International
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Agency

Technical Synthesis Report
Annex 34

Computer Aided Evaluation of HVAC System Performance

Energy Conservation in Buildings and Community Systems

34

Technical Synthesis Report Annex 34

Computer Aided Evaluation of HVAC System Performance

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Based on the Report Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings by Arthur Dexter and Jouko Pakanen

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. The mission of one of those areas, the ECBCS - Energy Conservation for Building and Community Systems Programme, is to facilitate and accelerate the introduction of energy conservation, and environmentally sustainable technologies into healthy buildings and community systems, through innovation and research in decision-making, building assemblies and systems, and commercialisation. The objectives of collaborative work within the ECBCS R&D program are directly derived from the on-going energy and environmental challenges facing IEA countries in the area of construction, energy market and research. ECBCS addresses major challenges and takes advantage of opportunities in the following areas:

- exploitation of innovation and information technology;
- impact of energy measures on indoor health and usability;
- integration of building energy measures and tools to changes in lifestyles, work environment alternatives, and business environment.

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date the following projects have been initiated by the executive committee on Energy Conservation in Buildings and Community Systems (completed projects are identified by (*)):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)

Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)
Annex 43: Testing and Validation of Building Energy Simulation Tools
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Built Environments and Communities
Annex 50: Prefabricated Systems for Low Energy / High Comfort Building Renewal

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

(*) - Completed

Annex 34: Computer Aided Evaluation of HVAC System Performance

This report contains a summary of the work of Annex 34: Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, the formal duration of which was from 1997 to 2001. It is mainly based upon the principal report of Annex 34 “Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings” by Arthur Dexter and Jouko Pakanen.

Scope

A previous study indicated that 20% - 30% energy savings in commercial buildings are achievable by re-commissioning of the HVAC systems to rectify faulty operation. Conventional strategies do not explicitly optimize performance and cannot respond to the occurrence of faults which cause performance to deteriorate. The objective of this Annex was to work with control manufacturers, industrial partners and/or building owners and operators to demonstrate the benefit of computer aided fault detection and diagnostic systems. Methods were incorporated either in stand alone PC-based systems or incorporated within a future generation of "smart" building control systems.

Subtasks included:

- Construct prototype performance validation systems: These were designed to assist with final stages of the commissioning or re-commissioning of HVAC systems. Test procedures were devised to check for correct operation and the absence of particular faults in the mechanical equipment and to assess performance.

- Construct prototype performance monitoring systems: Monitoring systems were designed to detect unsatisfactory performance by comparing current performance with predicted by a reference model. Different approaches to generate reference models were investigated.

- Interface prototype systems to building control systems: Interfaces were designed to connect the prototype systems to commercial control systems.

- Test and demonstrate performance validation and monitoring systems in real buildings:Field trials were proposed for both new, unoccupied buildings nearing completion and buildings which had been occupied for sometime. Long term monitoring also took place to determine their effectiveness in detecting and diagnosing faults that arise during normal operation.

Annex 34 Participants: Canada, Finland, France, Germany, Japan, Netherlands, Sweden, Switzerland, United Kingdom, and United States of America

Abbreviations

FDD	Fault Detection and Diagnosis
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
ECBCS	Energy Conservation in Buildings and Community Systems
BEMS	Building Energy Management Systems
PID	Position Infrared Detector
VAV	Variable Air Volume
AHU	Air Handling Unit
CAHU	Central Air Handling Unit
EMCS	Energy Management System
CAV	Constant Air Volume
PAT	Performance Audit Tools
DABO	Diagnostic Agent for Building Operators
BMS	Building Management System

Table of Contents

1 Introduction

The performance of a building can be unsatisfactory due to poor design or operation. Whilst it is difficult to address poor design in existing buildings, there is much scope for improving the operation of the building. Current strategies used by HVAC energy management systems often do not optimise performance. Failure to respond to faults can result in higher costs from excessive energy use and premature component failure. Alternatively pollution from leakage of refrigerants or inefficient combustion may also arise.

Re-commissioning of HVAC systems to rectify faulty operation can bring substantial energy savings; research suggests that 20-30% reductions could be possible. However identifying faults in HVAC systems is not simple.

Barriers to identifying HVAC faults

- The behaviour of HVAC plants and buildings is difficult to predict.
- HVAC designs are unique and so accurate mathematical models are difficult to produce and would cost too much.
- Detailed design data are seldom available.
- Measured data are unavailable and often a poor indicator of overall performance.
- Several faults may have similar symptoms.
- Some variables can't be measured directly.
- In many cases, the design intent is poorly specified.

A number of techniques for detecting and isolating faults were previously identified by the participants in IEA ECBCS Annex 25. These methods, based on simple models of correct operation, were developed using detailed computer simulation. Although they were tested on experimental data from laboratory HVAC plants, they were not tested on 'real' operational systems.

Annex 34 aimed to demonstrate that the application of fault detection and diagnosis (FDD) techniques has real economic and environmental benefits and that implementing performance evaluation schemes based on these FDD techniques is commercially and technically viable.

1.1 Annex 34 background and objectives

The Annex 34 research programme started in 1997 and was completed in 2001. Twelve countries contributed to the research – these were Belgium, China, Canada, Finland, France, Germany, Japan, Netherlands, Sweden, Switzerland, United Kingdom, and United States of America.

Typically 20%-30% energy savings in commercial buildings are achievable by re-commissioning of the HVAC systems to rectify faulty operation. Current strategies do not explicitly optimise performance and cannot respond to the occurrence of faults which cause performance to deteriorate.

The objective of Annex 34 was to work with control manufacturers, industrial partners and building owners and operators to demonstrate the benefit of computer aided fault detection and diagnostic systems in real building applications.

The specific objectives were to:

1. Clarify the needs of the users. Investigate the user-machine interface needed to ensure effective communication about fault conditions and remedial actions with plant room operators.
2. Assess the cost effectiveness and applicability of FDD methods, identifying potential constraints. Consider equipment and system level faults.

3 Construct prototype computer-aided performance evaluation systems that are able to detect inadequate performance and diagnose faults arising at different stages of the building life cycle (including FDD of factors causing a general degradation of performance).
4 Investigate the need and requirements for a framework defining a hierarchy for coordinating the information from independent FDD methods. This hierarchical framework would also arbitrate where conflicting diagnoses were encountered.
5 Demonstrate the robustness and commercial feasibility of performance evaluation systems through tests in real buildings.

1.2 Work undertaken

- Systems and sub-systems that were suitable for the demonstrations were identified.
- Robustness and feasibility of practical application of FDD methods were evaluated.
- Prototype performance validation and monitoring systems were constructed.
- The interfacing of the prototype systems to building control systems was investigated and designed.
- The performance validation and monitoring systems were tested and demonstrated in real buildings.
- Long-term trials of the performance monitoring systems were undertaken in some buildings to determine their effectiveness in detecting and diagnosing faults that arise during normal operation. In particular, practical problems associated with the identification of faults that result in performance degradation were investigated.
- The field trials were also used to determine which, and in what form, information should be provided to the plant operator at the man-machine interface.
- Performance validation and monitoring systems have been demonstrated off-line using data collected from the building and on-line, in the building or remotely.

1.3 Achievements

- Twenty-three prototype performance monitoring tools and 3 prototype performance validation tools were developed.
- 30 demonstrations took place in 20 buildings.
- 26 fault detection and diagnosis tools were tested in real buildings.
- 4 performance monitoring schemes were evaluated on 3 data sets from real buildings.
- A FDD test shell was developed to simplify the comparative testing of the FDD tools.

2 Requirements for a well designed fault detection and diagnosis system

2.1 Customer and user needs, interfaces and benefits

It is important to differentiate between the customers who will buy the Fault Detection and Diagnosis (FDD) tools; the end users who will use them; and the service providers who will use the tools to improve the service to their client. FDD techniques will be of limited use if the goals of customers or users are poorly defined or if the developer is unable to translate the FDD technique into a FDD tool that is adaptable to the users' needs.

Customers

The potential customers and their main goals are:

- **BEMS manufacturers** who want to incorporate FDD tools in future designs or provide fault detection and diagnosis services to their customers. In some countries BEMS manufacturers are closely involved in the operation of the HVAC system, in others they simply provide a product and services linked to the product.
- **Service companies** who want to reduce the cost of energy use and maintenance; improve their service through fault detection and diagnosis and better manage contracts with building owners.
- **Building owners or facilities managers** who want to maintain a comfortable internal environment minimising energy and maintenance costs. They will also want to better manage contracts with service companies and reduce the number of staff involved in operation management as well as improve their understanding of HVAC system operation.
- **Commissioning engineers** who want a better understanding of the operation of the equipment in practice; ensure the system is free of faults; and establish a baseline for system performance.

Users

Some users of FDD tools will have a sound knowledge of HVAC systems whilst others in commercial or administrative roles will have none. Hence a ‘good’ tool will be adapted to the needs of specific users. The type of user can be defined, for example, by the level of action that they must take; multiple building level; building level or plant level action.

The types of actions users at different levels might need to take can be classed as:

- Screening the performance of a large number of pieces of equipment,
- Detecting faults in a particular piece of equipment, or
- Trouble shooting and fixing equipment with known problems.

Often a tool will have a number of users. It is important that the tool is adaptable to the needs of each user. For example a tool used by a manager and a technician might require different interfaces for each user. The tool should be capable of adapting to the amount of time that the user has, use an appropriate language (e.g. technical versus non technical). The tool should also be easily customised to the specific needs of the user, for example, allowing the prioritisation of faults.

Convincing users of the benefits

FDD system development is in its infancy and hence there is no widespread recognition of the benefits of FDD. On the other hand some users may be under the false impression that their BEMS already has a diagnostic capability. When presenting the tool it is important to address these misconceptions and educate the potential user about the realistic benefits of the tool:

FDD needs to be presented as a tool for converting large amounts of existing BEMS data into useful knowledge. If it is presented as a revolutionary tool it may be perceived to be high risk. A focus on the user’s needs rather than fault detection will help to convince the user of potential benefits; for example the potential to save time, costs and improve occupant comfort. Only realistic benefits should be presented, for example the ability to:

1. Automate simple tasks which are time consuming if done manually.
2. Detect major faults.
3. Propose tentative diagnoses for the cause of the detected fault.
4. Make a conclusive diagnosis for the cause of the detected fault.

In practice most current tools or prototypes can only carry out some of the functions above and few, if any can carry out function 4.

Care should be taken to avoid presenting the tool as a replacement for an intelligent human user. For example most users will readily accept tools which automate the tedious task of checking raw data, whereas few would have confidence that the tool was able to do their job in accurately diagnosing a fault.

Users are likely to be confident in a simple, transparent tool that they understand. More effort is needed to give them the same confidence in a tool using complex FDD techniques.

Demonstration of tools in real buildings is also essential to building users' confidence in these tools. The case studies carried out as part of this Annex were an important first step in doing this.

2.2 Designing a user interface

Designing a user interface is likely to be an iterative process. The user interface should be split into a part that deals with the commissioning of the tool and a part that deals with the operation of the tool.

The interface for commissioning of the tool should enable the user to define:

- the type of HVAC plant to be monitored
- the way that measurements will be accessed
- design data and thresholds etc.

The user interface for running the tool must give different levels of access to the data, such as:

- a synthesis report
- in depth analysis of the data underlying the report
- raw data
- fault diagnosis or a list of corrective actions needed.

The level of information must be appropriate to the needs of the user. An on-line FDD tool will issue an alarm when the fault is detected; off-line FDD tools will only operate when activated by the user. The user interface must allow simple adjustment of the alarm thresholds to strike a balance between quick detection and generating false alarms.

2.3 Cost benefit analysis

Most of the costs of implementing an FDD tool arise from its installation and commissioning. This is caused largely by the difficulty of interfacing with existing databases to access measurements and other data needed to run the tool. This high cost is also encountered when implementing new control functions in an existing BEMS.

