.7.2, *Basic Operating Sequence of an AHU*, the outdoor air damper is positioned to the minimum position during heating mode or when outdoor conditions are not favorable for economizing in the cooling mode; it is modulated to meet the supply air temperature setpoint when the outdoor air temperature is lower than the supply air temperature setpoint, and is in the fully open position when outdoor air conditions are favorable for economizing. The positioning of the exhaust air damper follows the outdoor air damper. When the outdoor air damper is at the minimum position, the exhaust air damper is fully closed or opened slightly to relieve the pressure in the occupied space, and when the outdoor air damper is fully open, the exhaust air damper is fully open as well. Unlike the exhaust air damper, the return air damper works the opposite way, i.e., the return air damper is fully closed when the outdoor air damper is fully open and it is fully open when the outdoor air damper is at the minimum position.

The AHU controllers are preprogrammed with the basic sequencing operations to operate the AHU. Based on the outdoor and the indoor conditions, the damper controller dynamically estimates the control signal for each of the three dampers. Most AHUs do not have feedback controllers for the damper systems; therefore, there is no direct feedback from the dampers indicating that they have been positioned as signaled.

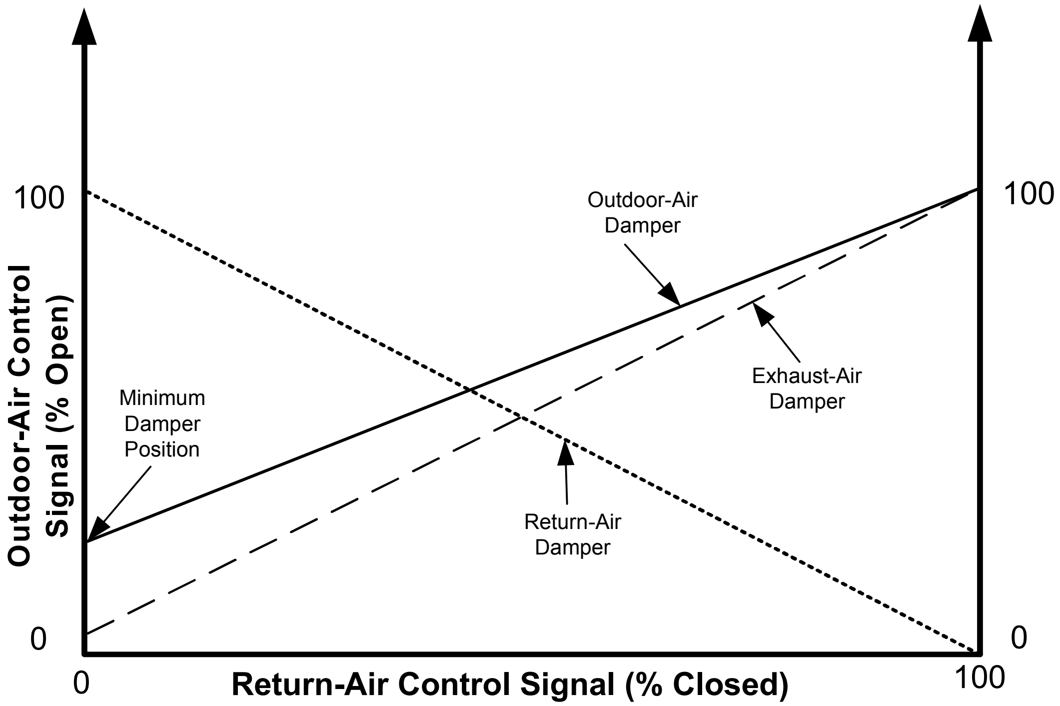

Figure 25: Relationship of the damper positions during normal operations

The behavior of faulty or malfunctioning dampers to a large extent depends on the configuration of the AHU and the type of fan systems it uses. Bushby et al. (2001) simulated faulty behavior of a VAV system with a three-fan configuration, the supply air, the return air and the exhaust air fans. The results from the simulation are shown in Figure 26.

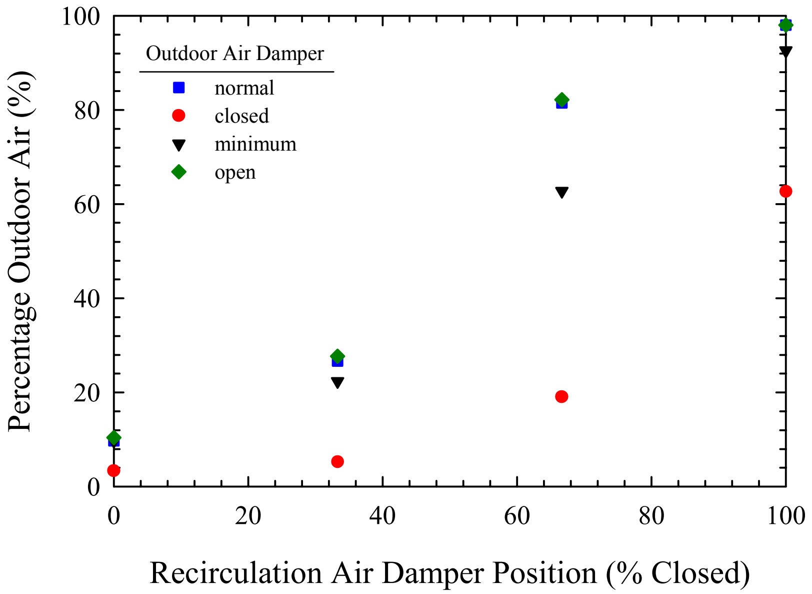

Figure 26: Outdoor air percentage as a function of return air damper position for various outdoor air damper faults (normal, stuck closed, stuck at the minimum position, and stuck fully open). (Bushby et al. 2001)

In Figure 26, the outdoor air percentage is defined as the mass flow rate of the outdoor air divided by mass flow rate of the supply air. The simulations were conducted for a normally operating outdoor air damper, and fault cases where the outdoor air damper is stuck fully closed, stuck at its minimum position, and stuck fully open. For the most part, the outdoor air percentages for stuck at minimum and stuck fully open cases appear to be similar to that for normal operation. Although there is no change in the outdoor air percentage, there will be an increase in the fan power consumption because of the increased pressure drop when the outdoor air damper is stuck at the minimum position. Also, when the outdoor air damper is stuck in the fully open position, it may not affect the outdoor air percentage, but this condition can lead to frozen coils during unoccupied hours when the fan system is not running.

The stuck fully closed case is clearly different from that of normal operation. Although the results shown in Figure 26 indicate that the outdoor air percentage is over 60% when both the outdoor air and the return air dampers are fully closed, the volume of total airflow is significantly lower. Bushby et al. (2001) reported that the total supply air flow rate dropped by almost 80% for the case where the outdoor air damper is stuck in a fully closed position.

Bushby et al. (2001) also simulated faults with the return air damper, as shown in Figure 27. The outdoor air percentages for both faults (stuck fully closed and stuck fully open) are significantly different from the outdoor air percentage for the normally operating damper system. If the return air damper is stuck in a fully open position, the percentage of outdoor air is significantly less than normal. This creates a big energy penalty, particularly when outdoor conditions are favorable for economizing. If the return air damper is stuck in a fully closed position, the percentage of outdoor air is nearly equal to 100% at all times, because the outdoor air damper can provide almost 100% of the supply air (Figure 27). The energy impact of this fault is even greater.

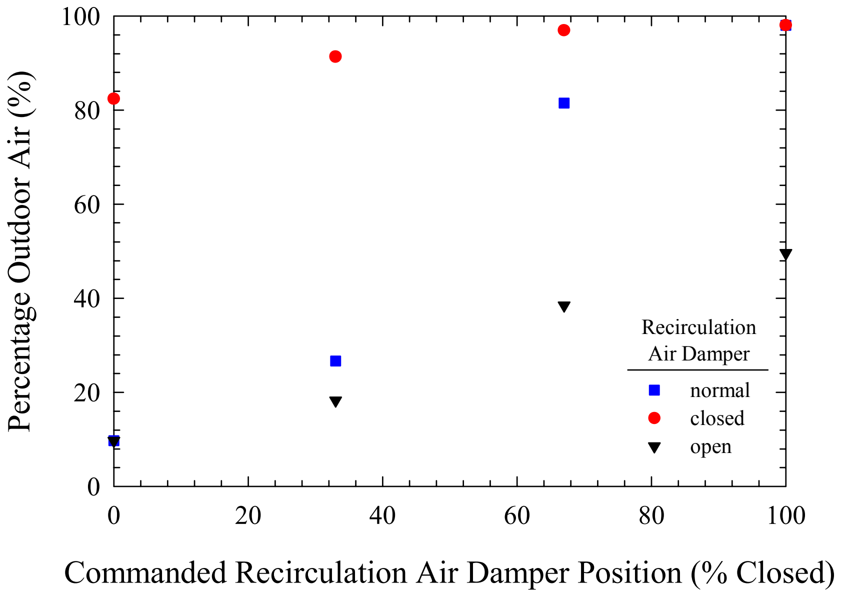

Figure 27: Outdoor air percentage as a function of return air damper position for various return air damper faults (normal, stuck closed, and stuck fully open). (Bushby et al. 2001)

The results from Bushby et al. (2001) represent one AHU configuration, and may or may not be valid for other system configurations and control strategies. For example, a constant air volume AHU without either the return air or the exhaust air fans could have a completely different signature. Also, systems with similar configurations can produce different pressure drops, power draws and outdoor air percentages depending on type of damper system and type of fan used. Therefore, the proposed methodology should be able to adapt to the system configuration in order to be effective in detecting and diagnosing faults.

7.10.2. General Approach for Detecting Malfunctioning or Faulty Dampers

As described in the previous section, it is difficult to distinguish between normal and faulty operations for certain faults (e.g., a damper stuck fully open or a damper stuck at minimum position). Although the outdoor air percentage is normal even under faulty operation, the power consumption of the supply fan increases because of the additional pressure drop. The methodology described in Section 7.7 was based on commonly found sensors in AHUs; therefore, it may not be able to detect the faulty damper operations in some cases. An alternate damper fault detection and diagnostic approach, which requires additional sensors, is presented in this section.

Unless the pressure drop across the outdoor air damper or the power consumption of the fan is monitored and compared to a reference model (normal operation), it is unlikely that the fault can be detected. In general, it is not common to have pressure drop sensors and power measurements. To implement this automated continuous commissioning process, however, the pressure drop across the damper or the power consumption of the fans must be monitored.

The increase in the power consumption and the change in the pressure drop because of improper damper operation depend on the configuration of the AHU. Therefore, to automate the continuous commissioning process, the behavior of the damper and the fan under normal and faulty operations must be characterized separately. The characterizations can be done off-line as a separate processes or they can be done on-line in an automated way as a part of the automated continuous process.

The overview of an on-line training and automated continuous commissioning process is shown in Figure 28. Before the automated continuous commissioning process is initiated, the on-line training process is used to characterize damper operation under normal and faulty conditions. To characterize the outdoor air damper operation, the pressure drop, the fan power consumption, and the OAF are monitored and used to develop a reference model. The process involved in developing a reference model is illustrated in more detail in Figure 29. After development of the reference model is complete, the reference model can be used to identify faulty and malfunctioning dampers.

The characterization of the normal behavior of the outdoor air damper is illustrated in Figure 29. The first step is to command the outdoor air damper to a fully closed position, then command the return air and exhaust air dampers to positions that correspond to a fully closed outdoor air damper position (refer to Figure 25). After the conditions reach steady state, monitor the pressure drop, power consumption and the OAF (which is a function of outdoor air, return air and mixed air temperatures) and store the data. Then command the outdoor air damper to open 10% and command the return air and the exhaust air dampers to correspond to the new outdoor air damper position. Wait for the conditions to reach steady state and store the monitored data. Change the outdoor air damper position to 20% open, and command the return air and exhaust air damper positions again to correspond to the new outdoor air damper position and continue the process until the outdoor air damper is fully open.

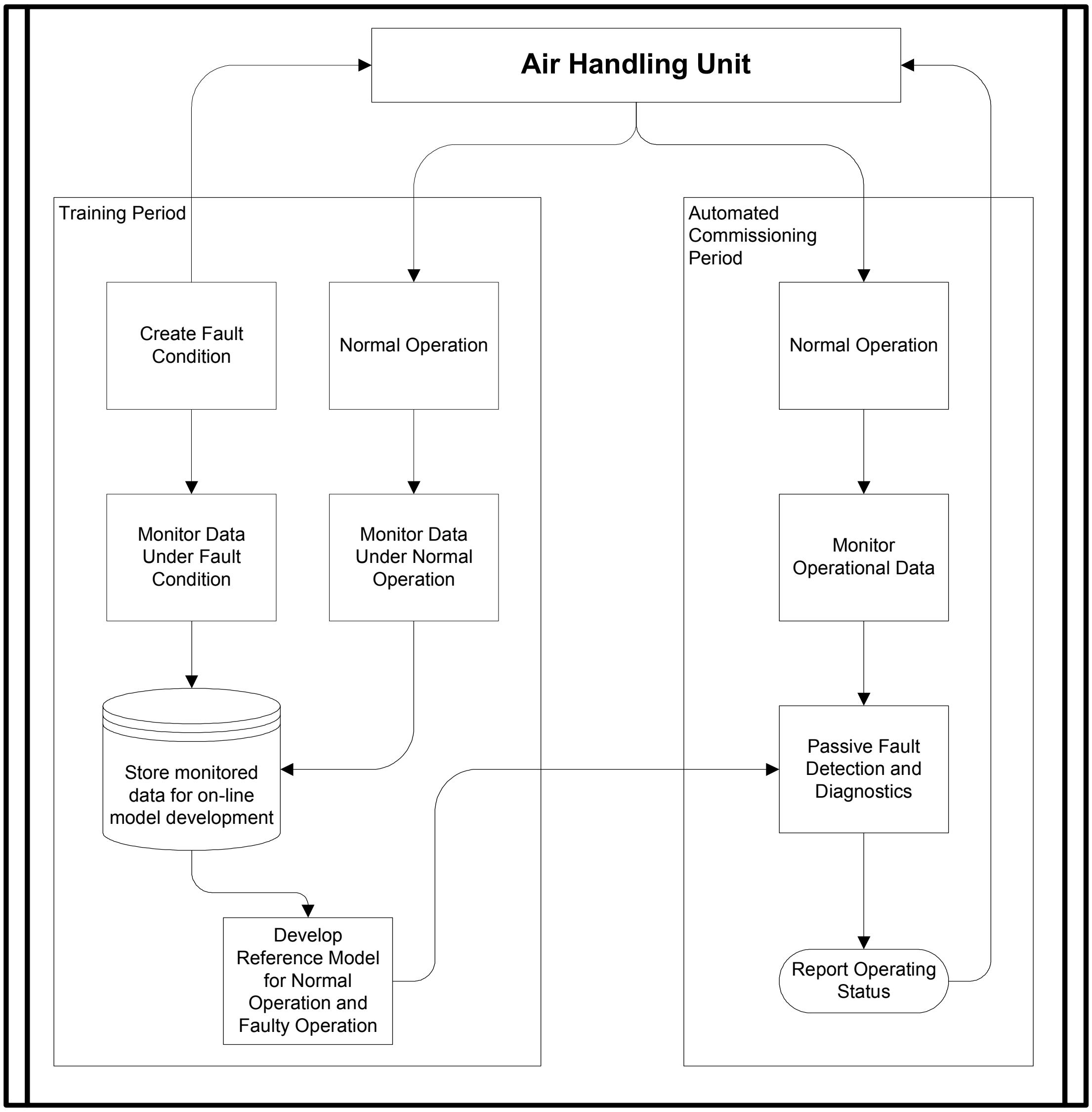

Figure 28: Overview of an on-line training and continuous commissioning process

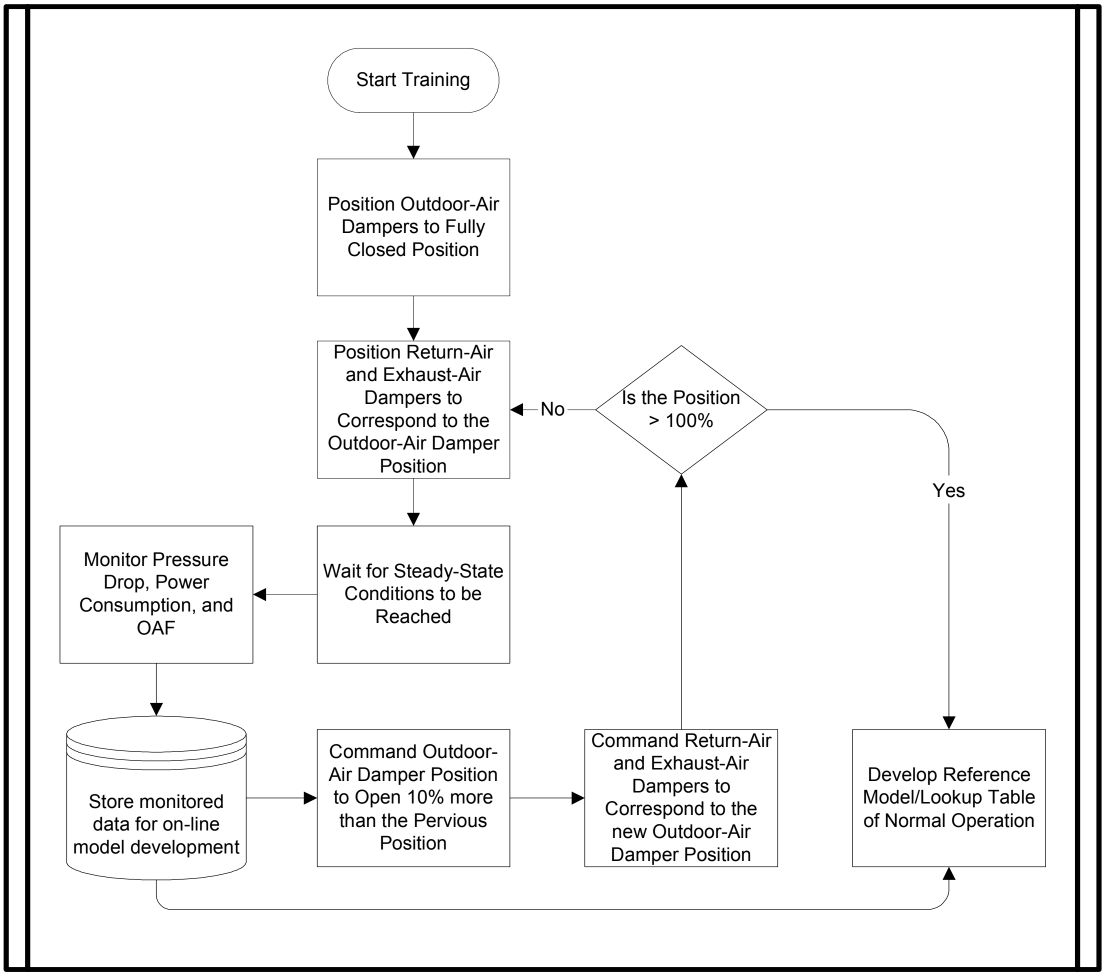

Figure 29: Overview of the process to develop a reference model to characterize the normal operation of an outdoor air damper

After the data for normal outdoor air damper operation are collected, a reference model of normal operation can be developed. The reference model can be an empirical model, based either on regression analysis or a lookup table. Since the stored data cover the entire range of normal operations (fully open to fully closed), a lookup table is likely a better choice because it is simpler to implement.

The procedure to build a reference model to characterize faulty behavior is similar to that described for normal operation. The characterization of outdoor air damper behavior when it is stuck in a fully closed position is illustrated in Figure 30. The first step is to command the outdoor air damper to a fully closed position and force it to remain in that position irrespective of the control signal. Then, command the return air and the exhaust air dampers to positions that correspond to a fully closed outdoor air damper position (refer to Figure 25). After steady-state conditions are reached, monitor and record the pressure drop, power consumption and outside air flow rate. Next, command the return air and exhaust air dampers to positions that correspond to 10% open outdoor air damper, while actually keeping the outdoor air dampers fully closed. Wait for the conditions to reach steady state and record the monitored data. Reposition the return air and the exhaust air dampers again to correspond to 20% open outdoor air damper, and continue the process until the outdoor air damper is fully open (100%). Using the data recorded, develop a lookup table that reflects the faulty operation of the outdoor air damper.

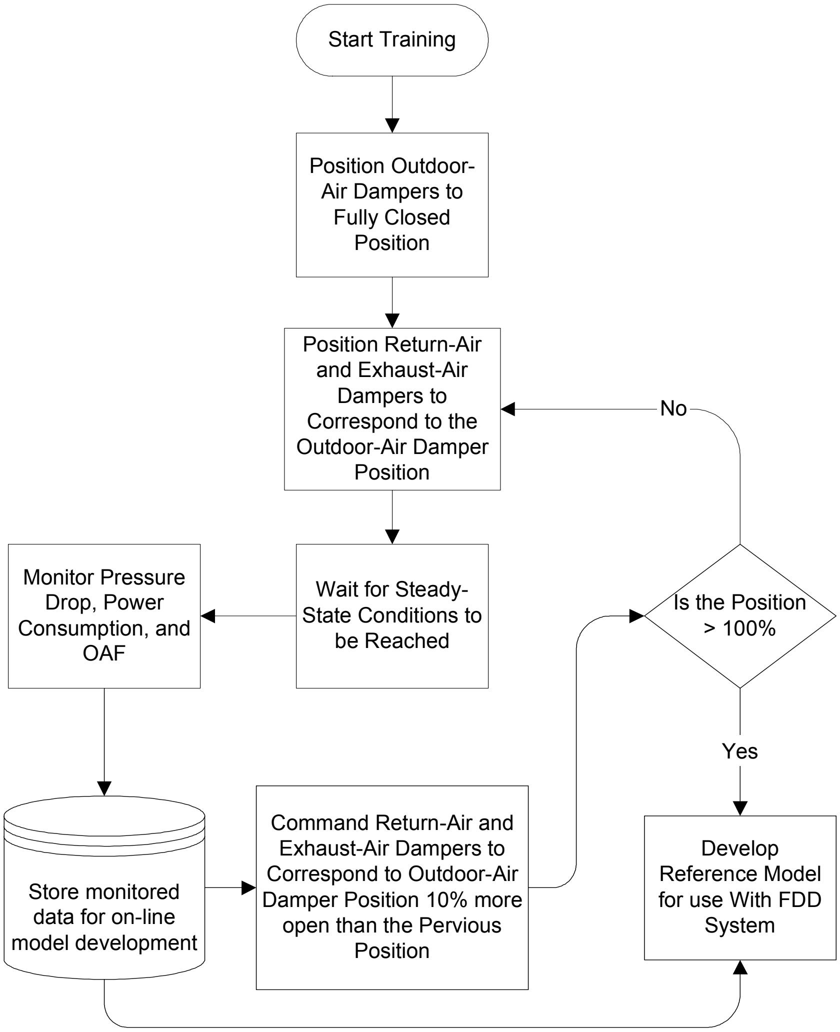

Figure 30: Overview of the process to develop a reference model to characterize the outdoor air damper stuck fully closed

7.10.3. Outdoor Air Damper Fault Detection and Diagnostics

Once the normal and faulty operation of the outdoor air damper system has been characterized, the automated continuous commissioning mode can be activated (Figure 28). The decision tree for detecting and diagnosing faulty operation is shown in Figure 31. Although the automated continuous commissioning process will identify improper operation, it may not be able to reconfigure the controls. Therefore, most problems will require some type of human intervention to repair or replace the faulty parts.

The first step in the automated continuous commissioning process is to validate all sensor measurements. If the sensor measurements are good, then estimate the signal value that controls the damper system, using the operating mode of the AHU (heating or cooling) and the indoor and outdoor conditions, and compare it to the actual measured signal value. If the measured signal value is incorrect, then there is a problem either with the controller or with the control algorithm. If the measured control signal matches the estimated control signal, then verify that the measured power consumption of the supply fan and the pressure drop across the outdoor air damper system match the values in the lookup table for normal operation. If they do, the outdoor air dampers are operating normally. If not, the conclusion is that the outdoor air damper is operating improperly. Then, the next step is to diagnose the cause of the fault by comparing the measured values of power consumption and pressure drop to the values in the lookup table for faulty operations. There are several techniques that can be used to match the measured and expected values of power and pressure drop. An efficient technique is to use fuzzy logic based rules.

As noted earlier, the automated continuous commissioning process can also be implemented just measuring the supply fan power consumption. This process is illustrated here with an example. The first step is to build a lookup table (Table 4) to characterize normal operations of the damper as described in Section 7.10.2 and shown in Figure 29. The next step is to build a lookup table (Table 4) to characterize the faulty behavior using a process similar to the one used to characterize normal operation. The characterization of outdoor air damper behavior when it is stuck in a fully closed position is illustrated in Figure 30. The values provided in Table 4 are for illustration only; they do not correspond to the values measured for any actual damper.

After the normal and faulty behaviors of the outdoor air damper are characterized in the form of a lookup table, detection and diagnosis of outdoor air damper problems can be automated. The first step in the detection process is to estimate the expected damper position signal and compare that to the actual damper signal. If the expected and the actual damper position signals match, then compare the actual measured power consumption to the value that corresponds to the damper signal in the lookup table (Table 4). For example, if the expected damper signal is 50% open and the measured supply fan power consumption is nearly equal to the 1,250 W, then it can be assumed that that the outdoor air damper is properly functioning. Suppose the expected damper signal is 50% open and the supply fan power consumption is about 1,650 W, which is greater than 1,550 kW for normal operation. Then, it can be concluded that there is a damper fault. The next step is to match the power consumption with the power consumption for fully closed and fully open operations from the lookup table (Table 4). Based on the comparison, we can conclude that the outdoor air damper is stuck in a fully closed position.

Use of pressure drop across the damper may also be useful in constructing an empirical diagnostic process. If we have both the power consumption and pressure drop the lookup function is a bit more complex (because another dimension is added), but the lookup function can be easily automated using a fuzzy logic based algorithm and the results should be superior.

Table 4: A Simple Lookup Table for Normal and Faulty Outdoor Air Damper Operation

Outdoor Air Damper Signal (% Open)	Normal Operation		Outdoor Air Damper Stuck Fully Closed		Outdoor Air Damper Stuck Fully Open	
	Outdoor Air Fraction	Supply Fan Power Consumption (Watts)	Outdoor Air Fraction	Supply Fan Power Consumption (Watts)	Outdoor Air Fraction	Supply Fan Power Consumption (Watts)
10	0.15	1,550	0.05	1,560	0.15	1,500
20	0.25	1,450	0.08	1,600	0.25	1,400
30	0.40	1,350	0.15	1,625	0.40	1,300
50	0.60	1,250	0.20	1,650	0.60	1,200
70	0.75	1,150	0.40	1,750	0.75	1,100
100	1.00	1,000	0.70	1,800	1.00	1,000

7.10.4. Other Damper Fault Detection and Diagnostics

Return air and exhaust air damper faults can also be identified and diagnosed using the process described for outdoor air dampers.

7.10.5. Background Information on Valves

In HVAC applications, valves are widely used to control fluid flow to heat exchangers (the coils) in AHUs (as shown in Figure 3) and to primary and secondary distribution systems. The valves can be two-way or three-way depending on the requirements. In an AHU, the zone thermostat activates the valves (i.e., selects cooling or heating mode) but the supply air temperature controls the amount of valve opening (i.e., by sending the control signal to the valve actuator). Unlike most damper controllers, valve controllers generally use closed loop feedback control, i.e., the valve opening is dynamically adjusted to maintain a predefined supply air setpoint. The impacts from improperly operating valves are not as severe as those of improperly operating dampers under some conditions. For example, in the cooling mode the impact of a leaking cooling valve is limited to periods of economizing (refer to Figure 4). However, like dampers, improperly operating valves, such as leaky valves, are difficult to detect.

