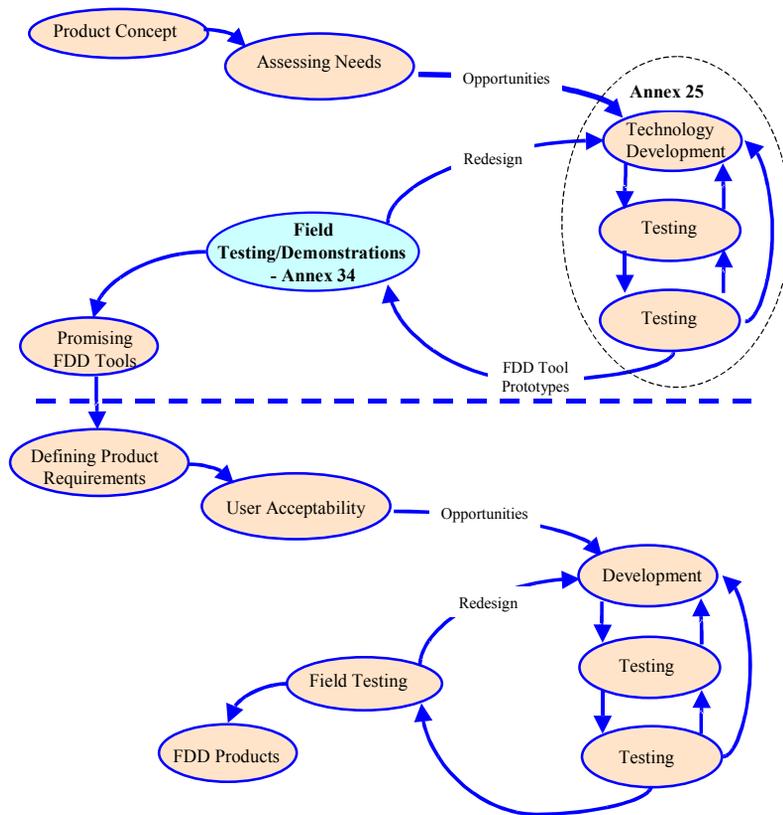


Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings



International Energy Agency
Energy Conservation in Buildings
and Community Systems
ANNEX 34

SYMPOSIUM 217

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Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings

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This report documents the results of co-operative work performed under the IEA Program for Energy Conservation in Buildings and Community Systems, Annex 34: “Computer-aided Evaluation of HVAC System Performance”

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Preface

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an International Energy Program. A basic aim of the IEA is to foster co-operation among the twenty-one IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D). This is achieved in part through a Program of collaborative RD&D consisting of forty-two Implementing Agreements, containing a total of over eighty separate energy RD&D projects. This publication forms one element of this Program.

ENERGY CONSERVATION IN BUILDINGS AND COMMUNITY SYSTEMS

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy consumption in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation method, as well as air quality and studies of occupancy.

THE EXECUTIVE COMMITTEE

Overall control of the RD&D Program is maintained by an Executive Committee, which not only monitors existing projects, but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (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 Inhabitant Behaviour with Regard to Ventilation*
- Annex 9 Minimum Ventilation Rates*
- Annex 10 Building HVAC Systems Simulation*
- Annex 11 Energy Auditing*
- Annex 12 Windows and Fenestration*
- Annex 13 Energy Management in Hospitals*
- Annex 14 Condensation*

Annex 15 Energy Efficiency in Schools*
Annex 16 BEMS – 1: Energy Management Procedures*
Annex 17 BEMS – 2: Evaluation and Emulation Techniques*
Annex 18 Demand Controlled Ventilating 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 Multizone 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 Energy Efficiency in Educational Buildings
Annex 30 Bringing Simulation to Application*
Annex 31 Energy Related Environmental Impacts 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 Control Strategies for Hybrid Ventilation in New and Retrofitted Office Buildings – Hybvent
Annex 36 Retrofitting in Educational Buildings – Energy Concept Adviser for Technical Retrofit Measures
Annex 37 Low Exergy Systems for Heating and Cooling of Buildings

ANNEX 34 COMPUTER-AIDED EVALUATION OF HVAC SYSTEM PERFORMANCE

This report summarises the work completed during Annex 34. The objective of the Annex was to develop HVAC fault detection and diagnosis tools, which are close to commercial products. The approach was to design a number of different computer-based demonstration systems that could be interfaced to HVAC processes in real buildings. By monitoring the operation of these demonstration systems, researchers were able to test a variety of fault detection and diagnosis methods and techniques in a real environment, find possible shortcomings and obtain new ideas for further development. Over fifty industrial partners, including controls and plant manufacturers, construction companies, and building owners and operators, participated in the thirty demonstrations that were completed. The report describes each demonstration system, identifies key issues associated with successful practical application and examines the potential for commercial exploitation. The programme of research, which involved research engineers from eleven countries, was completed in under four years.

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SECTION A: INTRODUCTION

A.L. Dexter

A.1 SUMMARY OF ACHIEVEMENTS AND GENERAL CONCLUSIONS

A.1.1 Achievements

- Twenty-three prototype performance monitoring tools and three prototype performance validation tools have been developed.
- Thirty demonstrations have taken place in twenty buildings.
- Twenty-six fault detection and diagnostic (FDD) tools have been tested in real buildings.
- Four performance monitoring schemes have been jointly evaluated on three documented data sets from real buildings.
- A test shell has been developed to simplify the comparative testing of the FDD Tools.

A.1.2 General conclusions

The design and development of FDD tools

- There are two basic approaches to the design of FDD tools: user-driven design or method-driven design. Different users may have very different goals. The design of any commercial FDD tool should be user-driven.
- The main beneficiaries of FDD are most likely to be building owners and operators, and service providers. The main commercial incentive for building controls manufacturers to develop FDD systems is to maintain or increase their competitiveness.
- It is very 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. Both fault detection and fault diagnosis appear 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 too 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 according 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.

A.2 BACKGROUND

The potential savings that would arise from improved management of energy use in buildings are considerable, even for a fraction of the building stock. For example, in one recent study, covering a modest number of commercial office buildings, energy savings of 20-30 % were attributed to re-commissioning of the HVAC systems to rectify faulty operation. Current supervisory strategies used by energy management systems do not explicitly optimise performance and cannot respond to the occurrence of faults that cause the performance to deteriorate. In such circumstances, the energy consumption may rise, comfort may be impaired and wear may increase, unless corrective action is taken.

The goal of this Annex is to reduce energy and environmental costs by ensuring that the design intent is achieved in the operation of buildings. There are two basic reasons why the performance of a building is often unsatisfactory: poor design and improper operation. The second cause of unsatisfactory performance is often neglected, although in practice there is considerable potential for improvement. Improvements in design generally only affect new buildings (or possibly existing buildings through major refurbishment's), whereas improved operation can benefit the whole of the building stock to which the technology in question can be applied. Costs associated with the operation of HVAC plants in buildings are not limited to the fuel and electricity consumed by the plant. Unnecessary wear, leading to premature component failure, increases costs through the embodied energy and material resources in the replacement of equipment and the indirect costs associated with the repair process (e.g. transport). Leakage of refrigerant or inefficient combustion gives rise to global and local pollution problems. All of which suggests the need for other indices, besides direct fuel and electricity costs, when assessing the performance of buildings.