This cost can be minimised through:

- Good documentation of existing databases.
- Using a good point naming convention.
- Reducing the amount of data needed for set-up and engineering.
- Re-use data from existing databases .
- In new buildings, the FDD tool can be commissioned in parallel with the control commissioning, reducing the need for extra data.

Most FDD tools can be implemented using existing hardware. Generally extra sensors for fault detection will not be needed. However they may be needed for unambiguous diagnosis and therefore extra costs may be incurred. There is usually a trade off between the number of extra sensors and the performance of the FDD tool.

The cost of FDD tools can be minimised by using existing software to carry out standard functions for acquisition, handling, presentation and transfer of data as well as detection and diagnosis.

Portability can allow fault detection diagnosis on specific components or packaged units such as chillers or other vapour-compression cooling equipment. Alternatively FDD tools can be permanently installed in a building and linked to the BEMS. Portable FDD devices currently have a better cost benefit ratio than permanently installed FDD tools. FDD systems for packaged units typically use low-cost sensors (temperature and pressure sensors). They can be used to detect faults on more than one piece of equipment, usually during a routine maintenance check or in response to a complaint by occupants.

Easily commissioned, generic FDD tools can be developed for mass-produced HVAC systems. For bespoke systems and buildings, generic FDD tools capable of detecting limited faults will be of low value to the users and the bespoke FDD system will incur a higher commissioning cost.

Additional costs will be incurred from training end users and installers of FDD tools and the operation and maintenance of tools.

Fault detection and/or diagnosis can occur at a number of levels and these have different cost benefit ratios:

- Fault detection tools for subsystems focus on frequently occurring, simple faults which are currently overlooked. These tools are dedicated to simple subsystems such as a single hydronic heating circuit, individual VAV boxes or air handlers. The cost benefit ratio of these systems could be good if they provide added functionality to the control system. It would be logical to deploy fault detection tools for the HVAC and refrigeration industry as a forerunner of FDD tools.
- Fault detection and diagnosis for subsystems are currently high cost as they require extra sensors. In the long term it might be expected that FDD tools will be integrated in individual equipment controllers, provide continuous monitoring and recommendations for the timing of servicing.
- Fault detection tools for buildings were developed as part of this Annex to detect faults at the building or multiple building level. Some have a good cost benefit ratio and could be deployed in the near-term.

2.4 Testing FDD tools by creating artificial faults

In order to prove a FDD tool is effective, and before commercialisation, it must be tested on a system with faults. Ultimately it must be verified by testing it in the presence of all the faults it is designed to handle. Faults can be classified into three types:

- Natural faults – these occur in a real process as a result of wear and tear or human errors in the design, construction and assembly and operation or maintenance of equipment.
- Artificial faults – are intentional man-made faults, implemented by introducing a faulty component or setting or by changing the process conditions. The latter method is usually preferred as it is difficult to find or manufacture components with specific faults.
- Simulated faults –are changes to the system that reproduce the symptoms of a natural fault. These are useful when it is physically impossible, expensive or dangerous to introduce the actual fault.

Testing an FDD system against natural faults in real HVAC systems is not really practical. Natural faults would need to occur frequently enough to allow all of the ‘typical’ cases to be tested. Also testing of faults caused by wear and tear would not be possible in short timescales. Introducing artificial faults is often the only viable means of testing an FDD tool in a real environment.

Control systems for HVAC systems are particularly susceptible to faults. This stems from the highly sophisticated nature of controls, control software and the range of complex components of integrated sub-systems.

Hardware or equipment faults are the most common in a mechanical system. Assuming that the product has no manufacturing faults, hardware can experience ‘abrupt faults’ or malfunctions, and ‘degradation faults’:

- Stuck valves, broken fan belts and burnt-out electric motors are examples of physical defects resulting in abrupt faults.
- Degradation faults tend to occur in moving parts or where fluid is passing a component.

Example: Introducing faults into an air handling unit
Twenty-two faults were introduced into a VAV AHU on the seventh floor of the Tokyo Electric Power Company building in Japan. Data sets collected through the BEMS at one-minute intervals were used to test FDD tools developed by Japanese researchers. The following list categorises the fault type, and shows the way the fault was introduced.

2.5 Commissioning FDD tools

Commissioning of FDD tools is defined as 1) setting up, 2) putting into operation, 3) testing and 4) maintaining a FDD tool on a specific system, so it can work according to its specification. These are four sequential phases. Each phase addresses a number of issues which are discussed in the section below.

Faults	Description of how fault was introduced
1. Wrong PID parameter setting	Manual PID parameter change
2. Fan speed decreasing (intended to simulate fan belt slipping)	Manual inverter signal setting
3. Inappropriate sensor location	Heating up a control thermostat
4. Erroneous wiring of a sensor	Reversed wiring
5. Control valve stuck	Setting by forcing the control signal
6. VAV damper stuck	Local manual setting
7. False AHU hatch opening	Manual open

Table 1: Example of fault introduction in Tokyo Electric Power Company building (Japan)

The commissioning of FDD tools excludes optimisation of the tool's performance or commissioning of the building, plant or control systems.

Table 2 shows a checklist of factors influencing the technical and organisational elements of commissioning.

Commissioning of FDD tools is most likely to be successful when the following recommendations are applied.

The people responsible for each action are indicated in brackets:

1. Limit commissioning to the most important faults in the application (developer, commissioning engineer, user/operator).
2. Use the BEMS for inputs to the HVAC system (commissioning engineer, user/operator).
3. Ensure additional hardware needed for commissioning, such as sensors, communication links, wiring etc is working correctly (commissioning engineer).
4. Consider allowing the user to select the values of thresholds for alarm generation.
5. Adjustment of these values by the user in the operation phase will give the user confidence in the FDD tool (user/operator).
6. Ensure the availability of design data, configuration data and controller-related data.(commissioning engineer).
7. Appoint a coordinator to identify the people that should be involved in commissioning at appropriate stages and to manage the commissioning process (coordinator).
8. Re-commission the tool after some experience has been gained (commissioning engineer).

Factors influencing the technical element of commissioning	**Factors influencing the organisational element of commissioning**
• Level of design information required • Level of data required and method used to extract data from system • Sensors needed • Specific operations that need to be in place before data acquisition • Selection of model parameters, optional parameters and thresholds • A knowledge of the control system and/or building operational modes • A knowledge of the nature of fault conditions • Required user settings	• Number and type of people involved • Timing of interdependent tasks • Legal issues between partners • Boundary conditions dictated by partners involved in building construction and operation • Total cost of the FDD commissioning process

Table 2: Checklist of factors affecting technical and organisational commissioning

Information

It is essential to be clear about the information needed if the FDD tool is applied to a specific building, plant or component. Table 3 shows the types of information which might be needed for commissioning. Much of this information is needed to develop the tool as well as to commission it.

Setting up	Putting into operation
Description of FDD tool: Documentation FDD tool implementation procedure Faults to be detected and/or diagnosed Discussion of the difficulties experienced or foreseen **Required information (for detection and diagnosis separately):** Building and HVAC plant design data: with an indication of its source Equipment manufacturers' data Simulation data On-site inspection data Configuration information for the plant and controller Controller parameters: set points, modes of operation, schedules, type of controller Point of information: data points and controller settings List of parameters that require setting and an indication of how their values should be selected List of default parameters Fault model data **Operational requirements:** Definition of the specific operation conditions needed for setting-up Communication issues Customisation for a specific user **Sensors to be used:** Additional sensors needed for fault detection Additional sensors needed for diagnosis Type of sensors Accuracy of sensors **Measurement data acquisition and pre-processing:** Description of how the data are to be obtained in the building Validation of measurements **Post-processing:** Extent of dat processing Extent of data-base required **Operator training:** Level of expertise assumed of the installer and/or user	**Expert knowledge:** FDD tool implementation procedure tool is put into operation? **Identification of parameters using** List of fault-tree model parameters that require identification List of fault model parameters that require identification Requirements for the acquisition of training data Training description Who does the training? Additional sensors used for training Discuss the pitfalls and possible **Selection of thesholds and parameters:** List all parameters that must be selected List all thresholds that must be selected Guidelines regarding threshold selection with remarks about their relationships to false alarms and missed faults **User interface:** Threshold settings for alarm handling Visualisation scheme

Testing	Maintenance
Validating the operation of the FDD tool: Fault-free test procedure Sensor validation procedure **Fault conditions:** Specific faults to be tested **User's influence:** Thresholds settings Alarm handling User feedback from field trials **Documentation of acceptance test**	**Database:** History Statistics **User friendliness** How easy is it to understand and to explain? How easy is it to modify and update? **Maintenance strategy:** Help facilities

Table 3: Issues to be considered in the four commissioning phases for FDD

2.6 Information needs and data access

The FDD tool receives information as 'encoded data' which it stores and processes. This data is then used to generate a data output that can be translated as information.

Design information	Operational information
Building data: • Physical characteristics of the building or zone, use of the building, location of the building **HVAC system design data:** • Installed power, manufacturer' data **Configuration information:** • Plant and control system topology **BEMS information:** • Measured data points and controller settings (address, status, attributes), communication parameters **On-site inspection data:** • Visual features important for the FDD method, which differ from design information	**Mode of operation:** • Schedules, occupation profiles **Controller parameters:** • Set-points, types of controllers
FDD method parameters **Thresholds:** • Steady-state detection thresholds, fault detection thresholds, alarm thresholds **Time constants** • Low-pass filters, required duration of faulty behaviour **Training parameters:** • Pre-processing parameters, fault-free and faulty model parameters, learning parameters (when to adapt and when to stop adaptation, initialisation etc.) **User interface parameters:** • Visualisation parameters, threshold settings, alarm handling	**Measurements** Type and number of sensors for detection Additional sensors for diagnosis Additional sensors for training Sampling rate of data acquisition Validation of measurements

Table 4: Information classes which may be required for commissioning

FDD tools require data to be digitally or analogue encoded. It is assumed that all the information needed by an FDD tool can be encoded in this way. For FDD tools required information includes design, measurement, configuration, control sequencing data and sources such as design documentation, BEMS etc.

Limitations of FDD tools will result from an inability to encode some 'information' into appropriate 'data'. The tool must be flexible enough to handle data which evolves over the building's lifetime as its characteristics (equipment or parameters) change.

Definitions

Data objects - *items in a data model*

Data dictionary - *a collection of descriptions of the data compiled for the benefit of FDD tool designers, programmers and users.*

Data modelling - *the analysis of data objects used in a specific context and the relationship between these data objects.*

Relational database - *a set of tables from which data can be accessed or reassembled in many different ways without having to re-organise the database tables. Structured Query Language (SQL) statements are used for interactive queries for information from a relational database and for collating data for reports.*

2.6.1 Encoding information

The need for standardised encoding and decoding of information became apparent when Annex 34 participants tried to share information in order to test and validate FDD tools.

Various approaches were considered and a data set standard was established using the following rules:

1 All the measurements are included in ASCII data files. Each line in the file contains data sampled at different times.
2 The first entry in each line is the time stamp; several standard formats are acceptable
a MM/DD/YY HH:MM:SS.SSSSSS
b DD.MM.YY HH:MM:SS
c YYMMDD HHMM
d Seconds
3 The measurements follow the time stamp on each line and are delimited by any valid ASCII character not found in the ASCII representation of floating point numbers. For example "," helps Microsoft Excel interpret comma separated values (.csv).
4 The design value for each measurement is included in the first row of the file.
5 Lines starting with the ASCII character "*" designate comment lines.
6 The ASCII string "NaN" is used in place of measurements when no valid numbers are available (for example when the measured value is outside of the sensor range).

A normalised database is organised into tables such that the results are unambiguous and as intended. The data set standard outlined above is the basic level of normalisation and is a 'First Normal Form' (1NF).