Unlike damper faults, some faults such as valves stuck fully open or fully closed can be detected by extending the methodology presented in Section 7.7. Also, stuck valves manifest more readily because of a direct impact on the comfort of occupants, while leaky valves are difficult to detect unless the leaky is severe (greater than 30%).

Bushby et al. (2001) simulated leakage through the cooling coil valve of a VAV system for two different inlet air conditions (15 ºC and 20 ºC or 59 ºF and 68 ºF) with the chilled water (CW) temperature at 6 ºC (43 ºF) as shown in Figure 32. The supply air fan speed was held at 100%, the return air fan speed was held at 90%, and the exhaust air fan speed was held at 100%. The results indicate that unless the leakage is significant (>30% which corresponds to a temperature difference of about

1ºC), the temperature drop across the coil is within the measurement accuracies of commercially used temperature sensors. However, if the supply air fan speed can be reduced, then the temperature drop will correspondingly increase, which will allow for smaller leakages to be detected.

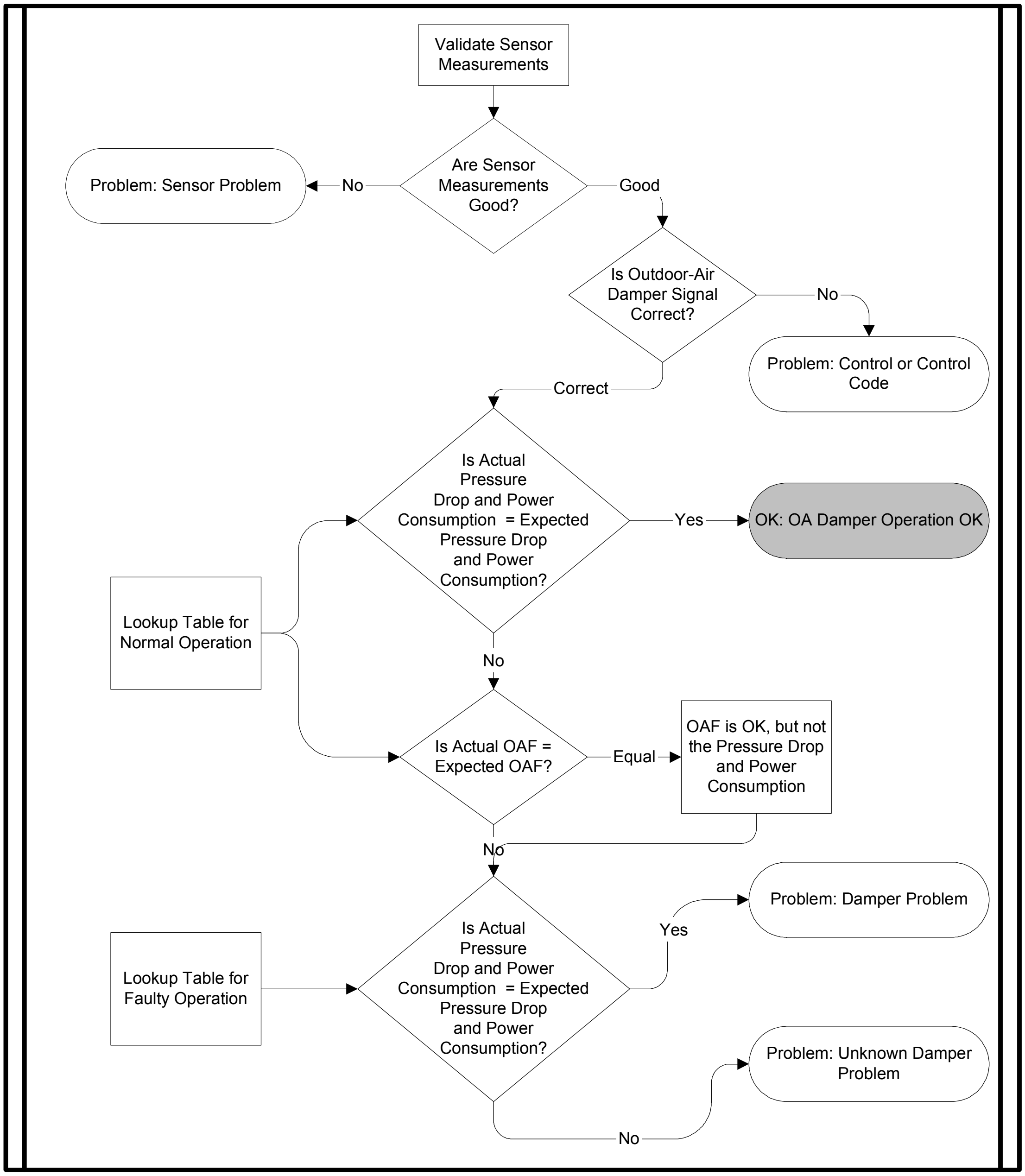

Figure 31: Decision tree to detect and diagnose outdoor air damper faults

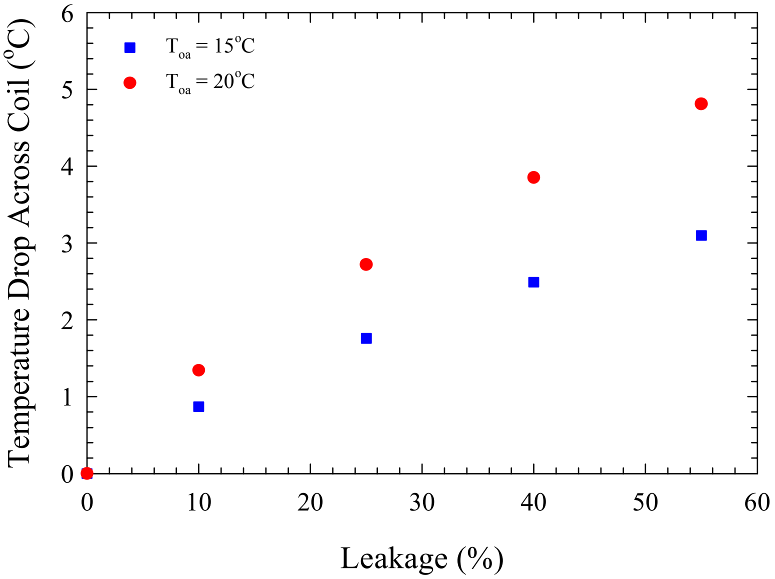

Figure 32: Temperature drop across the cooling coil as a function of the cooling coil valve leakage for inlet air temperatures to the coil of 15 °C and 20 °C (Bushby et al. 2001)

The reported results for simulated leakage through the heating coil valve are shown in Figure 33. Because the hot water (HW) temperature is higher (60 ºC or 140 ºF), the temperature differences across the coil are also higher. Again, if the supply air fan speed is reduced, then the temperature difference will increase further. In most AHUs, the temperature of the air between the heating and the cooling coils is not measured (as shown in Figure 3). In order to detect the heating valve leakage in the cooling mode, an addition air temperature sensor between the two coils is required.

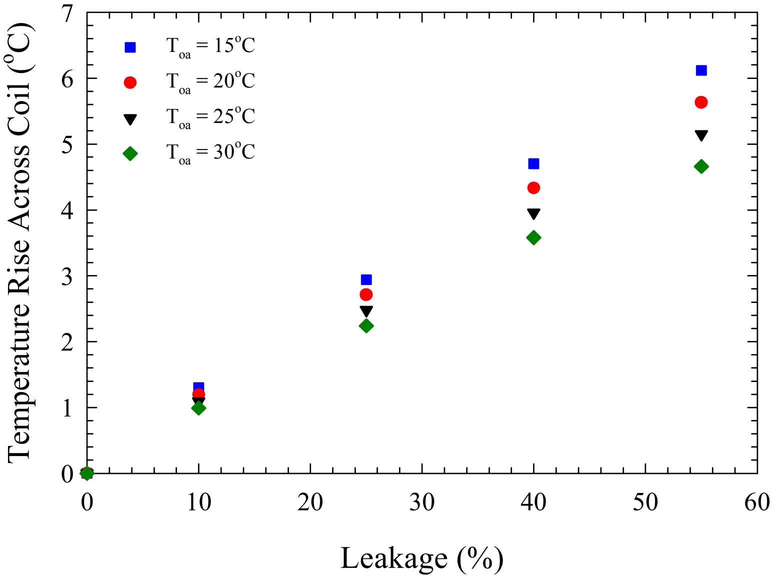

Figure 33: Temperature drop across the heating coil as a function of the heating coil valve leakage for four different inlet-air temperatures to the coil (between 15 °C and 30 °C) (Bushby et. al. 2001)

7.10.6. General Approach for Identifying Faulty and Malfunction Valves

The methodology described in Section 7.7 to detect faults with ventilation and economizer operations is based on sensors that are commonly found in AHUs and does not include faults with valves. In the next section, the previously presented methodology is extended using additional passive and proactive diagnostic tests to isolate stuck or leaky valves. In addition to the sensors shown in Figure 3, an additional temperature sensor between the two coils is required to detect a leaky HW valve.

7.10.7. Fault Detection and Diagnostics for Valves

In this section a general approach to detecting and diagnosing improper chilled and hot water valve operations is presented.

Chilled Water Valve FDD Approach

The methodology presented in Section 7.7 detects a problem with supply air temperature but does not isolate the cause of the problem. So, the starting point for the process presented in this section assumes that the AHU is in the cooling mode and is unable to maintain the supply air temperature at its setpoint. The first step in the process is to check if the supply air temperature is above the mixed air temperature as shown in Figure 34. If it is, then check if the heating and cooling are simultaneously ON. If heating is ON, then the process terminates with a problem state. If heating is not ON, then it checks for a leaky HW valve (as described in Section 7.10.8). If the HW valve is found to be leaky, the process terminates in a problem state. If there is no leak in the heating valve, the proactive process to check if the CW valve is stuck fully closed is activated as described later in this section.

If the supply air temperature is less than the mixed air temperature, then check if the supply air temperature is less than or greater than the supply air setpoint temperature. If the supply air is less than the supply air setpoint temperature, the proactive process to check if the CW valve is stuck fully open is activated as described later in this section. If the supply air temperature is greater than the supply air setpoint temperature, check if the CW supply temperature is equal to CW supply setpoint. If the CW supply temperature is greater than the setpoint, then check if the CW valve signal is at 100%. If the signal is at 100%, then the proactive process to check if the CW valve is stuck in a partial open (closed) position is activated as described later in this section. If the signal is not at 100%, then proactively command the CW valve to 100% open position (i.e., force the control signal to 100%) and wait for steady-state conditions to be reached. At this point, if the supply air temperature is still greater than the supply air setpoint, then activate the proactive process to check if the CW valve is stuck in a partially open (also partially closed) position. If the supply air temperature is less than or equal to the supply air setpoint, then the process terminates with a message to check the control logic for CW valve control.

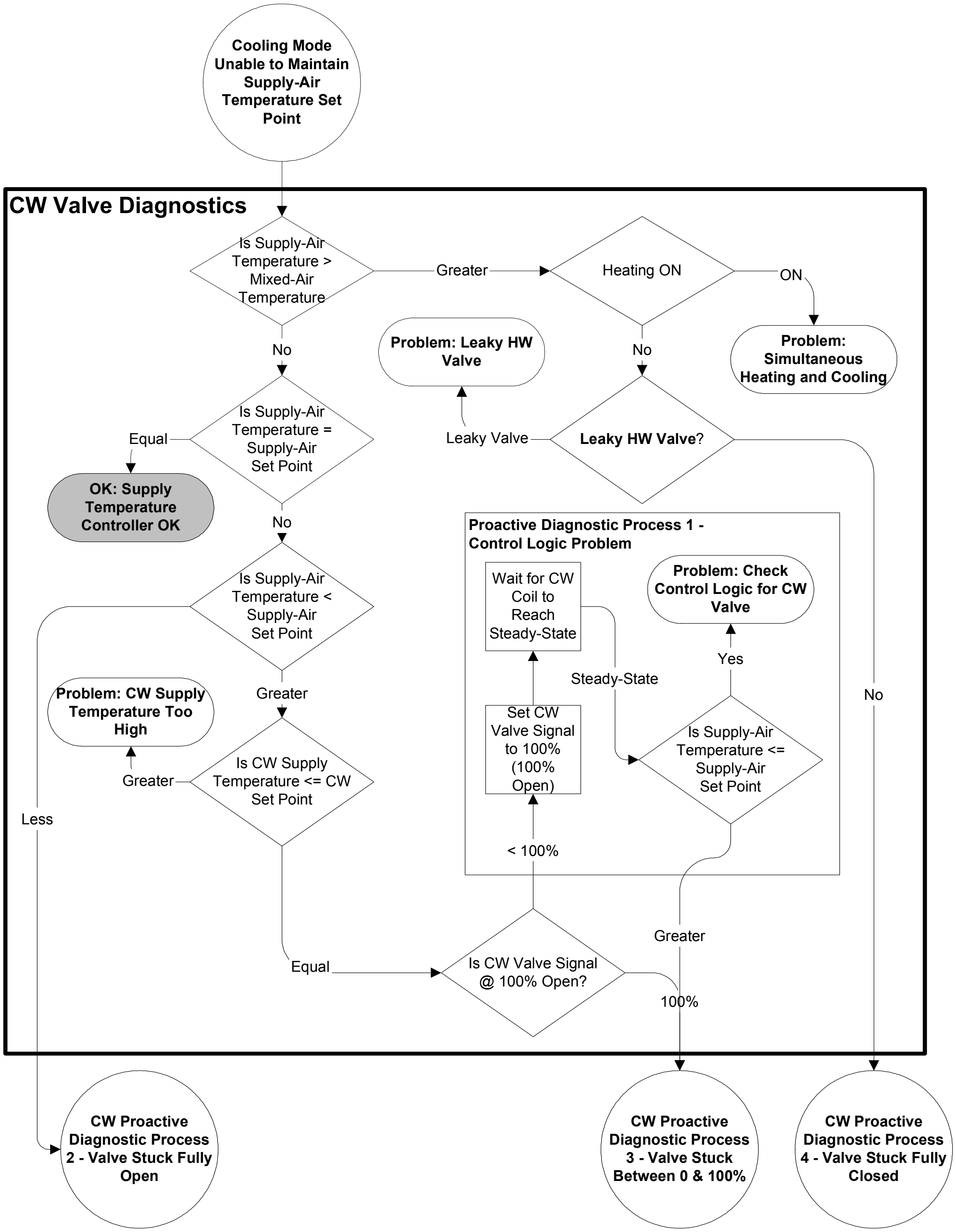

Figure 34: Overview of the chilled water valve diagnostic tree

If the supply air temperature is less than the supply air temperature setpoint, then the proactive process to check if the CW valve is stuck fully open is activated as shown in Figure 35. The first step in the process is to check if the CW valve signal is 100%; if it is, the process terminates with a message to check the CW valve control logic. If the CW valve signal is not 100%, then command the CW valve to a fully closed position (0% signal) and wait for steady-state conditions to be achieved. After steady state is reached, check if the temperature drop across the coil is nearly zero. If it is, then conclude that the controller is unable to control the valve position properly to maintain the supply air temperature setpoint. So, the process terminates with a message to check the CW valve controller or control logic.

If the temperature difference across the cooling coil is not approximately zero when the CW valve is commanded to 0%, then conclude that the valve is not modulating properly. Then command the CW valve to open fully. After steady-state conditions are achieved, check if the temperature difference is the same as when the CW valve was completely closed. If it is, then there is further proof that the CW valve is not modulating and is stuck more likely at a position near fully open. If the temperature difference is not nearly the same, then conclude that the valve is not modulating properly and terminate the process with a message to check the valve.

If at conclusion of the process in Figure 35, the CW valve is at 100% and the supply air temperature is greater than the supply air setpoint, then activate the proactive process to check if the CW valve is stuck partially open (or closed) (shown in Figure 36). The first step in the process is to check if the temperature drop across the cooling coil is nearly the same as the design temperature drop; if it is, then the cooling coil may be undersized. If the temperature drop is lower than the design temperature drop, then close the CW valve completely and wait for steady-state conditions to be achieved. If the temperature drop across the coil is zero, then conclude that the CW valve may not be modulating to a fully open position, the chilled water coil is fouled, or the CW valve needs adjustment. If the temperature drop across the coil is not zero, check if the difference is the same as before the valve was commanded to a fully closed position. If it is the same, then conclude that the valve is stuck partially open (or closed).

If at conclusion of the process in Figure 35 the supply air temperature is greater than the mixed air temperature, heating is not ON, and the HW valve is not leaking, then activate the proactive process to check if the CW valve is stuck fully closed (shown in Figure 37). The first step in the process is to check if the CW valve signal is zero; if it is, then terminate the process with a message to check the CW valve control logic. If the CW valve signal is not zero, then command the CW valve to a fully open position. After steady-state conditions are achieved, check the temperature drop across the cooling coil. If the difference is nearly zero, then conclude that the valve is stuck fully closed. If the difference is not zero, then activate the proactive process to check if the CW valve is stuck partially open (or closed) (shown in Figure 36 and described previously).

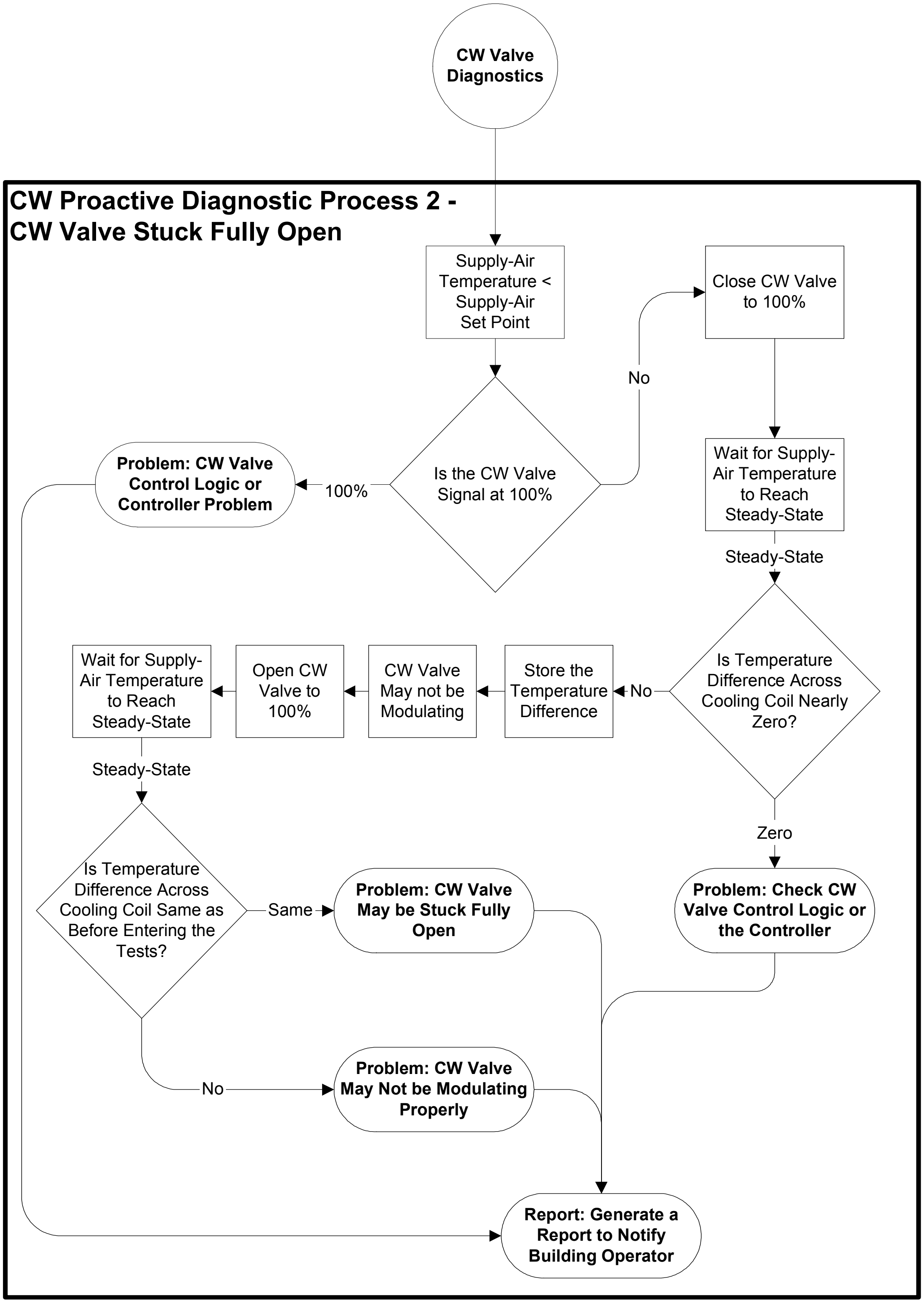

Figure 35: Proactive diagnostic process to detect a chilled water valve stuck fully open

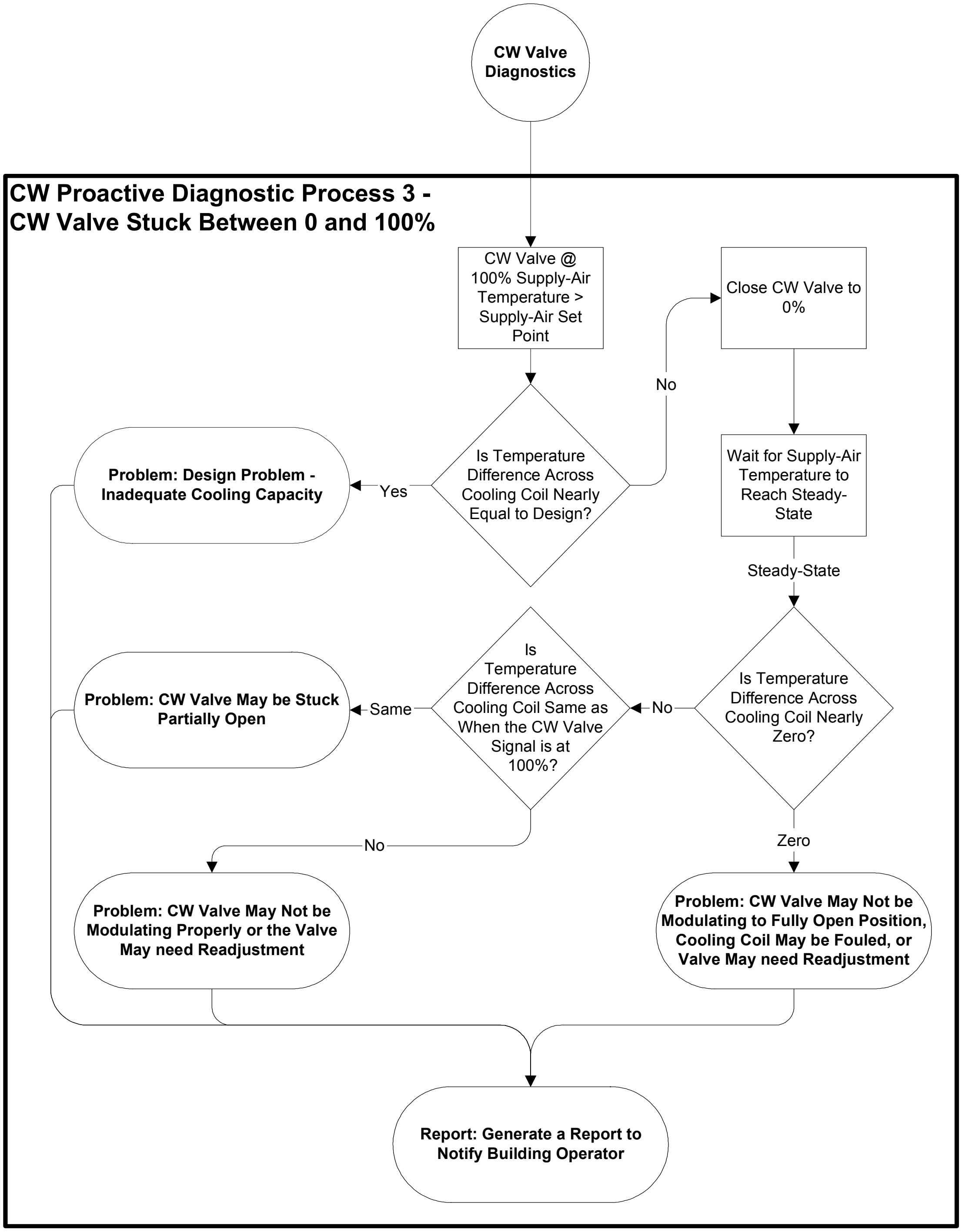

Figure 36: Proactive diagnostic process to detect a chilled water valve stuck partially open (or closed)

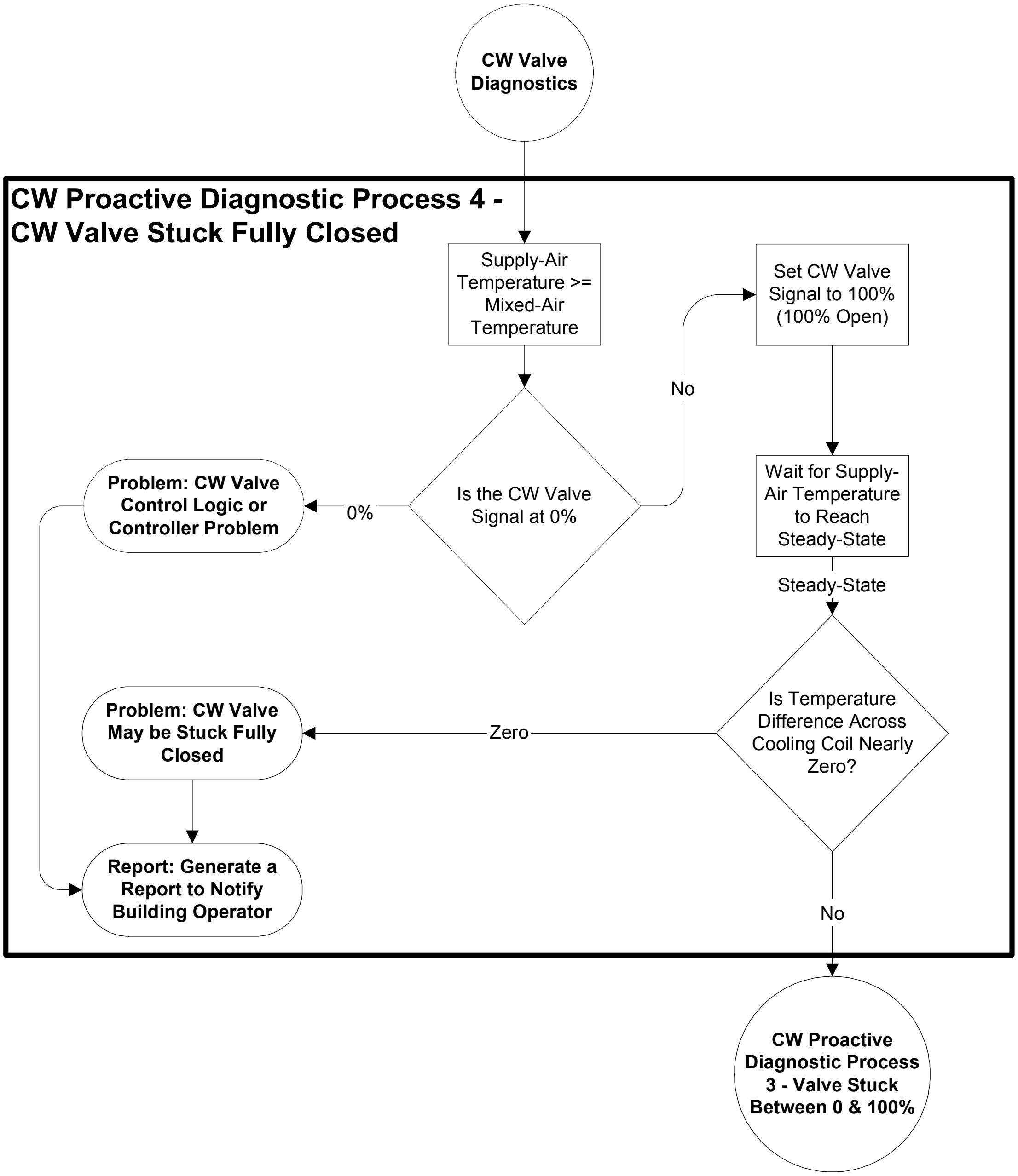

Figure 37: Proactive diagnostic process to detect a chilled water valve stuck fully open

Hot Water Valve FDD Approach

The process to identify malfunctioning and faulty hot water valves is shown in Figure 38 to Figure 41. The approach is similar to that for detecting faults with a chilled water valve described in the previous section.