The problems associated with identifying faults in HVAC systems are more severe than those that occur in most process control applications. The behaviour of HVAC plants and buildings is more difficult to predict. Accurate mathematical models cannot be produced since most HVAC designs are unique and financial considerations restrict the amount of time and effort that can be put into deriving the model. Detailed design information is seldom available, and measured data from the actual plant are often a poor indicator of the overall behaviour, since test signals cannot usually be injected during normal operation and buildings are subject to seasonal disturbances. The prediction of faulty behaviour is even more problematic since some types of faults cannot be introduced in a realistic manner, and the deliberate insertion of faults may lead to an unacceptable increase in energy costs or occupant discomfort. Another problem is that many variables cannot be measured accurately and some measurements are not available. For example, air and water flow rates are measured in relatively few

systems. This is a particular problem in fault diagnosis since the presence of some faults may be very difficult to detect using the available measurements and, with a limited number of measurements, several faults may have similar symptoms. For example, the air temperature drop across a cooling coil is not very sensitive to a reduction in the water flow rate caused by fouling of the tubes of the coil, and any observed change might also be a result of drift in the chilled water supply temperature. Variables, which cannot be measured directly, are often only crudely estimated. For example, the widespread use of single-point air temperature sensors to indicate average values over the entire cross-section of a large duct can result in biased estimates of the average air temperature. The behaviour of HVAC equipment may also be highly non-linear. For example, an incorrectly sized damper will have a non-linear installed characteristic. In addition, the behaviour of the plant will vary as its mode of operation changes. For example, the relationship between zone air temperature and the position of the valve in the re-heating coil in a terminal box will be very different to the relationship between zone air temperature and the position of the VAV damper. There are also constraints on the operation of most of the equipment. For example, there will be a lower limit imposed on the position of the fresh air dampers; the supply air temperature must not drop below a specified value. Finally, in most cases, the design intent is poorly specified. Maintaining thermal comfort levels does usually not equate to tight control of zone air temperature. The importance of closely controlling intermediate variables such as supply air temperature is usually unknown. It is therefore difficult to quantify the economic cost of operating an air-conditioning system in the presence of faults that do not cause catastrophic failure but result in poor thermal comfort or over-active control.

Early detection of the faults can prevent energy wastage and avoid occupant discomfort. However, there is a real risk of incorrect diagnosis, when faced with such high levels of uncertainty, and the cost of failing to diagnose a fault must be weighed against the cost of having to respond to a false alarm. The plant operator may even turn-off the FDD system if there are too many false alarms. One of the main requirements of any HVAC fault diagnosis scheme is therefore that it should generate very few false alarms.

A number of different techniques for detecting and isolating faults have been successfully developed by the participants in IEA Annex 25. The techniques make use of simple, on-line models of correct operation to detect faults. Diagnosis is based either on on-line models of different faults or on expert rules. These techniques were developed using detailed computer simulation and have been tested using experimental data from laboratory HVAC plants. However these methods had not been tested in a realistic on-line situation. Before the potential of applying such techniques can be realised in practice, it must first be demonstrated that the identification of faults has genuine economic and environmental advantages, and that the implementation of performance evaluation schemes based on these methods of detecting and diagnosing faults is commercially viable and technically feasible.

A.3 AIMS AND OBJECTIVES

The main aim of the Annex is to work with control manufacturers, industrial partners, and/or building owners and operators to demonstrate the benefits of on-line

performance evaluation in real building applications. The FDD methods developed in Annex 25 will be combined into robust performance evaluation systems and incorporated into either stand-alone PC based supervisors or into the outstations of a future generation of “smart” building control systems. The use of these performance evaluation systems for both commissioning and ongoing fault detection and diagnostics will be investigated.

The specific objectives are:

- 1) To clarify the needs of the users and to investigate the nature and requirements of the man-machine interface necessary to assure effective communication with plant room operators regarding fault conditions and the need for remedial action.
- 2) To assess the cost effectiveness and practical applicability of FDD methods so that their commercial viability can be determined and any potential economic constraints can be identified. Both equipment and system level faults will be considered.
- 3) To construct prototype computer-aided performance evaluation systems that are able to detect unsatisfactory performance and diagnose faults arising at different stages of the building life cycle (i.e., design, installation, commissioning, and operation), including the detection and diagnosis of faults that lead to a gradual degradation of the performance.
- 4) To investigate the need and requirements for a hierarchical framework for the performance evaluation systems to co-ordinate and interpret information from independent FDD methods and arbitrate in circumstances where conflicting diagnoses are encountered.
- 5) To demonstrate the robustness and commercial feasibility of the performance evaluation systems by testing them in real buildings.

A.4 SUMMARY OF WORK UNDERTAKEN

Three phases of work were identified for Annex 34. A six-month preparation phase, a thirty-six month working phase and a six month reporting phase.

A.4.1 Preparation phase

P1 The identification of systems and subsystems that were suitable for the demonstrations

Resource requirements and potential customer benefits were taken into account when selecting the most appropriate systems/subsystems for the demonstrations. Where appropriate, sensitivity studies were performed to determine the relationships between the magnitudes of selected faults and their effect on performance; and to examine the ability of FDD methods to detect particular types and sizes of faults.

P2 The evaluation of FDD methods in terms of robustness and feasibility of practical application

The feasibility of various methods was assessed in terms of practical issues such as their effect on normal operation and energy/fuel consumption, the necessity for human interaction, the need for on-site training, the applicability to different types of faults and HVAC processes, their diagnostic capabilities, the ease of configuring them for new applications and of embedding and integrating them into the building control system, the need for additional instrumentation and robustness. The methods that prove to be most effective for particular applications were demonstrated in the working phase.

A.4.2 Working phase

W1 The construction of the prototype performance validation systems

Prototype performance validation systems, which were designed to assist with the final stages of the commissioning or re-commissioning of HVAC plants, were produced for use on the selected target systems/subsystems. Test procedures were devised to check for correct operation and the absence of particular faults in the mechanical equipment, and to assess the control performance.

W2 The construction of the prototype performance monitoring systems

Prototype performance monitoring systems, which were designed to detect unsatisfactory performance by comparing current behaviour with that predicted by a reference model of the correctly operating plant, were produced for the selected target systems and subsystems. Different approaches to generating reference models of correct behaviour were investigated.

W3 Interfacing the prototype systems to building control systems

Interfaces were designed to connect the prototypes to commercial building control systems. Several different methods of implementation were investigated such as stand-alone PC-based software, code incorporated in the supervisor of the building control system, and code embedded in the outstations of the building control system. Particular attention was paid to “Open System” approaches to the designs.

W4 Testing and demonstrating the performance validation and monitoring systems in real buildings

Field trials were undertaken in both new, unoccupied, buildings nearing completion and buildings that have been occupied for some time. In the new buildings, the effectiveness of the performance validation systems was assessed by using them during the final stages of commissioning, in parallel with conventional procedures. In the older buildings, the prototype systems were tested by re-commissioning the HVAC systems.

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 (test signals were introduced by on-site manual intervention where this is necessary)
- on-line, in the building or remotely, under the control of the researcher in the building and under the control of the end-user with guidance from the researcher
- in the building under the control of the end-user alone.

A.5 SUMMARY OF THE DEMONSTRATION SYSTEMS

The summaries are listed according to the type of building in which the demonstration took place and the name of the country in which the FDD tool was developed. A more detailed description of the demonstrations is given in Section C: Case Studies. Each of the demonstration has been given a unique number in the case of countries involved in more than one demonstration.