2.6.2 FDD Test Shell and equipment templates

A large amount of is effort required to extract data from an information source and insert it into the FDD tool. Annex 34 developed the FDD Test Shell as a method to compare and evaluate FDD tools by facilitating access to this data.

The Test Shell uses a Windows-based Dynamic Data Exchange (DDE) server program. DDE enables two running applications to share the same data as long as they both conform to the same communication standard.

The Test Shell accepts data from one of a variety of data source programs and presents this to the FDD tool's implementation programs. This allows flexibility when choosing the program in which to develop an FDD tool (for example, Visual Basic, Pascal, MATLAB or C++).

The Test Shell platform includes a File Data Source program that uses the standardised approach to encoding information discussed in section 2.6.1.

The File Data Source program maps data to the appropriate standard template; it maps file columns to cells, converts units and sets default cell values for data not included in the file.

Standard templates have been established for vapour-compression cycles and AHU. As an example,

Table 5 shows the standard template developed for vapour-compression cycles.

Cell	Measurement	Units
1	Time	HH:MM:SS
2	Suction pressure	kPa
3	Liquid pressure	kPa
4	Suction temperature	° C
5	Liquid temperature	° C
6	Evaporator inlet water/air temperature	° C
7	Evaporator outlet water/air temperature	° C
8	Condensor inlet water/air temperature	° C
9	Evaporator outlet water/air temperature	° C
10	Evaporator outlet water/air temperature	° C
11	Evaporating temperature	° C
12	Condensing temperature	° C

Table 5: Vapour compression cycle template

2.7 Sensor validation

The FDD methods investigated in this Annex rely on data measured by sensors installed in the HVAC systems. The reliability of the method therefore strongly depends on the reliability of the measurements. Inaccurate or incorrect measurements will result in failure of the FDD method to detect faults, inconsistent system monitoring or a high rate of false alarms.

The validation of sensors is therefore a critical first step in the commissioning of FDD tools. It is therefore necessary to look specifically at the factors that must be considered during the validation of sensors for the application of FDD methods.

Different levels of sensor accuracy may be acceptable for different FDD tools, but good accuracy is particularly important when setting the reference state during commissioning. Specifying unnecessarily high sensor accuracy, however, will impact on the cost to benefit ratio of the FDD tool.

Definitions

Sensor - *a device that receives energy from the measured medium and converts this to a signal which can be transmitted to a place where data is stored and processed.*

Measurement system - *the sensor plus the devices used for data storage and processing.*

Sensor validation - *assessment of the performance of the measurement system and disturbances during measurements.*

2.7.1 Types of sensor faults

Many sensor faults are not specific to the sensor type and can arise regardless of the measurement arrangement. These generic sensor faults are described below:

- **Location faults** – these are very common. Although the sensor works it does not give a representative reading due to incorrect placement. Non-representative readings are obtained when, for example, the sensor is placed near heating or cooling coils, or in ducts with insufficient air flow.
- **Electrical installation faults** – where the electrical connections linking the measurement system to the control system are faulty, sensor and measurement faults may also arise. Bad solder joints, unshielded cables and incorrect power supply are all examples of this type of fault.
- **Sensor-related faults** – may be caused by broken sensors, unsuitable sensors, incorrect design or errors in installation. This type of fault typically causes output drift, bias, no signal or a completely wrong signal.

The overall accuracy of a measurement system will always depend on the worst (most inaccurate) component of the system.

2.7.2 Methods for sensor validation

Several methods are possible for sensor validation. The following methods were most commonly used by the participants in Annex 34.

1 **Temporary and permanent physical redundancy**
Several sensors that measure the same quantity are installed. Every sensor is paired with a validation sensor of a similar type, adjacently placed. The sensors need to stay in the system for several days.

2 **Manual checking of sensors**
Is used to compare the measurement sensor reading to that of a calibrated reference sensor. It is convenient to use the BEMS including the wiring that collects the data. This approach has the advantage that it allows detection of errors in the sensor as well as in the wiring. The sensor should be calibrated with a reference sensor or a well known reference state (e.g. an ice-bath). Manual on-site checking is not possible if the reference states can only be achieved in a laboratory.

3 **Diagnostic tests**
Can be applied where the HVAC components are assumed to be fault free. Test cycles are performed, for example by turning a valve to its closed position and checking if the temperatures at the inlets and outlets of the valve are plausible.

4 **Analytical redundancy**
Is based on calculating differences between analytic and physical values using the laws of physics. Violation of the laws indicates a sensor fault. Sufficient sensors need to be included in the measurement system to enable inference of the analytic values.

5 **Automatic sensor validation**
Covers a range of techniques which have the advantage of being unaffected by plant faults:

- Sensors that use a micro-controller to produce information with high accuracy,
- Self-validating sensors that can perform internal diagnostics, measurement correction and generate standard metrics describing the measurement quality, and
- Self-tuning sensors.

Estimation errors

It is not always possible to measure the variables needed for a FDD tool as the sensors might not be available or direct measurement might be impossible. Examples of this are measurement of the water flow rate to an individual coil or the mass flow rate of air flowing down a duct. In such cases variables must be estimated from indirect measurements; a degree of error, as well as potential faults, may arise from estimation.

- **Model-based estimation** of an unmeasured variable uses knowledge of its relationship to other measured variables. For example, an airflow rate might be estimated from the fan control signal in a VAV system. The accuracy of such estimates depends on the accuracy of the model describing the relationship between the measured and unmeasured variables, and the accuracy of the measurements.
- **Estimating spatial averages** - the output of a single sensor is often used to represent the average value of a variable over a large area or volume. For example, a single-point air temperature sensor might be used as an indicator of the average value of the air over the entire cross-section of a large duct. This can result in a biased estimate of the average air temperature. The magnitude of the offset errors might also vary with operating conditions (e.g. the position of upstream dampers or the speed of the fan).

- **Estimating steady-state values** - Fault detection and diagnosis is often based on the steady-state behaviour of the HVAC equipment. Transients often occur during the operation of HVAC systems; the sensor outputs must therefore be processed to obtain the steady-state values. Three methods are often used:

a) The output of the sensor is passed through a steady-state detector to determine whether the system is sufficiently close to steady-state for the measurement to be used for diagnosis. This approach can often eliminate much of the test data because HVAC equipment operates in an unsteady-state much of the time. The size of the estimation errors depends on the value of the threshold used in the steady-state detector.

b) The sensor output is passed through a low-pass filter to remove any high frequency transients. The filtering will also distort any low frequency changes in the measured variable and can result in significant measurement errors.

c) The measured inputs to the system are pre-processed to allow the required information about the steady-state relationship between input and output to be extracted from the transient data obtained from the sensors. The size of the estimation errors depend on the accuracy of the model assumed in the design of the pre-processor.

2.8 Selecting thresholds for FDD schemes

Thresholds are needed to prevent false alarms from being generated by uncertainties such as modelling and measurement errors and mode detection errors. There are a number of threshold types:

Fault detection thresholds

Differences between the estimated and measured values of a process variable that are larger than the detection threshold produce evidence of a fault.

Mode detection thresholds

This type of threshold determines the mode of operation of the system. For example if a particular variable is above a certain threshold value the system will be in heating mode, and otherwise it will not be in heating mode.

Alarm generation thresholds

An alarm is generated whenever the probability of the fault being present exceeds the alarm threshold. A number of methods are available for selecting thresholds, but none of them are entirely satisfactory. Three basic methods are described below:

Heuristic methods should be used only if the available data is representative of all the possible operating conditions. These methods are often used to determine suitable steady-state detection thresholds. Default values of the thresholds are either based on expert knowledge or historical data from similar HVAC systems or from the same system at different times.

These default values are then tuned by trial and error testing to adjust the false alarm rate.

Statistical methods are based on confidence intervals and hypothesis testing using estimates of the means or standard deviations of the parameters. Training data is often used to estimate the means and standard deviations.

Again, fault-free, representative data must be available for the system under test.

User selection of the thresholds by adjusting default values is allowed by many FDD tools. The user can modify alarm generation thresholds to achieve appropriate alarm rates and fault sensitivity.

This approach has the disadvantage that thresholds might be adjusted inappropriately. For example detection of too few faults, putting occupant comfort at risk, or too frequent detection of faults stretching the resources of maintenance staff. Some faults are more sensitive to uncertainties than others; if the user adjusts the threshold of the most sensitive fault, the FDD may not be sufficiently sensitive to other faults.

Alternatively, allowing the user to adjust the value of a single factor which in turn adjusts the relative values of individual thresholds limits too much intervention.

Thresholds may need to be varied as the operating conditions change. Expert rules for the non-linear behaviour of HVAC systems can be applied.

2.9 Control system faults

The two main types of faults in building control, hardware faults and software faults, can arise in any phase of the control system life cycle. Unless they are eliminated in the early development and installation phases, faults will become manifest during the application of controls.

Hardware faults generally occur in the application phase, whereas software faults are common in all three phases of the life cycle. The effects of programming errors in the system software can first be observed in the production phase; execution errors are manifest in all three phases; and the effects of poor tuning will be apparent mainly during the implementation phase. Table 6 summarises the main types of hardware and software faults that can occur and some causes.

Hardware faults	Description of hardware	Cause or effect of fault
Actuator faults	Actuators drive the dampers or valves in an air-conditioning system. In VAV systems defects in damper and cooling/heating valve actuator leads to temperatures higher/lower than the set-point.	Can be caused by thermal ageing of M&E components, short circuits, broken connections in electronic components and motors, elastic and fatigue failures in the mechanical links and worn out moving-parts.
Interface failure	Failure in communication networks of building control system	Complex. Diagnosis and trouble-shooting methods depend on system type. Might result from faults in cabling/interface cards or power supply fluctuations. Electrical connectors can become loose, resulting in short or open circuits. Ageing of switches leading to signal transmission errors.
Controller hardware faults	In modern control systems, the controller is built from digital electronic devices.	hort-circuits, broken circuits, degradation and burn-out of components, loose interface connections and battery failure can lead to incorrect values of the control signal or no control signal to the actuator. Thermal ageing of electric components causing problems in analogue controllers. Digital controllers susceptible to failure of integrated circuits and power supply faults.

Table 6: Building Control System Faults: Hardware and Software Faults

Software faults	Description of software fault	Cause or effect of fault
Programming errors	1. Incorrectly implemented control algorithms 2. Inappropriate initialisation of parameter estimators in adaptive controllers 3. Inappropriate range of control signal values 4. Control sampling interval too short 5. Incorrectly set and re-set flags for directing program flow 6. Inappropriate step size for control algorithms involving iteration 7. Incorrect scheduling of plant start-up/stop times and sequencing of modes of operation of control 8. Errors in implementing software control logic.	1. Actuator driven in wrong direction 2. Non-convergence or incorrect generation of parameter estimates 3. Generic fault 4. Generic fault 5. Generic fault 6. If step too small – very long execution times result. Poor convergence/wrong result from large steps. 7. Generic fault 8. Wrong decisions and logic inferences. Unconsidered conditions and cases
Execution failure	1. Incorrectly received input signals 2. Delayed response to control command 3. Unavailability of data to execute the control program 4. Persistent erratic or abrupt changes in control signal 5. Execution errors, such as: a. computational errors e.g. computing square root of a negative number/division by zero. b. operational errors e.g. writing to a copy-protected area/assigning a string to a numerical value. c. algorithm errors d. truncation and accumulation errors	1. Generic fault 2. Generic fault 3. Data may have been deleted, corrupted or interpreted incorrectly. The result is improper control action. 4. Over-regulation preventing process output from reaching stable state.
Poor tuning	1. Inappropriate selection of parameters for control strategies.	1. Oscillation of local and supervisory control loops

Table 6: Building Control System Faults: Hardware and Software Faults

2.10 Hierarchical FDD schemes

The development of automated fault detection and diagnosis tools is still in its infancy, but it is expected that FDD tools will one day be a standard feature of BEMS. BEMS systems are already designed using a hierarchical approach. The hardware and system intelligence is distributed throughout the building and FDD tools will need to conform to this hierarchy. The hierarchy should integrate the distributed intelligence to produce a comprehensive and consistent picture of the state of all HVAC equipment and systems in a building.