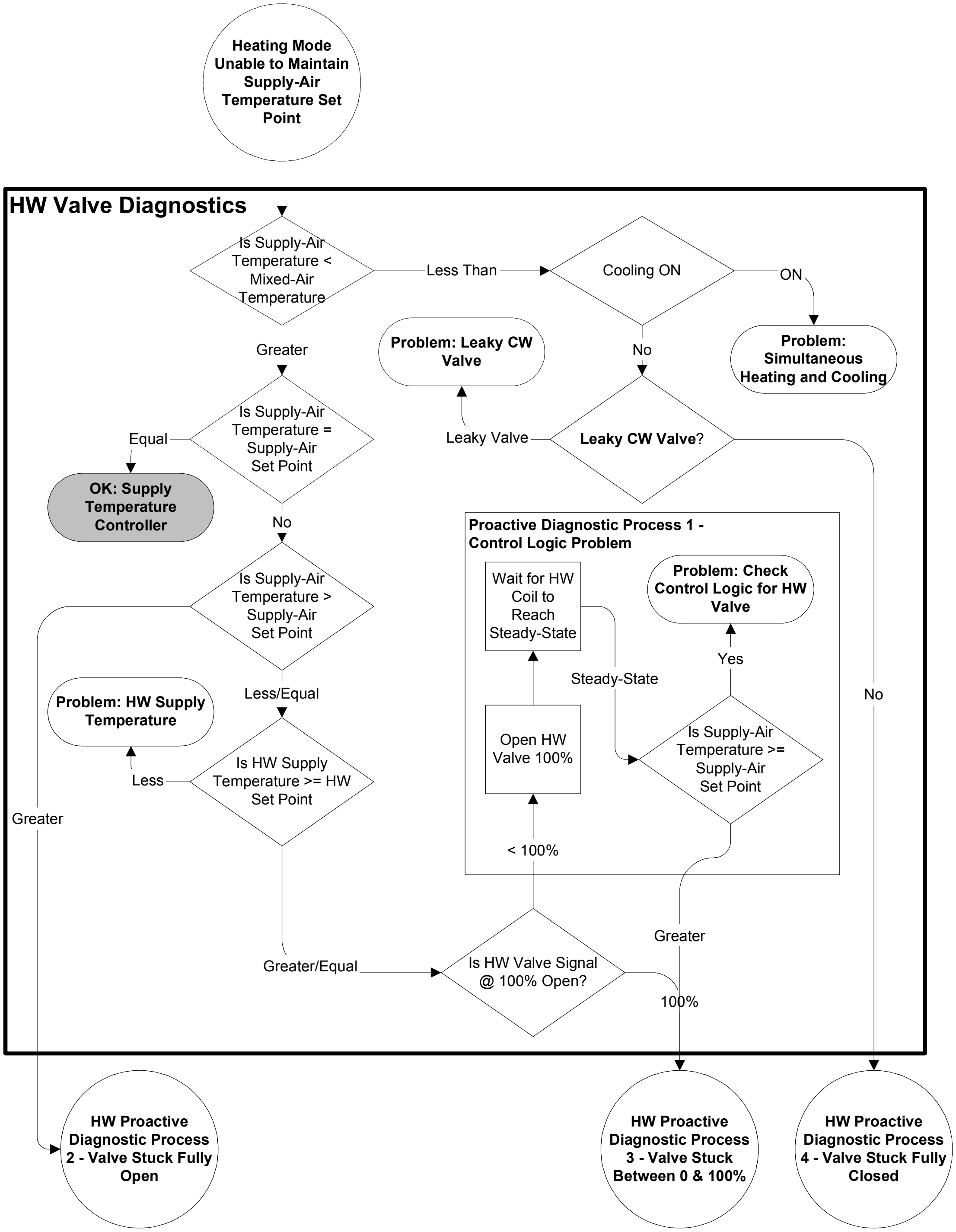

Figure 38: Overview of the hot water valve diagnostic tree

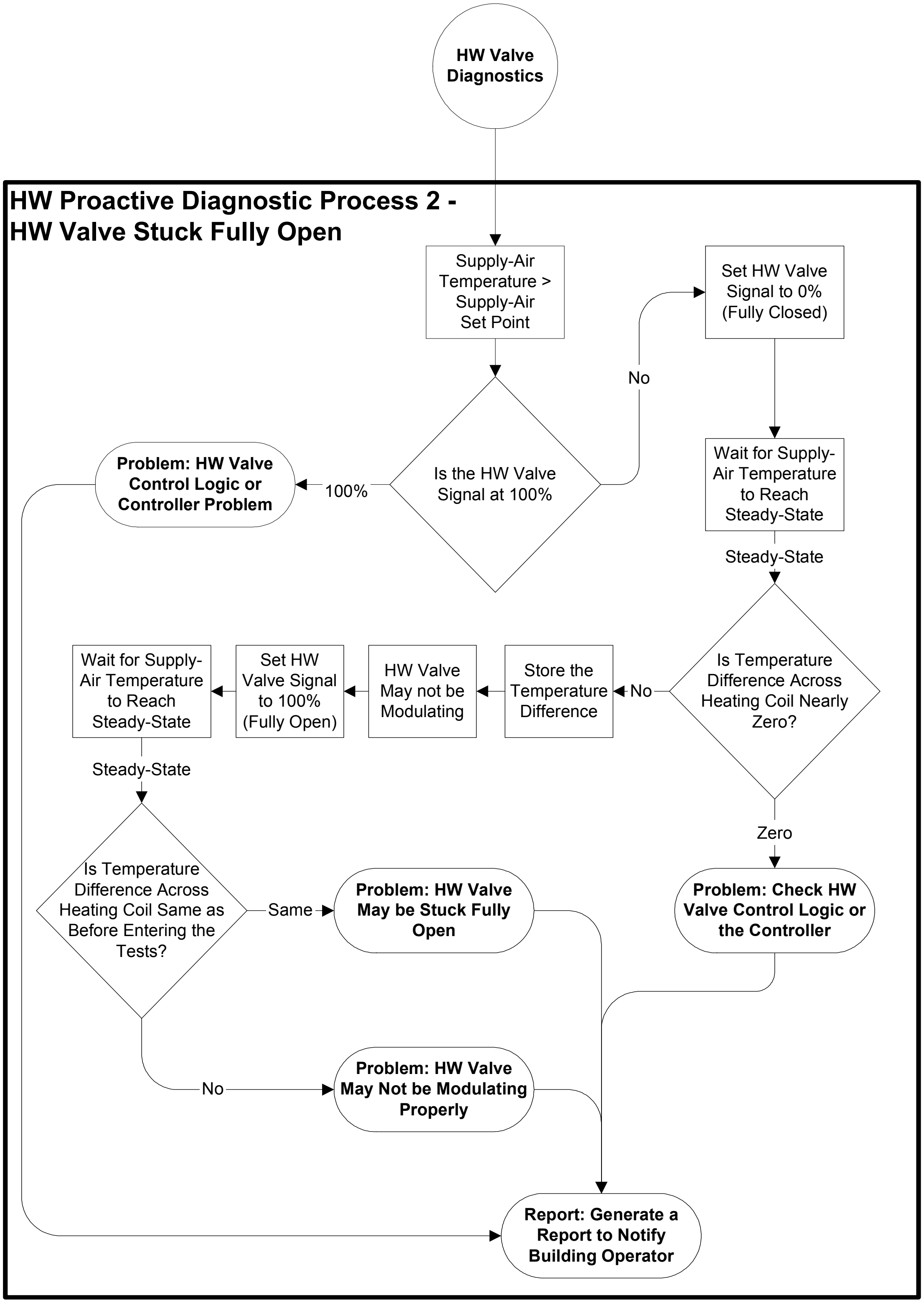

Figure 39: Proactive diagnostic process to detect a hot water valve stuck fully open

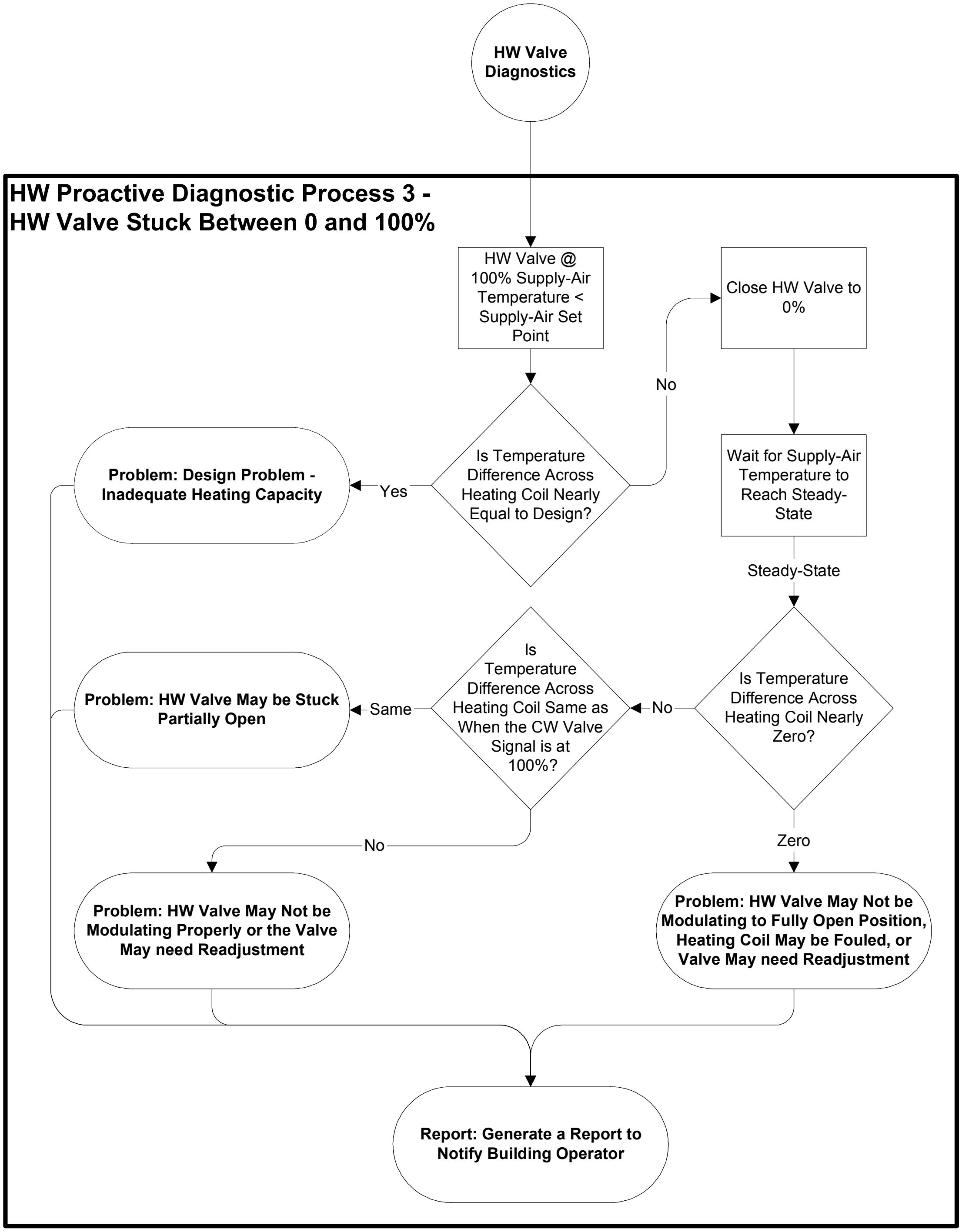

Figure 40: Proactive diagnostic process to detect a hot water valve stuck partially open (or closed)

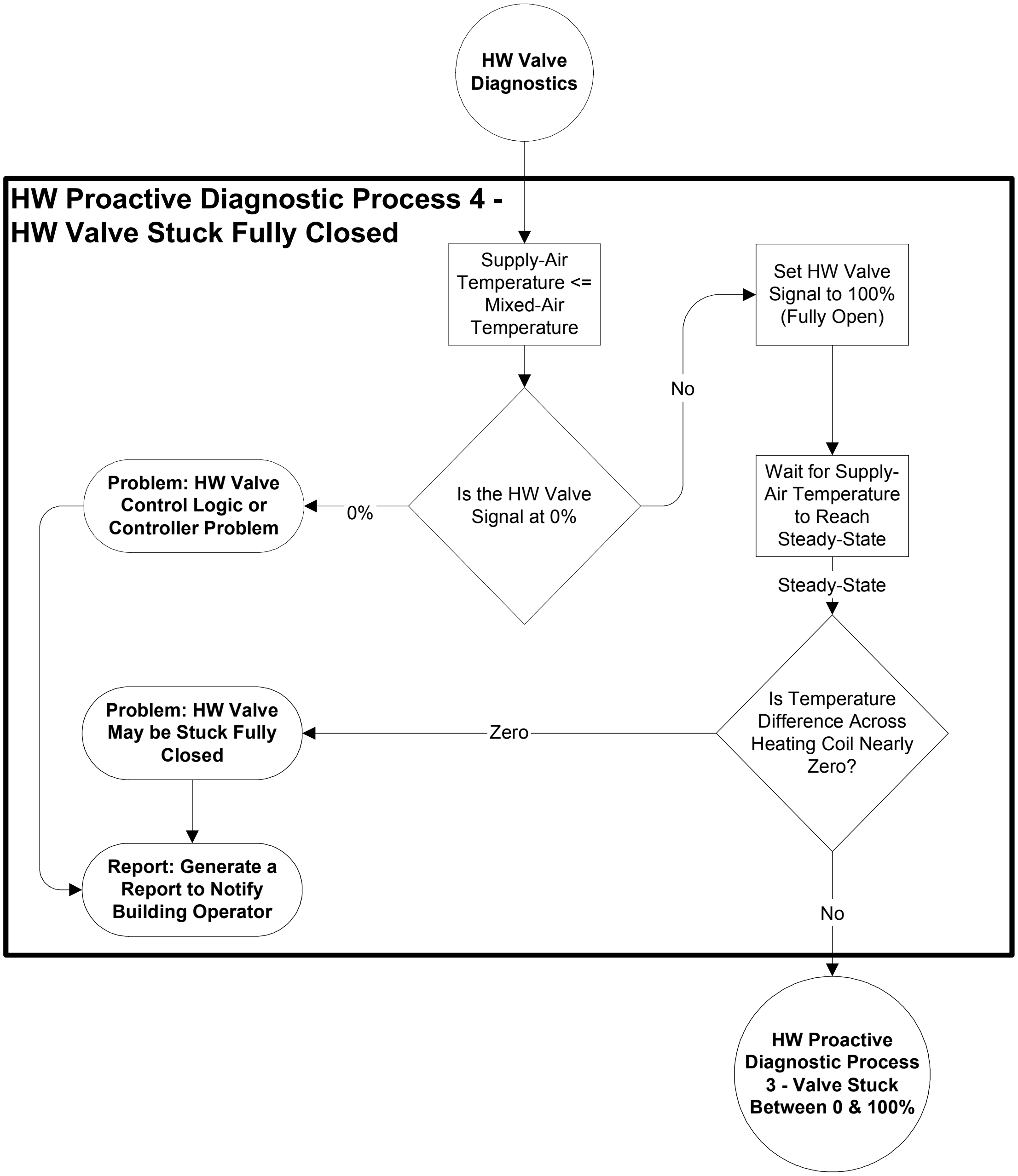

Figure 41: Proactive diagnostic process to detect a hot water valve stuck fully open

7.10.8. FDD Approach to Detect Leaky Valves

The proactive process to detect and diagnose leaky valves is illustrated in Figure 42. The first step in the proactive process is to command the valve to a fully closed position. If the supply air fan can be modulated, then reduce the fan speed to 50%. After the conditions reach steady state, compute the temperature drop across the coil (difference between the mixed air and supply air temperatures). If the temperature difference is nearly zero, then conclude that there is no leak. If the difference is greater than zero, then the valve is leaky. In order to estimate the amount of leakage, a lookup table is required. The lookup table can be developed using the on-line training method described in Section 7.10.2 (*General Approach for Detecting Malfunctioning or Faulty Dampers*). If a lookup table is available, then the next step is to estimate the leakage and report it to the building operator.

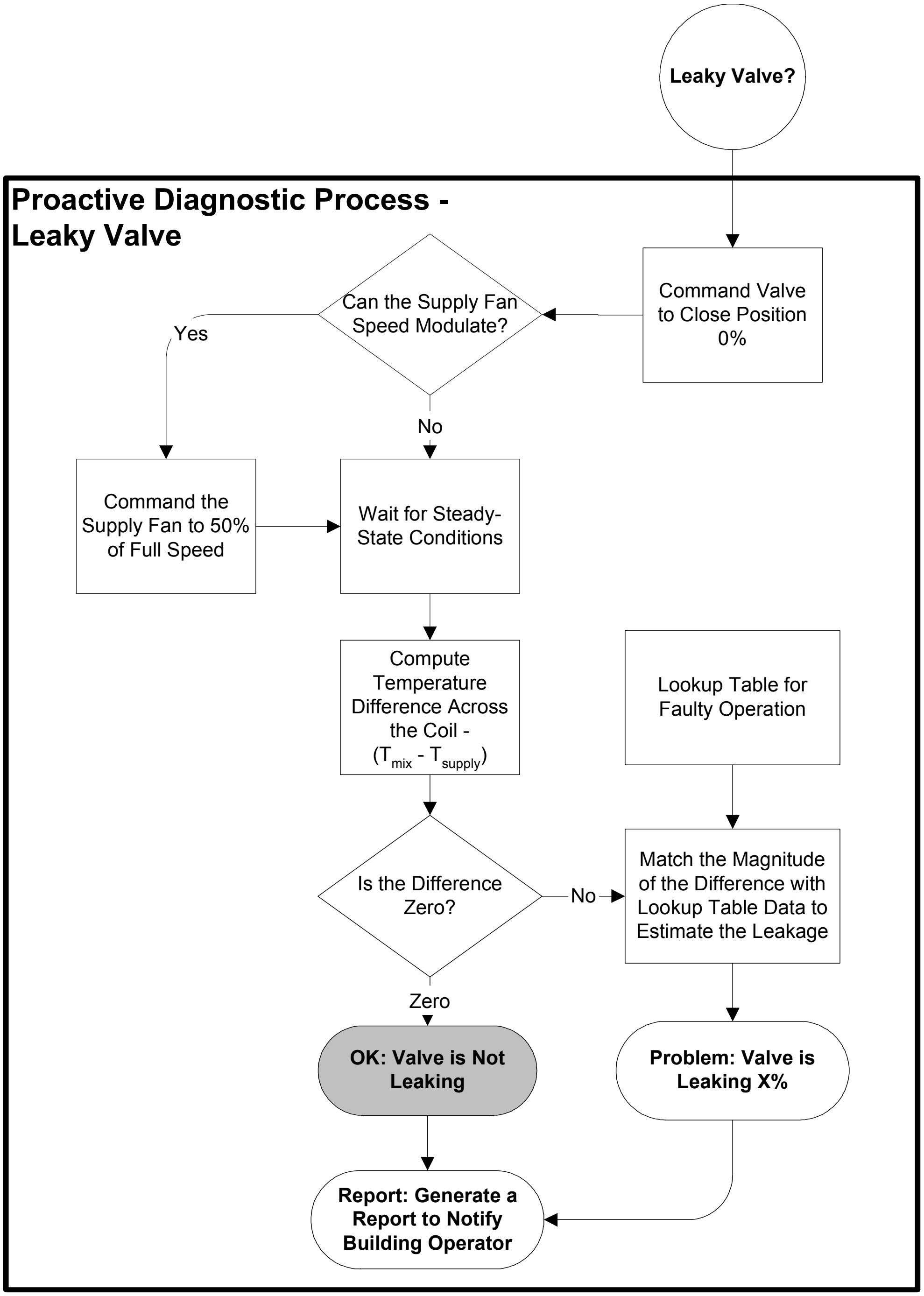

Figure 42: Decision tree to detect and diagnose leaky valves

7.11. Selection of Thresholds and Tolerances

Tightening the tolerances on values of the measured variables can increase the sensitivity of these methods for detecting faults. This, however, will also increase the probability of false alarms. This trade off arises because of noise and bias in measurements. Properly adjusting these tolerances and the sensitivity is critical to achieve the balance between these two factors desired by the user. Because noise and bias are unique to each specific combination of sensor and data acquisition equipment installed on an HVAC system and the environment in which it operates, selection of tolerances may vary from building to building or even between HVAC units in the same building. In the OAE, tolerances for each measured and static input variable are used to generate estimated uncertainties that are propagated through all calculations and tests. For example, to test if the outdoor air temperature is greater than the return air temperature, not only should the outdoor air temperature be greater than the return air temperature, but the uncertainty of the test should also be less than a specified threshold. The uncertainly thresholds and tolerances on each variable can be user specified.[3] By specifying the tolerances and adjusting the uncertainty thresholds, false alarms can be reduced or sensitivity of detecting increased.

7.12. Prototype Demonstration of Proactive Diagnostics

A prototype implementation of a proactive diagnostic procedure, which sets the foundation for automated continuous commissioning is presented in Appendix D. The prototype application is limited to isolating temperature sensor problems as described in Section 7.9. A full description of the prototype, as well as instructions for navigating through the demonstration application (refer to application provided on the compact disk) has been developed.

7.13. Compiling and Managing Data for Commissioning

7.13.1. Background

Numerous computer software applications have been developed over the years to help individual disciplines within the architectural, engineering, and construction (AEC) community perform their respective tasks, for example computer aided design programs, energy performance simulation programs, and construction and facility management programs. However, these applications were typically developed using independent platforms and protocols, and are unable to freely exchange information from one application to another. Efforts to define standards for sharing building design and construction data have been ongoing for many years. New impetus has been given to these efforts by the AEC community and organizations like the International Alliance for Interoperability.[4] Luskay and Forester (2001) provided a

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[3] Actually, although the OAE method, in principle, provides for adjusting tolerances individually, in the OAE software, all tolerances are adjusted simultaneously when the user selects a sensitivity level for the tool.

[4] http://www.iai-international.org/iai_international/

detailed review of related studies, research and development toward greater computer application interoperability. They also developed a detailed data model using the Industry Foundation Classes (IFC) to classify each data point within a chilled water system and a VAV air distribution system. If the proposed model is adopted within the IFC model, it would represent a big step towards automating aspects of the commissioning process for those two building systems. In addition, the data model can also work as a building block for developing data models of other building systems.

In this section, we describe current procedures used to compile and manage the data necessary for commissioning and to develop an automated continuous commissioning process. Discussion of the problem at hand is presented in Section 7.13.2. The data required to verify the performance of the building systems is presented in Section 7.13.3. In Section 7.13.4, a brief description of the current commissioning practice is provided, followed by a generic process to manage data and information flow in Section 7.13.5.

7.13.2. Discussion of the Problem

A vast amount of information about selection, performance, and operation of building systems is generated during the design and construction process (Luskay and Forester 2001). However, much of the information is poorly organized and seldom archived for future use. Automated continuous commissioning procedures require design data as well as performance data continuously. Therefore, effective data management is critical for any tool or system capable of automating the commissioning of building systems.

Currently, commissioning providers typically search through numerous project design documents to extract the information needed for commissioning specific systems and equipment. Sometimes the required information cannot be found anywhere in the project documents, and the commissioning provider must contact the design team or equipment manufacturer to obtain the needed information. This data gathering process can consume a substantial portion of the time spent in commissioning.

In addition, building commissioning services today remain largely a niche market. While some individual firms have successfully applied information technology (e.g., computers, databases, and easy-to-use interfaces) to the management of commissioning data, such systems have not been widely or successfully marketed. Firms performing commissioning have tended to invent their own in-house methods for managing commissioning data and use their improved methods for competitive advantage rather than marketing them.

The application of information technology to managing commissioning data can help foster a transition of commissioning services from niche market to accepted mainstream industry practice. Commissioning is complex and time consuming, particularly for buildings with central systems. Effectively applying information technology can structure and simplify the process, thereby making it less time consuming and costly, and thus lowering one of the important barriers to its widespread use.

Other ways in which information technology can help expand the use of commissioning are in harnessing the inherent efficiencies of electronic data transfer and retrieval. One aspect of electronic data transfer that is examined closely in this section is the electronic acquisition of data from contract documents, which potentially could eliminate what is currently a time consuming manual process. Other major benefits of computer based approaches to managing this data relate to the timeliness of data and the potential for efficient retrieval of up-to-date information from geographically disbursed sets of players that are involved in any building project. Finally, while many industries have moved from using paper based processes to relying on hand-held computing and communication devices, the process used by most commissioning providers remains paper based. A key step towards exploiting the efficiency improvements inherent in these hand-held devices is defining the underlying data models and usage scenarios needed for these commissioning activities.

7.13.3. Data Requirements

The data required to verify the performance of building systems include design data, equipment performance characteristics, sequencing operations, and measured equipment performance data. These data requirements can be classified into two broad categories: 1) static data and 2) continuously measured data.

Static Data

Static or set-up data refers to static information about the project, the building design, and its constituent systems and equipment. Automated tools for continuous commissioning need this set-up data before they can become operational. Static data can be further broken down as design and operational data. Examples of design data include design flow rates, design capacities, and rated efficiencies. Examples of static operation data include control setpoints.

Currently, most static data are manually gathered. While some commissioning agents use specialized data acquisition systems to collect performance data for functional tests, most read the data manually. In the future, as standard data models are defined and widely used, it will be possible to acquire much of the static data from electronic contract documents. The principal impediment to file sharing currently is the lack of standards for representing this information electronically. Two efforts currently underway to address this need for information and data communications standards are the International Alliance for Interoperability's development of Industry Foundation Classes (IFCs) and the American Society of Heating, Refrigerating and Air Conditioning Engineers' (ASHRAE) Guideline Project 20P, XML Definitions for HVAC&R.

Continuously Measured Data

In order to monitor and verify proper operation of building systems continuously, automated tools for continuous commissioning require measured data. The measured data includes any information that is required to establish the performance of the building systems. Examples of measured data include temperatures, pressures, flow rates, and power consumption.

In the future, if advanced metering technologies can lower the cost of automated metering, monitoring a larger set of conditions and parameters may become feasible and cost effective. Developments expected to help bring about these changes include continued miniaturization and improved economies of mass production for data loggers and sensors and the increased use of wireless communications for data collection within buildings (Kintner-Meyer and Brambley 2002). A large part of the cost of automated metering involves installation of wiring between sensors and data acquisition systems. Developments that promise to lower the costs of data acquisition include use of wireless communications for sensors, rapid growth in wireless local area networks (on which building data can potentially piggyback and be made accessible via the Internet), and self-powered sensors (i.e., sensors that do not require wiring to obtain power to operate).

These developments will lower the cost barriers to permanently deploying building sensors and the capabilities to read them, as opposed to using the sensors only for one-time commissioning of new buildings. Even for buildings with building automation systems (BAS), these technologies are likely to make it cost effective to add additional sensors in situations where previously they were considered cost prohibitive.

7.13.4. Current Commissioning Practice

The commissioning process is described in Sections 3.3 (for new construction) and 3.4 (for existing buildings). The commissioning process ideally begins early in the design phase and continues through the warranty phase of a project, and possibly throughout the life of the building.

A vast amount of information pertaining to system and equipment selection, performance, and operation is generated during design and construction, much of which is essential for commissioning and proper system operation.

Design phase information is typically located within the design documentation, contract documents, specifications, and drawings. Much of this information will be used during design review and performance testing to ensure each system operates per the original intent.