FACTORY BUILDINGS

GERMANY

An FDD Tool based on a Life Cycle Approach

University of Stuttgart

Contact person: Robert Grob

Email address: Robert.Grob@po.uni-stuttgart.de



Type of building

Factory assembling computer systems

Type of HVAC system

VAV air-conditioning system

Type of subsystem

Air-handling unit

Faults considered

Stuck valves or dampers, coil fouling, leaky valves or dampers, bias or drift on temperature, humidity and pressure sensors

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnosis based on expert rules

Intended end-user

Maintenance personnel and building/plant operators

HOTELS

FRANCE

Demonstration 2

FDD for Hotel

CSTB, EDF, and ARIPA

Contact person: Hossein Vaezi-Nejad

Email address: vaezi@cstb.fr



Type of building

Hotel

Type of HVAC system

Electrical convectors and electrical floor heating system

Type of subsystem

Entire system

Faults considered

12 faults, selected by the end-user, that lead to increased operating costs or comfort degradation

FDD tools developed

Performance monitoring tool

FDD method

Detection and diagnosis based on expert rules

Intended end-user

Hotel manager

LABORATORY BUILDINGS

FRANCE

Demonstration 5

An artificial neural network -based fault detection diagnostic tool

Ecole des Mines de Paris

Contact person: Dominique Marchio

Email address: marchio@cenerg.ensmp.fr



Type of building

Laboratory building

Type of HVAC system

VAV air-conditioning system

Type of subsystem

AHU

Faults considered

Air-side and water-side fouling of cooling coil, slipping fan belt, valve faults, sensor faults

FDD tools developed

Performance monitoring tool

FDD method

Detection using artificial neural networks and residual analysis

Intended end-user

Building/plant operator

LABORATORY BUILDINGS

The NETHERLAND

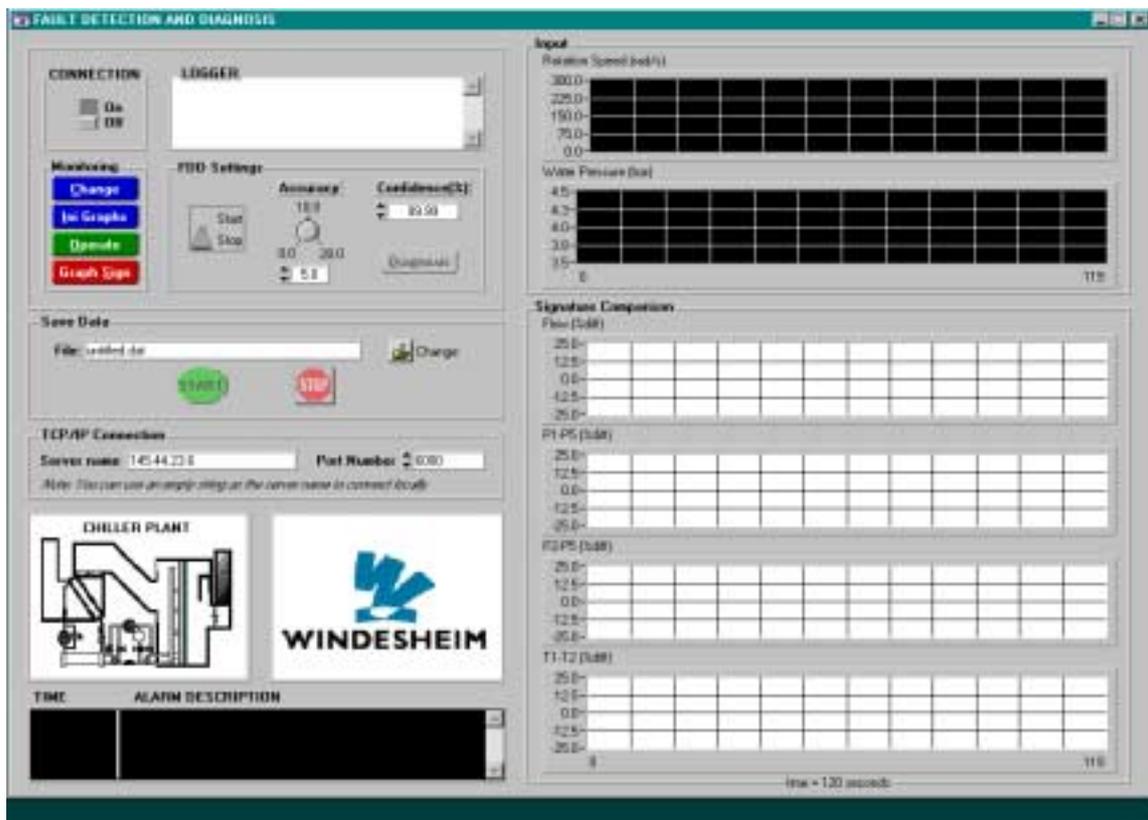
Demonstration 1

Remote Monitoring and FDD on a Laboratory TNO-chiller

TNO

Contact person: Henk Peitsman

Email address: H.Peitsman@bouw.tno.nl



Type of building

Laboratory

Type of HVAC system

Air-cooled reciprocating chiller

Type of subsystem

All subsystems

Faults considered

Water-side and air-side fouling of the coils

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnosis by case-based reasoning

Intended end-user

Students of universities and polytechnics, and service company personnel

LABORATORY BUILDINGS

SWITZERLAND

Demonstration 1

QMBFD: a Qualitative Fault Detection Tool

Siemens Building Technology, L&S Division

Contact person: Peter Gruber

Email address: GruberP@ch.sibt.com



Type of building

Laboratory

Type of HVAC system

CAV laboratory system

Type of subsystem

AHU

Faults considered

Valve or damper stuck, or with restricted range, sensor offsets, excessive control signal oscillations