When implementing a hierarchical tool in a BEMS it is necessary to consider where in the BEMS hierarchy the FDD scheme should be located and the type or architecture needed to enable multiple FDD tools to work cooperatively. Information exchange will be a key to coordinating the output of multiple FDD tools and BMES manufacturers are currently trying to standardise the information exchange protocols.

Most stand-alone FDD modules have an embedded hierarchy that simplifies the process for inferring the state of operation of a system.

Example
Most of the prototype FDD tools developed in Annex 34 used stand-alone software whilst some have a hierarchical structure. For example a hierarchical FDD tool for VAV boxes was developed; the system is integrated within the hierarchical orfanisation of the BEMS and is aimed at detecting faults in VAV boxes with limited diagnosis. Only the diagnosis output and certain data are transferred to the central network where they are processed. This tool has functional hierarchy (i.e. the intelligence of the tool is divided in a hierarchical structure) and physical hierarchy (i.e. the intelligency of the tool is implemented at different physical levels of the BEMS hierarchy.

Implementation of FDD schemes in BEMS requires consideration of the physical hierarchy of distributed control systems. Figure 1 shows a schematic diagram of a distributed control system with embedded FDD tools. FDD schemes residing at different physical levels in the control system hierarchy are distinguished by the type of input data they accept, the relative level of sophistication of their diagnostic algorithms, and the frequency at which the schemes are invoked. These characteristics define the functional hierarchy of FDD schemes. More “intelligent” actions and knowledge are implemented at higher levels in the hierarchy where the available data have less detail. These higher-level schemes might be implemented on a periodic basis such as once an hour, once a day, or once a week. At lower levels the actions require less reasoning because they are specific to a particular device. Here the data would be available on a nearly continuous basis and lower-level schemes could be executed each time the data were updated.

Although not shown in Figure 1, sensor level diagnostics and so-called smart sensors represent another layer in the physical hierarchy. The aspects of an FDD scheme that define its functionality may be considered to be generic; however, implementation of an FDD scheme in a distributed control system requires consideration of the specific physical hierarchy of each BEMS product. As the technology is transferred to industrial partners, implementation issues will gain importance and the physical hierarchy of the control system will play a prominent role in shaping the characteristics of commercialized FDD applications.

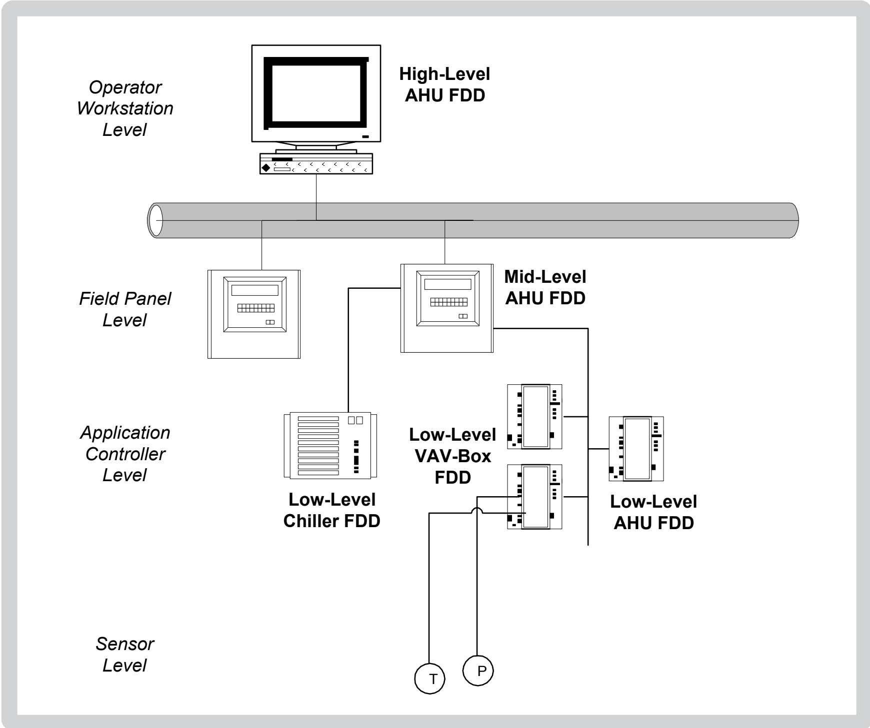

Figure 1: Distributed control system architecture showing stand-alone FDD tools embedded at different levels of the control system.

The development of stand-alone FDD tools was a logical starting point for improving the operation of HVAC systems. However, deploying many stand-alone FDD schemes which are not integrated can lead to building operators becoming frustrated by the seemingly conflicting information that may be produced. Also building operators lack the time needed to monitor many different FDD modules. Automated diagnostic capabilities that integrate and summarise information provided by related FDD schemes are needed. As the technology matures, it is anticipated that FDD modules will be ubiquitously deployed throughout the distributed control system.

Integrating the diverse information made available by stand-alone FDD modules into a clear and consistent description of overall building performance is the next important challenge faced by researchers and product developers in this area. Hierarchical FDD schemes capable of treating potentially conflicting information from multiple stand-alone FDD modules are envisioned as the likely response to that challenge.

2.11 Overview of artificial intelligence techniques used in FDD

Fault detection relies on comparing the actual performance of a system with the 'reference' value. The reference conditions are established using a 'model' which represents the ideal system performance. Once a fault has been detected it must be diagnosed and located. A range of techniques, which may be incorporated within the 'reference' model approach, are used for this. These techniques are summarised below but are discussed fully in the earlier ECBCS Annex 25.

Reference: Liddament, M (1998), Real Time Simulation of HVAC Systems for Building Optimisation, Fault Detection and Diagnostics, IEA, ECBCS, Annex 34

1 **Neural networks** - consist of large interconnected networks of simple, typically non-linear units. They can be trained to learn the functional mapping of inputs to outputs using input/output training pairs. In FDD, neural networks have been used to model processes and classify operating data (for example as normal or faulty).

2 **Fuzzy logic** - a fuzzy model is a set of rules describing the relationship between a set of inputs and a set of outputs in qualitative terms:

- Implicit fuzzy models relate the observed symptoms to the faults
- Explicit fuzzy models describe the system when it is operating correctly or with faults.

3 **Expert and rule based systems** – are FDD methods which applies rule-based knowledge. The number of rules and complexity of the rule-base defines whether the system is referred to as ‘rule-based’ or ‘expert’.

4 **Case based reasoning** - case based reasoning methodologies model human reasoning to develop intelligent computer systems.

5 **Bond graphs** - this method represents a unified approach to modelling engineering systems. Linear, non-linear or qualitative systems of equations can be derived from the bond graph model.

6 **Qualitative methods** – these are used when the process can not be described analytically in a satisfactory way. These methods usually involve three phases: transforming measured data into qualitative values; storing the correct behaviour of the process and checking discrepancies between observed and correct behaviour.

The advantages and disadvantages of each method are described in Table 7.

2.12 Effects of new technologies on fault diagnostic systems

A number of technological trends are facilitating FDD product design. The internet for example makes it possible to create decentralised building automation systems where services can be accessed from remote servers. Web technology may also replace existing interfaces opening up opportunities for illustration of FDD methods using text, pictures, sound and video animation. The utilisation of Local Area Networks and short range wireless communication will enable capture of more sensor information and realisation of the benefits of increased mobility possible from hand-held devices with wireless internet access, such as mobile phones.

Type of FDD Method	Advantages of FDD method	Disadvantages of FDD method
Fuzzy logic schemes	Can take uncertain, non-linear behaviour of HVAC systems into account. Easier to commission as fuzzy logic is fairly generic Easy to combine with expert knowledge about symptoms with knowledge from measured data. Software implementation of fuzzy logic is computationally undemanding.	Generates less precise results compared to other methods. Rule based descriptions not as concise asquantitative methods.
Neural networks training	Can effectively model non-linear systems. No need to know the detailed physics of system. Robust no noise.	Require huge amounts of data.
Expert and rule based systems. situations.	Easy to add, edit and present rules. Choice in the way rules are evaluated. User interface. Error handling during rule editing and execution.	Difficulty in finding a complete set of rules for complex
Case based reasoning faults. obtain	Can monitor unforseen faults and transform them into new fault models so that the database develops.	Mathematical model of the system must be derived to detailed information about
Bond graphs	Can start with a simplified model. Enables a unified modelling process, capable of dealing with any situation. The mathematical model is easy to derive and solve.	A graphical language must be learned. The method is not universally accepted.
Qualitative methods	Can be used where the process is too complex for analytical description.	

Table 7: Advantages and disadvantages of Fault Detection and Diagnosis schemes using different methods

3 Case studies

This section uses some of the thirty demonstration case studies to illustrate the lessons learned by the participants in Annex 34. The annex achievements included:

- 23 prototype performance monitoring tools and 3 prototype performance validation tools were developed.
- 30 demonstrations took place in 20 buildings.
- 26 fault detection and diagnosis tools were tested in real buildings.
- Four performance-monitoring schemes were evaluated on 3 data sets from real buildings.

Table 8 summarises the characteristics of all 30 case studies carried out as part of Annex 34.

Table 8: Key features of Annex 34 case studies

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
Factory	Germany	VAV air conditioning system	Air-handling unit	• Stuck valves or dampers • Coil fouling • Leaky valves or dampers • Bias or drift on temperature • Humidity and pressure sensors	Performance monitoring tool	Fault detection and diagnosis based on expert rules	Maintenance personnel and building/ plant operators
Hotel	France	Electrical convectors and electrical floor heating system	Entire system	12 faults selected by end-user that lead to increased operating costs or comfort degradation	Performance monitoring tool	Detection and diagnosis based on expert rules	Hotel manager
Laboratory	France	VAV air conditioning system	AHU	• Air-side and water-side fouling of cooling coil • Slipping fan belt • Valve faults	Performance monitoring tool	Detection using artificial neural networks and residual analysis	Building/ plant operator
Laboratory	Netherlands	Air-cooled reciprocating chiller	All Subsystems	• Sensor faults • Water-side • Air-side fouling of coils	Performance monitoring tool	Fault detection and diagnosis by case reasoning	Students of universities and polytechnics, and service personnel
Laboratory	Switzerland	CAV laboratory system	AHU	• Valve or damper stuck or with restricted range • Sensor offsets • Excessive control signal oscillations	Performance monitoring tool	Qualitative model-based fault detection	Building operator
Laboratory	UK	VAV air-conditioning system	AHU	• Stuck valves and damper • Leaky valves and dampers • Water-side fouling • Faulty static pressure sensor over oscillatory control signal	Performance monitoring tool	Diagnosis based on parameter innovation Diagnosis using physical models and expert rules	Experienced building/ plant control engineer

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
Laboratory	USA	Air-cooled chiller	All Subsystems	• Slipping fan belt • Air-side condenseer fouling • Water-side evaporator fouling • Liquid line restriction • Refrigerant overchange or underchange	On-site or remote performance monitoring tool	Fault detection using models and nearest neighbour or	Building operators, technicians or service personnel
Laboratory	USA	VAV air conditioning system	AHU	• Low fan • Pump or motor efficiency • Power transducer error • Water-side fouling • Leaking valve or damper • Unstable or disconnected control loop	Performance monitoring tool	Fault detection based correlating electrical power and air flow Motor speed and control signals Fault diagnosis using expert rules	Building operators and service personnel
Office building complex	Belgium	VAV system with radiators and fan-coil units	AHU, VAV box, BEMS	• Fan non-operational • Stuck valves • Temperature and pressure sensor drift • Incorrect control action • Incorrect operation of equipment • Bad placement of sensors	Performance validation tool	Manual checking and fault isolation using an off-line expert rules	HAVC system operators and maintenance personnel
Office	Canada	VAV air-conditioning system	VAV terminal box	• Control system and actuators faults • Poorning of the air temperature and flow controllers • Faulty damper and actuator	Performance monitoring tool	Fault detection and diagnosis based on performance indices and expert rules	Building operators and service company personnel
Office	Canada	VAV air-conditioning system	Air-handling unit	• Faulty flow and temperature sensor • Thrty faults associated with the temperature and humidity sensors • Dampers	Performance monitoring tool	Fault detection and diagnosis based on expert rules and performance indices	Building operators and service company personnel