During the construction phase, equipment performance and operating data are most often manually extracted from plans and specifications or identified through on-site observation (e.g., meters gauges, trend data, etc.) as part of site assessments or functional testing. In many situations the required information is either poorly organized or often not even available. While automated commissioning is not dependent on acquiring set-up data electronically, such a capability could streamline the set-up process and make it feasible and advantageous to use more extensive setup data, thereby reducing time requirements for data collection, reducing data transcription errors, and improving data accuracy.

The development of standard methods and procedures for recording, storing, and transferring equipment data throughout design and construction will facilitate improved management of, and access to, this data during commissioning as well as future building operation.

7.13.5. A Generic Process to Manage Data and Information Flow

In this section, a generic process is presented to streamline the data and information flow to automated continuous commissioning tools. As described in Luskay and Forester (2001), engineering data and system information that are critical for commissioning and verifying system performance are continually generated and revised as the design process moves forward.

Common sources for the static data required for commissioning include:

1. contract documents (e.g., Owner's Project Requirements, Design Narrative, Basis of Design);
2. plans and specifications;
3. contractor submittals; and
4. as-built drawings.

Metered data can be read directly from the building automation systems or collected using stand alone data acquisition equipment. To effectively automate the continuous commissioning process, both static and metered data should be readily available in electronic format.

The data management process should capture all pertinent information needed to fully commission building systems and provide convenient storage in an electronic format. To facilitate electronic storage, a suitable data schema for use with computer based tools must be defined. The data schema should use a common, accepted protocol for identifying and classifying data and parameters. By using a standard protocol, the automated tools can read and exchange data seamlessly.

The design and development of a data schema is beyond the scope of this project, but refer to Luskay and Forester (2001) for some examples. For defining a generic process to manage the data and information flow, suitable data schemas are assumed available for the building systems.

The proposed process requires all relevant data for commissioning a system to be archived continuously throughout pre-design, design, bidding, construction, and commissioning. A generic representation of the data model is shown in Figure 43.

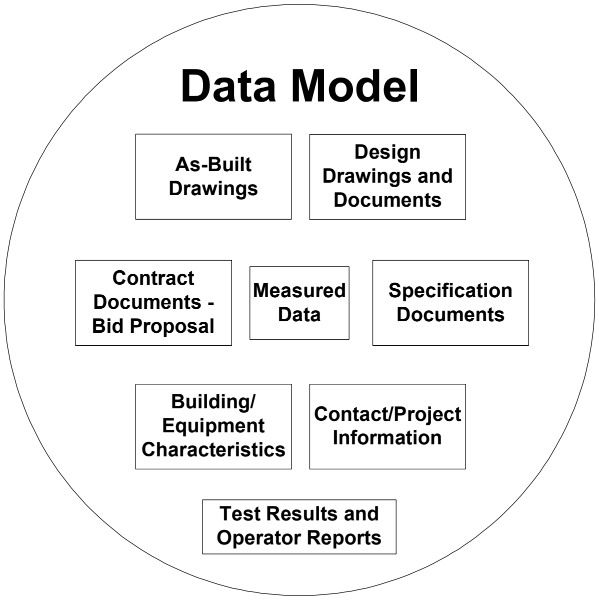

Figure 43: Generic data model showing the information it stores

The data model should conveniently hold the static design data represented by the various boxes in Figure 43 as well as the dynamic performance data that is continuously measured. The data model should be capable of maintaining the relational information between the building systems and sub-systems and also be capable of storing the functional tests requirements to commission the building systems and sub-systems continuously. In addition, the data model should also be capable of storing the test results continuously and maintaining a life cycle of changes made to the various systems in the building.

Once the data model is defined and populated with all the relevant data either electronically or manually, it can then be used by automated continuous commissioning tools as shown in Figure 44.

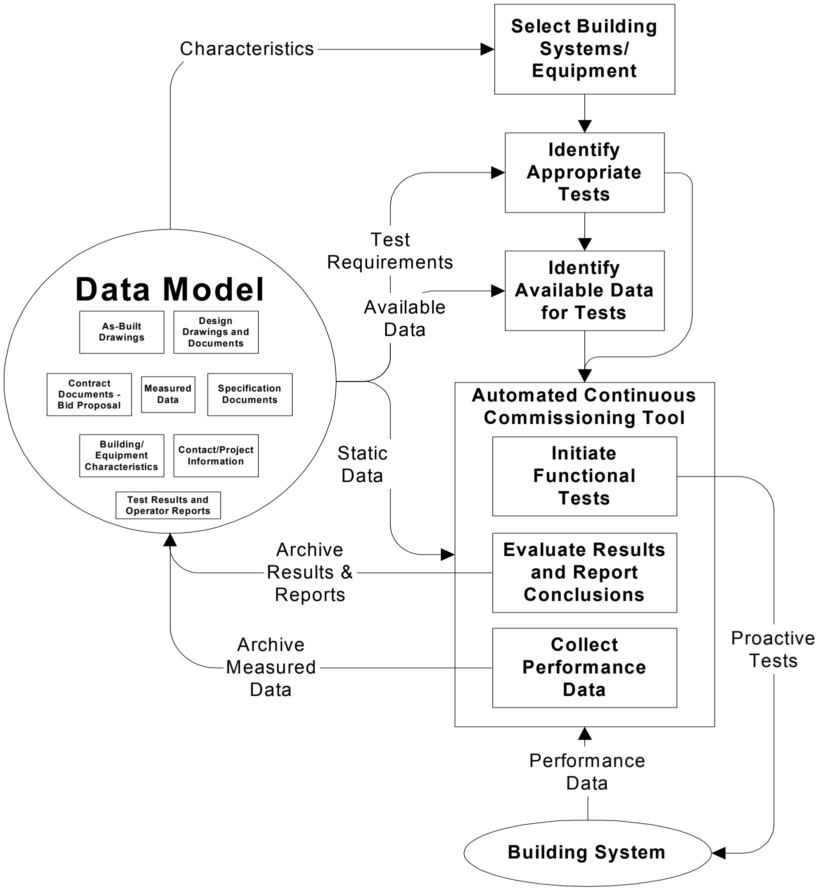

Figure 44: Generic process that shows how the data model can be used by automated continuous commissioning tools

The first step in extracting the relevant information from the data model is to identify the building system of interest. Then using the information in the model, the tests and data required for commissioning the system continuously are identified and performed. Like the static data, the measured data also must be stored in an electronic format for later use. The frequency at which the measured data are collected and stored depends on the specific functional tests and the type of building system.

If the process described here is adopted, automated tools could be used effectively to continuously commission building systems and operate them optimally at all times.

Methodology Demonstration

A demonstration of the proposed data management process for a chilled water system is outlined below. The system consists of a chiller, chilled water pump, and cooling tower.

The information for each piece of equipment needed for commissioning and system operation is separated into four categories:

1. Data needed to perform specific functional tests;
2. Data needed to confirm that the installed equipment meets contract document requirements;
3. Data identified for continuous commissioning; and
4. Data of interest to understand system operation and design.

Data for Functional Tests

The type of information needed to perform functional tests typically includes engineering data, operating parameters, and setpoints. For example, if a full load capacity test were to be performed on a chiller, the baseline data against which actual performance would be measured consists of design chilled water supply and return temperatures, design condenser water entering and leaving temperatures, design chilled water and condenser water flow rates, as well as chilled water and condenser water temperature setpoints. Most of this information comes directly from the contract documents, drawings, and specifications. Having the ability to search electronically for and extract the desired data from the source documents and input the data directly into a template for a functional test would greatly reduce the time currently spent on this task. A list of the data identified for use in functional tests for chillers, chilled water pumps and cooling towers can be found in Appendix E.

Compliance with Contract Documents

The data necessary to verify compliance with contract documents as well as ensure that the equipment passes the initial start-up procedures prior to performing a functional test typically includes engineering data and operating characteristics. For example, a commissioning provider would verify that the equipment outlined in the contractor’s submittals met the voltage, amperage, and efficiency requirements specified in the contract documents. This information would also be compared to actual measured values during the initial checkout and start-up procedures. For example, motor amperage would be measured and compared to nameplate amperage to ensure that the equipment is running at design conditions. Most of this information comes directly from contract documents, drawings, specifications, and manufacturer’s cut sheets and catalogs. A list of the data identified for use in verifying compliance and initial system checkout for chillers, chilled water pumps and cooling towers can be found in Appendix E.

Continuous Commissioning Data

Once the systems have been functionally tested and determined to meet the original design intent, actual operating conditions can be monitored continuously and compared to design to ensure that the equipment operates correctly under normal operating conditions. For example, measured values for the chiller input power, chilled water supply temperature, chilled water return temperature, and flow rates can be used to calculate chiller efficiency, i.e., the power input per ton of refrigeration.

The monitored performance can then be compared to the design performance curve provided by the manufacturer to verify that the equipment is operating properly. In addition, comparisons can be made with empirical models or models based on physical principles. Much of the baseline information comes directly from contract documents, drawings, specifications, and manufacturer's cut sheets and catalogs. The measured data could come from the central building automation system or independent monitoring equipment. A list of the data recommended for continuous monitoring to evaluate system operation under normal operating conditions for a chillers, chilled water pumps and cooling towers is provided in Appendix E.

Other Data

It may be desirable to collect and retain certain data even though the data may not be an engineering parameter or information used in a specific functional test (e.g., text describing the sequence of operations or system configuration). Many times it proves useful to consult this data in the future during equipment change out or a remodel in order to understand the original design intent. Example data include:

- sequences of operations and system descriptions, which can be used for development of functional performance tests or to understand the original design intent at some point in the future;
- chiller weight, which can be used during a future remodel to determine whether the existing structure can adequately support additional equipment;
- the original design noise class rating for a particular piece of equipment, which can be used to ensure that a replacement unit meets the design noise criteria; and
- specific operating parameters and limitations, which can be used to develop safety limits and alarms, e.g., a chiller evaporator low pressure cut-out setpoint.

This type of data can be classified into three general categories:

1. information in text or graphic formats such as sequences of operations, system descriptions, O&M manuals, and operating curves;
2. performance data for proper system operation (such as maximum operating conditions) that can be used to help troubleshoot system operation, identify safety criteria, and develop alarm criteria; and
3. non-energy related performance criteria such as equipment dimensions, noise criteria, and seismic criteria.

The same methods used to identify, collect, store, and retrieve functional test data or to verify compliance can be applied to this data as well. Most of this information comes directly from contract documents, drawings, specifications, manufacturer's cut sheets and catalogs. A list of the data for a chilled water system that may be used to help building operators understand system operation and design can be found in Appendix E.

Data Management Demonstration

During prefunctional verification, the commissioning provider checks the submittals and installed equipment against the contract documents to ensure compliance and to verify that each piece of equipment has passed a general check out procedure and is ready for functional testing. Most of the information used as the baseline in prefunctional verification can be found in the owner's project requirements, design narrative, specification documents, and CAD drawings. These data once stored in the data model can then be imported into other commissioning documents or automated software tools. Under an IFC standard, each piece of information would be uniquely classified so that any IFC compatible software application could search for it. This would include but not be limited to spreadsheets, word processing documents, CAD drawings, manufacturer cut sheets, or even building simulation programs.

The commissioning provider also develops a test procedure prior to functionally testing equipment. Typically, each test procedure is customized based on design capacities, efficiencies, temperature setpoints, flow rates, and the actual sequence of operations for the equipment. The test results are used to evaluate system performance and establish whether the equipment or system meets the owner's project requirements and acceptance criteria. Again, most of the information used to establish performance criteria for functional tests can be found in the owner's project requirements, design narrative, specification documents, and CAD drawings.

The examples that follow are intended to identify some of the data that need to be collected for commissioning and show how the extracted source data are used in prefunctional verification and functional test procedures. Example 1 illustrates a sample of the data needed for a chiller; Examples 2, 3, and 4 illustrate how the data from Example 1 (and data from Appendix E) are used in prefunctional verifications for a chiller, a chilled water pump, and a cooling tower; and Example 5 provides a sample functional test procedure and data collection form for a chiller and a cooling tower. A chilled water system was selected for demonstration because it consists of several components common to all chilled water systems. In addition, the data for the chilled water pump can be applied to any pump. The forms shown are representative of those used in commissioning. The data recorded on these forms would be included in the data model (see Figure 43) and managed by the software, making data sharing easier, data access quicker, data quality assurance more reliable, and data collection a one-time activity for each data element, rather than something that may be repeated often because of inadequate data management.

Example 1: Example Data

Currently most of the data necessary for commissioning are strewn throughout many documents and must be collected manually. The sample data for a typical centrifugal chiller, which is one of the major components of the chilled water system, is shown in Table 5. This table represents information for which the data model in Figure 43 would need to accommodate (refer to Appendix E for data pertaining to pumps and cooling tower).

The data are categorized into four different groups:

1. data needed to perform specific functional tests;
2. data needed to confirm installed equipment meets the contract intent;
3. data identified as needed for continuous commissioning; and
4. additional data that is of general interest.

The first column in the tables describes the static or measured data variable along with its units. The second column indicates whether the data variable is a number (either integer or real), text string, or text memo (narrative text). The third column shows some example values for the data variables and the fourth column indicates the type of test. The shaded lines identify data elements that are used in the prefunctional verification and functional test procedures described in Examples 2–5 below.

Once the data elements shown in Table 5 are collected and stored in a database based on the data model, they would become readily available to the test procedures automated in commissioning tools that use compatible data models (see Figure 44).

Table 5: Sample data collection form for a centrifugal chilled water system

Data Point Description	Data Type	Example Values	Test Procedures
Centrifugal Chiller			
1. Data Needed to Perform Specific Functional Tests			
Design chilled water supply temperature (°F)	Number	44 °F	Full load capacity
Design chilled water return temperature (°F)	Number	60 °F	Full load capacity
Minimum chilled water supply temperature setpoint (°F)	Number	44 °F	Full load capacity, Chilled water temperature reset
Maximum chilled water supply temperature setpoint (°F)	Number	49 °F	Chilled water temperature reset
Design maximum chilled water flow (gpm)	Number	675 gpm	Full load capacity
Design condenser water entering temperature (°F)	Number	80 °F	Full load capacity
Design condenser water leaving temperature (°F)	Number	90 °F	Full load capacity
Maximum condenser water entering temperature setpoint (°F)	Number	80 °F	Full load capacity, Condenser water temperature reset
Minimum condenser water entering temperature setpoint (°F)	Number	65 °F	Condenser water temperature reset
Design maximum condenser water flow (gpm)	Number	1350 gpm	Full load capacity, Tube bundle fouling test
2. Data Needed to Confirm Installed Equipment with Contract Documents			
Chiller make and model #	Narrative Text	Make - Mfgr Model - XYZ	Prefunctional test
Design full load capacity (tons)	Number	450 tons	Prefunctional test
Design full load efficiency (kW/ton)	Number	0.56 kW/ton	Prefunctional test
Refrigerant Type	Number	R-22	Prefunctional test
Rated full load input kW (kW)	Number	251.1 kW	Prefunctional test
Compressor motor voltage (volts)	Number	460 volts	Prefunctional test, Voltage imbalance
Compressor motor phase	Number	3 phase	Prefunctional test
Compressor motor amperage (amps)	Number	345 amps	Prefunctional test, Maximum amp check
Design maximum evaporator water pressure drop (ft H_2O)	Number	19 ft	Prefunctional test
Design maximum condenser water pressure drop (ft H_2O)	Number	31 ft	Prefunctional test
3. Data Identified for Continuous Commissioning			
Chilled water supply temperature	Number	--	Continuous monitoring
Chilled water return temperature	Number	--	Continuous monitoring
Chilled water flow	Number	--	Continuous monitoring
Condenser water entering temperature	Number	--	Continuous monitoring
Condenser water leaving temperature	Number	--	Continuous monitoring
Condenser water flow	Number	--	Continuous monitoring
Chiller kW	Number	--	Continuous monitoring
Chiller Performance Data	Graph/Table/Matrix	--	Continuous monitoring
4. Data of Interest to Understand System Operation and Design			
Sequence of Operations 1. Start-up/shut down/restart/cut-out 2. Interlocks (chillers, pumps, CTs, failure mode) 3. Chiller operation (lead/lag/staging) 4. Compressor loading control 5. Chilled water temperature reset	Narrative Text	--	
System operating schedule	Narrative Text	--	
Chiller sound spectrum graph/table	Graph/Table/Matrix	--	
Installation, O&M Manuals	Manuals/Books	--	
Evaporator low pressure cut-out (psi)	Number	26.0 psi	
Condenser high pressure cut-out (psi)	Number	140.0 psi	
Design minimum chilled water flow (gpm)	Number	400 gpm	
Design minimum condenser water flow (gpm)	Number	950 gpm	
Design chiller noise class (NC)	Number	NC-60	
Compressor motor speed (RPM)	Number	1760 RPM	
Design compressor motor efficiency (%)	Number	94.0%	
Chiller factory performance test certification	Text Document	--	
Chiller weight (lb)	Number	46000 lb	
Chiller operating speed (RPM)	Number	1760 RPM	
Chiller isolator compressibility factor (lb/in)	Number	30667 lb/in	
Chiller isolator minimum static deflection (in)	Number	1.5 in	
Design chiller vibration transmissibility (%)	Number	10%	
System description and options	Narrative Text	--	
Design criteria	Narrative Text	--	

Example 2: Chiller Prefunctional Verification

Model Verification

Table 6 is representative of tables used in commissioning to record data and perform verification of the model of chiller submitted in the bid and installed. The equipment tag, CH-1, identifies the particular chiller to which this table refers. Rows and columns labeled with 1, 2, or 3 identify data corresponding to the chiller as specified in the design documents, as submitted, and as actually installed in the building, respectively. When all entries for 1, 2 and 3 are reasonably close or equal, as shown in Table 6, the equipment submitted and installed matches the specification. Note that the data in the shaded cells comes from Table 5 and are used to determine acceptance of the actual values. The manual and visual verification process illustrated here could be automated in tools based on a suitable data model.

Examples 2, 3, and 4 illustrate how engineering data are used to perform prefunctional verifications for each piece of equipment. The values in the shaded cells in each table represent data that could be extracted from a data collection form, or directly from the applicable software specific application built upon the data model (e.g., spreadsheet, document, CAD drawing, etc.), and inserted into the prefunctional verification form in the appropriate place. Automated commissioning tools could automatically collect this data and perform the verification tests, and even provide printed output similar to these tables (if desired).

Table 6: Table for prefunctional model verification for a chiller.

1 = as specified, 2 = as submitted, 3 = as installed. Complete each entry. Enter note number if deficient.

Equipment Tag →		CH-1
Manufacturer	1	Manufacturer A
	2	Manufacturer B
	3	Manufacturer C
Model Number	1	Model XYZ
	2	Model ABC
	3	Model ABC
Serial Number	3	CH123456789

Equipment Tag →		CH-1		
		1	2	3
Chiller Capacity	tons	**450**	450	450
Chiller Motor Specifications	Volts	**460**	460	460
	Amps	**345**	340	340
	Phase	**3**	3	3
	Full load kW	**251.1**	249	249
Full load Efficiency	kW/ton	**0.56**	0.55	0.55
Refrigerant Type		**R-22**	R-22	R-22

The equipment submitted and installed matches the specifications: ☒YES ☐NO

Operational Checks

In addition to verifying the specifications for the equipment installed compared to the equipment specified, commissioning requires that other equipment operating conditions be checked prior to performing functional tests to ensure test results will be accurate. Chiller condenser and evaporator tube bundle fouling is described here as an example.

The steps to check for tube bundle fouling in the condenser or the evaporator are as follows. Take pressure drop readings across the tube bundles from the testing and balancing (TAB) report and plot the values on the manufacturer's differential pressure charts. By comparing the flow rate (e.g., in gpm) to those shown on the charts, the pressure drop can be verified as acceptable. Compare those flow rates to the ones measured with the TAB's flow meter. If the actual flow from the TAB meter is more than 10% less than the design values (as found on the differential pressure chart), conclude that there is a clogged strainer or fouled tubes. While performing this check out manually, the data are recorded in a form like the one shown in Table 7. Data entry as well as comparisons of measured and manufacturer's design values could be automated, providing the commissioning agent with an electronic record and printed file of the results. Again note that the data highlighted in the shaded cells comes from Table 5.

Table 7: Representative table for recording data necessary for evaluating whether the evaporator and condenser have clogged strainers or fouled tubes.

	Chiller CH-1		**Chiller ______**	
	Condenser	Evaporator	Condenser	Evaporator
Design Differential Pressure	**31 ft**	**19 ft**		
Design Flow Rate	**1350 gpm**	**675 gpm**		
Measured Flow from TAB meter	1425 gpm	685 gpm		
TAB flow within 10% of design?	**Yes**	**Yes**		
Measured Differential Pressure	35 ft	25 ft		
Flow from Manufacturer's Chart	1450 gpm	710 gpm		
TAB flow within 10% of Manufacturer's Chart?	**Yes**	**Yes**		
Strainer checked and found clean?	Yes	Yes		

Example 3: Chilled Water Pump Prefunctional Verification

Model Verification

Table 8 is representative of tables used in commissioning to record data and perform verification of the model of chilled water pump submitted in the bid and installed in the chilled water system. The equipment tag, CHWP-1, identifies the particular pump to which this table refers. Rows and columns are labeled with 1,2 and 3 as described in Example 2. When all entries for 1, 2 and 3 are reasonably close or equal, the chilled water pump submitted and installed matches the specification. The data in shaded cells comes from the data points for the chilled water pump outlined in Appendix E and are used to determine acceptance of the actual values.

Table 8: Table for prefunctional model verification for a chilled water pump.

1 = as specified, 2 = as submitted, 3 = as installed. Complete each entry. Enter note number if deficient.

Equipment Tag →		CHWP-1
Manufacturer	1	Manufacturer A
	2	Manufacturer A
	3	Manufacturer A
Model	1	Model XYZ
	2	Model ABC
	3	Model ABC
Serial Number	3	P#45-BB123

Equipment Tag →		CHWP-1		
		1	2	3
Pump Capacity	GPM	**765**	770	780
Net Pump Head	FT	**110**	115	125
Pump Motor Specifications	Volts	**460**	460	460
	Amps	**45.6**	45	43
	Phase	**3**	3	3
	HP	**40**	40	40
	Motor Efficiency (%)	**94.5**	93.8	93.8
Pump NPSH	FT	**5**	6	6.5
Pump Impeller Size	in	**10.3**	10.5	11

The equipment submitted and installed matches the specifications: ☒YES ☐NO

Operational Checks

In addition to verifying the specifications for the chilled water pump installed compared to the equipment specified, commissioning requires that other equipment operating conditions be checked prior to performing functional tests, as designated in Table 9. These tests are typically performed by both visual inspection and field measurements. For example, the direction of rotation of the pump can be checked visually, but pump voltage and amperage must be measured. Results are recorded in a form like the one shown in Table 9. The data model in Figure 43 would provide space for these data elements. Data entry as well as comparisons of measured and manufacturer's design values can be automated, providing the commissioning agent with an electronic record and printed file of the results. The shaded data come from the data points for the chilled water pump outlined in Appendix E and are used to determine acceptance of the measured values.

Table 9: Representative table for verification of proper start-up operation of a chilled water pump.

Check if Okay. Enter comment or note number if deficient.

Check **Equipment Tag →**	**CHWP-1**	**Contr.**
Pump rotation is correct		
Pump has no unusual noise or vibration		
No leakage around fittings		
Valves that require a positive shut-off are verified to not be leaking when closed		
All status indicators are functioning		
The HOA switch properly activates and deactivates the unit		
All safeties and interlocks operate correctly		

Check Equipment Tag →	CHWP-1	Contr.
Record full load running amps for pump. **45.6** rated FL amps x **1.15** srvc factor = _______ (Max amps). Running less than max?		
Check pump motor voltage: Rated = **460** Actual = ______ Within 5%?		
Check pump motor voltage imbalance: %Imbalance = 100 x [(Vaverage – Vlowest) / Vaverage] Imbalance less than 2%?		
Specified sequences of operation and operating schedules have been implemented with all variations documented		
Specified point-to-point checks have been completed and documentation record submitted for this system		

The checklist items are all successfully completed for given trade: ☐YES ☐NO

Example 4: Cooling Tower Prefunctional Verification

Model Verification

Table 10 is representative of tables used in commissioning to record data and perform verification of the model of cooling tower submitted in the bid and installed in the chilled water system. The equipment tag, CT-1, identifies the particular cooling tower to which this table refers. Rows and columns are labeled with 1,2 and 3 as described in Examples 2 and 3. When all entries for 1, 2 and 3 are reasonably close or equal, the cooling tower submitted and installed matches the specification. The data in shaded cells comes from the data points for the cooling tower outlined in Appendix E and are used to determine acceptance of the actual values. As with Examples 2 and 3, the manual and visual verification process illustrated here could be automated in tools based on a suitable data model.

Table 10: Representative table for prefunctional model verification of a cooling tower.

1 = as specified, 2 = as submitted, 3 = as installed. Complete each entry. Enter note number if deficient.

Equipment Tag →		CT-1
Manufacturer	1	Manufacturer A
	2	Manufacturer A
	3	Manufacturer A
Model	1	Model XYZ
	2	Model XYZ
	3	Model XYZ
Serial Number	3	CT#AS-1500

Equipment Tag →		CT-1		
		1	2	3
Tower Capacity	tons	**1500**		
Fan Motor Specifications	Volts	**460**		
	Amps	**24**		
	Phase	**3**		
	HP	**20**		
	Motor Efficiency (%)	**90.0**		
Temperature Difference	°F	**10**		
Approach Temperature	°F	**9**		
Sump Heater Input	kW	**12**		

The equipment submitted and installed matches the specifications: ☐YES ☐NO

Operational Checks

In addition to verifying the specifications for the cooling tower installed compared to the equipment specified, commissioning requires that other operating conditions be checked prior to performing functional tests, as designated in Table 11. These tests are typically performed by both visual inspection and field measurements. For example, the direction of rotation of the fan can be checked visually, but fan motor voltage and amperage must be measured. Results are recorded on a form like the one shown in Table 11. Data entry as well as comparisons of measured and manufacturer's design values can be automated, providing the commissioning agent with an electronic record and printed file of the results. The shaded data come from the data points for the cooling tower outlined in Appendix E and are used to determine acceptance of the measured values.

Table 11: Representative table for verification of proper start-up operation of a cooling tower.

Check if Okay. Enter comment or note number if deficient.

Check **Equipment Tag →**	**CT-1**	**Contr.**
Fan rotation is correct		
Fan has no unusual noise or vibration		
No leakage around fittings		
Valves that require a positive shut-off are verified to not be leaking when closed		
All status indicators are functioning		
The HOA switch properly activates and deactivates the unit		
All safeties and interlocks operate correctly		
Record full load running amps for fan. **24.0** rated FL amps x **1.15** srvc factor = ________ (Max amps). Running less than max?		
Check fan motor voltage: Rated = **460** Actual = _______ Within 5%?		
Check fan motor voltage imbalance: %Imbalance = 100 x [(Vaverage – Vlowest) / Vaverage] Imbalance less than 2%?		
Variable frequency drive – refer to VFD checkout sheet for cooling tower fan		
Specified sequences of operation and operating schedules have been implemented with all variations documented		
Specified point-to-point checks have been completed and documentation record submitted for this system		

The checklist items of Part 5 are all successfully completed for given trade: ☐YES ☐NO

Example 5: Chilled Water System Functional Test Procedure

The following examples illustrate how engineering data would be used to develop, or adapt and use, a functional test procedure to verify system compliance. Compliance is verified by comparing test results to the acceptance criteria. Table 12 is a representative form for recording data from functional tests and providing design data for comparison. The shaded values in the table represent the data that could be extracted from a data collection form as illustrated in Table 5, from a shared project database (based on an appropriate data model), or directly from applicable software specific application (e.g., spreadsheet, document, CAD drawing, etc), and used in the function test procedure and analysis. The design data are typically the basis for verifying system performance. Design values, taken from a form like Table 5, are shaded in Table 9. In automated tools, these values would become automatically available to the functional test analytic procedures. In the manual process, measured values are entered into the blanks following the design values. Differences between these values are then calculated and compared to the acceptance criteria, which also are provided in the Table 12. Data entry as well as analytic calculations and comparisons to design values could be automated, providing the commissioning agent with more streamlined accurate data management and an electronic record and printed file of the results.