FDD tools developed

Performance monitoring tool

FDD method

Qualitative model-based fault detection

Intended end-user

Building operator

LABORATORY BUILDINGS

UNITED KINGDOM

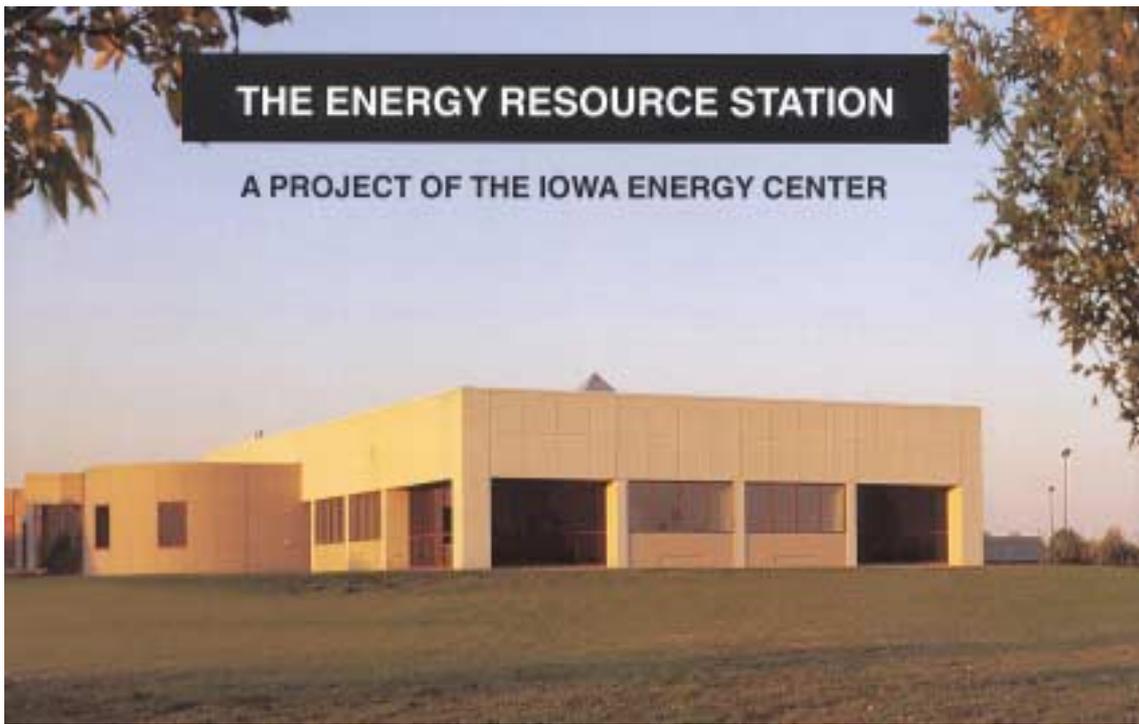
Demonstration 3

A First Principles Model-based FDD Tool

Loughborough University

Contact person: Jon Wright

Email address: J.A.Wright@lboro.ac.uk



Type of building

Laboratory test facility

Type of HVAC system

VAV air-conditioning system

Type of subsystem

AHU

Faults considered

Stuck valves and dampers, leaky valves and dampers, water-side fouling, faulty static pressure sensor, over oscillatory control signal, slipping fan belt

FDD tools developed

Performance monitoring tool

FDD methods

Diagnosis based on parameter innovation

Diagnosis using physical models and expert rules

Intended end-user

Experienced building/plant control engineer

LABORATORY BUILDINGS

UNITED STATES OF AMERICA

Demonstration 3

MATCh: Model-based Assessment Tool for Chillers

National Institute of Standards and Technology (NIST)

Contact person: Natascha Castro

Email address: Natascha.Castro@nist.gov



Type of building

Laboratory test facility

Type of HVAC system

Air-cooled chiller

Type of subsystem

All subsystems

Faults considered

Air-side condenser fouling, water-side evaporator fouling, liquid line restriction, refrigerant overcharge or undercharge

FDD tools developed

On-site or remote performance monitoring tool

FDD method

Fault detection using physical models and nearest neighbour or prototype classifier

Fault diagnosis using expert rules

Intended end-user

Building operators, technicians or service personnel

LABORATORY BUILDINGS

UNITED STATES OF AMERICA

Demonstration 4

An FDD Tool based on Electrical Power Measurements

Massachusetts Institute of Technology

Contact person: Les Norford

Email address: lNorford@mit.edu



Type of building

Laboratory test facility

Type of HVAC system

VAV air-conditioning system

Type of subsystem

AHU

Faults considered

Low fan, pump or motor efficiency, power transducer error, water-side fouling, leaking valve or damper, unstable or disconnected control loop

FDD tools developed

Performance monitoring tool

FDD method

Fault detection based on correlating electrical power and air flow, motor speed and control signals

Fault diagnosis using expert rules

Intended end-user

Building operators and service company personnel

OFFICE BUILDINGS

BELGIUM

QG-MET Building in Namur

Université de Liege, Fondation, Universitaire Luxembourgeoise

Contact person: Jean Lebrun

Email address: j.lebrun@ulg.ac.be



Type of building

Office building complex

Type of HVAC system

VAV system with radiators and fan-coil units

Type of subsystem

AHU, VAV box, BEMS

Faults considered

Fan non-operational, stuck valves, temperature and pressure sensor drift, incorrect control action, incorrect operation of equipment, bad placement of sensors, control system and actuators faults

FDD tools developed

Performance validation tool

FDD method

Manual checking and fault isolation using an off-line expert rules

Intended end-user

HVAC system operators and maintenance personnel

OFFICE BUILDINGS

CANADA

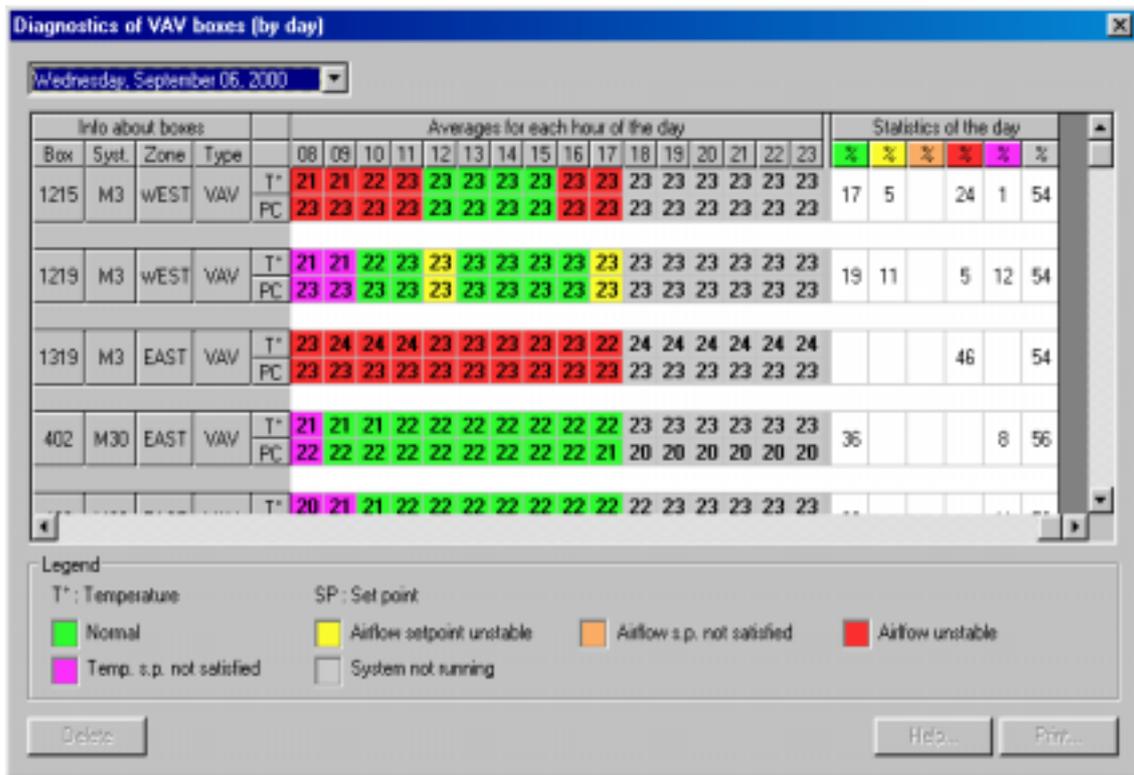
Demonstration 1

A Fault Detection and Diagnosis Tool for VAV Boxes

CEDRL

Contact person: Daniel Choinere

Email address: dchoinie@nrca.gc.ca



Type of building

Office building

Type of HVAC system

VAV air-conditioning system

Type of subsystem

VAV terminal box

Faults considered

Poor tuning of the air temperature and flow controllers, faulty damper and actuator, faulty flow and temperature sensor

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnosis based on performance indices and expert rules

Intended end-user

Building operators and service company personnel

OFFICE BUILDINGS

CANADA

Demonstration 2

A Fault Detection and Diagnosis Tool for AHU

CEDRL

Contact person: Daniel Choinere

Email address: dchoinie@nrca.gc.ca



Type of building

Office building

Type of HVAC system

VAV air-conditioning system

Type of subsystem

Air-handling unit

Faults considered

Thirty faults associated with the temperature and humidity sensors, dampers, valves and actuators, controllers, coils, filters and pumps