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
				• Valves and actuators • Controllers • Coils • Filters and pumps			
Office	China	Central chilled water system with water-cooled condensers	All subsystems	Bias and drift in any of the water temperature and flow rate sensors	Off-line sensor validation tool	Statistical analysis and minimisation of mass and energy balance residual	BMS suppliers, commissioning engineers, maintenance engineers and plant operators
Office	France	Electrically powered air-conditioning	Air-handling units and fan coil units	Thirteen end-user selected faults that impact on user comfort and operating costs	Performance monitoring tool	Fault detection based on expert rules	Experienced building/ plant operator
Commercial Office	Japan	VAV air-conditioning system	AHU and VAV box	Actuator failures Sensor failures Controller failures	Performance monitoring support system	Fault diagnosis based on stochastic qualitative reasoning	HVAC system operators and maintenance personnel
Office	Japan	VAV air-conditioning system	AHU and VAV box	Actuator failures Sensor failures Controller failures	Performance monitoring support system	diagnosis based on qualitative casual reasoning and sign-directed graphs	HVAC system operators and maintenance personnel

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
Research & Development Centre	Japan	VAV air-conditioning system	VAV box	Stuck damper	Embedded performance monitoring system	Fault detection based on statistical analysis of residuals	HVAC system operators and product suppliers
Office	Sweden	CAV air-conditioning system	AHU	• Stuck or leaking mixing-box dampers • Stuck or leaking heating and cooling coil valvesLow heating water supply temperature • Reduced (or increased) cooling water flow • Incorrect supply air temperature or flow rate • Errors in the sequencing logic • Incorrect exhaust air temperature	Performance monitoring tool	Fault detection using physical models and analysis of filtered residuals Fault diagnosis based on the fault direction space method	Building operators and service company personnel
Office	Switzerland	CAV air-conditioning system	AHU with heat recovery wheel	• Valve or damper stuck, or with restricted range • Sensor offsets • Excessive control signal oscillations	Performance monitoring too	Qualitative model-based fault detection	Building operator
Office	Switzerland	CAV air-conditioning system	AHU with heat recovery wheel with radiators and heating	36 faults including: • Wrong supply air temperature or humidity • Wrong pressure • Simultaneous heating or cooling • Excessive energy consumption • Zone too hot or cold • Defective sensor	Performance monitoring (audit) tool	Fault detection and diagnosis using an expert system	Building operator

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
			and chilled in three zones AHU cooling coil subsystem				
Commercial Office	UK	CAV air-conditioning system	AHU cooling coil subsystem	• Leaky valve • Fouled coil • Faulty supply air temperature sensor	Performance monitoring tool	Detection and diagnosis based on physical model and expert rules	Experienced building/ plant operator
Commercial Office	UK	CAV air-conditioning system	AHU cooling coil subsystem	• Leaky valve • Fouled coil • Valve stuck open • Midway or closed	Performance monitoring and automated commissioning tool	Detection based on fuzzy expert rules Diagnosis based on generic fizzy models	Commissioning engineer employed by building operator or BEMS manufacturer
College	Finland	CAV air-conditioning system	AHU	• Blocked coil or valve • Partially open valve • Faulty sensor	Performance validation tool	Fault diagnosis based on a fault-sympton tree - expert rules	HVAC system operators or maintenance personne
Vocational School	Finland	District heating system	All subsystems	• High energy consumption • Poor control performance	Performance monitoring system	Detection based on expert rules	Plant foreman

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
School	France	Hot-water heating system with radiators	All subsystem	• Boost too early • Overheating and under-heating at start of occupancy • Overheating and under-heating during occupancy • Heating outside of occupancy	Performance monitoring tool	Detection based on expert rules	Municipal service terms (experienced building/ plant
College	USA	VAV or CAV air-conditioning system	AHU	• Stuck on leaky valve or damper • Temperature sensor faults • Sizing faults • Faults in the sequencing logic • Incorrect chilled or hot water supply temperature • Operator error	Performance monitoring tool	Fault detection based on expert rules	Building operators and service company personnel
Indoor Swimming Pool	France	Hot water system	All subsystems	• Loss of hall temperature control during occupancy • Hall temperature too low at start of occupancy • Heating of hall when unoccupied • Hall humidity out of range • Loss of water temperature control during occupancy • Water temperature too low at start of occupancy • Heating of water when unoccupied • Water quality out of range	Performance monitoring tool	Fault detection and diagnosis based on expert rules	Municipal service teams and building/ plant operators

Demonstration Building	Country	HVAC System Type	Type of Subsystem	Faults Considered	FDD Tools Developed	FDD Method	Intended End-User
Indoor and Outdoor Swimming Pools	Netherlands	Heating system using combinded heat and power gas boilers and heat pump	All subsystems	Incorrect functioning of the control system Excessive energy use Low efficiency of the individual installations	Performance monitoring tool	Fault detection and diagnosis based on expert rules	Swimming pool operators and service companies
National Film Board Complex	Canada	Chilled water plant	Water-cooled centrifugal chiller	• Condenser fouling • Evaporator fouling • Refrigerant overcharge or leakage • Air in the system	Performance monitoring tool	Fault detection and diagnosis using statistical modelling and pattern recognition	Building operator and facilities manager
Residential and Office	Finland	District heating and oil heating systems	All subsystems	All typical faults	Internet-based performance monitoring tool	Off-line fault diagnosis using a knowledge-based system	Building owners, HVAC system operators or maintenance personnel
Various	USA	Packaged rooftop air-conditioners	All subsystems	• Refrigerant leakage or over charging • Fouled condenser coil ormalfunctioning fan • Fouled evaporator filter or malfunctioning fan • Compressor wear • Non-condensables in the refrigerant • Liquid line restriction	Embedded performance monitoring tool	Diagnostics based on either a statistical rule-based method, a sensitivity ratio method or expert rules	Building operators or service company personnel

3.1 Case study A1[1]: A performance monitoring tool for hotels

This case study provides an example of a tool which is well-tailored to the needs of the end user. As a result the user was confident about the tool's usefulness and requested extra functionality after the demonstration period.

Reference: Dexter A and Pakanen J (2001) Case Study C9, Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, IEA, ECBCS, Annex 34

Characteristics of test building, plant and control system

The tool was tested in a hotel, located in the French Alps with 44 rooms, a restaurant, shop and hall.

An energy management control system (EMCS) controls heating, hot water systems, lighting in shop, ventilation in the restaurant and load shedding. It also monitors comfort in each room and electricity use.

The HVAC system consists of underfloor heating and hot water tanks all of which run on off-peak (low tariff) electricity. Electric convectors, with 2 set points (comfort and economy) are also provided in each room. Settings can be changed by the occupant using controls in the room, or the hotel manager via the central PC.

Figure 2: Case Study Hotel, France

End user

The hotel manager, who has limited technical knowledge about the HVAC system, was the intended user of the tool. The user interface reflects this and version 2 of the software can only work with the hotel's building control system.

Faults to be identified

Discussions with hotel managers and manufacturers of energy management control systems helped identify and prioritise the faults that should be detected in a hotel building. Twelve faults were identified.

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[1] *For more information about expert systems see: Liddament M (1999), Technical Synthesis Report Annex 25: Real Time Simulation of HVAC systems for Building Optimisation, Fault Detection and Diagnostics, IEA ECBCS*

Sensors used

Typical HVAC system grade sensors common in electric heating systems and water tanks were used. These were part of the EMCS, so incurred no extra cost.

FDD method

The method aimed to detect the symptoms of faults which could increase the cost of operation or reduce comfort. The source for data about symptoms was deliberately restricted to the EMCS. The tool did not aim to diagnose symptoms but to leave it to service staff to establish the primary cause of symptoms. The procedure used is outlined below:

1. The following temperatures were measured by the EMCS:
   - Indoor air temperatures and temperature set-points in all rooms at 10-minute intervals,
   - Outside air temperature,
   - Hot water tank temperature in four tanks,
   - Water meter index, and
   - Electric meter index.
2. Measurements were filtered to eliminate inconsistent values.
3. Operating modes (heating mode, occupied/unoccupied mode etc) were estimated.
4. Thresholds for the FDD rules were estimated.
5. Faults were detected by applying if/then rules.
6. Likely causes of faults were suggested.

Design data and training data needed

No design data or training data were required.

User interface

The user interface was developed in Microsoft Excel with feedback from the hotel manager. It has 3 windows presenting different levels of information:

- Window 1 - gives the user an overview of the hotel's rooms and main equipment. It also presents monthly performance results and allows the user to prioritise maintenance tasks.
- Window 2 - provides more detailed weekly information.
- Window 3 - displays a fault-orientated graph with trend measurements to help the user to diagnose the fault.

User selected parameters

The user needs to define the following parameters:

1. Indoor temperature set-points
2. Normal occupancy schedules
3. Number, capacity and minimum temperature of hot water tanks.

Threshold selection methods

Thresholds can be easily adjusted by choosing High Normal or Low. All the thresholds are then automatically estimated based on the set points or user selected parameters.

Results of trials

The method was evaluated with simulated data. The initial software was tested off-line with the hotel's data and then validated on-line in the hotel.

User satisfaction

The tool has helped the hotel manager detect several major faults. The hotel manager was satisfied with the tool and has requested additional functionality.

3.2 Case study B: A tool for detecting and diagnosing building underperformance

This case study provides a good example of a tool that is technically viable in the chosen application but, as with many of the tools researched in Annex 34, had high commissioning costs.

Reference: Dexter A and Pakanen J (2001) Case Study C23, Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, IEA, ECBCS, Annex 34

Characteristics of test building, plant and control system
This tool was tested in a medium-sized office building in Steinhausen, Switzerland.

The HVAC system consists of one central air-handling unit (CAHU) with constant air volume supplying conditioned air to the office, a heat recovery wheel, an electric pre-heater and a heating and cooling coil. The tool was applied to the CAHU, the chiller and three zones with additional radiator heating and chilled ceilings.

End user
The tool was intended to support the building manager, who would use the printed output reports. It was planned to install a final version of the tool remotely. This would be run overnight to generate a printed report.

Faults to be identified
The tool was designed to detect and diagnose a total of 36 faults in the three applications or zones it was applied to. Table 9 below shows the faults detectable by zone or application:

Zone 1/2/3	Number of faults	CAHU	Number of faults	Chiller	Number of faults
Too hot/cold	2	Supply too hot/cold	2	Evaporator pressure too low	1
Too much heating /cooling	2	Too humid/dry	8	Condensor pressure too high	1
Sensor defect or offset	4	Simultaneous heating/cooling	1		
Cooling or heating ineffective	2	Wrong control combinations	2		
Higher energy use	2	Sensor error or offset Exceeded energy use Pressure too high/low	5 2 2		
Total number of faults detectable	12		22		2

Table 9: Number and type of detectable faults

The tool does not rely on user input during the monitoring and therefore, in most cases, the output will be a list of possible, not exact, causes.

Sensors used

The tool required 25 sensors for detection and an additional 35 sensors for diagnosis of faults; this reflects the large number of faults that were being considered. Table 10 shows how these sensors were distributed.