Table 12: Representative table for recording data associated with functional tests of a chilled water system.

Full Load Test: Perform the following tests and measurements by forcing each chiller to its maximum capacity. Typically it is best to perform these tests during a near-peak cooling day. Any false loading should be done gradually to avoid overloading systems. Loading can be done by some combination of increasing the building load (e.g., by lowering cooling setpoints), heating the building, manipulating cross-over valves between the chilled water and condenser water piping, or manipulating the chilled water mixing valve on the chilled water return line.			
CHILLERS	**CH-1**		
1. Leaving chilled water (CHW) temp, design / measured. Acceptance: ±5% of design	**44°F** / _______		
2. Entering CHW temp, design / measured. Acceptance: ±5% of design	**60°F** / _______		
3. Delta (entering - leaving) CHW temp, design / measured. Acceptance: ±10% of design	**16°F** / _______		
4. Evaporator water flow rate, design gpm / measured gpm. Acceptance: ±5% of design	**675 gpm** / _______		
5. Chiller cooling capacity, design tons / calculated tons. Acceptance: ±10% of design	**450 tons** / _______		
6. Chiller input power, design kW / measured kW. Acceptance: ±10% of design	**251.1 kW** / _______		
7. Chiller full load efficiency, design kW/ton / calculated kW/ton. Acceptance: ±10% of design	**0.56 kW/ton** / _______		
COOLING TOWERS	**CT-1**		
8. Design ambient air temperature (°F, Tdb/Twb)	**90°F** / **71°F**		
9. Measured ambient air temperature (°F Tdb/Twb)	_____ / ______		
10. Entering tower water (CW) temp, design / measured	**90°F** / _______		
11. Leaving tower water temp, design / measured	**80°F** / _______		
12. Delta (leaving - entering) CW temp, design / measured. Acceptance: ±10% of design	**10°F** / _______		
13. Tower water flow rate, gpm, design / measured. Acceptance: ±10% of design	**3600 gpm** / _______		

Prototype Demonstration of the Data Extraction Process

The scope of the work was to develop the framework for data management but not to develop data management tools. The following demonstration illustrates how data can be stored and accessed selectively for specific commissioning tasks. The demonstration shows how data can be viewed and accessed in a hierarchical manner and extracted to support specific commissioning tasks. Although the demonstration only enables the user to view the data extracted for specific purposes, by analogy the user should be able to infer that the extracted data could be used for manual commissioning or transferred directly to tools that automatically implement commissioning tasks. The active parts of this demonstration implementation are limited to chilled water systems and their subsystems as outlined above (i.e., centrifugal chiller, pump, cooling tower).

Description of the Tool

This demonstration has been implemented in a Microsoft Excel Spreadsheet using the Visual Basic for Applications (VBA) programming language. The spreadsheet shows the hierarchal relationship between the building, its various systems, and the sub-systems of each system. The process demonstrated corresponds to the process of extracting data that has been stored in a database based on an accepted data model such as shown in Figure 43. Data extraction is part of the overall process for managing and using the data model to support commissioning, which is shown for automated continuous commissioning in Figure 44.

Data have been stored in the spreadsheet (which is analogous to data stored in a database). Buttons are used to provide access to this data for specific equipment (e.g., a centrifugal chiller) for specific purposes (e.g., a prefunctional test). The demonstration software accesses the data for the equipment and use selected by the user. The commissioning information included in the demonstration covers information necessary for prefunctional tests, functional tests, and continuous commissioning tests for centrifugal chillers, pumps, and cooling towers.

Data are already stored in the spreadsheet in this example, and the spreadsheet illustrates access to this data. However, the demonstration does not show original collection and storage of this data. It is assumed that the data could have populated the database by a potential application utilizing standard data mining techniques. Even so, even a fully developed tool with the limited capabilities of this spreadsheet could be useful in managing data for HVAC system commissioning as done manually today. Such a tool would organize data, ensuring that it only needs to be collected once, and provide convenient access to the data as needed during the course of commissioning. Taking this concept a step further, such a database could be used to store and provide data automatically for automated commissioning tools as shown in Figure 44.

Overview of the Tool

Figure 45 shows the tool's Building Level screen with a button[5] for each of the major building systems: HVAC, electrical, access and security, and miscellaneous. Only the HVAC Systems button is active in this demonstration.

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[5] Any button that is enabled works like a toggle switch, i.e., when clicked once, the sub-subsystems under that category become visible, and when clicked a second time the subsystems are hidden.

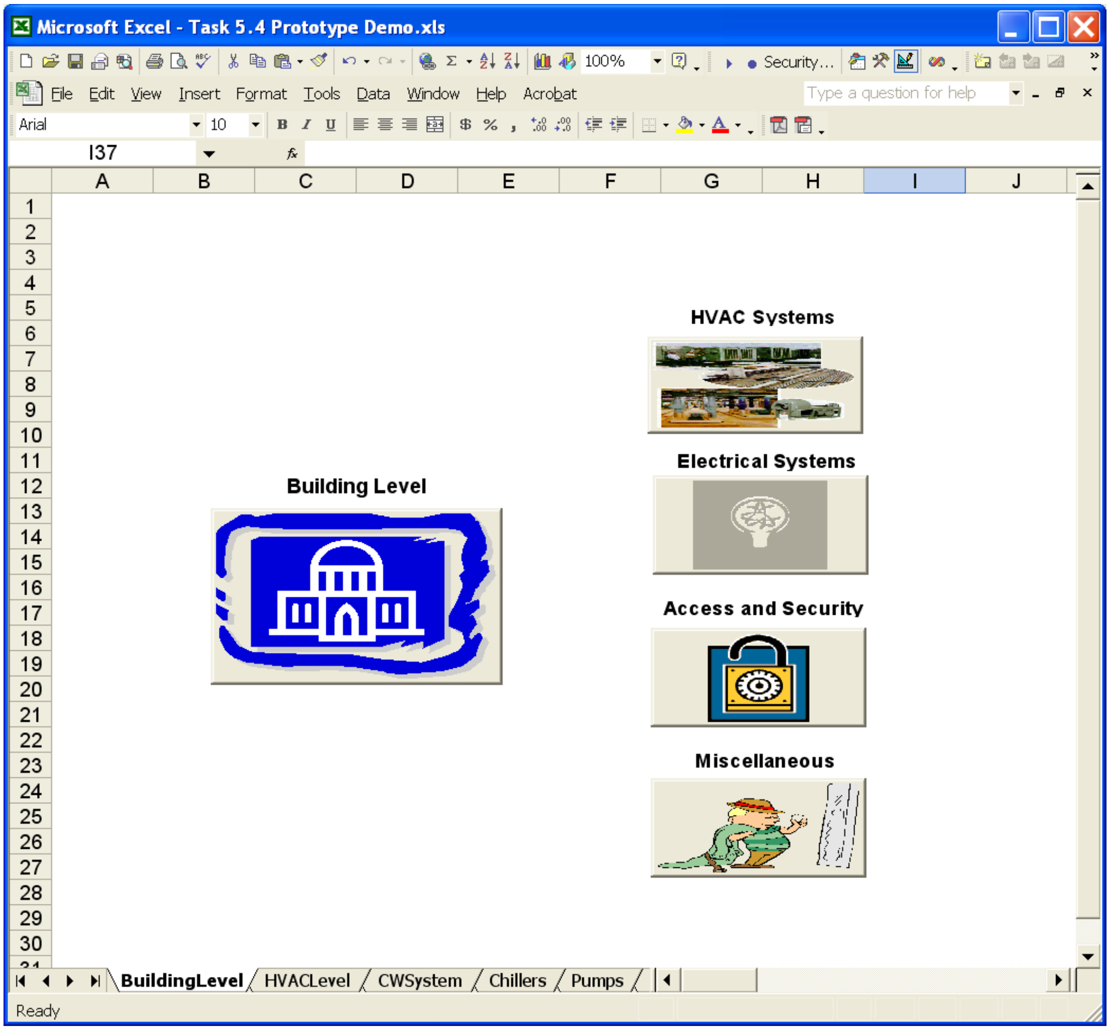


Figure 45: Screen shot of the prototype implementation of the data management process – Building Level

Clicking the HVAC Systems button displays the HVAC Systems screen (Figure 46) which contains buttons for each of the HVAC sub-systems: Chilled water, hot water, air distribution, and miscellaneous. On this screen, only the Chilled Water Systems button is active in this demonstration.

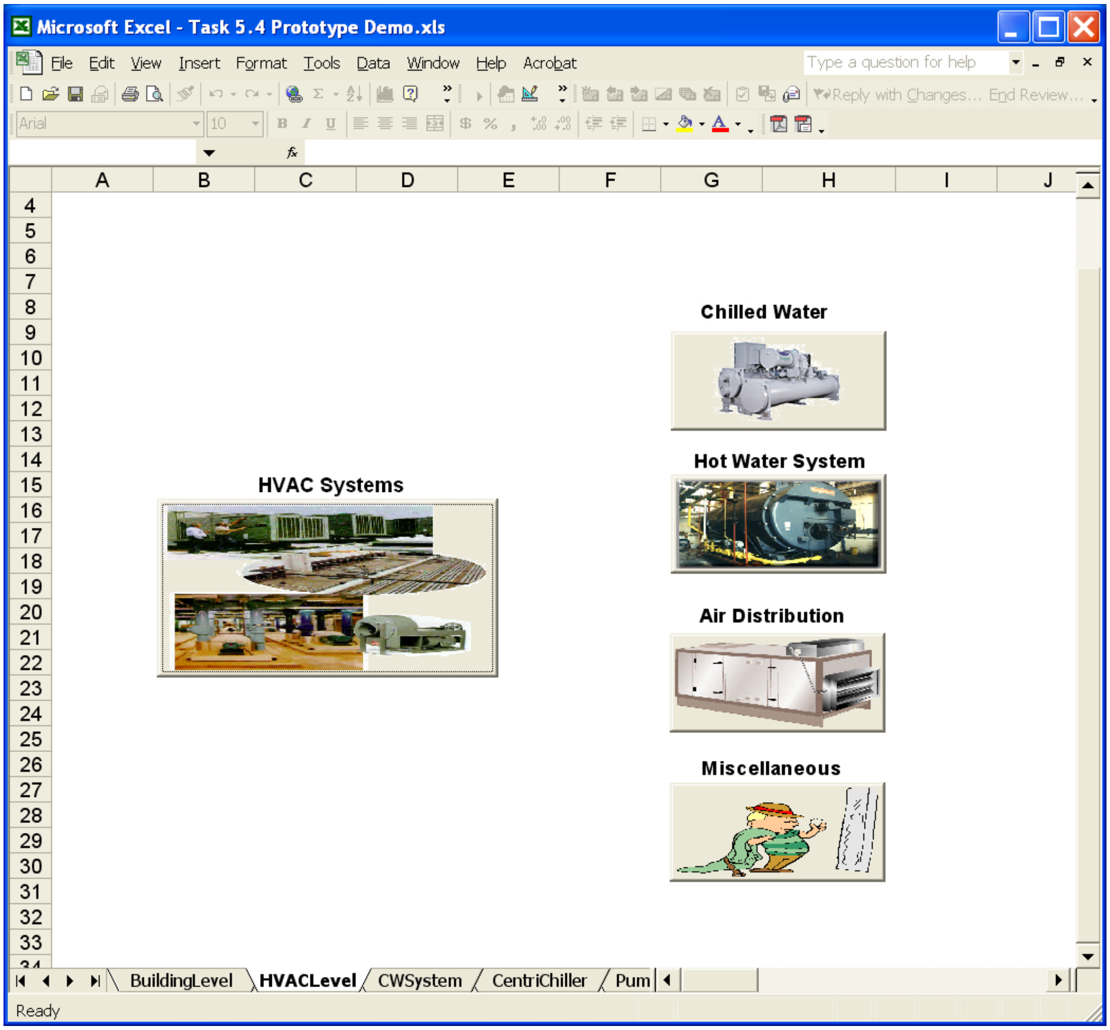


Figure 46: Screen shot of the HVAC system level information

Clicking the Chilled Water button displays the Chilled Water System screen (Figure 47) which contains buttons for each type of the chilled water system components: chillers, pumps, cooling tower, and miscellaneous.

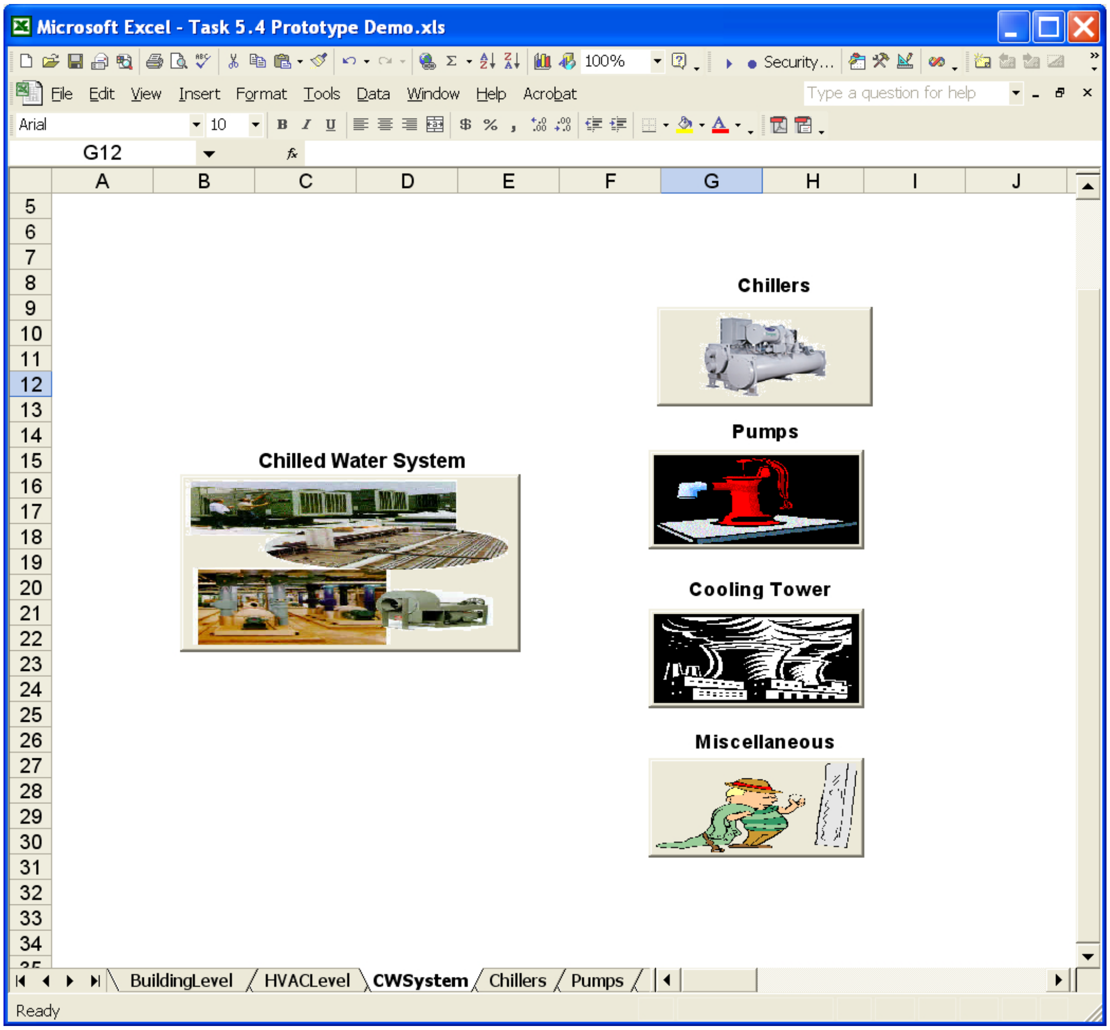


Figure 47: Screen shot of the chilled water system and its major components

Clicking the Chillers button displays the Chillers screen which contains a button for each type of chiller: reciprocating, centrifugal, absorption, and other.

Clicking the Centrifugal button (the only active button in this demonstration) display four additional buttons (Figure 48), one for each generic category of commissioning data: data used for functional tests; data used for prefunctional tests; data used for continuous commissioning (CCx); and other data of interest.

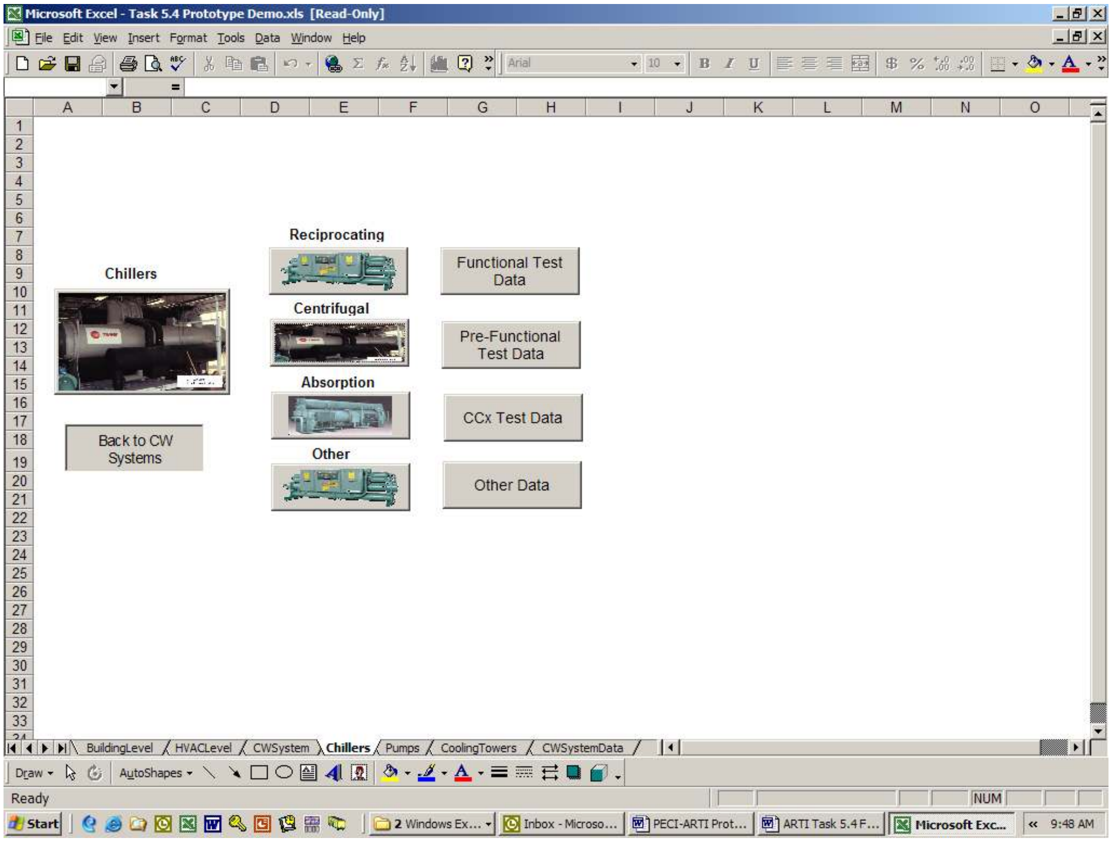
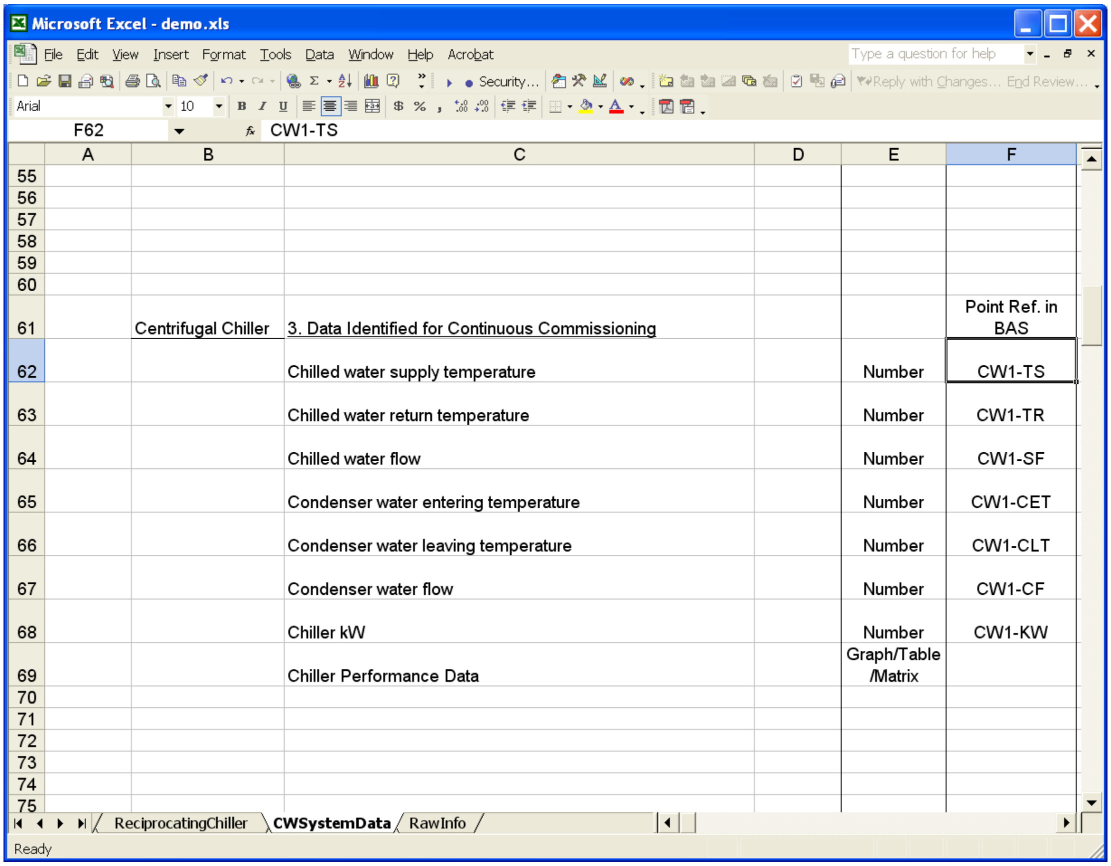


Figure 48: Shot of the screen for accessing information for centrifugal chillers

Clicking on the CCx Test Data button displays the list of points necessary for continuous commissioning a centrifugal chiller (see Figure 49).



F62 CW1-TS

	A	B	C	D	E	F
55						
56						
57						
58						
59						
60						
61		Centrifugal Chiller	3. Data Identified for Continuous Commissioning			Point Ref. in BAS
62			Chilled water supply temperature		Number	CW1-TS
63			Chilled water return temperature		Number	CW1-TR
64			Chilled water flow		Number	CW1-SF
65			Condenser water entering temperature		Number	CW1-CET
66			Condenser water leaving temperature		Number	CW1-CLT
67			Condenser water flow		Number	CW1-CF
68			Chiller kW		Number	CW1-KW
69			Chiller Performance Data		Graph/Table /Matrix	
70						
71						
72						
73						
74						
75						

Figure 49: Screen shot showing the list of points required for continuous commissioning of a centrifugal chiller. Also shown are the example names of the corresponding points in the building automation system.

This demonstration includes navigational buttons (labeled, for example, “Back to Chillers” and “Back to CW Systems”) that let you back up the organizational hierarchy and then “drill down” into information for other system types and components.

8. Conclusions

8.1. Summary

A significant amount of information is generated, collected, and used during the commissioning process to ensure systems and buildings are designed, constructed, and operated in a manner that will meet the owner's requirements. The development of automated and continuous commissioning tools will reduce the time and cost associated with commissioning and enhance system performance over the life of a building. The current research set out to determine key enabling components essential for developing tools that automate significant parts of building system commissioning, and to demonstrate the prototype tools and procedures in bench tests.

The research identified methodologies that could be used to develop commissioning tools for the four problems and processes that emerged as the top candidates for automation within the commissioning process:

1. faulty economizer operation;
2. malfunctioning sensors;
3. malfunctioning valves and dampers; and
4. project data management.

The current research established that the need and desire for automated tools to help reduce the time and cost associated with commissioning is prevalent in the commissioning community. It also established that fault detection and data management techniques can be integrated to develop proactive fault detection tools that can use measured data, design data, and equipment operating parameters to perform actual functional tests to improve system diagnosis. Methodologies for detecting system operation faults were developed and demonstrated through flow diagrams and simplified mock-up applications. Data management techniques were demonstrated through examples illustrating how prefunctional and functional test forms could be populated with design information and equipment operating parameters.

Key accomplishments and conclusions associated with fault detection methodologies include the following.

- Development of a generic process for automating continuous commissioning and its application to several specific HVAC components.
- Detailed diagrams and descriptions of diagnostic logic for detecting and diagnosing faults with HVAC equipment are provided. These include diagnostics for economizing, ventilation, heating and cooling in AHUs, as well as generic diagnostic methods for dampers and valves.
- The use of proactive (as compared to passive) processes to isolate faults and extend diagnoses is described. These proactive processes can be activated based on the findings of passive fault detection and diagnostic processes. By triggering

proactive processes this way, their execution can be controlled to minimize their intrusion on normal operations.

- A method for developing and using empirical models to detect damper and valve performance problems is developed and illustrated in a simple example.
- Automation of part of the diagnostic logic developed in this report has been implemented in an example software process. This example is provided on a CD included with this report.

Key accomplishments and conclusions associated with data management methodologies include:

- Development of a generic process to compile, organize, and manage the data required for commissioning.
- A prototype software demonstration for a specific HVAC sub-system to show how this data might be organized and accessed in a software tool.
- Integration of automated continuous commissioning tools with data management models will require that developers of automated tools and developers of the data management models work closely together to ensure that that all needs are adequately met.

It is evident that significant additional research and development are necessary to produce automated tools and develop an implementation framework around an automated continuous commissioning process. Automated commissioning tools are important to producing performance gains in commercial buildings, and the potential for practical application of these tools by building operators and commissioning providers is high. However, resistance to new technology and practices exists in every market segment. As a result, an important element in the implementation strategy will be market transformation initiatives to train building operators and commissioning providers to integrate the new tools into their existing practices.

8.2. Future Research

The focus of the current research concentrated on developing methodologies for automated tools for two primary commissioning issues: system operation fault detection and data management. Opportunities for future research for each topic are outlined below.

8.2.1. Fault Detection

The current research developed methodologies for detecting malfunctioning economizers, faulty sensors, and faulty valves and dampers. The first step is to validate the methodologies for fault detection and diagnostic logic presented in this report. Validation includes initially testing the methodologies in mock-up software tools in laboratory and field settings to verify their performance, and to empirically investigate the selection of tolerances and their influence on detection sensitivity and the rate of false alarms. Validation will also promote the extension of the methodologies to additional equipment and systems.

The development of comprehensive automated fault detection software tools must interface with existing tools (such as building automation systems and data collection devices) as well as building operators. Initially, the proposed tools should be somewhat adaptable to individual operators' abilities. The key to gaining wide acceptance of something new is not to overwhelm a user with something that is far above their comprehension or comfort level. Hence, tool development should coincide with enhanced training of building operators on the theory behind the diagnostics and how to resolve the problem identified by the tool. Training could include on-line assistance and access to background information, functional test procedures, and information relating to optimum system operation. As the building operators become more educated, the tools can become more sophisticated and powerful.

To that extent, the next logical step would be to integrate the automated tools for detecting and diagnosing faults into a continuous commissioning process. This will require collaboration with building operation staff committed to using this new approach, and then completing the continuous commissioning loop by taking actions to correct faults detected using these automated tools. These operators will be critical to the long term development of automated continuous commissioning and its promise to lower initial commissioning costs and improve the system efficiency over the life of the building.