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnosis based on expert rules and performances indices

Intended end-user

Building operators and service company personnel

OFFICE BUILDINGS

CHINA

Automatic Evaluation of Sensors in Chilling Systems

Hong Kong Polytechnic University

Contact person: Shengwei Wang

Email address: beswwang@polyu.edu.hk



Type of building

Office building

Type of HVAC system

Central chilled water system with water-cooled condensers

Type of subsystem

All subsystems

Faults considered

Bias and drift in any of the water temperature and flow rate sensors

FDD tools developed

Off-line sensor validation tool

FDD method

Statistical analysis and minimisation of mass and energy balance residuals

Intended end-user

BMS suppliers, commissioning engineers, maintenance engineers and plant operators

OFFICE BUILDINGS

FRANCE

Demonstration 3

FDD for Office

CSTB, EDF

Contact person: Hossein Vaezi-Nejad

Email address: vaezi@cstb.fr



Type of building

Office building

Type of HVAC system

Electrically powered air-conditioning system

Type of subsystem

Air-handling units and fan-coil units

Faults considered

Thirteen end-user selected faults that impact on user comfort and operating costs

FDD tools developed

Performance monitoring tool

FDD method

Fault detection based on expert rules

Intended end-user

Experienced building/plant operator

OFFICE BUILDINGS

JAPAN

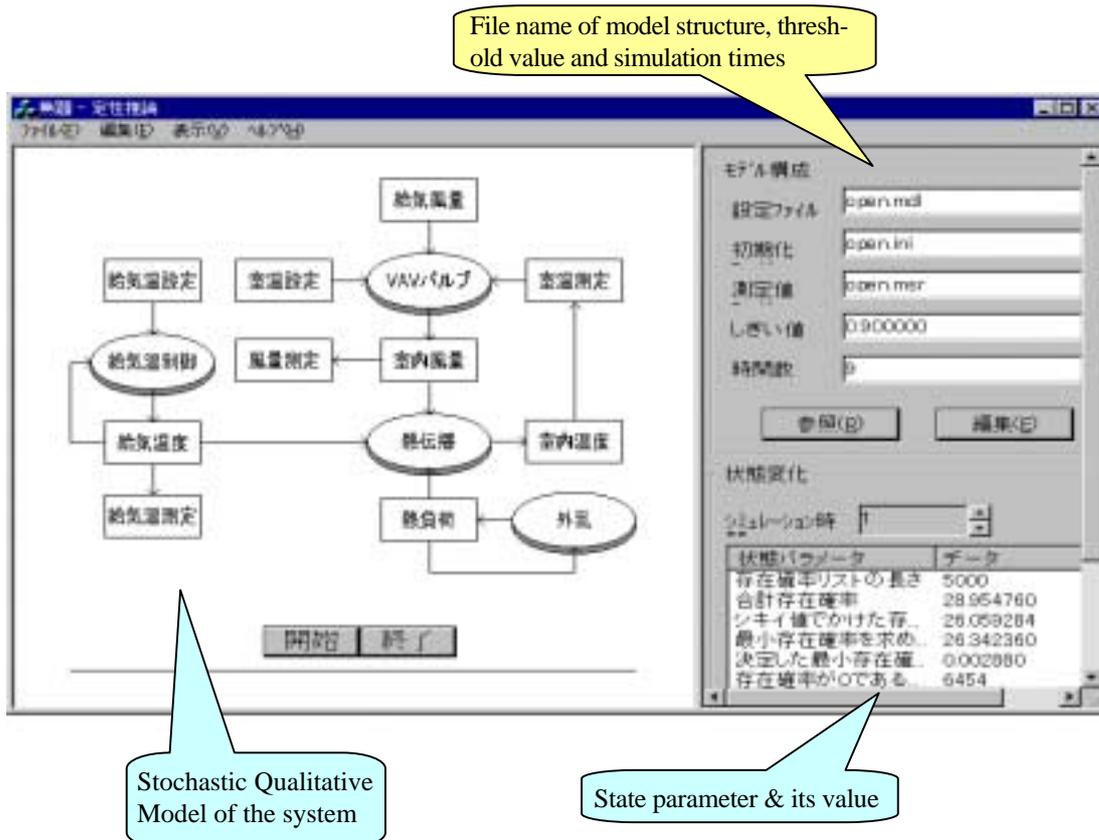
Demonstration 1

Fault Detection and Diagnosis using Stochastic Qualitative Reasoning

Yamatake 1 Building Systems Corporation

Contact person: Fusachika Miyasaka

Email address: shiozaki@atc.Yamatake1.co.jp



Type of building

Commercial office building

Type of HVAC system

VAV air-conditioning system

Type of subsystem

AHU and VAV box

Faults considered

Actuator failures, sensor failures, controller failures

FDD tools developed

Performance monitoring support system

FDD method

Fault diagnosis based on stochastic qualitative reasoning

Intended end-user

HVAC system operators and maintenance personnel

OFFICE BUILDINGS

JAPAN

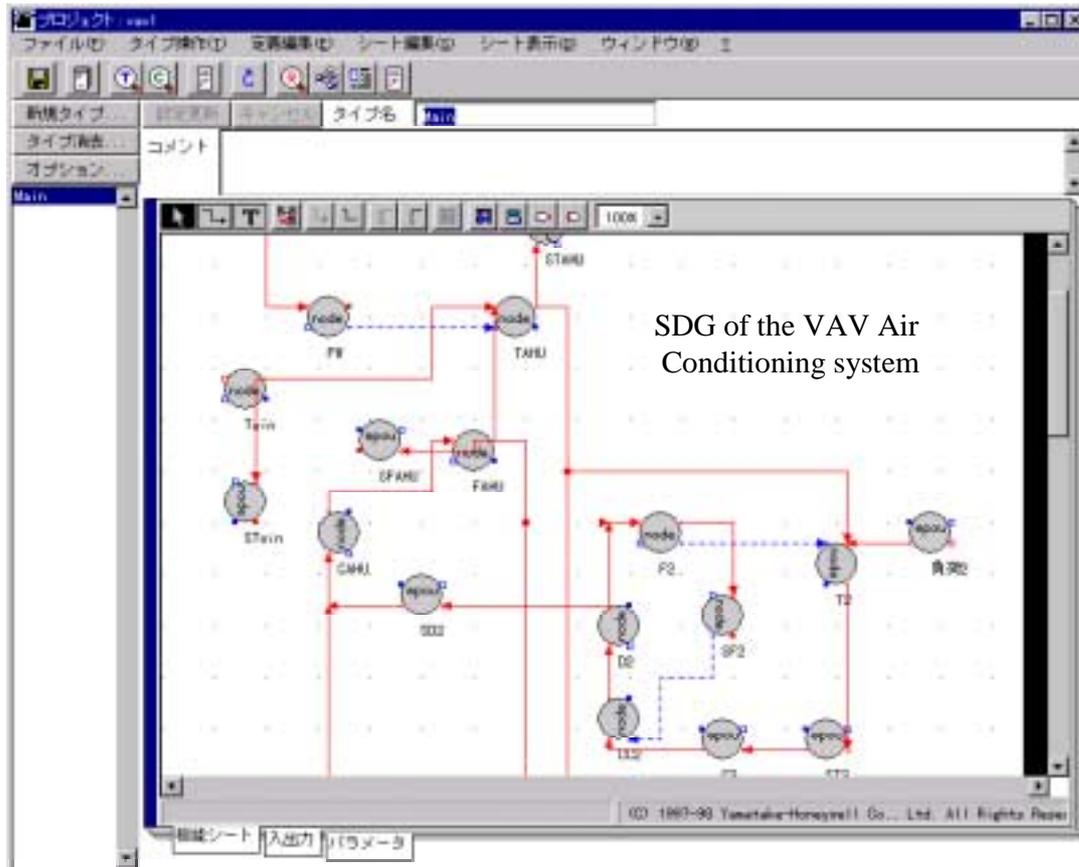
Demonstration 2

Faults Diagnosis by Qualitative Causal Reasoning

Yamatake 1 Corporation

Contact person: Jun'ichi Shiozaki

Email address: shiozaki@atc.Yamatake 1.co.jp



Type of building

Commercial office building

Type of HVAC system

VAV air-conditioning system

Type of subsystem

AHU and VAV box

Faults considered

Actuator failures, sensor failures, controller failures

FDD tools developed

Performance monitoring support system

FDD method

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

Intended end-user

HVAC system operators and maintenance personnel