	Zone 1/2/3	CAHU	Chiller
Number and type of point needed for detection	Temperatures Control signals Operation mode **9**	Temperatures Control Signals Operation mode Humidity Pressure, speed **12**	Status Pressure Load **4**
Number and type Temperatures of extra points needed for localisation and diagnosis	Temperatures Local commands CO2 **12**	Temperatures Operation mode alarms Control signals **14**	 Pressure **9**

Table 10: Number and type of points needed for detection and diagnosis

FDD method

The tool, called Performance Audit Tool (PAT), was based on an expert system[2]. The method is based on 5 components:

1. **Data component** – loads trend data from the BEMS into the PAT trend data database using existing packages. Detects invalid and missing data.
2. **Configuration information component** – provides a user-interface for entering configuration information, such as points, plants and zones, into the configuration database.
3. **Knowledge component** – captures diagnostic knowledge in the form of decision trees stored in a knowledge base. Knowledge bases exist for underperformance of the zone, CAHU and chiller unit. Users only see the database interface and only those responsible for maintaining the knowledge base would see the underlying 'expert shell system'.
4. **Audit component** – draws on information from the configuration base and knowledge base to interpret and evaluate trend data. Exports this data to the results database.
5. **Results component** – holds cases of underperformance and likely causes. These are automatically presented in an easily understood report.

The prototype uses Microsoft Access for the trend data archive, configuration database and results database.

Design data and training data used

The following design data were derived from plans and is stored in the configuration database:

- Design parameters
- Identifiers
- Configuration parameters

[2] For more information about expert systems see: Liddament M (1999), Technical Synthesis Report Annex 25: Real Time Simulation of HVAC Systems for Building Optimisation, Fault Detection and Diagnostics, IEA ECBCS.

No training data was required. Default parameters were based on expert knowledge.

User interface

There are two user interfaces:

- A set up (commissioning) interface – allowing loading of information from the configuration database to set up the audit.
- An online user interface – on starting the program, the user is guided through a simple graphical interface and required to confirm certain inputs. Results of audits are stored in Microsoft Access tables from which reports can be obtained.

User selected parameters

The user can select the site and time period for the audit.

Threshold selection methods

Thresholds must be selected for deviations and integrated deviations; sensor offsets, set point changes, actuator positions; persistence of faulty behaviour; and the number of missing or invalid data. Thresholds are based on expert knowledge.

Results of trials

A prototype with limited diagnostic capability was tested in the building. Faults were not injected but the tool analysed recorded data and detected several faults; incorrect room temperature set points, delayed response from the zone controller and short periods of unnecessary heating. An incorrect control combination for the heat recovery wheel and heating valve was also detected.

An accurate diagnosis of these faults could not be not made due to lack of information. However the office trials demonstrated that the tool was able to detect different faults.

User satisfaction

The tool was able to deliver the primary objective of fault detection. However the time needed to set up and commission the tool was high for a number of reasons:

- The configuration and design information had to be entered manually as it could not be retrieved from other databases (the BEMS system was quite old).
- The stability of the PC environment and communication with the BEMS was unreliable.
- There was no graphical interface for the user to change or update the knowledge base. Graphical documentation of new rules was performed using separate software.

The prototype version of PAT was not developed to a full product because of the onerous commissioning process. However the core of the tool, the knowledge base, is valuable and could be easily re-used in the development of a new version.

3.3 Case study C: Stand-alone or BEMS-integrated FDD tool for packaged chiller units

This case study provides an example of a tool developed for detecting faults on a packaged chiller unit, either as a stand alone tool or via incorporation with the BEMS.

Reference: Dexter A and Pakanen J (2001) Case Study C29, Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, IEA, ECBCS, Annex 34

Characteristics of test unit, plant and control system

This tool was tested in a test facility in Maryland, USA; a 12-ton air-cooled liquid chiller with a constant two-stage reciprocating compressor was used. The chiller is designed for low temperature operation and is located outdoors adjacent to a building.

FDD method

A two-step FDD method, using a rule based fault diagnosis algorithm and “k nearest-neighbour classification.”

End user

The tool is designed for use by building operators, technicians or service staff. It can be integrated with an existing BEMS or used as a stand-alone tool

Faults to be identified

Five faults were selected:

1 Fouling of the air-side condensor
2 Fouling of the water-side evaporator
3 Liquid-line restriction
4 Refrigerant overcharge
5 Refrigerant undercharge

Sensors used

A large number of sensors were used for model validation. However, in order to minimise the costs of implementing the FDD method, the measurements critical to good fault detection and diagnosis were determined. These critical measurements are shown Table 11.

Measurement location	Description	Units
Compressor outlet temperature (R22)	Type T thermocouple	°C
Condensor inlet fan1 temperature (air)	Type T thermocouple	°C
Condensor outlet fan1 temperature (air)	Type T thermocouple	°C
Subcooler outlet to evaporator temperature (R22)	Type T thermocouple	°C
Compressor inlet temperature (R22)	Type T thermocouple	°C
Subcooler expansion valve inlet temperature (R22)	Type T thermocouple	°C
Evaporator outlet temperature (water)	Type T thermocouple	°C
Evaporator inlet temperature (water)	Type T thermocouple	°C
Condensor inlet (R22)	Pressure transducer (0-500)	psia
Compressor low stage inlet (R22)	Pressure transducer (0-300)	psia
Flow rate to evaporator (R22)	Turbine flowmeter (1.0-10.0)	gpm
Flow rate to subcooler (R22)	Turbine flowmeter (0.5-5.0)	gpm

Table 11: Measurements made to facilitate FDD.

Design data used

The heat transfer coefficients, geometry of the heat exchangers, flow rates and system temperatures for the refrigerant, air and glycol were inputted.

Training data needed

Training data for normal and fault conditions were required, as well as variations in outdoor conditions, temperature and humidity. The following conditions were experimentally simulated for various fault modes:

- Condensor fouling at incremental levels from 10% to 50%
- Evaporator fouling at incremental levels from 10% to 40%
- Liquid line restriction at incremental levels from 5% to 25%
- Refrigerant charge at different incremental levels

User interface

The tool uses a ‘command line’ user-interface in Matlab software.

User selected parameters

The user should select alarm thresholds.

Threshold selection methods

Thresholds must be specified and diagnostic rules hard coded into the program.

Results of trials
The tests showed reliable detection of most fault types. Diagnosis of detected faults was also good. The liquid line restriction fault was the most challenging to detect and diagnose.

Table 12 Shows the percentage correct detection and diagnosis for each fault.

Fault	Level	Percentage correct detection%	Percentage of faults detected with correct diagnosis %	Percentage correct detection & diagnosis%
Normal	N/A	100%		
Condenser fouling	10%	0%		0.0%
	20%	39.50%	100%	39.5%
	30%	93.50%	95.72%	89.5%
	40%	86.50%	100%	86.5%
	50%	100%	100%	100%
Evaporator fouling	10%	0%	%	0
	20%	0%	%	0
	30%	100%	99.50%	99.5%
	40%	100%	95.50%	95.5%
Liquid line	10%	0%		0
restriction	20%	0%	25.89%	0
	30%	56.00%	85.59%	14.5%
	40%	59.00%	55.23%	50.5%
	50%	86.00%	100%	47.5%
	45lb	100%	83.00%	100%
Refrigerant	50lb	100%	82.50%	83.0%
undercharge	55lb	100%	95.50%	82.5%
	60lb	100%	100%	95.5%
	65lb	100%	100%	100%
	70lb	100%	100%	100%
	75lb	100%	100%	100%
	80lb	100%	100%	100%
	85lb	100%		100%
	90lb	0%		0
	95lb	0		0
	100lb	0		0
	105lb	0	1.0%	0
Refrigerant	110lb	100%	94.0%	1.0%
overcharge			98.0%	94.0%

Table 12: Results of FDD for five key faults

3.4 Case study D: FDD for Variable Air Volume terminal boxes

This case study illustrates the use of artificial faults for testing an FDD tool for a VAV air conditioning system. It also suggests that certain niche markets might more readily exploit FDD than others.

Reference: Dexter A and Pakanen J (2001) Case Study C17, Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, IEA, ECBCS, Annex 34

Characteristics of test unit, plant and control system

This tool was tested in an 11-storey building in Yokohama, Japan. Most of the building is used as office space and the gross floor area is 38000m2.

Each floor typically has two VAV air handling units for the south and north zone. The VAV AHU has four sophisticated sub-systems to control: 1) indoor air temperature 2) supply air temperature 3) re-set of supply air temperature 4) speed of fan invertors.

FDD method

Fault diagnosis was based on qualitative causal reasoning and sign-directed graphs.

End user

The tool is designed for use by building operators and product suppliers. It could be integrated with an existing BEMS but is designed to be embedded in a local controller attached to a VAV unit or in an outstation for controlling multiple VAV units.

Fault detection in VAV systems is made difficult by their inaccessible location in ceiling spaces. Therefore a real need for this type of tool exists.

Faults to be identified

Faults were investigated by introducing artificial faults to the system in such a way that one fault or a combination of faults occurred daily at 14:00 hours over an 8-week period:

- Stuck damper at fully opened position
- Stuck damper at fully closed position
- Stuck damper at half opened position
- Simultaneous combinations of the above

Sensors used

Airflow meters through the VAV unit and room temperature sensors were used to transmit signals to the local outstation where digital signals were available.

Training data used

Training data for about a week's duration during normal HVAC system operation are needed. A minimum requirement for training data was not well-defined.

User interface

The tool was developed to detect simple VAV faults with a simple user interface. Fault detection in VAV systems is made difficult by their inaccessible location in ceiling spaces. A tool that allows maintenance staff to simply detect faults is useful, even without diagnosis.

User selected parameters

Users are not required to enter parameters.

Results of trials

The tool successfully detected and diagnosed faults. Faults persist for two hours after introduction. ‘Soft’ faults such as a damper stuck half opened were difficult to detect as the consequent, small room temperature change remained close to the set point.

User satisfaction

The tool attracted interest from a manufacturer of control products as demand amongst maintenance staff for such a tool is high.

3.5 Case study E: FDD for air-handling units

This tool optimises detection of thirty faults in an air handling unit by applying custom designed FDD methods and reducing data traffic on control networks.

Reference: Dexter A and Pakanen J (2001) Case Study C3, Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings, IEA, ECBCS, Annex 34

Characteristics of test unit, plant and control system

The tool was tested in a building in Quebec, Canada. The field test was carried out on the air -handling unit serving the offices.

The AHU has outdoor mixing and return air dampers, hydronic cooling and heating coils, supply and return fans, an air filter section, an air plenum section and an electronic humidifier.

FDD method

The FDD method uses expert rules that are grouped according to the operating mode of the air-handling unit. The rules are grouped into 11 sets or modules. This allows full or partial implementation of specific rule modules depending on the level of sophistication of the BEMS and facilitates changes or re-use. Figure 2 shows the tool's architecture.