8.2.2. Data Management

Although there are several efforts underway to define standards for identifying and classifying building design and construction data, these efforts have yet to provide a comprehensive data model that incorporates information and attributes that are unique to commissioning building systems and equipment. For example, the International Alliance for Interoperability and the BS-8 project[6] are working to develop the Industry Foundation Classes (IFC) HVAC extension schemata that will extend the IFC object data model and allow interoperability with building energy and other building performance simulation tools. Many of the data points used by simulation programs are the same as those identified in the current research as being integral to the commissioning process. However, the data models need to be extended to include additional attributes that are unique to commissioning building systems and equipment. The ability of automated tools to access and exchange information freely depends on continued development and acceptance of additional data models for all systems that are to be commissioned. Hence, future work should target continual expansion of the data schema.

As a foundation of robust data models are developed for various building systems and equipment, software applications can be developed to organize and manage data in actual commissioning processes. As new tools are developed, the need remains to demonstrate that effective data management and automated tools can reduce the time and cost associated with collecting and using this data during commissioning and system operation. The tools can initially focus on specific equipment and tasks and

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[6] http://eetd.lbl.gov/btd/iai/bs8

be enhanced to incorporate multiple data streams as additional schemas become available.

New data management tools should also be integrated with emerging automated fault detection and diagnostic tools to develop automated, proactive continuous commissioning tools. A proactive tool would use design data and system operating parameters to actually perform a functional test should a fault be detected, and to help isolate the cause of the problem. As discussed above, there will also be a need to provide additional training and resources to building operators to ensure they understand what the tools are telling them and how to fix the problems.

9. References

Andelman, Richard, P. Curtiss, and J. Kreider. 1995. ASHRAE Research Project 808: Report Demonstration Knowledge Based Tool for Diagnosing HVAC Operations and Maintenance (O&M) Problems in Small Office Buildings. October 1995. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), Atlanta, Georgia.

Bluetooth Special Interest Group. 2001. The Official Bluetooth Web Site. http://www.bluetooth.com.

Brambley, M.R., R.G. Pratt, D.P. Chassin, , and S. Katipamula. 1998. Automated Diagnostics for Outdoor Air Ventilation and Economizers. *ASHRAE Journal*, Vol. 40, No. 10, pp. 49–55, October 1998.

Brambley, M.R., R. Briggs, S. Katipamula, C. Dasher, L. Luskay, and L. Irvine. 2002. Investigating Strategies for Automating Commissioning. *10th National Conference on Building Commissioning Conference Proceedings.* May 8–10, 2002. Portland Energy Conservation Inc. Portland, Oregon.

Brightbill, Lon. 2000. Using Information Technology to Enhance Commissioning. *8th National Conference on Building Commissioning Conference Proceedings.* Portland Energy Conservation Inc. Portland, Oregon.

Brown, Bruce and Marge. 2000. Wireless PDA Communications. *ZD Net, PC Magazine*. June 16, 2000. http://www.zdnet.com/pcmag/stories/solutions/0,8224,2576012,00.html.

Bushby, S.T, N.S. Castro, J. Schein and J. House. 2001. Using the Virtual Cybernetic Building Testbed and FDD Test Shell for FDD Tool Development. NISTIR 6818. National Institute of Standards and Technology, Gaithersburg, MD.

Croarkin, C and P. Tobias, technical editors. 2002. *NIST/SEMATECH e-Handbook of Statistical Methods*, Section 2.5.5. National Institute of Standards and Technology and SEMATECH. http://www.itl.nist.gov/div898/handbook/.

Gertler, J. 1998. *Fault Detection and Diagnosis in Engineering Systems*. Marcel Dekker, New York.

Issermann, R. 1984. Process Fault Detection Based on Modeling and Estimation Methods—A Survey. *Automatica*, Vol. 20, No. 4, pp. 387–404.

Kao, J.Y., and E.T. Pierce. 1983. Sensor Errors: Their Effects on Buildings Energy Consumption. *ASHRAE Journal* 25(12): 42–45.

Katipamula, S., R.G. Pratt, D.P. Chassin, Z. T. Taylor, K. Gowri, and M.R. Brambley. 1999. Automated Fault Detection and Diagnostics for Outdoor Air Ventilation Systems and Economizers: Methodology and Results from Field Testing. *ASHRAE Transactions*, Vol. 105 Pt. 1.

Katipamula, S., R.G. Pratt, and J. Braun. 2000. Building Systems Diagnostics and Predictive Maintenance. *CRC Handbook of Heating Ventilation, and Air Conditioning*. Ed. Jan F. Kreider CRC Press, New York, NY.

Kennedy, R. L., Y. Lee, B. Van Roy, C. D. Reed, and R. P. Lippmann. 1998. *Solving Data Mining Problems through Pattern Recognition*. Prentice Hall, Upper Saddle River, New Jersey, 1998

Kintner-Meyer, M. and M. Brambley. 2002. Pros & Cons of Wireless. *ASHRAE Journal* 44(11), pp. 54–59.

Luskay, L. and J. Forester. 2001. *TRP-1032 - Identification and Preservation of Building Design Information for Use in Commissioning and Operations*, American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, GA.

Motorola, Inc. 2001. Bluetooth wireless technology. http://www.motorola.com/bluetooth; 2001.

Piette, Mary Ann. 1996. Commissioning Tools for Life-Cycle Building Performance Assurance. *4th National Conference on Building Commissioning Proceedings*. St. Pete Beach, FL. April 29-May 1, 1996.

Portland Energy Conservation Inc. (PECI) 1997. *Commissioning for Better Buildings In Oregon*. Oregon Office of Energy, Salem, Oregon.

———. 1998. *Energy Design Resources Design Brief Building Commissioning*. Southern California Edison.

Pratt, Rob, Srinivas Katipamula, Michael Brambley, and Steven Blanc. 2000. Field Results from Application of the Outdoor Air/Economizer Diagnostician for Commissioning and O&M. *8th National Conference for Building Commissioning Proceedings*.

Rossi, Todd. 1999. Deployment of Diagnostics for Commercial Buildings: New Business Opportunities. *Diagnostics for Commercial Buildings: Research to Practice Conference Proceedings*.

Rossi, T.M. and J. E. Braun. 1996. Minimizing Operating Costs of Vapor Compression Equipment With Optimal Service Scheduling. *International Journal of Heating, Ventilating, and Air Conditioning and Refrigerating Research*. Vol. 2, No. 1, pp. 3–26.

Santos, J. Jay, E. Lon Brightbill, and Larry Lister. 2000. Automated Diagnostics from DDC Data - PACRAT. *8th National Conference on Building Commissioning Proceedings*.

StatSoft, Inc. 2001. *Electronic Statistics Textbook.* Tulsa, OK: StatSoft. http://www.statsoft.com/textbook/stathome.html.

———. 2001. *Statistica – StatSoft Company Background.* StatSoft Inc., Tulsa, OK. http://www.statsoftinc.com/history.html.

Stum, Karl. 1999. Diagnostics and Commissioning. *Diagnostics for Commercial Buildings: Research to Practice Conference Proceedings*.

———. 2000. Commissioning Tools for Managing Design, Construction and Implementation. *8th National Conference of Building Commissioning*.

U.S. Department of Energy (US DOE) and Portland Energy Conservation, Inc. (PECI). 1998. *Model Commissioning Plan and Guide Commissioning Specifications*, version 2.05, Portland Energy Conservation Inc., Portland, Oregon.

Usoro, P.B., L.C. Schick, and S. Negahdaripour. 1985. An Innovation-Based Methodology for HVAC System Faults Detection. *Journal of Dynamics Systems, Measurement, and Control*. Transactions of the ASME 107: 284–285.

10. Appendices

Appendix A – System Problems Matrix

Appendix B – New Construction Process Matrix

Appendix C – Existing Building Process Matrix

Appendix D – Sensor Diagnostic Prototype

Appendix E – Commissioning Data for Chilled Water Systems

Table 1. Problems With Systems and Equipment

	MAIN CATEGORY WEIGHTS (relative to each other)----->			10	6								8	6	3	8	
	SUB-CATEGORY WEIGHTS (relative to each other)----->					5	5	3	4								
	See number key below--->	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
	Problems of Systems and Equipment	**Prevalence of Equipment or Feature**	**Prevalence of Problems**	**Average Equipment-Problem Prevalence**	**Propensity to Reoccur**	**Negative Impact on Energy**	**Negative Impact on IAQ**	**Negative Impact on Comfort**	**Negative Impact on O&M**	**Weighted Average of all Impacts**	**Cost of Correcting the Problem** (post-installation)	**Source of Cost**	**Impact to Cost Ratio**	**Potential for Reduced Cx Cost**	**Potential for Improved Data Quality**	**Likelihood of Not Being Detected w/o Cx**	**Overall Score**
1	**Building Automation System**	3.63															
	Faulty control sequences		3.50	3.56	2.25	3.57	2.57	3.00	2.71	2.97	2.33	3.50	1.27	3.00	3.00	3.14	111
	Sensor and actuators not calibrated		3.13	3.38	2.88	3.00	2.43	2.71	2.71	2.71	2.00	3.00	1.36	2.86	2.50	3.00	111
	Improper setpoint settings (space; discharge temperature, static pressure, etc.)		3.14	3.38	3.29	3.57	2.71	2.57	2.14	2.81	1.33	3.50	2.11	2.43	2.33	2.86	115
	Improperly applied or nonexistent temperature & pressure resets		2.71	3.17	2.14	3.00	2.14	2.00	1.71	2.27	1.67	3.50	1.36	2.29	2.83	3.00	102
	Hunting		2.43	3.03	2.14	1.57	1.43	1.57	2.14	1.66	1.17	3.50	1.43	2.17	2.80	3.00	100
	Excessive cycling		2.00	2.81	1.67	1.67	1.17	1.50	2.50	1.69	1.40	3.80	1.20	2.80	2.80	2.80	95
	Less than optimum scheduling		2.88	3.25	2.75	3.71	1.14	1.57	1.43	2.04	1.17	3.50	1.75	2.14	2.67	2.57	104
	Simultaneous heating/cooling		2.38	3.00	2.00	3.57	1.00	1.43	1.14	1.87	1.50	3.50	1.24	3.14	3.00	3.57	108
	Improper sequencing and staging		2.71	3.17	1.86	3.14	1.57	1.57	2.00	2.13	1.50	3.50	1.42	2.86	2.67	3.00	103
	Ineffective night time control strategies		2.63	3.13	1.88	3.14	1.00	1.43	1.29	1.77	1.00	3.50	1.77	2.43	2.50	3.00	103
	Inefficient control sequences		3.75	3.69	2.00	3.43	2.14	2.00	2.14	2.50	1.83	3.50	1.36	2.57	3.17	3.29	111
	Alarms not programmed		2.50	3.06	1.25	1.43	1.14	1.57	2.29	1.57	1.33	3.50	1.18	2.00	1.67	2.29	83
	Inaccurate graphics		2.00	2.81	1.14	1.14	1.00	1.14	1.57	1.20	1.67	3.50	0.72	1.00	1.50	1.57	64
	Intersystem interlocks not programmed or not working		2.57	3.10	1.43	2.00	1.14	1.29	2.14	1.66	1.33	3.50	1.24	2.00	2.00	2.43	87
2	**Chiller & Cooling Tower and Primary Loop**	2.86															
	Uncalibrated or malfunctioning sensors and actuators		3.00	2.93	2.86	3.14	1.71	1.86	2.50	2.34	1.80	3.20	1.30	2.67	3.00	2.83	105
	Excessive cycling of CT fans		2.14	2.50	1.71	2.14	1.00	1.00	3.00	1.81	1.40	3.80	1.29	2.67	2.67	3.00	94
	Fan, CT, pump and chiller staging poorly		2.57	2.71	1.29	3.00	1.43	1.14	2.33	2.05	1.40	3.80	1.47	3.00	2.67	3.00	97
	Hunting of condenser water mixing valve		2.00	2.43	1.71	2.14	1.00	1.00	1.83	1.53	1.40	3.80	1.09	2.83	2.83	3.33	95
	Chilled water reset faulty, inefficient or non-existent		3.43	3.14	2.29	3.57	1.57	1.00	2.00	2.16	1.60	3.80	1.35	2.50	2.83	3.33	106
	Condenser water reset faulty, inefficient or non-existent		3.57	3.21	2.14	3.43	1.00	1.14	2.00	1.97	1.60	3.80	1.23	2.33	2.67	3.17	102
	CT sump heater malfunction		1.57	2.21	1.29	2.14	1.00	1.00	2.17	1.61	1.60	3.80	1.01	1.67	1.83	1.83	68
	Faulty piping and valve arrangements		2.43	2.64	1.00	2.57	1.29	1.29	1.50	1.71	3.00	3.80	0.57	1.50	1.83	2.83	74
	CT low water alarm malfunction		1.29	2.07	1.57	1.00	1.00	1.14	2.67	1.42	1.00	3.80	1.42	1.67	1.83	2.17	74
	CT fan vibration alarm malfunction		1.29	2.07	1.57	1.00	1.00	1.29	2.67	1.44	1.40	3.80	1.03	1.67	1.83	1.67	67
	Chiller efficiency not meeting specifications		2.00	2.43	1.57	3.29	1.14	1.29	1.50	1.88	3.20	3.80	0.59	2.67	2.67	3.33	89
	Inability to maintain chilled water setpoint		1.43	2.14	1.86	1.86	1.71	2.57	2.67	2.13	2.40	3.80	0.89	2.50	2.50	2.17	80
	Oversized pumps		2.86	2.86	1.00	2.57	1.00	1.00	1.33	1.54	2.80	3.80	0.55	2.50	2.33	3.33	88
3	**Heating Hot Water Plant**	2.86															
	Faulty boiler controls		2.25	2.55	1.75	3.00	1.00	1.57	2.83	2.12	2.20	3.80	0.96	3.00	2.67	2.17	87
	Uncalibrated or malfunctioning sensors		2.88	2.87	2.75	3.00	1.43	1.86	2.50	2.22	1.60	3.20	1.39	2.83	2.83	2.83	104
	Flawed bypass piping arrangements		2.14	2.50	1.33	2.43	1.14	1.43	2.00	1.77	3.00	3.80	0.59	1.67	2.00	3.17	79
	Improper mixing valve operation		2.00	2.43	1.57	2.43	1.00	1.71	2.33	1.86	1.80	3.20	1.03	2.00	2.67	2.67	83
	Improper boiler staging		2.75	2.80	2.00	3.00	1.00	1.43	2.17	1.94	1.40	3.80	1.38	2.50	2.17	2.67	94
	Improper pump operation		1.86	2.36	1.71	2.43	1.00	1.43	2.33	1.81	1.20	4.00	1.51	2.50	2.67	2.50	89
	Inability to maintain heating water setpoint		1.86	2.36	2.00	2.43	1.43	2.57	2.50	2.18	2.40	3.80	0.91	2.67	2.83	1.83	82
	Improper setpoints		2.75	2.80	3.14	3.43	1.29	1.86	2.17	2.22	1.20	3.80	1.85	3.00	2.67	3.00	112
4	**Air Handler**	3.67															
	Uncalibrated or malfunctioning sensors or actuators		3.38	3.52	3.00	3.29	2.86	2.43	2.50	2.82	1.60	3.20	1.76	2.50	2.83	3.00	115
	Malfunctioning economizer and dampers		3.50	3.58	3.00	3.43	2.71	2.43	2.17	2.75	2.40	3.80	1.14	3.00	2.50	3.17	114
	Faulty or improper ventilation control strategy		3.38	3.52	2.25	3.43	3.14	2.43	2.00	2.83	1.40	3.80	2.02	2.83	2.83	3.33	117
	Improper duct static pressure control sequences or setpoints		3.00	3.33	2.14	3.29	2.14	2.00	1.67	2.34	1.20	3.80	1.95	2.50	2.33	3.17	109
	Inadequate low load modulation		2.67	3.17	1.67	2.50	2.00	1.83	1.40	1.98	1.00	3.80	1.98	1.80	2.60	3.00	100
	Improper ramp time on VFD		1.86	2.76	1.29	1.29	1.14	1.00	1.17	1.17	1.00	3.80	1.17	1.17	1.67	3.00	81
	Faulty reset / restart functions on VFD		2.00	2.83	1.43	1.14	1.29	1.14	1.83	1.35	1.20	3.80	1.12	1.17	1.83	2.50	78
	Heating or cooling coil valve hunting		2.14	2.90	2.14	1.57	1.43	1.43	1.50	1.49	1.20	3.80	1.24	2.00	2.67	3.33	98
	Heating or cooling coil valve leak-by		2.14	2.90	2.14	2.86	1.14	1.43	1.33	1.74	1.20	3.80	1.45	2.83	2.67	3.67	108
	Faulty interlocks with fire alarm or smoke dampers		2.00	2.83	1.29	1.17	1.17	1.00	1.20	1.15	1.20	3.80	0.95	1.17	2.00	2.00	73
	Optimum start sequences not functioning		3.25	3.46	2.13	2.86	1.57	1.57	1.33	1.89	1.00	3.80	1.89	2.00	2.83	3.00	107
	Night low limit control not functioning		2.38	3.02	1.88	2.57	1.29	1.43	1.33	1.70	1.00	3.80	1.70	1.83	2.50	3.00	98
	Simultaneous heating/cooling from poor sequencing		2.75	3.21	1.88	3.14	1.14	1.57	1.33	1.85	1.20	3.80	1.54	2.83	2.67	3.67	110
	Malfunctioning control of building pressure		3.14	3.40	2.14	2.43	2.14	2.43	2.33	2.32	1.60	3.80	1.45	2.50	2.83	3.00	106
	Inefficient filter selection		2.38	3.02	1.88	2.14	2.14	1.29	1.83	1.92	2.00	3.80	0.96	1.17	1.83	2.67	83
	Inability to maintain discharge temperature setpoint		2.29	2.98	1.86	2.14	1.29	2.86	1.67	1.90	2.40	3.80	0.79	2.33	2.50	1.83	83
	Inadequate airflow		2.13	2.90	1.50	2.43	2.86	2.86	2.50	2.65	2.60	3.80	1.02	3.00	2.67	2.67	93
5	**Large Packaged Unit (20 ton or larger)**	2.57															
	Uncalibrated or malfunctioning sensors or actuators		3.00	2.79	3.13	3.29	2.86	2.57	2.50	2.85	1.60	3.20	1.78	2.50	2.83	3.00	108
	Malfunctioning economizer and dampers		3.75	3.16	3.13	3.43	2.86	2.14	2.00	2.70	2.40	3.80	1.12	2.83	2.50	3.33	111
	Faulty or improper ventilation control strategy		3.25	2.91	2.63	3.00	3.29	2.14	1.83	2.66	1.40	3.80	1.90	2.83	2.67	3.17	110
	Improper duct static pressure control sequences or setpoints		2.86	2.71	2.14	3.00	2.00	1.86	1.50	2.15	1.20	3.80	1.79	2.50	2.67	3.17	103
	Inadequate low load modulation		2.67	2.62	1.67	2.33	2.17	1.83	1.20	1.93	1.00	3.80	1.93	1.60	2.40	3.20	94
	Improper ramp time on VFD		1.86	2.21	1.29	1.29	1.14	1.00	1.17	1.17	1.00	3.80	1.17	1.00	1.67	3.17	76
	Faulty reset / restart functions on VFD		2.00	2.29	1.43	1.00	1.29	1.14	1.67	1.27	1.00	3.80	1.27	1.17	1.67	2.33	72
	Faulty interlocks with fire alarm or smoke dampers		2.00	2.29	1.29	1.17	1.17	1.00	1.40	1.19	1.20	3.80	0.99	1.33	2.00	2.33	71
	Optimum start sequences not functioning		3.13	2.85	2.00	2.86	1.43	1.71	1.50	1.92	1.20	3.80	1.60	2.33	2.83	3.00	100
	Night low limit control not functioning		2.50	2.54	1.63	2.71	1.29	1.57	1.50	1.81	1.00	3.80	1.81	1.83	2.50	2.50	88
	Simultaneous heating/cooling from poor sequencing		2.50	2.54	1.88	3.00	1.14	1.57	1.50	1.85	1.00	3.80	1.85	2.50	2.67	3.67	104

	MAIN CATEGORY WEIGHTS (relative to each other)----->			10	6								8	6	3	8	
	SUB-CATEGORY WEIGHTS (relative to each other)----->					5	5	3	4								
	See number key below--->	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
	Problems of Systems and Equipment	**Prevalence of Equipment or Feature**	**Prevalence of Problems**	**Average Equipment-Problem Prevalence**	**Propensity to Reoccur**	**Negative Impact on Energy**	**Negative Impact on IAQ**	**Negative Impact on Comfort**	**Negative Impact on O&M**	**Weighted Average of all Impacts**	**Cost of Correcting the Problem (post-installation)**	**Source of Cost**	**Impact to Cost Ratio**	**Potential for Reduced Cx Cost**	**Potential for Improved Data Quality**	**Likelihood of Not Being Detected w/o Cx**	**Overall Score**
	Malfunctioning control of building pressure		2.71	2.64	2.00	2.29	1.71	2.14	2.00	2.03	1.20	3.80	1.69	2.33	3.00	3.17	100
	Inefficient filter selection		2.38	2.47	2.00	2.57	2.14	1.43	1.83	2.07	2.20	3.80	0.94	1.50	1.83	2.83	81
	Inability to maintain discharge temperature setpoint		2.29	2.43	1.86	2.29	1.43	2.86	1.83	2.03	2.40	3.80	0.85	2.00	2.50	2.33	80
	Inadequate airflow		2.13	2.35	1.38	2.14	2.86	2.71	2.67	2.58	2.40	3.80	1.07	2.50	2.67	2.50	83
	Poor communication between BAS & built-in packaged controls		3.43	3.00	1.57	2.83	1.83	2.17	1.80	2.18	2.40	3.80	0.91	3.00	3.00	2.17	91
	Improper refrigerant charge		1.86	2.21	2.29	2.29	1.29	2.43	2.17	1.99	2.00	3.80	0.99	3.00	2.67	2.50	90
6	**Small Packaged Unit (3-20 tons) and Split Systems**	3.14															
	Faulty economizer operation		3.88	3.51	3.13	3.00	2.86	2.00	1.67	2.47	1.60	3.40	1.54	3.17	2.83	3.50	122
	Uncalibrated or malfunctioning sensors or actuators		3.13	3.13	3.13	2.71	2.43	2.33	2.17	2.43	1.60	3.20	1.52	2.50	2.67	3.17	111
	Improper outside air control		3.50	3.32	2.38	2.86	2.86	2.00	1.50	2.39	1.60	3.80	1.49	2.67	2.67	3.33	110
	Inadequate airflow over coil		2.29	2.71	1.57	2.14	1.43	2.17	2.17	1.94	1.60	3.80	1.21	2.83	2.67	2.67	93
	Improper refrigerant charge		1.86	2.50	2.43	2.43	1.29	2.17	2.50	2.06	1.20	3.80	1.72	2.67	2.67	2.17	95
	Dirty condenser coil		2.75	2.95	3.13	2.57	1.29	1.67	2.17	1.94	1.20	3.80	1.62	1.83	2.50	1.83	94
	Programmable controls not programmed properly		3.00	3.07	2.63	2.71	1.71	2.33	2.17	2.22	1.00	3.80	2.22	2.17	2.50	2.50	105
	Improperly equipped with low-ambient controls		2.00	2.57	1.17	2.00	1.33	1.00	1.60	1.53	1.60	3.80	0.96	1.60	2.20	2.40	76
7	**Air Terminal Units**	3.00															
	Uncalibrated or malfunctioning sensors		3.00	3.00	2.88	2.71	2.29	2.83	2.00	2.44	1.40	3.20	1.74	2.67	2.83	3.00	110
	Heating coil valve hunting		2.00	2.50	1.71	1.43	1.00	1.67	1.40	1.34	1.20	3.80	1.11	2.33	2.83	3.17	92
	Heating coil valve leak-by		2.00	2.50	2.00	2.57	1.00	1.67	1.50	1.70	1.20	3.80	1.41	3.17	2.83	3.33	102
	Simultaneous heating/cooling from poor sequencing		2.13	2.56	1.50	2.71	1.00	1.67	1.33	1.70	1.00	3.80	1.70	3.00	2.83	3.17	100
	Auto-zero and auto-diagnostics not enabled		2.50	2.75	1.29	1.71	1.67	1.60	1.83	1.71	1.00	3.80	1.71	2.00	2.50	3.00	92
	Inability to maintain space temperature setpoint		2.43	2.71	2.00	1.86	1.86	3.00	2.67	2.25	1.60	3.80	1.41	2.67	2.50	1.50	86
	Inconsistent flow readings from bad flow station or inlet conditions		2.86	2.93	1.57	2.14	2.86	2.50	2.50	2.50	1.40	3.80	1.79	2.83	2.83	3.00	103
8	**Economizer--Air**	3.71															
	Uncalibrated or malfunctioning sensors		3.25	3.48	3.13	3.00	2.71	2.33	1.67	2.48	1.60	3.20	1.55	2.67	3.00	3.33	118
	Improper enthalpy control settings		3.57	3.64	2.86	2.86	1.86	1.67	1.33	1.99	1.40	3.80	1.42	2.17	2.83	3.33	113
	Improper change-over temperature settings		3.43	3.57	2.71	3.00	2.00	1.67	1.33	2.08	1.40	3.80	1.48	2.17	2.50	3.33	111
	Uncalibrated or malfunctioning valves or dampers and actuators		3.38	3.54	3.00	3.29	2.86	2.33	2.33	2.77	1.60	3.20	1.73	2.67	2.83	3.17	117
9	**Variable Volume Water System** (secondary loop--pumps and piping)	2.33															
	Uncalibrated or malfunctioning sensors or actuators		3.14	2.74	2.86	2.86	1.29	1.83	2.33	2.09	1.40	3.20	1.49	2.50	2.83	2.83	103
	Inadequate low load modulation of VFDs		3.00	2.67	1.71	2.86	1.71	1.50	1.50	1.96	1.20	3.80	1.64	2.67	2.50	2.67	95
	Faulty or inefficient differential pressure control sequences or setpoints		3.14	2.74	1.71	3.00	1.43	1.33	1.33	1.85	1.80	3.80	1.03	2.83	3.00	3.33	99
	Inadequately sized secondary bypass or valve arrangements		1.86	2.10	1.14	2.00	1.43	1.33	1.67	1.64	3.00	3.80	0.55	2.50	2.17	3.33	80
	Faulty pump staging		2.14	2.24	1.71	2.29	1.14	1.17	1.67	1.61	1.40	3.80	1.15	2.33	2.17	2.33	81
	Unnecessary 3-way valves and bypasses		2.71	2.52	1.57	3.14	1.29	1.33	1.67	1.93	2.80	3.80	0.69	2.17	2.17	3.17	85
	Oversized pumps		3.00	2.67	1.29	3.29	1.14	1.17	1.80	1.93	2.60	3.80	0.74	2.33	2.17	3.00	85
10	**Programmable Thermostat**	2.29															
	Improper fan switch settings (auto-manual-off)		2.75	2.52	3.38	3.14	2.29	2.33	1.33	2.32	1.20	3.80	1.94	2.00	2.17	2.83	102
	Optimum start and stop not being utilized		3.25	2.77	2.50	2.43	1.57	2.00	1.50	1.88	1.20	3.80	1.57	2.00	2.17	3.17	99
11	**Domestic Hot Water Heating**	4.00															
	Improper flue damper operation		1.83	2.92	1.43	1.57	1.00	1.00	1.67	1.32	1.00	3.40	1.32	1.33	2.00	2.00	78
	Improper mixing valve operation		2.00	3.00	1.50	1.71	1.00	1.33	1.67	1.43	1.20	3.80	1.19	1.83	2.50	2.33	86
	Improper temperature setpoints		2.75	3.38	2.38	2.29	1.00	1.67	1.50	1.61	1.00	3.80	1.61	2.00	2.17	2.00	95
12	**Heat Recovery Units** (run-around, heat wheels, etc.)	1.43															
	Faulty or unoptimized sequence of operations		3.17	2.30	2.17	3.50	1.17	1.20	1.60	1.96	1.00	4.00	1.96	2.60	2.40	3.20	100
	Uncalibrated or malfunctioning sensors		2.83	2.13	2.67	2.83	1.50	1.20	1.80	1.91	1.25	3.25	1.53	2.40	2.50	3.20	97
	Uncalibrated or malfunctioning valves and actuators		2.50	1.96	2.67	3.00	1.50	1.20	2.00	2.01	1.50	3.25	1.34	2.20	2.25	3.20	92
13	**Exhaust Fan System**	4.00															
	Unoptimized scheduling		3.25	3.63	2.38	3.29	2.00	1.83	1.50	2.23	1.00	3.80	2.23	1.83	2.17	2.83	109
	Faulty back-draft damper		2.17	3.08	2.00	2.17	1.43	1.60	1.80	1.76	1.20	3.80	1.47	1.80	1.80	2.80	93
	Improper room pressurization		3.14	3.57	2.43	2.14	3.14	2.67	2.00	2.50	1.60	3.80	1.56	3.00	2.83	2.67	111
	Improper control sequences with other fans and dampers		3.25	3.63	1.75	2.86	2.57	1.67	1.50	2.24	1.40	3.80	1.60	2.83	2.83	2.83	108
14	**Parking Garage Ventilation**	1.71															
	Inefficient control strategies		3.00	2.36	1.83	2.83	1.83	1.20	1.60	1.96	1.00	4.00	1.96	2.20	2.00	2.60	90
	Malfunctioning equipment (fans and controls)		2.33	2.02	2.00	2.33	3.17	1.20	2.40	2.39	1.50	4.00	1.60	2.20	1.80	1.80	78
15	**Commercial Refrigeration**	2.00															
	Unoptimized defrost cycles/schedules		3.14	2.57	2.50	3.00	1.00	1.00	1.67	1.75	1.60	3.80	1.09	2.50	2.67	3.00	96
	Unoptimized floating head pressure controls		2.86	2.43	2.17	3.17	1.00	1.00	1.33	1.72	2.00	3.80	0.86	2.40	2.20	2.80	88
	Unoptimized compressor sequencing		2.57	2.29	2.17	2.50	1.00	1.00	1.50	1.56	2.00	3.80	0.78	2.67	2.67	2.67	87
	Faulty cooler and case door closure controls		2.57	2.29	2.33	2.67	1.00	1.00	2.17	1.76	2.20	3.80	0.80	1.80	2.00	2.00	76
	Improper refrigerant charge		2.29	2.14	2.33	2.83	1.00	1.17	2.67	1.96	1.60	3.80	1.23	2.67	2.67	2.67	91
	Faulty condenser fan staging		2.29	2.14	1.67	2.17	1.00	1.00	1.67	1.50	1.40	3.80	1.07	2.50	2.67	2.67	84
16	**Lighting Controls**	3.00															
	Not zoned per specifications		2.33	2.67	1.17	2.67	1.00	1.40	1.20	1.61	2.50	4.00	0.64	1.80	2.20	2.40	75
	Expected sequences don't work		3.17	3.08	1.50	3.17	1.00	1.60	2.20	2.03	1.50	4.00	1.35	2.60	2.20	2.40	92
	Schedules not optimized by zone		3.29	3.14	1.83	3.00	1.00	1.40	1.60	1.80	1.25	4.00	1.44	2.40	2.60	3.00	100
	Poorly located or calibrated photocell sensors		2.86	2.93	2.00	2.83	1.00	2.00	1.75	1.89	1.50	4.00	1.26	1.80	1.60	2.40	86
	Poor switch zoning		2.71	2.86	1.33	2.67	1.00	1.40	1.75	1.74	2.25	4.00	0.77	1.75	2.25	1.75	74