OFFICE BUILDINGS

JAPAN

Demonstration 3

An FDD Tool for VAV Terminal Boxes

Kyoto University

Contact person: Harunori Yoshida

Email address: nori@archi.kyoto-u.ac.jp



Type of building

Research & Development Centre

Type of HVAC system

VAV air-conditioning system

Type of subsystem

VAV box

Faults considered

Stuck damper

FDD tools developed

Embedded performance monitoring system

FDD method

Fault detection based on statistical analysis of residuals

Intended end-user

HVAC system operators and product suppliers

OFFICE BUILDINGS

SWEDEN

An FDD Tool for Air-handling Units

KTH, SP

Contact person: Per Isakson

Email address: poi@bim.kth.se



Type of building

Office building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU

Faults considered

Stuck or leaking mixing-box dampers, stuck or leaking heating and cooling coil valves, low 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

FDD tools developed

Performance monitoring tool

FDD method

Fault detection using physical models and analysis of filtered residuals

Fault diagnosis based on the fault direction space method

Intended end-user

Building operators and service company personnel

OFFICE BUILDINGS

SWITZERLAND

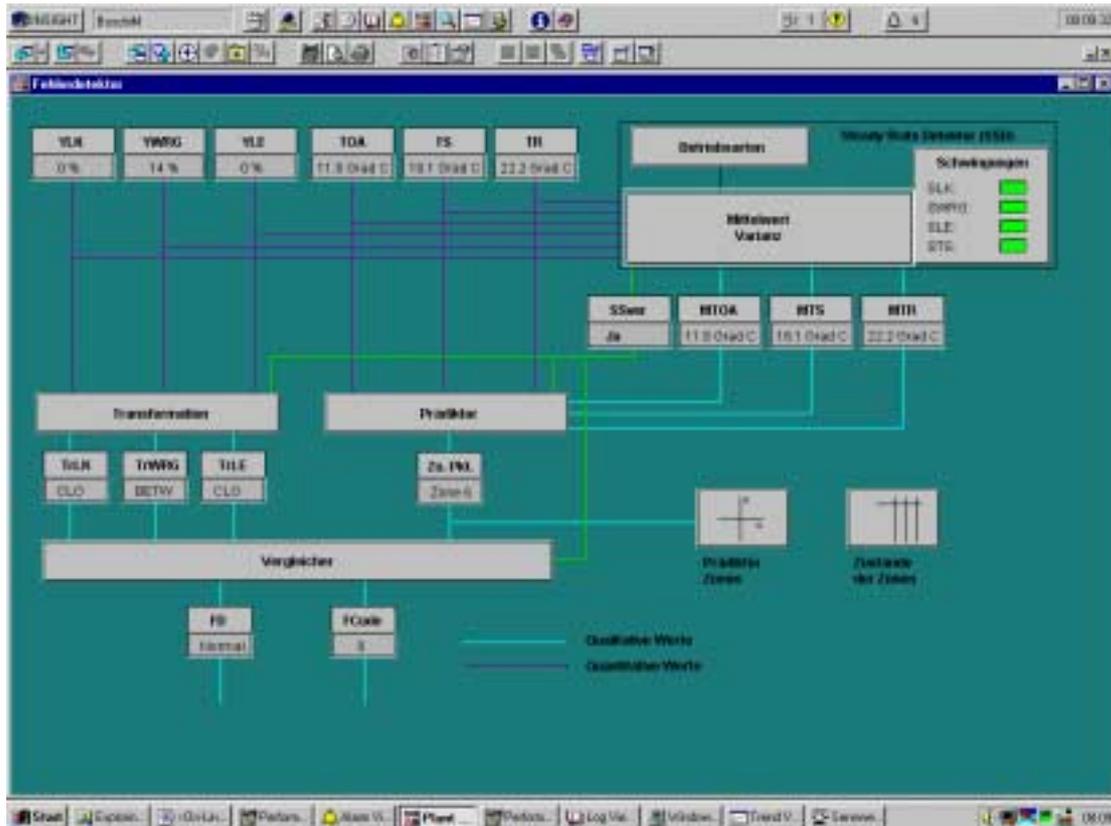
Demonstration 2

QMBFD: a Qualitative Fault Detection Tool

Siemens Building Technology, L&S Division

Contact person: Peter Gruber

Email address: GruberP@ch.sibt.com



Type of building

Office Building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU with heat recovery wheel

Faults considered

Valve or damper stuck, or with restricted range, sensor offsets, excessive control signal oscillations

FDD tools developed

Performance monitoring tool

FDD method

Qualitative model-based fault detection

Intended end-user

Building operator

OFFICE BUILDINGS

SWITZERLAND

Demonstration 3

PAT: a Performance Audit Tool

Siemens Building Technology, L&S Division

Contact person: Peter Gruber

Email address: GruberP@ch.sibt.com



Type of building

Office Building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU with heat recovery wheel with radiators and heating and chilled ceilings in three zones

Faults considered

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

FDD tools developed

Performance monitoring (audit) tool

FDD method

Fault detection and diagnosis using an expert system

Intended end-user

Building operator

OFFICE BUILDINGS

UNITED KINGDOM

Demonstration 1

A First Principles Model-based FDD Tool

Loughborough University

Contact person: Jon Wright

Email address: j.a.wright@lboro.ac.uk



Type of building

Commercial office building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU cooling coil subsystem