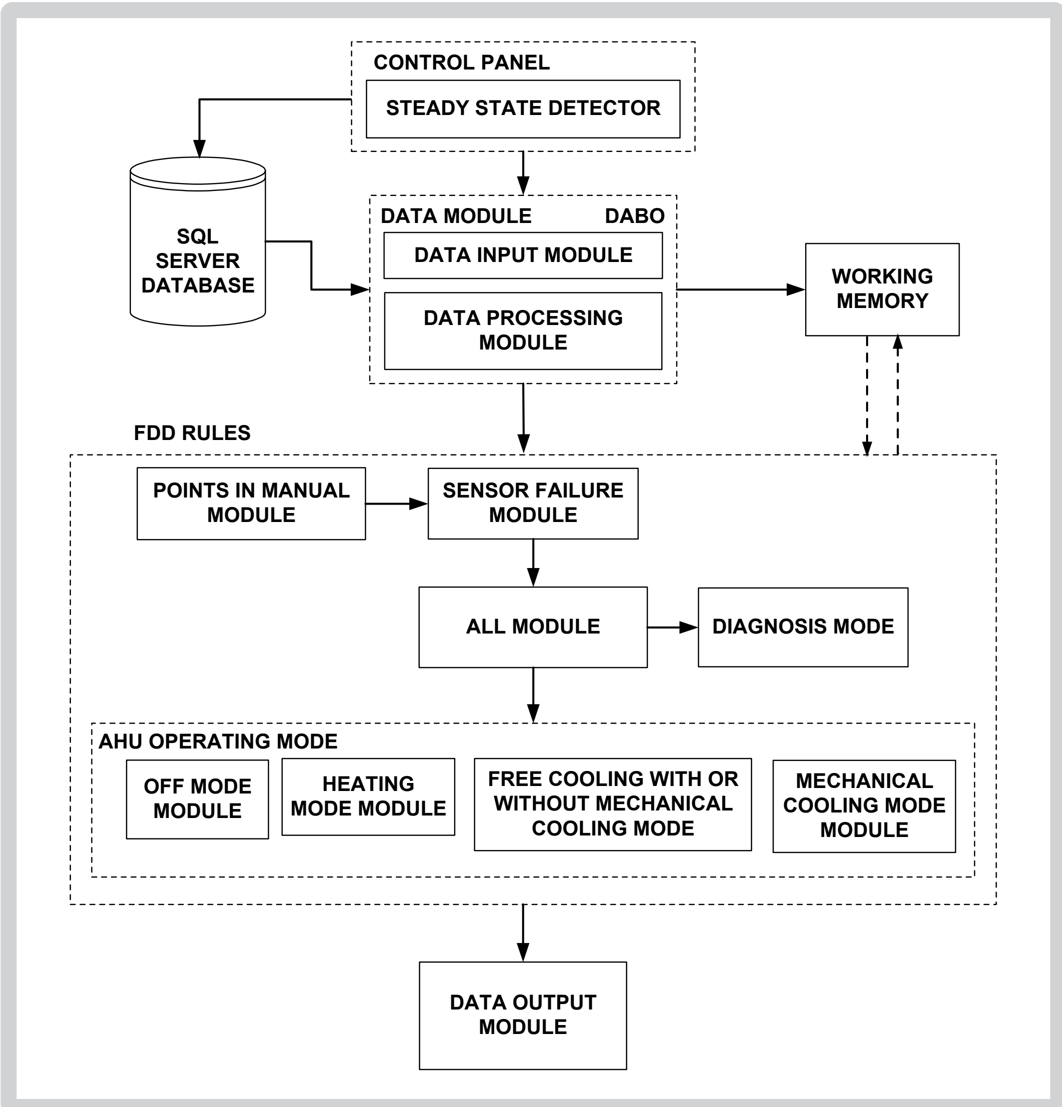

Figure 2: Modular architecture of the AHU FDD system

Figure 2 shows the following modules:

- Data Module - retrieves data needed by the expert rules from an SQL database, filters data and calculates the average of each point.
- Points in Manual Module - consist of rules which determine if a measured point is set in manual or default automatic mode on the control system. A fault is indicated when the point is in manual mode.
- Sensor Module - verifies if the measured temperature, humidity and pressure signals are within the prescribed limits.
- All Module - runs a set of rules before the remaining rule modules to verify if the controllers and supply air temperature set points are stable. It also verifies control signals for dampers and coils and identifies single faults (such as stuck damper position).
- Diagnosis Module - allows the expert system to identify sensor calibration faults.
- Other rule modules - are called upon depending on the AHU's operating mode (off / heating / free cooling / mechanical cooling mode).

End user

The tool is designed for building operators and service company staff. The tool is a module of an existing system 'Diagnostic Agent for Building Operators' (DABO) which serves as an interface between the end-user, the energy management control system/database and the fault detection and diagnosis software.

Faults to be identified

The tool was designed to detect symptoms to diagnose 30 faults, including:

- Temperature and humidity sensors faults (outside, return, mixed and supply air),
- Damper and actuator faults (mixing, exhaust and outdoor),
- Valve and actuator faults (heating, cooling and humidifier),
- Control (heating, cooling and humidifier valves, mixing and outdoor damper, supply air temperature),
- Coil (heating, cooling and humidifier),
- Outside air infiltration, and
- Pump failure.

Sensors used

The following sensors and control signals are used by the FDD tool (data are recorded in a SQL database every 10 minutes):.

- Supply and return fan air-flow,
- Return and outside air enthalpy,
- Set point outside air minimum,
- Mixing, supply, return air-temperature. set-point,
- Return air humidity set point,
- Outside, return and supply air humidity,
- Humidifier control,
- Valves and Dampers position status,
- Outside, mixed, return and supply air temperature,
- Heating, cooling coil valve control,
- Outside air damper control,
- Mixed and outside air damper control,
- Control valves unstable,
- Control dampers unstable,
- Control humidifier unstable,
- Humidifier control set point unstable,
- Supply air temperature. set point unstable,
- Supply air temperature. unstable,

- Fault code,
- Diagnosis mode, and
- Current transmitter pump.

Design data used

Design data are needed to set the following configuration parameters:
- Air handling system and control strategies,
- Set-point values (temperature, humidity, outdoor airflow rates), and
- Winter and summer design temperatures.

User interface

Figure 3 shows the current version of the user interface.

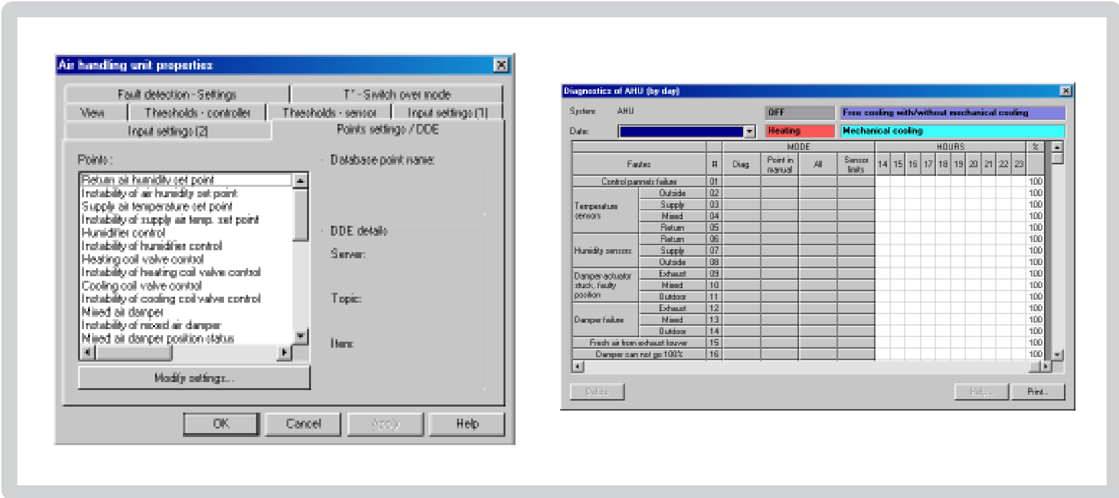

Figure 3: Illustration of user interface

User selected parameters

The following parameters must be specified:
- Maximum and minimum return air temperatures in winter and summer,
- Temperature rise across the supply and return fans,
- Fresh air damper position at minimum ventilation, and
- Threshold on control values and sensor inputs.

Threshold selection method

Thresholds were manually selected after analysing normal operating data.

Results of trials

The validity and robustness of the tool under were tested for one year. Sensors were verified and faults introduced. An SQL database linked to the building control system was used to collect data – this was then linked to the user interface. Problems were encountered with filtering monitored data. Further work would therefore be needed on the testing of this tool.

4 Evaluation of Fault Detection and Diagnosis Tools

The development process for a fault detection and diagnosis (FDD) tool begins with an assessment of user needs and benefits. The design process is usually iterative and involves:

- Developing a product concept and performance specification,
- Testing early iterations quickly and at low cost, using simulation tools,
- Building a hardware prototype for laboratory-based testing of faults, particularly those that can not be simulated, in a controlled manner, and
- Field testing of an improved tool before finalising the design.

Performance criteria and an approach to evaluation are needed for all three types of testing. For some applications, such as the aerospace and nuclear power industries, the consequences of inadequate testing could be catastrophic. Failures in HVAC systems are much less likely to result in injury or death and therefore building owners and users are less willing to pay the premium associated with extensive testing and immediate detection.

Figure 4 illustrates the FDD tool development process and shows the areas on which Annex 34 and previously Annex 25 (IEA ECBCS 1996) focused.

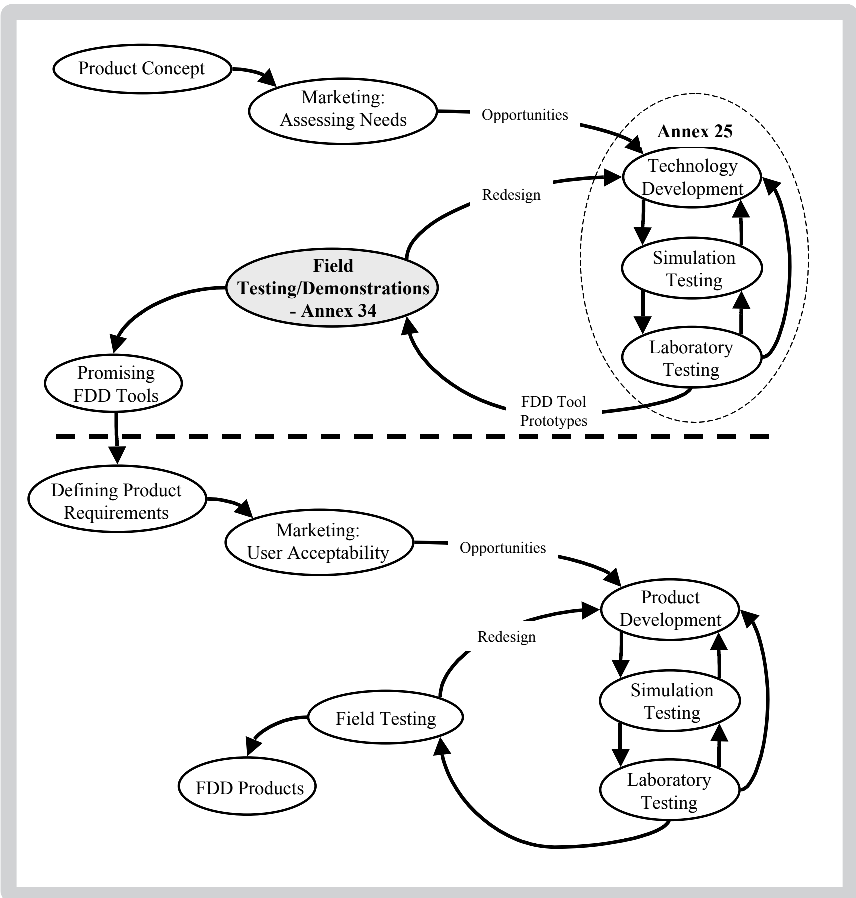

Figure 4: FDD tool development process and areas on which Annex 34 and Annex 25 have focused.

Reference: Liddament, M (1998), Real Time Simulation of HVAC Systems for Building Optimisation, Fault Detection and Diagnostics, IEA, ECBCS, Annex 34

The checklist shown in Table 13 can be used by FDD tool designers and/or purchasers for evaluating the capability of a tool to meet specific diagnostic needs.

General
- Which faults can be detected?
- Which faults can be diagnosed?
- Under which conditions can these faults be detected and diagnosed?
- Does the tool performance depend on operating point, whether or not the system or equipment is operating in steady state, etc.?

Sensors
- What measurements are needed?
- How will sensor accuracy impact the performance of the tool?
- At what frequency must data sampling take place?

Configuration
- What design data are needed
- How many parameters must the user define (i.e., thresholds, model parameters, etc.)?
- Are training data required? If so, how much and under what conditions should it be collected?