	MAIN CATEGORY WEIGHTS (relative to each other)----->			10	6								8	6	3	8	
	SUB-CATEGORY WEIGHTS (relative to each other)----->					5	5	3	4								
	See number key below--->	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
	Problems of Systems and Equipment	**Prevalence of Equipment or Feature**	**Prevalence of Problems**	**Average Equipment-Problem Prevalence**	**Propensity to Reoccur**	**Negative Impact on Energy**	**Negative Impact on IAQ**	**Negative Impact on Comfort**	**Negative Impact on O&M**	**Weighted Average of all Impacts**	**Cost of Correcting the Problem (post-installation)**	**Source of Cost**	**Impact to Cost Ratio**	**Potential for Reduced Cx Cost**	**Potential for Improved Data Quality**	**Likelihood of Not Being Detected w/o Cx**	**Overall Score**
	Inadequate use of occupancy sensors		3.14	3.07	1.67	2.50	1.00	1.40	1.25	1.57	2.00	4.00	0.79	1.60	1.60	2.20	79
	Occupancy sensors poorly located or adjusted		2.71	2.86	2.17	2.50	1.00	2.00	2.25	1.91	1.50	4.00	1.27	2.20	1.80	2.00	86
17	**Fire Alarm**	3.83															
	Faulty interlocks to fans and air handlers		2.25	3.04	1.25	1.00	1.00	1.00	2.33	1.31	1.67	4.00	0.79	2.00	1.33	1.67	74
	Specified alarms and communications offsite don't all work		2.25	3.04	1.50	1.00	1.00	1.00	2.33	1.31	1.67	4.00	0.79	2.00	1.33	2.00	78
	Fire/smoke damper malfunction		2.75	3.29	1.75	1.00	1.00	1.00	2.00	1.24	1.33	4.00	0.93	2.00	1.33	2.00	83
	Fire door malfunction		2.00	2.92	1.75	1.00	1.00	1.00	2.00	1.24	1.33	4.00	0.93	1.33	1.33	1.67	72
	Elevator interlocks malfunction		1.75	2.79	1.50	1.00	1.00	1.00	2.00	1.24	1.33	4.00	0.93	1.33	1.33	1.67	70
	Missing devices required by code		2.25	3.04	1.00	1.00	1.00	1.00	2.00	1.24	1.67	4.00	0.74	2.00	1.33	2.33	77
	Misc devices don't alarm (smoke detectors, heat detector, etc.)		1.75	2.79	1.50	1.00	1.00	1.00	2.00	1.24	1.00	4.00	1.24	2.00	1.33	2.00	79
18	**Emergency Power**	2.50															
	Specified circuits or equipment not energized to generator or UPS		2.00	2.25	1.00	1.20	1.20	1.00	2.75	1.53	2.67	4.00	0.57	2.00	1.50	2.00	66
	Generator not coming up to acceptable power in specified time		1.80	2.15	1.20	1.20	1.00	1.00	2.50	1.41	2.00	4.00	0.71	2.00	1.50	1.50	63
	Malfunction of automatic transfer switch		2.00	2.25	1.00	1.20	1.40	1.00	2.75	1.59	2.00	4.00	0.79	1.50	1.25	1.25	58
	Malfunction of UPS		1.80	2.15	1.00	1.20	1.00	1.00	3.00	1.53	1.67	4.00	0.92	1.75	1.25	1.50	61
19	**Envelope & Insulation**	3.43															
	Improper placement of insulation		2.60	3.01	1.00	2.17	1.67	1.80	1.20	1.73	2.75	3.25	0.63	1.25	1.25	2.25	70
	Inadequate level of insulation		1.80	2.61	1.00	3.00	1.17	1.80	1.60	1.92	3.25	3.25	0.59	1.25	1.25	2.50	68
	Incorrect type of insulation		1.60	2.51	1.00	1.83	1.17	1.00	1.20	1.34	3.75	3.25	0.36	1.25	1.25	2.50	65
	Improper vapor barrier location or placement		2.60	3.01	1.00	1.67	2.67	1.80	1.60	1.97	3.75	4.00	0.52	1.25	1.25	2.25	70
	Improper pressure relationships and moisture intrusion		2.60	3.01	1.60	1.67	3.00	2.40	2.20	2.31	3.00	4.00	0.77	1.60	2.00	2.80	84
	Bulk water leakage without drain or air drying potential		1.80	2.61	1.00	1.67	2.83	1.80	2.40	2.21	3.75	4.00	0.59	1.50	1.25	2.00	66

General Notes:

1 These inputs are based primarily on expert judgement.
2 Minimum Score: 1 (a score of 1 indicates little to no impact or occurrence)
3 Maximum Score: 4 (a score of 4 indicates significant impact or occurrence)

Column Key:

I *Prevalence of Equipment or Feature* refers to how
II *Prevalence of Problems* refers to how common is the problem when the particular feature or equipment is present
III *Average Equipment-Problem Prevalence* is a calculated value in which the scores for each category are added together and then averaged
IV *Propensity to Reoccur* refers to how likely is the problem to reoccur again after being fixed
V *Negative Impact on Energy Problems* refers to the effect the problem has on energy issues
VI *Negative Impact on IAQ Problems* refers to the effect the problem has on indoor air quality issues
VII *Negative Impact on Comfort Problems* refers to the effect the problem has on occupant comfort issues
VIII *Negative Impact on O&M Problems* refers to the effect the problem has on operation and maintenance issues
IX *Weighted Average of all Impacts* is a calculated value in which the score for each sub-category is multiplied to the weighting for that category, aggregated, and then divided by the total weighting for all of the categories
X *Cost of Correcting the Problem* refers to how costly it is to fix the problem. Score range: 1 - <$1,000; 2 - $1,000 to $5,000; 3 - $5,000 to $10,000; 4 - >$10,000
XI *Source of Cost:* 1=Means Cost Estimator; 2=Past Projects; 3=Expert Judgement; 4=Rough Estimate
XII *Impact to Cost Ratio* is a calculated value in which the weighted average score for all impacts is divided by the cost to fix the problem
XIII *Potential for Reduced Cx Cost* refers to whether a tool is likely to minimize time spent by either commissioning provider, owner, and/or contractor, which in turn reduces the cost of the project. Also includes any reduction in construction schedule.
XIV *Potential for Improved Data Quality* refers to whether a tool can enhance current methods and procedures for collecting, storing, transferring, and the usage of data within the commissioning process
XV *Likelihood of Not Being Detected w/o Cx* refers to whether a problem would normally be identified if the system or equipment were not commissioned
XVI *Overall Score* is a calculated value in which the score for each main category is multiplied to the weighting for that category and then aggregated

Table 2. New Construction Commissioning Processes Potential for Automation

WEIGHTS (relative to each other)----->	8	7	5	6	
See number key below--->	I	II	III	IV	V
Cx Processes	**Potential for Reduced Cx Cost**	**Potential for Improved Archiving/ Sharing of Data**	**Potential for Improved Data Collection**	**Reduce Change Orders**	**Overall Score**
Pre-Design Phase					
Develop RFP and/or RFQ to select Cx provider	1.50	1.50	1.50	1.00	36
Cx scoping meeting	1.25	1.50	1.50	1.25	36
Develop, distribute and track owner's project	2.25	2.75	2.75	2.00	63
Design Phase					
Develop design phase Cx plan	1.50	1.25	1.25	1.25	35
Develop, distribute and track design narrative, basis of design and design record documentation	2.50	2.75	2.25	2.50	66
Design review					
Review all design documents including Owners Project Requirements, Design Basis, Design Narrative, drawings, specifications	2.25	2.75	2.25	3.00	67
Fill in data collection sheets with Performance Criteria needed to verify Owners Proj. Requirements are met and data necessary to perform verification	2.50	3.00	3.25	2.50	72
Input all findings into an issues log	2.25	3.00	2.75	2.25	66
Distribute issues log to all involved parties	1.75	2.75	2.25	1.75	55
Revise issues log as individual findings are discussed, reviewed, and resolved	2.00	2.25	2.25	1.75	54
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.50	2.75	2.25	1.50	52
Retain data collection sheets for future reference and inclusion in the Commissioning Record	1.50	2.50	2.25	1.50	50
Develop Cx specifications					
Review or assist in developing specifications for issues relating to quality assurance, training, O&M documentation, commissioning, and equipment performance criteria	2.50	2.50	2.00	2.75	64
Select generic boiler plate specification language for the types of equipment and systems being installed	2.50	2.25	1.75	1.50	54
Develop new specification language for equipment and systems if boiler plates are not available	2.50	2.25	1.75	1.75	55
Use design information as needed to modify specifications to meet criteria for specific pieces of equipment and systems	2.50	2.25	2.50	2.25	62
Distribute specifications to all parties involved	1.50	2.50	2.00	1.25	47
Construction Phase					
Scoping meeting	1.00	1.50	1.25	1.50	34
Develop construction phase Cx plan	2.00	2.50	2.00	1.75	54
Submittal review (comments and track responses)					
Review all submittals to ensure Owners Requirements are met	2.00	1.75	2.25	2.00	52
Update data collection sheets with pertinent information needed to verify Owners Requirements and perform functional tests	2.33	3.00	3.00	2.33	69
Update issues log with new findings as necessary	2.25	2.25	2.25	2.00	57
Distribute updated issues log to all involved parties	1.75	2.50	1.75	1.75	51
Revise issues log as individual findings are discussed, reviewed, and resolved	2.00	2.50	2.50	2.50	61
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.50	2.25	2.00	1.50	47
Retain data collection sheets for future reference and inclusion in the Commissioning Record	1.50	2.50	2.25	1.50	50

WEIGHTS (relative to each other)----->	8	7	5	6	
See number key below--->	I	II	III	IV	V
Cx Processes	**Potential for Reduced Cx Cost**	**Potential for Improved Archiving/ Sharing of Data**	**Potential for Improved Data Collection**	**Reduce Change Orders**	**Overall Score**
On-going meetings	2.00	1.67	1.67	2.00	48
Monitor coordination drawing development	1.67	2.00	2.00	2.67	53
Change order and RFI review					
Review all change orders and requests for information (RFI's) to ensure Owners Requirements are met	2.25	2.25	2.50	2.00	58
Update data collection sheets with pertinent information needed to verify Owners Requirements and perform functional tests	2.67	3.00	3.00	2.00	69
Update issues log with new findings as necessary	2.25	2.00	2.00	1.50	51
Distribute updated issues log to all involved parties	2.00	2.50	1.75	1.50	51
Revise issues log as individual findings are discussed, reviewed, and resolved	2.00	2.50	2.25	1.75	55
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.75	2.75	2.00	1.50	52
Retain data collection sheets for future reference and inclusion in the Commissioning Record	1.75	2.75	2.25	1.50	54
Construction observation	2.33	2.00	2.00	1.67	53
Construction checklists generation					
Select generic boiler plate construction checklists	2.50	2.25	2.00	1.25	53
Develop new construction checklists for equipment and systems if boiler plates are not available	2.00	2.50	2.25	1.25	52
Use updated design information to modify all checklists as needed to meet criteria for specific pieces of equipment	2.25	2.25	2.00	1.25	51
Construction checklists execution					
Perform checkout tests according to procedures outlined on the test sheets	2.75	3.00	3.00	2.00	70
Retain complete checklist sheets for future reference and inclusion in the Commissioning Record	2.25	3.25	3.00	1.75	66
Update issues log with new findings as necessary	1.75	2.25	2.25	1.50	50
Distribute updated issues log to all involved parties	1.75	2.75	2.00	1.50	52
Revise issues log as individual findings are discussed, reviewed, and resolved	1.75	2.50	2.50	1.50	53
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.50	2.75	2.50	1.25	51
Functional test form development					
Select generic boiler plate functional tests	3.33	2.67	2.33	1.00	63
Develop new functional tests for equipment and systems if boiler plates are not available	2.67	2.67	2.67	1.00	59
Use updated design information and Owners Requirements to modify all functional tests as needed to meet criteria for specific pieces of equipment	2.33	3.00	2.67	1.00	59
Functional testing					
Perform functional tests according to procedures outlined on the test sheets	3.00	2.75	2.50	1.50	65
Retain complete functional test sheets for future reference and inclusion in the Commissioning Record	2.75	3.00	3.00	1.50	67
Update issues log with new findings as necessary	2.25	2.25	2.25	1.25	53
Distribute updated issues log to all involved parties	2.00	2.50	2.00	1.00	50
Revise issues log as individual findings are discussed, reviewed, and resolved	2.25	2.50	2.25	1.25	54
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.25	2.75	2.25	1.00	47
Develop, maintain and distribute issues log	2.33	3.33	2.67	1.00	61
Review O&M manuals (comment and track responses)	1.33	2.00	1.67	1.00	39

WEIGHTS (relative to each other)----->	8	7	5	6	
See number key below--->	I	II	III	IV	V
Cx Processes	**Potential for Reduced Cx Cost**	**Potential for Improved Archiving/ Sharing of Data**	**Potential for Improved Data Collection**	**Reduce Change Orders**	**Overall Score**
Ensure adequate training	1.33	1.67	1.67	1.00	37
Compile Systems Manual					
Include Owners Requirements, Design Basis, Design Narrative, commissioning specifications, commissioning report, and any other detailed documentation developed during the design process	1.50	2.25	2.50	1.00	46
Include fabrication drawings, equipment submittals, O&M manuals, start-up and shutdown procedures	1.50	2.25	2.75	1.00	48
Compile Commissioning Record					
Include all completed equipment construction checklists and functional test sheets	1.75	2.75	2.50	1.33	54
Include updated and complete issues log	1.75	2.75	2.00	1.33	51
Write final commissioning report	1.67	2.67	2.00	1.33	50
Warranty Period					
Seasonal testing					
Perform functional tests according to procedures outlined on the test sheets	3.00	3.25	3.00	2.00	74
Retain completed functional test sheets for future reference and inclusion in the Commissioning Record	2.50	3.25	3.00	2.00	70
Update issues log with new findings as necessary	1.75	2.25	2.25	1.33	49
Distribute updated issues log to all involved parties	1.50	2.50	2.00	1.00	46
Revise issues log as individual findings are discussed, reviewed, and resolved	1.75	2.50	2.50	1.00	50
Retain a complete copy of the issues log for future reference and inclusion in the Commissioning Record	1.00	2.75	2.25	1.00	45
Near warranty end review	1.67	2.67	1.67	1.00	46

General Notes:

1 These inputs are based primarily on expert judgement.
2 Minimum Score: 1 (a score of 1 indicates little to no impact or occurrence)
3 Maximum Score: 4 (a score of 4 indicates significant impact or occurrence)

COLUMN KEY

I	*Potential for Reduced Cx Cost* refers to whether a tool is likely to minimize time spent by either commissioning provider, owner, and/or contractor, which in turn reduces the cost of the project. Also includes any reduction in construction schedule.
II	*Potential for Improved Archiving/Sharing of Data* refers to whether a tool can enhance current methods and procedures for storing and transferring data
III	*Potential for Improved Data Collection* refers to whether a tool can enhance current methods and procedures for collecting data
IV	*Reduce Change Orders* refer to whether a tool can enhance the current overall design and design review processes to improve design development, specifications, and minimize miscommunication between designer and contractor
V	*Overall Score* is a calculated value in which the score for each category is multiplied to the weighting for that category and then aggregated

Table 3. Existing Buildings Commissioning Processes Potential for Automation

WEIGHTS (relative to each other)----->	8	6	7	
See number key below----->	I	II	III	IV
Retrocommissioning Processes	**Potential for Reduced Cx Cost**	**Potential for Improved Archiving/ Sharing of Data**	**Potential for Improved Data Collection**	**Overall Score**
Planning				
Develop project goals and scope	1.00	2.17	1.83	34
Develop RCx team/Hire Cx provider	1.00	1.83	1.67	31
Collect and review facility documentation	1.50	2.67	2.33	44
Develop Cx plan/Hold scoping meeting	1.33	2.17	1.83	37
Investigation Phase				
Perform site assessment				
Physically inventory all energy consuming equipment and fill in equipment data sheets	2.00	3.33	2.67	55
Review facility documentation and fill in data sheets	1.83	3.33	2.67	53
Interview facility staff and fill in data sheets	1.67	3.17	2.50	50
Develop initial findings and energy calculations				
Use data gathered during the site assessment to identify deficiencies and opportunities	2.67	3.17	2.50	58
Input findings into Findings Log	2.33	3.50	2.67	58
Use data gathered during the site assessment to savings estimates for each finding	2.50	3.17	2.67	58
Estimate implementation costs for each finding regardless of whether cost savings are associated with it or not	2.67	3.17	2.67	59
Develop and present interim report	1.75	2.50	2.00	43
Develop diagnostic monitoring and test plan				
Select generic boiler plate functional tests and monitoring points	2.67	3.00	2.83	59
Use findings to develop specific functional tests and monitoring points	2.50	2.83	2.33	53
Use data gathered during the site assessment as parameters for system operation when developing general and specific functional tests and monitoring points	2.80	2.60	2.60	56
Implement diagnostic monitoring and test plan				
Perform general and specific functional tests	2.83	3.33	3.00	64
Collect monitored data using BAS and/or data loggers	3.33	3.50	3.33	71
Use functional test and monitoring data results to confirm initial findings and identify additional findings	3.17	3.17	2.67	63
Update findings log as necessary	2.67	3.33	2.83	61
Retain copies of the functional test and monitoring results for future reference and inclusion in the final report	2.50	3.50	2.83	61
Findings log				
Input all findings into findings log	2.67	3.33	2.83	61
Distribute findings log to all involved parties	2.33	3.17	2.33	54
Update findings log as individual findings are discussed, reviewed, and resolved	2.50	3.33	2.67	59
Retain copies of the findings log for future reference and inclusion in the final report	2.00	3.50	2.67	56
Select cost-effective opportunities for implementation				
Perform simple payback calculations on findings with energy savings	2.67	3.00	2.33	56
Perform a cost/benefit analysis for findings without energy savings	2.50	3.00	2.33	54
Implementation Phase				

WEIGHTS (relative to each other)----->	8	6	7	
See number key below----->	I	II	III	IV
Retrocommissioning Processes	**Potential for Reduced Cx Cost**	**Potential for Improved Archiving/ Sharing of Data**	**Potential for Improved Data Collection**	**Overall Score**
Implement improvements	1.67	1.33	1.00	28
Retest and remonitor				
Use information from finding calculations as parameters for proposed system operation	2.33	3.00	2.80	56
Assess functional test and monitoring results performed prior to implementation of changes	2.80	3.00	2.80	60
Assist and/or manage improvement implementation	2.80	2.60	2.20	53
Perform functional tests and monitor systems and compare results with previous values to determine if deficiency has been resolved	3.20	3.20	3.00	66
Identify additional findings as necessary	2.60	2.80	2.60	56
Update findings log as individual findings are discussed, reviewed, and resolved	2.40	3.20	2.40	55
Retain copies of the findings log for future reference and inclusion in the final report	2.00	3.00	2.40	51
Retain copies of the new functional test and monitoring results for future reference and inclusion in the final report	2.00	3.20	2.60	53
Update building documentation				
Update all changes made to system control sequences, proposed O&M modifications, functional test and monitoring results which can be used as system benchmarks for future operation.	1.80	3.20	2.80	53
Include fabrication drawings, equipment submittals, O&M manuals, start-up and shutdown procedures if the solution required major system modification and/or equipment installation	1.60	3.20	2.80	52
Include updated and complete findings log	1.80	3.40	2.20	50
Complete final report	1.60	2.60	2.00	42

General Notes:

1 These inputs are based primarily on expert judgement.
2 Minimum Score: 1 (a score of 1 indicates little to no impact or occurrence)
3 Maximum Score: 4 (a score of 4 indicates significant impact or occurrence)

COLUMN KEY

I	*Potential for Reduced Cx Cost* refers to whether a tool is likely to minimize time spent by either commissioning provider, owner, and/or contractor, which in turn reduces the cost of the project
II	*Potential for Improved Archiving/Sharing of Data* refers to whether a tool can enhance current methods and procedures for storing and transferring data
III	*Potential for Improved Data Collection* refers to whether a tool can enhance current methods and procedures for collecting data
IV	*Overall Score* is a calculated value in which the score for each category is multiplied to the weighting for that category and then aggregated

Prototype Demonstration of Proactive Diagnostics

Background

As describe in the main report, an automated continuous commissioning process includes at least four basic steps: 1) continuous monitoring and detection of abnormal operations, including detection of faults and degradation of performance; 2) confirming the presence of the fault and diagnosis of its cause; 3) evaluation of the impact of the abnormal operation; and 4) proactive reconfiguration of controls. Several researchers have developed tools that address the first two steps in the continuous commissioning process (Katipamula et al. 2000) and a few have also integrated the third step (Rossi and Braun 1996 and Katipamula et al. 1999) in their tools. The last step, the proactive diagnostics and reconfiguration of controls, has not been widely discussed nor implemented.

Proactive diagnostics involves automatically initiating changes to cause or to simulate operating conditions that may not occur for some time, thus producing results that might not be available for months in a passive testing mode. Because proactive tests are intrusive in nature, some building owners and operators may consider this to be disruptive to the normal operation of their building systems. Also, implementation of proactive diagnostics is more complex than diagnostics based on passive observation because they require two-way communication with the mechanical systems. These characteristics are some of the reasons why proactive diagnostics for heating, ventilating and air conditioning have not been actively researched.

These concerns, however, can be addressed and tools with proactive diagnostics can be developed. As part of the current research effort, a prototype demonstration is developed in a Microsoft Excel spreadsheet using Microsoft's Visual Basic for Applications language.

A prototype implementation of a proactive diagnostic procedure, which sets the foundation for automated continuous commissioning is presented below. The implementation is limited to isolating temperature sensor problems as described in Section 7.9. This report provides a brief description of how to use the spreadsheet tool.

Major Features of the Prototype Implementation

The major features of the implementation include: 1) identification of a temperature sensor problem (outdoor , return , or mixed air temperature sensor); 2) exercising a proactive diagnostic process described in Section 7.9 to isolate the problem sensor; and 3) estimating the bias in the sensor measurement, if the sensor is biased.

The demonstration uses hourly data for an air handling unit (AHU) produced by simulation over a one-year period. There are a total of four hourly data sets included with the tool for demonstration purposes: 1) fault free; 2) biased outdoor air temperature; 3) biased return air temperature sensor; and 4) biased mixed air temperature.

Description of the Tool

The method described in Section 7.9 uses a set of rules to first identify if any of the three temperature sensors is faulty. If a fault exists, the tool isolates the faulty sensor, using a proactive diagnostic process. After identifying the faulty sensor, the process uses historical data to check if the fault is caused by a systematic bias in the sensor measure (a common problem in the field).

The user interface of the prototype is divided in two parts: 1) the left side, which includes the required inputs, buttons to activate processing, and a textual summary of the conclusion; and 2) the graphic display of results (right side) as shown in Figure D1.