Faults considered

Leaky valve, fouled coil, faulty supply air temperature sensor

FDD tools developed

Performance monitoring tool

FDD method

Detection and diagnosis based on physical model and expert rules

Intended end-user

Experienced building/plant operator

OFFICE BUILDINGS

UNITED KINGDOM

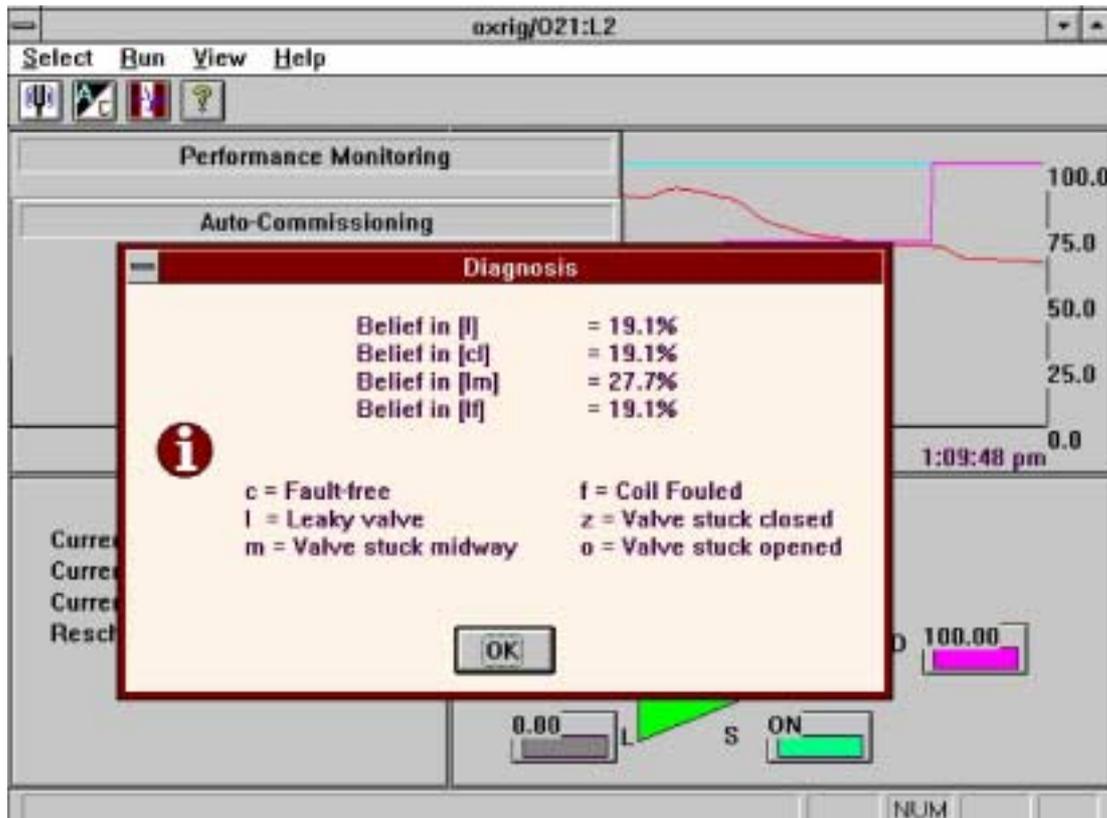
Demonstration 2

PMAC: a Performance Monitoring and Automated commissioning Tool

University of Oxford

Contact person: Arthur Dexter

Email address: arthur.dexter@eng.ox.ac.uk



Type of building

Commercial office building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU cooling coil subsystem

Faults considered

Leaky valve, fouled coil, valve stuck open, midway or closed

FDD tools developed

Performance monitoring and automated commissioning tool

FDD method

Detection based on fuzzy expert rules

Diagnosis based on generic fuzzy models

Intended end-user

Commissioning engineer employed by building operator or BEMS manufacturer

SCHOOLS

FINLAND

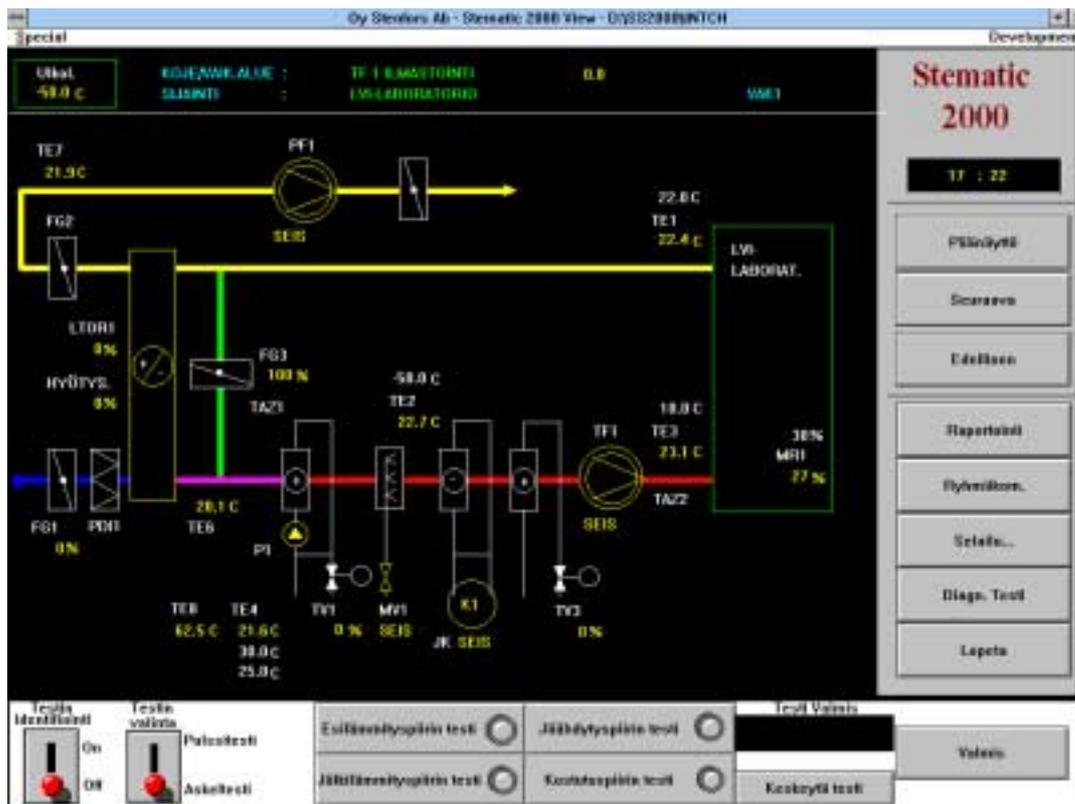
Demonstration 1

Fault Diagnosis Using On-line Diagnostic Tests

VTT Building and Transport

Contact person: Jouko Pakanen

Email address: jouko.pakanen@vtt.fi



Type of building

College building

Type of HVAC system

CAV air-conditioning system

Type of subsystem

AHU

Faults considered

Blocked coil or valve, stuck valve, partially open valve, faulty sensor

FDD tools developed

Performance validation tool

FDD method

Fault detection based on statistical analysis of residuals

Intended end-user

HVAC system operators or maintenance personnel

SCHOOLS

FINLAND

Demonstration 3

AREKA: A Performance Monitoring Tool for Energy-Efficient Building Use

VTT Building and Transport

Contact person: Mrs. Satu Paiho

Email address: Satu.Paiho@vtt.fi



Type of building

Vocational school

Type of HVAC system

District heating system

Type of subsystem

All subsystems

Faults considered

High energy consumption, poor control performance

FDD tools developed

Performance monitoring system

FDD method

Fault diagnosis based on a fault-symptom tree – expert rules

Intended end-user

Plant foreman

SCHOOLS

FRANCE

Demonstration 1

EMMA for School

CSTB, ADEME

Contact person: Hossein Vaezi-Nejad

Email address: vaezi@cstb.fr



Type of building

School buildings

Type of HVAC system

Hot-water heating system with radiators

Type of subsystem

All subsystems

Faults considered

Boost too early, overheating and under-heating at start of occupancy, overheating and under-heating during occupancy, heating outside of occupancy

FDD tools developed

Performance monitoring tool

FDD method

Detection based on expert rules

Intended end-user

Municipal service teams (experienced building/plant controls operators)

SCHOOLS

UNITED STATES OF AMERICA

Demonstration 1

APAR: AHU Performance Assessment Rules

NIST, CSTB

Contact person: John House or George.Kelly

Email addresses: john.house@energy.iastate.edu and george.kelly@nist.gov



Type of building

College building

Type of HVAC system

VAV or CAV air-conditioning system

Type of subsystem

AHU

Faults considered

Stuck or leaky valve or damper, temperature sensor faults, sizing faults, faults in the sequencing logic, incorrect chilled or hot water supply temperature, operator error

FDD tools developed

Performance monitoring tool

FDD method

Fault detection based on expert rules

Intended end-user

Building operators and service company personnel

SWIMMING POOLS

FRANCE

Demonstration 4

EMMA for Swimming Pool

CSTB

Contact person: Hossein Vaezi-Nejad

Email address: vaezi@cstb.fr



Type of building

Indoor swimming pool

Type of HVAC system

Hot water system

Type of subsystem

All subsystems

Faults considered

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.