Table 13: Checklist of factors affecting the cost of an FDD tool

It is difficult to analyse the cost-benefit of individual characteristics because information about fault occurrence is limited and the technology is relatively new; the cost of additional sensors is easily determined but the cost associated with tuning a model or method using training data is difficult to establish. The user interface will also affect the cost of the tool.

Performance criteria

Performance criteria for HVAC systems could include the following:

1. Minimum detectable fault level.
2. Percentage of time with correct diagnoses for a specified fault level.
3. Percentage of time with incorrect diagnoses when a specified fault (and fault level) is present.
4. Percentage of false alarms.

Conditions for testing should also be specified. The data documentation should include information about the severity of the fault and the external driving conditions.

Simulation and laboratory data, unlike degradation methods, allow faults to be introduced in a controlled manner. Field data can be used for abrupt faults if the equipment is otherwise operating normally. During testing, it is possible to assess the impact of design changes such as the number and type of sensors, data filtering, and approach for characterizing expected behaviour. Methods using models to predict expected behaviour give better performance overall but the associated training needs have higher costs.

It is sometimes difficult to apply quantitative performance criteria, particularly in real buildings. Meaningful evaluations of FDD tools are best performed using well-documented data sets for which the operational status is known. In addition, quantitative performance of tools with user-defined thresholds can only be established if the thresholds are determined through training and then remain fixed while testing with a different set of data. In addition independent evaluation of tools by a party not involved in their development can yield valuable information about the strengths and weaknesses of the tool.

5 Potential for commercial exploitation

Figure 5 shows a route map for a typical commercialisation process. When commercialising Fault Detection and Diagnosis tools developers will need to address five principal issues:

1 What are the potential cost savings?

Potential customers will have to justify the investment in an FDD system, as for any other building technology, on the basis of cost -benefit analysis and this should be at least estimated. Savings will arise from the reduced costs of operating, energy, in house or out-sourced maintenance, less wear and tear as well as from minimising down-time and improving the comfort and hence the productivity of occupants.

Customers need to be satisfied that the savings can be realised in their building. Assurance can be provided through demonstrations in real buildings, robust case studies, detailed engineering audits and calculations based on the customer's system.

2 Who is the customer?

The purchaser of an FDD tool is likely to be different to the user. The user of a tool designed to troubleshoot problems with a chiller in a large office building is likely to have different needs to that using a tool to identify energy waste across a portfolio of buildings. The purchaser is obviously an important 'user' but care must be taken to also retain a focus on the needs of the end-user.

3 What is the source of input data?

The cost of sensors can be reduced by using those in place for an existing building management system (BMS). Whether existing sensors are appropriate for the FDD method will need to be assessed. The existing BMS might also be used as a data collection device to minimise costs, although some customers might be concerned that its operation might be affected by the FDD method.

4 What is the system cost?

The overall cost of the system – real or perceived is clearly important in any cost-benefit analysis. All additional equipment and software needs to be considered. Initial assessment and auditing costs, training, installation, configuration, ongoing maintenance, and support costs are often overlooked. The cost of ongoing operation is also an important issue: customers will want to see a net time saving from use of the tool.

Costs can be assigned in such as way as to reduce the perception of risk to the user: payment for the tool can be made upfront; in increments (for example monthly); or shared (along with the savings) by the customer and the FDD provider.

5 What is the system reliability?

Potential customers will want to know how often the system will generate false alarms. In some cases, too many false alarms will render a good FDD method useless in practice. However, reliability also includes the certainty that the method will identify the problems it promises to identify. If it fails to find serious problems, it will not be useful.

Improving the commercial potential of FDD tools

Annex 34 has taken FDD from the point of basic research (Annex 25) to a point where it can be commercialised. Technology developers now need to work with commercial interests develop effective products that will compete successfully in the market, and have a real impact on the energy performance of buildings. Many of the industrial partners involved in Annex 34 have shown real interest in making progress with commercialising FDD tools.

Some important next steps that will ensure commercialisation of FDD technologies include:

- Continued partnership between researchers and their industrial partners to conduct effective demonstrations of FDD methods in the field.
- Commercialisation activities by industrial partners - including definition of market and product requirements, market research to identify how to best target customers, and product development.
- Continued role for government policy and R&D organisations in promoting FDD; the societal incentives for improved building performance through FDD are in some cases stronger than the energy or cost saving incentives for technology adoption.
- Continued dialogue between researchers, industrial partners, government policy and R&D organisations about technological development.

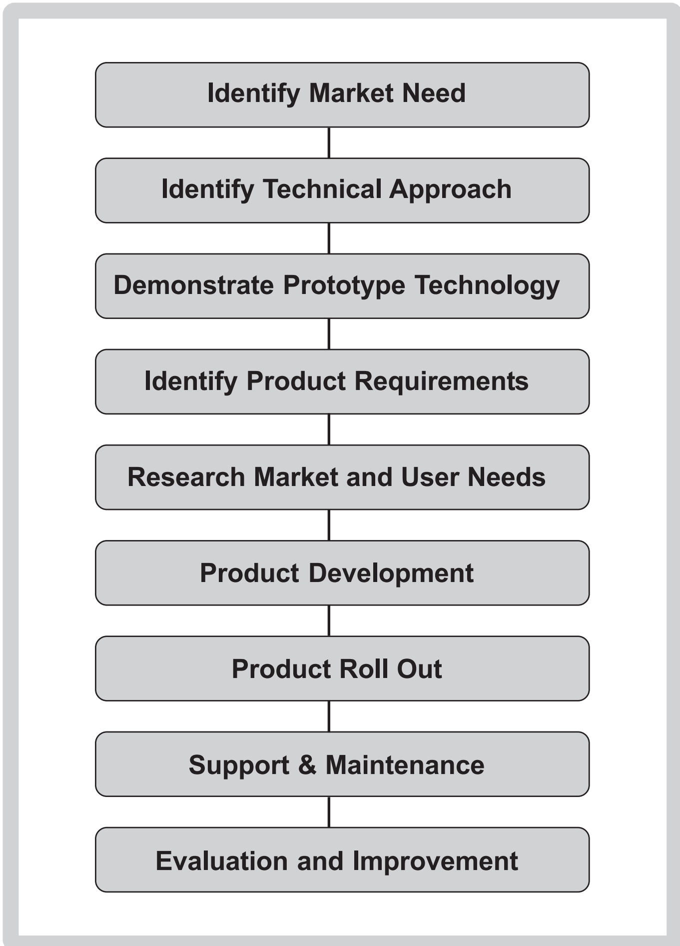

Figure 5: Route Map for Typical Commercialisation Process

6 Conclusions

The design and development of FDD tools

- There are two basic approaches to the design of Fault Detection and Diagnosis (FDD) tools: method driven or user-driven design. The latter approach should be taken when designing any commercial FDD tool.
- Building owners, operators and service providers are most likely to benefit from FDD. Manufacturers have a commercial incentive to develop FDD tools to remain or become more competitive.
- It is difficult to diagnose some faults from normal operating data in custom-designed HVAC plant. In many cases, it may only be possible to detect, rather than diagnose, faults. Fault detection and fault diagnosis appears to be possible in the case of mass-produced items of equipment such as rooftop air-conditioners.
- Sensitivity of the thermal performance to some faults is extremely low and even fault detection, when it is based on currently available thermal measurements, may be impossible in some sub-systems.
- It is difficult to specify the appropriate fault sensitivity for a particular application since the precise economic cost of failing to detect a fault and of having to deal with a false alarm is usually unknown. In practice, the end-user should be able to adjust the alarm thresholds.
- The FDD tool must take into account the mode of operation of the HVAC system (for example, in free cooling mode, in occupancy, near steady-state), if false alarms are to be avoided.
- FDD tools, which are developed using expert knowledge, must be thoroughly validated to check that their knowledge base is complete and consistent. Application of specific rules should be avoided if the FDD tool is based on expert rules. Systematic methods of rule generation and rule simplification should be adopted when the HVAC system is complex and has a large number of operating modes. A hierarchical rule-based system should be used whenever the number of rules becomes very large.
- The final decision made by the FDD Tool must be based on data collected at more than one operating condition, if unambiguous results are to be obtained and false alarms are to be avoided. Intelligent alarm generation is essential if the demands of the end-user are to be satisfied.
- HVAC FDD tools should have modest on-line computational demands. The building energy management software is usually distributed throughout the outstations (field panels) of the building energy management and control system and most outstations have relatively little available processing power. The more powerful PC-based supervisors must time-share their resources between several tasks. Schemes that use on-line optimisation to train the reference models are usually unsuitable for implementation in the outstations of the building energy management and control system.
- With the exception of high-level FDD tools, such as whole building energy monitors, integrating the diverse information made available by stand-alone FDD modules into a clear and consistent description of the overall building performance is likely to be one of the next important challenges that developers of FDD tools will face. Such schemes will require higher-level FDD modules that employ conflict resolution techniques to reason about the true cause of an alarm.

- Implementation of FDD tools in the building energy management and control system requires consideration of the functional hierarchy of the tool and the physical hierarchy of the distributed control system.

The commissioning and testing of FDD tools

- Few FDD schemes are entirely generic and most need to be set-up or commissioned. The number of application dependent parameters must be kept to a minimum and the use of application specific detection thresholds should be avoided. Manual tuning usually requires specialist knowledge and can be extremely time consuming in the case of many of the more sophisticated schemes. The cost of setting-up and operating the FDD tool should be taken into account in any cost-benefit analysis.

- The amount of information (design data, measurement information, configuration data, control sequencing, etc.) needed by an FDD tool, and the effort required to extract this information from its source and to insert it in the FDD tool, should not be underestimated. There is a need for an integrated database, which is populated with the information required by the FDD tools, that would evolve over the lifetime of the building to reflect its current characteristics, and has a standard interface for accessing the data.

- Measurement errors are a major obstacle to the successful application of FDD tools in HVAC systems. The FDD scheme must take measurement errors into account unless sensor faults can first be detected and eliminated. Validation of the sensors must be the first step in the commissioning process. Regular re-validation of the sensors is advisable.

- Systematic methods of assessing FDD tools are only possible if the test data are labelled as faulty or correct before the tool is applied. The user is also being assessed when FDD schemes with user-adjustable thresholds are evaluated. It is essential that the data sets used to set-up such FDD tools are not the same as those that are used to assess the tools.

- Artificial faults must be introduced if the FDD Tool is to be tested in a real building. Some natural faults occur infrequently and it is difficult to check their presence and determine their size.

The use of FDD tools

- The presence of some faults can only be detected using existing sensors when special test signals are injected into the HVAC control system. In practice, this may only be possible during commissioning or re-commissioning.

- In most applications, the end-user must be able to adjust the rate at which non-safety-critical faults are identified so that it is no greater than the rate at which it is possible to deal with them. It should be noted that user-selected thresholds are nearly always adjusted to control the alarm rate, not the false alarm rate.

Ideally, user-selected thresholds should take account of the strength of belief in the presence of the fault, as well as the rate at which alarms are generated. FDD tools based on expert rules must be validated on-line with user-selected thresholds if they are to provide the necessary flexibility. In most HVAC applications, faults that can only be detected for a small proportion of the time may still be important. For example, although a leaky valve can only be detected when the valve is nearly closed, and this may occur infrequently, the effect of the leakage on energy consumption may be significant.

The International Energy Agency (IEA) Energy Conservation in Buildings and Community Systems Programme (ECBCS)

The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Co-operation and Development (OECD) in 1974, with the purpose of strengthening co-operation in the vital area of energy policy. As one element of this programme, member countries take part in various energy research, development and demonstration activities. The Energy Conservation in Buildings and Community Systems Programme has sponsored various research annexes associated with energy prediction, monitoring and energy efficiency measures in both new and existing buildings. The results have provided much valuable information about the state of the art of building analysis and have led to further IEA sponsored research.

www.ecbcs.org