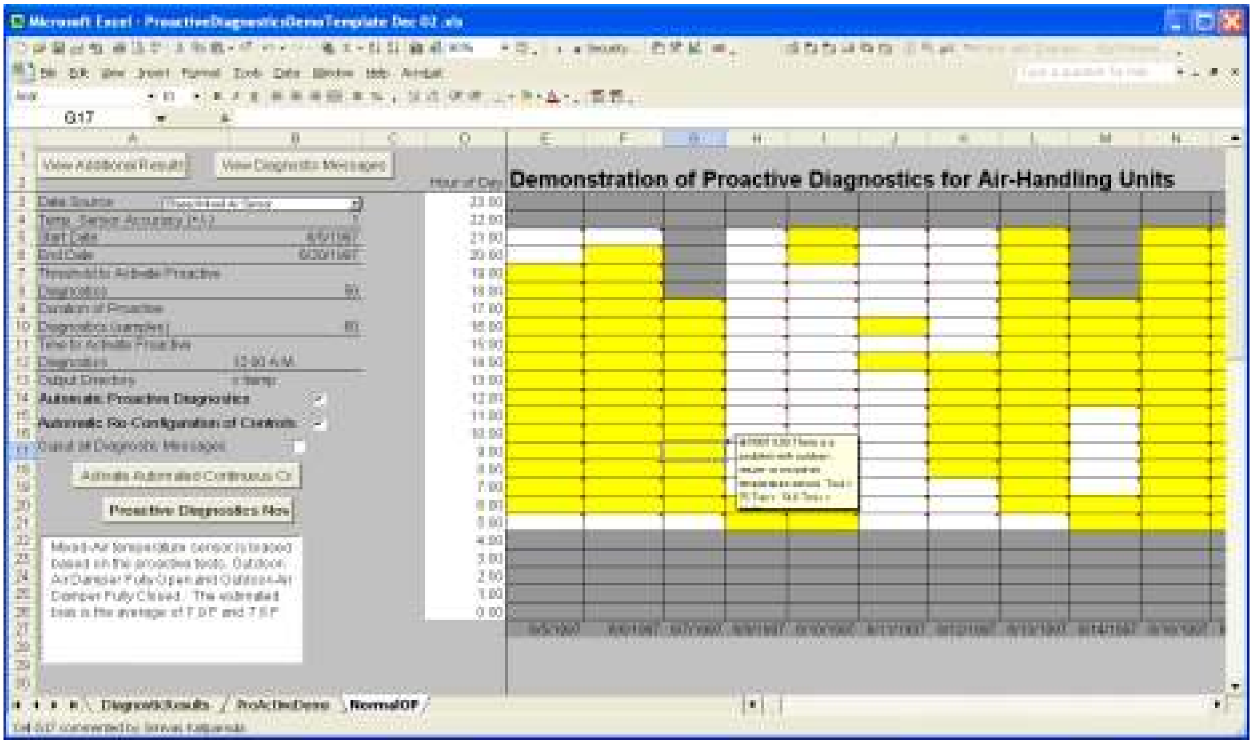


Figure D1 – Screen Shot of the Interface for the Demonstration of the Proactive Diagnostic Process

The input section enables the user to select the source data (i.e., fault free, biased outdoor air temperature sensor, biased return air temperature sensor, or biased mixed air temperature sensor case). For the "faulty" data sets, the sensor fault starts midway through the year (around the first week of June). The user can also select the time span for running the diagnostics by providing the start and end dates. The threshold for activating the proactive diagnostic process must be set as well. Because the proactive diagnostic process is intrusive, it should not be activated unless the fault persists for a reasonable time. The threshold is intended to provide the capability to adjust how many times the fault must be observed before the tool concludes that a fault actually exists. This is to prevent enabling the intrusive proactive testing unnecessarily and providing false alarms based on a single or small number of fault detections, any of which might be a false positive. In addition, the user can also specify the duration of the proactive diagnostic period (i.e., the number of time steps, in this case hours, that the proactive test will be performed over). Both the proactive diagnostic threshold and duration of the proactive diagnostic period are specified in hours in this implementation because the simulated data are hourly. In a real tool, a shorter time step could be used for data collection and as a unit for specifying these input parameters.

Although a provision for entering the time of day to activate the proactive diagnostic process is shown on the interface, it has not been implemented for this demonstration tool. In a real tool, however, this capability would be important to enable the user to select the time during which to run proactive diagnostics (e.g., at night while the building is unoccupied).

A control also is provided for the user to choose between automatic activation of proactive tests or manual activation. By checking the automatic proactive diagnostics check box, the process goes into automatic proactive diagnostic mode if a fault exists and persists for the duration specified by the threshold. If the box is not checked, the process only does passive diagnostics and proactive diagnostics must be activated manually by clicking on the “Proactive Diagnostics Now” button.

The results of the diagnostic process both active and proactive are shown on the right side of the screen in Figure D1. The date is shown on the horizontal axis and the hour of day is shown on the vertical axis. As a result, each cell represents a specific hour. Colors are used to indicate that a fault has been detected during an hour with different colors identifying different types of faults. In this demonstration, white indicates that no fault was detected and yellow indicates a sensor problem was detected. The right side of the screen is similar to the economizer diagnostics display that is used in the Outdoor Air/Economizer (OAE) module of the Whole Building Diagnostician (WBD) (see Brambley et al. 1998 and Katipamula et al. 1999).

How to Use the Tool

Open Excel. Before opening the file for the demonstration tool, check to see that the Visual Basic Analysis add-ins are installed. To do this, click on “Add-Ins…” on the Tools menu on the menu bar. The Add-Ins dialog box will appear. If the Analysis ToolPak-VBA is not checked, click your mouse on the check box to mark it. Click on the OK button to close this dialog. You are now ready to begin the demonstration.

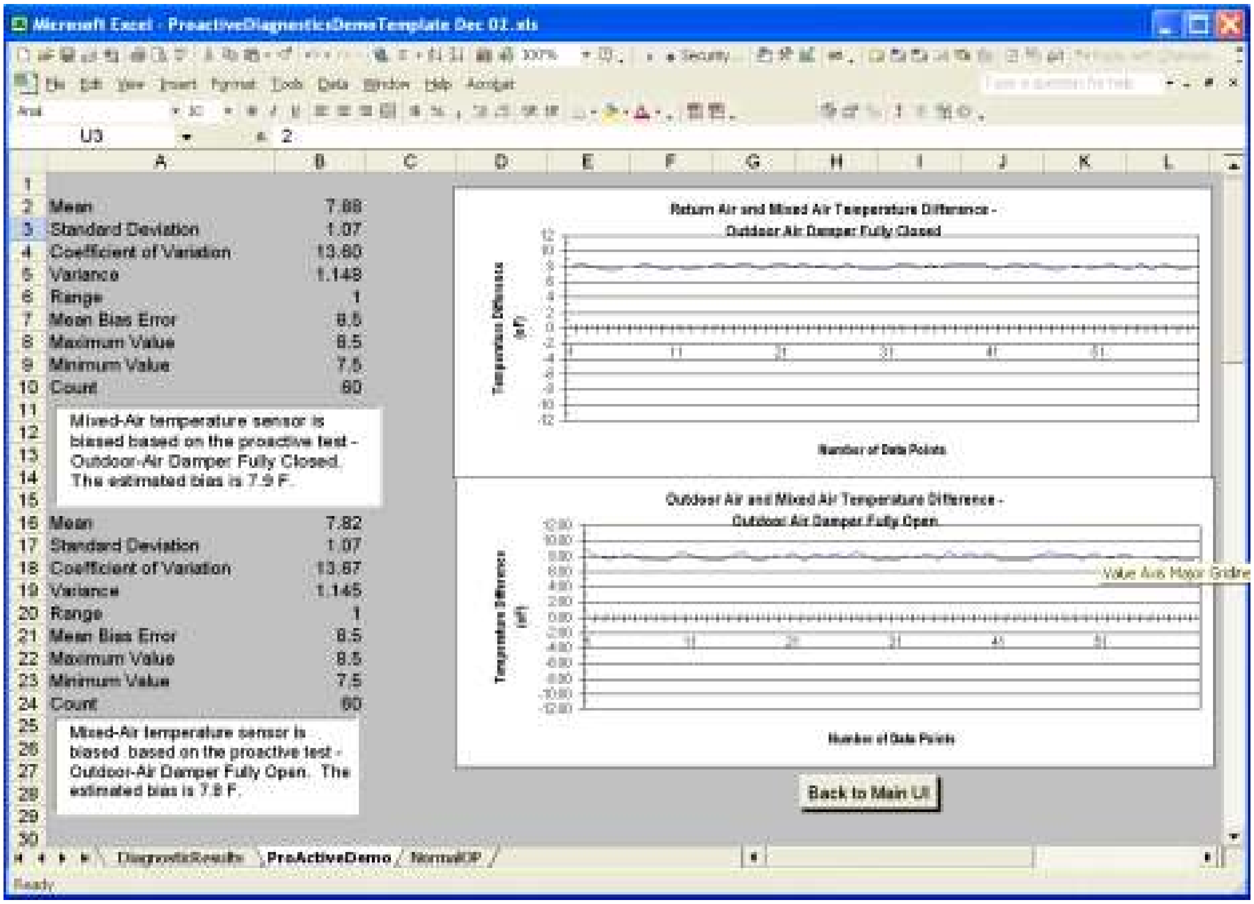
Open the Excel spreadsheet file. It should open on the NormalOP sheet. If it does not, click on the NormalOP tab to display that page. The Excel Window should look similar to the screen displayed in Figure D1.

Before proceeding, make sure you have a **C:\temp** directory on your computer. If not, create one. If you try to run the demonstration without this directory, the tool will stop and ask you to create the directory before it will run. Once you have created the C:\temp directory, you can proceed with the demonstration.

Select a data source from the drop down menu (or use the one already selected). Specify the input values you desire or use the values already listed (recommended for first time users). Make sure that the start and end dates are sufficiently spaced that the total number of hours between them is greater than both the number of hours specified in the "Threshold to Activate Automated Diagnostics" and the "Duration of Proactive Diagnostics." After selecting the proper inputs, the data can be processed by clicking on the "Activate Automated Continuous Cx" button. The hourly data are then processed and the results displayed on the right side of the screen as processing proceeds. As the tool changes between passive and active diagnostics, it will alert you and ask you with a dialog box to confirm the change. Simply click the "OK" button on the dialog. When processing is complete, the tool will display a box indicating so. Results can then be viewed by scrolling on the graph or by reading the text that identifies the overall conclusion in the pane on the left wide of the window.

Additional results can be viewed, which should provide the user insight into how the conclusions were drawn. These results can be seen by clicking on the "View Additional Results" button. This will transfer you to the ProActiveDemo sheet (see Figure D2). This sheet provides plots of the measured return air and mixed air temperatures when the outdoor air damper is fully closed and the outdoor air and mixed air temperatures when the outdoor air damper is fully open. The page also shows the raw data from which these graphs are developed as well as various statistics for the measurements. When done viewing this page, the user can return to the main user interface by clicking on the "Back to Main UI" button.

The passive diagnostic results associated with the individual hours can be viewed in tabular form by clicking on the "View Diagnostic Messages" button (Figure D3) or by pausing the cursor over an individual cell in the graphic display to view the diagnosis for that cell.



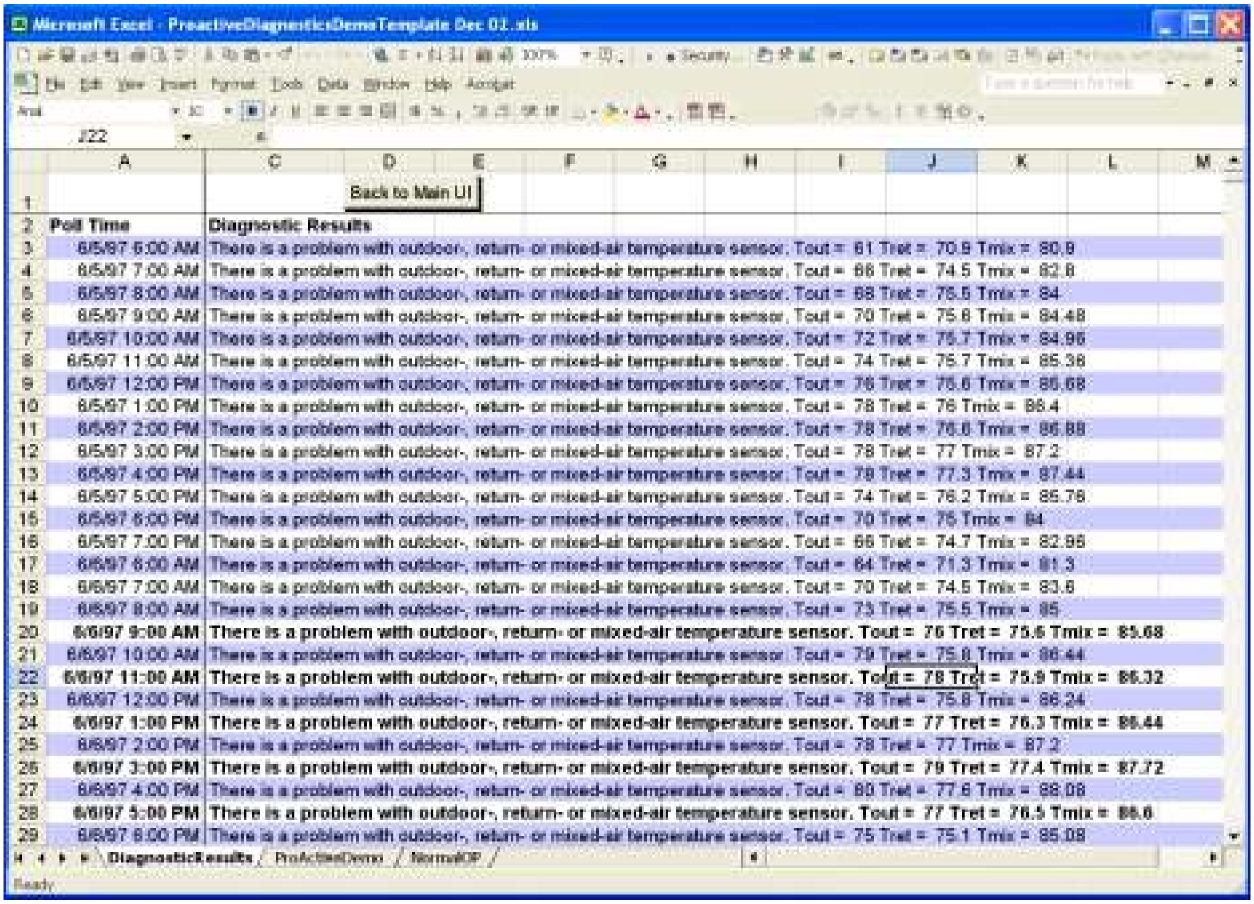
Mean	7.88
Standard Deviation	1.07
Coefficient of Variation	13.60
Variance	1.148
Range	1
Mean Bias Error	8.5
Maximum Value	8.5
Minimum Value	7.5
Count	60

Mixed-Air temperature sensor is biased based on the proactive test - Outdoor-Air Damper Fully Closed. The estimated bias is 7.9 F.

Mean	7.82
Standard Deviation	1.07
Coefficient of Variation	13.67
Variance	1.145
Range	1
Mean Bias Error	8.5
Maximum Value	8.5
Minimum Value	7.5
Count	60

Mixed-Air temperature sensor is biased based on the proactive test - Outdoor-Air Damper Fully Open. The estimated bias is 7.8 F.

Figure D2 – Additional Results Showing how the Conclusions were Drawn



	A	C
1		
2	Poll Time	Diagnostic Results
3	6/5/97 6:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 61 Tret = 70.9 Tmix = 80.9
4	6/5/97 7:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 66 Tret = 74.5 Tmix = 82.8
5	6/5/97 8:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 68 Tret = 75.5 Tmix = 84
6	6/5/97 9:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 70 Tret = 75.6 Tmix = 84.48
7	6/5/97 10:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 72 Tret = 75.7 Tmix = 84.96
8	6/5/97 11:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 74 Tret = 75.7 Tmix = 85.38
9	6/5/97 12:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 76 Tret = 75.6 Tmix = 85.68
10	6/5/97 1:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 76 Tmix = 86.4
11	6/5/97 2:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 76.6 Tmix = 86.88
12	6/5/97 3:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 77 Tmix = 87.2
13	6/5/97 4:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 77.3 Tmix = 87.44
14	6/5/97 5:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 74 Tret = 76.2 Tmix = 85.76
15	6/5/97 6:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 70 Tret = 75 Tmix = 84
16	6/5/97 7:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 66 Tret = 74.7 Tmix = 82.96
17	6/6/97 6:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 64 Tret = 71.3 Tmix = 81.3
18	6/6/97 7:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 70 Tret = 74.5 Tmix = 83.6
19	6/6/97 8:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 73 Tret = 75.5 Tmix = 85
20	**6/6/97 9:00 AM**	**There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 76 Tret = 75.6 Tmix = 85.68**
21	6/6/97 10:00 AM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 79 Tret = 75.8 Tmix = 86.44
22	**6/6/97 11:00 AM**	**There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 75.9 Tmix = 86.32**
23	6/6/97 12:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 75.8 Tmix = 86.24
24	**6/6/97 1:00 PM**	**There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 77 Tret = 76.3 Tmix = 86.44**
25	6/6/97 2:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 78 Tret = 77 Tmix = 87.2
26	**6/6/97 3:00 PM**	**There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 79 Tret = 77.4 Tmix = 87.72**
27	6/6/97 4:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 80 Tret = 77.6 Tmix = 88.08
28	**6/6/97 5:00 PM**	**There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 77 Tret = 76.5 Tmix = 86.6**
29	6/6/97 6:00 PM	There is a problem with outdoor-, return- or mixed-air temperature sensor. Tout = 75 Tret = 75.1 Tmix = 85.08

Figure D3 – Diagnostic Results Associated with Each Hour of the Day

Limitations and Disclaimer

The prototype implementation is intended only for demonstration that the methods described in the main report can be used to develop fully automated tools. Although the spreadsheet has been widely tested on Windows 2000 and Windows XP with both Office 2000 and Office XP, there is a potential that it may not run on some computers. Also, if the inputs are not properly specified, the results may be meaningless. Providing an inconsistent set of inputs may cause the spreadsheet to lockup or crash.

Although the methodology was tested using hourly data, it can be implemented for any selected frequency of data collection and processing interval. The thresholds to active the proactive diagnostics depend on the system on which it is deployed and to a certain extent on the preferences of the individual operator. As noted in the main report, the tolerances and thresholds for both passive and proactive diagnostics are key to successful implementation of automated continuous commissioning tools. Additional research in both laboratory and in the field is essential to support widespread development of such tools.

Engineering Data for Chilled Water Systems

Data Point Description	Data Type	Example Values	Test Procedures
Typical Centrifugal Chiller			
1. Data Needed to Perform Specific Functional Tests			
Design chilled water supply temperature (°F)	Number	44 °F	Full load capacity
Design chilled water return temperature (°F)	Number	60 °F	Full load capacity
Minimum chilled water supply temperature setpoint (°F)	Number	44 °F	Full load capacity, Chilled water temperature reset
Maximum chilled water supply temperature setpoint (°F)	Number	49 °F	Chilled water temperature reset
Design maximum chilled water flow (gpm)	Number	675 gpm	Full load capacity
Design condenser water entering temperature (°F)	Number	80 °F	Full load capacity
Design condenser water leaving temperature (°F)	Number	90 °F	Full load capacity
Maximum condenser water entering temperature setpoint (°F)	Number	80 °F	Full load capacity, Condenser water temperature reset
Minimum condenser water entering temperature setpoint (°F)	Number	65 °F	Condenser water temperature reset
Design maximum condenser water flow (gpm)	Number	1350 gpm	Full load capacity
2. Data Needed to Confirm Installed Equipment with Contract Documents			
Chiller make and model #	Narrative Text	Make - Mfgr Model - XYZ	Prefunctional test
Design full load capacity (tons)	Number	450 tons	Prefunctional test
Design full load efficiency (kW/ton)	Number	0.56 kW/ton	Prefunctional test
Refrigerant Type	Number	R-22	Prefunctional test
Rated full load input kW (kW)	Number	251.1 kW	Prefunctional test
Compressor motor voltage (volts)	Number	460 volts	Prefunctional test, Voltage imbalance
Compressor motor phase	Number	3 phase	Prefunctional test
Compressor motor amperage (amps)	Number	345 amps	Prefunctional test, Maximum amp check
Design maximum evaporator water pressure drop (ft H_2O)	Number	19 ft	Prefunctional test
Design maximum condenser water pressure drop (ft H_2O)	Number	31 ft	Prefunctional test
3. Data Identified for Continuous Commissioning			
Chilled water supply temperature	Number	--	Continuous monitoring
Chilled water return temperature	Number	--	Continuous monitoring
Chilled water flow	Number	--	Continuous monitoring
Condenser water entering temperature	Number	--	Continuous monitoring
Condenser water leaving temperature	Number	--	Continuous monitoring
Condenser water flow	Number	--	Continuous monitoring
Chiller kW	Number	--	Continuous monitoring
Chiller Performance Data	Graph/Table/Matrix	--	Continuous monitoring
4. Data of Interest to Understand System Operation and Design			
Sequence of Operations 1. Start-up/shut down/restart/cut-out 2. Interlocks (chillers, pumps, CTs, failure mode) 3. Chiller operation (lead/lag/staging) 4. Compressor loading control 5. Chilled water temperature reset	Narrative Text	--	
System operating schedule	Narrative Text	--	
Chiller sound spectrum graph/table	Graph/Table/Matrix	--	
Installation, O&M Manuals	Manuals/Books	--	
Evaporator low pressure cut-out (psi)	Number	26.0 psi	
Condenser high pressure cut-out (psi)	Number	140.0 psi	
Design minimum chilled water flow (gpm)	Number	400 gpm	
Design minimum condenser water flow (gpm)	Number	950 gpm	
Design chiller noise class (NC)	Number	NC-60	
Compressor motor speed (RPM)	Number	1760 RPM	
Design compressor motor efficiency (%)	Number	94.0%	

Engineering Data for Chilled Water Systems

Data Point Description	Data Type	Example Values	Test Procedures
Chiller factory performance test certification	Text Document	--	
Chiller weight (lb)	Number	46000 lb	
Chiller operating speed (RPM)	Number	1760 RPM	
Chiller isolator compressibility factor (lb/in)	Number	30667 lb/in	
Chiller isolator minimum static deflection (in)	Number	1.5 in	
Design chiller vibration transmissibility (%)	Number	10%	
System description and options	Narrative Text	--	
Design criteria	Narrative Text	--	
Typical Chilled Water Pump			
1. Data Needed to Perform Specific Functional Tests			
Pump capacity (gpm)	Number	765 gpm	Full load capacity, Trim impellers
Pump differential pressure setpoint (ft H_2O)	Number	40 ft	Chilled water pressure reset, Trim impellers
Impeller size (in)	Number	10.3 in	Trim impellers
Pump deadhead pressure (ft H_2O)	Number	90 ft	Trim impellers
2. Data Needed to Confirm Installed Equipment with Contract Documents			
Pump make and model #	Narrative Text	Make - Mfgr Model - XYZ	Prefunctional test
Net pump head (ft H_2O)	Number	110 ft	Prefunctional test
Pump NPSH (ft H_2O)	Number	5 ft	Prefunctional test
Pump motor horsepower (hp)	Number	40 hp	Prefunctional test
Pump motor voltage (volts)	Number	460 volts	Prefunctional test, Voltage imbalance
Pump motor phase	Number	3 phase	Prefunctional test
Pump motor amperage (amps)	Number	45.6 amps	Prefunctional test, Maximum amp check
Motor service factor	Number	1.15	Prefunctional test
Design pump motor efficiency (%)	Number	94.5%	Prefunctional test
3. Data Identified for Continuous Commissioning			
Pump pressure differential	Number	--	Continuous monitoring
Pump motor voltage	Number	--	Continuous monitoring
Pump motor amperage	Number	--	Continuous monitoring
VFD certified performance curve	Graph/Table/Matrix	--	Continuous monitoring
Pump VFD speed	Number	--	Continuous monitoring
4. Data of Interest to Understand System Operation and Design			
System operating schedule	Narrative Text	--	
Sequence of Operations 1. Start-up/shut down/restart/cut-out 2. Interlocks (chiller, lead/lag, failure mode) 3. Sensor and actuator calibration 4. Pump operation (lead/lag staging) 5. Pump flow control (VFD, max/min)	Narrative Text	--	
Pump spec sheet and curve	Graph/Table/Matrix	--	
Chilled water test and balance (TAB) report	Text Document	--	
Design VFD full load efficiency (%)	Number	98.5%	
Design pump noise class (NC)	Number	NC-35	
Pump motor speed (RPM)	Number	1780 RPM	
Installation, O&M Manuals	Manuals/Books	--	
System description and options	Narrative Text	--	
Design criteria	Narrative Text	--	
Pump weight (lb)	Number	1540 lb	
Pump operating speed (RPM)	Number	1780 RPM	
Pump isolator compressibility factor (lb/in)	Number	1030 lb/in	
Pump isolator minimum static deflection (in)	Number	1.5 in	
Pump sound spectrum graph/table	Graph/Table/Matrix	--	
Design pump vibration transmissibility (%)	Number	35%	

Engineering Data for Chilled Water Systems

Data Point Description	Data Type	Example Values	Test Procedures
Typical Cooling Tower			
1. Data Needed to Perform Specific Functional Tests			
Condenser water flow (gpm) at full fan flow	Number	3600 gpm	Full load capacity
Condenser water inlet temperature (°F) at full fan flow	Number	90 °F	Full load capacity
Condenser water outlet temperature (°F) at full fan flow	Number	80 °F	Full load capacity
Design outside air dry-bulb temperature (°F) at full fan flow	Number	90 °F	Full load capacity
Design outside air wet-bulb temperature (°F) at full fan flow	Number	71 °F	Full load capacity
Maximum condenser water temperature setpoint (°F)		80 °F	Full load capacity, Condenser water temperature reset
Minimum condenser water temperature setpoint (°F)		65 °F	Condenser water temperature reset
Design full load condenser water temperature difference (°F)	Number	10 °F	Full load capacity
Design full load tower approach temperature (°F)	Number	9 °F	Full load capacity, Condenser water temperature reset
2. Data Needed to Confirm Installed Equipment with Contract Documents			
Cooling tower make and model #	Narrative Text	Make - Mfgr Model - XYZ	Prefunctional test
Design full load capacity (tons)	Number	1500 tons	Prefunctional test
Fan motor horsepower (hp)	Number	20 hp	Prefunctional test
Fan motor voltage (volts)	Number	460 volts	Prefunctional test, Voltage imbalance
Fan motor phase	Number	3 phase	Prefunctional test
Fan motor amperage (amps)	Number	24.0 amps	Prefunctional test, Maximum amp check
Motor service factor	Number	1.15	Prefunctional test
Design fan motor efficiency (%)	Number	90.0%	Prefunctional test
Sump heater input power (kW)	Number	12 kW	Prefunctional test
3. Data Identified for Continuous Commissioning			
Cooling tower performance test certification	Text Document	--	Continuous monitoring
Fan performance curve	Graph/Table/Matrix	--	Continuous monitoring
Tower performance data	Graph/Table/Matrix	--	Continuous monitoring
Condenser water entering temperature	Number	--	Continuous monitoring
Condenser water leaving temperature	Number	--	Continuous monitoring
Condenser water flow	Number	--	Continuous monitoring
Outside air dry-bulb temperature	Number	--	Continuous monitoring
Outside air wet-bulb temperature	Number	--	Continuous monitoring
Cooling tower fan voltage	Number	--	Continuous monitoring
Cooling tower fan amperage	Number	--	Continuous monitoring
4. Data of Interest to Understand System Operation and Design			
Design total pressure at inlet center line (ft H_2O)	Number	--	
Design static lift (ft H_2O)	Number	--	
Design cooling tower noise class (NC)	Number	NC-25	
Fan motor speed (RPM)	Number	1770 RPM	
Design cooling tower vibration transmissibility (%)	Number	60%	
Sequence of Operations 1. Start-up/shut down/restart/cut-out 2. Interlocks (chiller, lead/lag, failure mode) 3. Tower fan operation (lead/lag staging) 4. By-pass valve operation and control 5. Sump heater operation and control 6. Condenser water temperature reset	Narrative Text	--	
System description and options	Narrative Text	--	
Design criteria	Narrative Text	--	
System operating schedule	Narrative Text	--	
Cooling tower weight (lb)	Number	12584 lb	
Cooling tower operating speed (RPM)	Number	1050 RPM	

Engineering Data for Chilled Water Systems

Data Point Description	Data Type	Example Values	Test Procedures
Cooling tower isolator compressibility factor (lb/in)	Number	8390 lb/in	
Cooling tower isolator minimum static deflection (in)	Number	1.5 in	
Cooling tower sound spectrum graph/table	Graph/Table/Matrix	--	
Condenser water test and balance (TAB) report	Text Document	--	
Installation, O&M Manuals	Manuals/Books	--	

Sources of Information

Owner Project Requirement Narrative (Design Intent); Design Narrative; Basis of Design; Contract Document Drawings; Specifications; Submittals; O&M Manuals; Manufacturer's Data; As-built Drawings; Change Orders; Test and Balance Report