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnosis based on expert rules

Intended end-user

Municipal service teams and building/plant operators

SWIMMING POOLS

The NETHERLANDS

Demonstration 2

A Tool to Improve the Energy Efficiency and Performance of Swimming Pools

TNO

Contact person: Henk Peitsman

Email address: H.Peitsman@bouw.tno.nl



Type of building

Indoor and outdoor swimming pools

Type of HVAC system

Heating system using combined heat and power, gas boilers and heat pump

Type of subsystem

All subsystems

Faults considered

Incorrect functioning of the control system, excessive energy use, low efficiency of the individual installations

FDD tools developed

Performance monitoring tool

FDD method

Fault detection and diagnostic based on expert rules

Intended end-user

Swimming pool operators and service companies

VARIOUS TYPES OF BUILDING

CANADA

Demonstration 3

DABO: Diagnostic Agent for Building Operation

CEDRL

Contact person: Daniel Choinere

Email address: dchoinie@nrca.gc.ca



Type of building

National Film Board Complex

Type of HVAC system

Chilled water plant

Type of subsystem

Water-cooled centrifugal chiller

Faults considered

Condenser fouling, evaporator fouling, refrigerant overcharge or leakage, air in the system

FDD tools developed

Performance monitor tool

FDD method

Fault detection and diagnosis using statistical modelling and pattern recognition

Intended end-user

Building operator and facilities manager

VARIOUS TYPES OF BUILDING

FINLAND

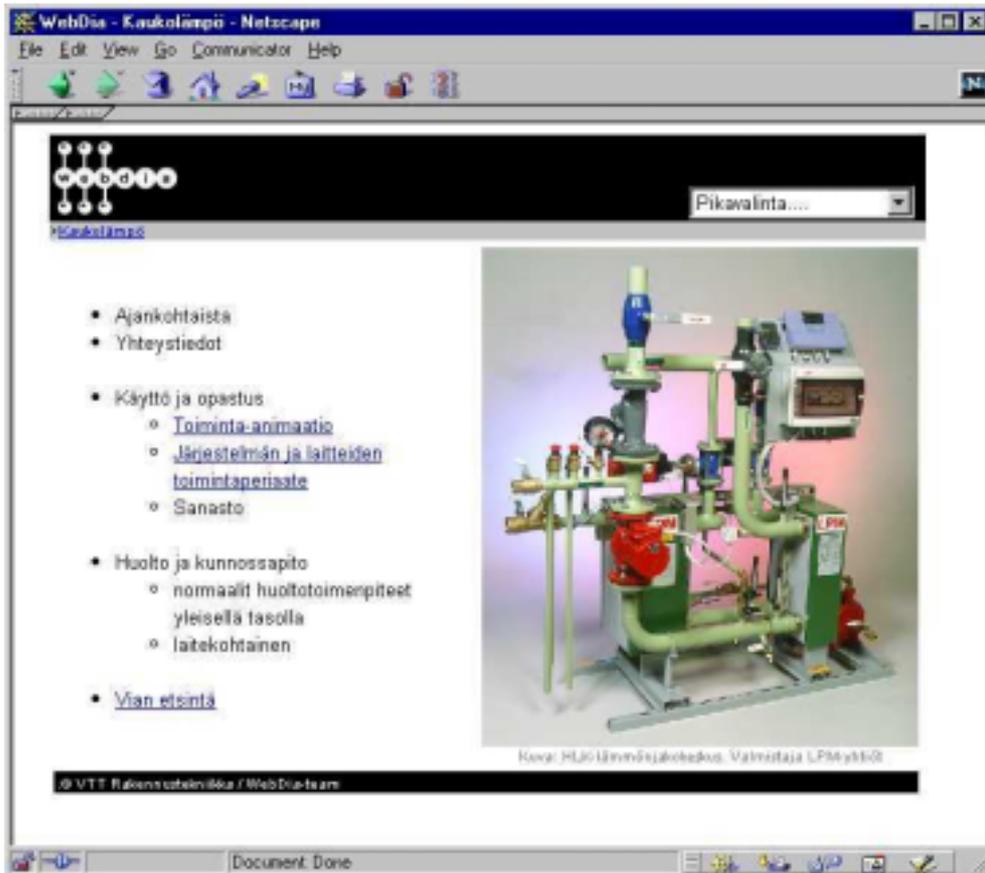
Demonstration 2

WebDia: an Internet-based FDD Tool

VTT Building and Transport

Contact person: Jouko Pakanen

Email address: jouko.pakanen@vtt.fi



Type of building

Residential and office buildings

Type of HVAC system

District heating and oil heating systems

Type of subsystem

All subsystems

Faults considered

All typical faults

FDD tools developed

Internet-based performance monitoring tool

FDD method

Off-line fault diagnosis using a knowledge-based system

Intended end-user

Building owners, HVAC system operators or maintenance personnel

VARIOUS TYPES OF BUILDING

UNITED STATES OF AMERICA

Demonstration 2

Automated Diagnostics for Packaged Rooftop Air Conditioners

Purdue University

Contact person: Jim Braun

Email address: jBraun@ecn.purdue.edu



Type of building

Various buildings

Type of HVAC system

Packaged rooftop air-conditioners

Type of subsystem

All subsystems

Faults considered

Refrigerant leakage or overcharging, fouled condenser coil or malfunctioning fan, fouled evaporator filter or malfunctioning fan, compressor wear, non-condensables in the refrigerant, liquid line restriction

FDD tools developed

Embedded performance monitoring tool

FDD method

Diagnostics based on either a statistical rule-based method, a sensitivity ratio method or expert rules

Intended end-user

Building operators or service company personnel

A.6 DEFINITION OF TERMS

AHU

Air-handling unit

Alarm

An indication of the presence of a fault.

Alarm generation

The generation of alarms based on the results of the fault detection and/or diagnosis.

BEMS

Building Energy Management System

Building control system

The system controlling the operation of the HVAC equipment.

Building/plant operator

The person in charge of the day-to day operation of the HVAC system and other building services.

Commissioning

The testing of the system to ensure that it is working correctly according to the design intent. Usually involves the injection of test signals.

DDC

Direct Digital Control

Disturbance

An unknown (and uncontrolled) input acting on the system.

Facilities Manager

The person who has overall control over the use and operation of the building.

Failure

Permanent interruption of a system's ability to perform a required function under specified operating conditions.

Fault

Unpermitted deviation of at least one characteristic property or parameter of the system from acceptable/usual/standard condition.

Fault detection

Determination of the presence of one or more faults in the system.

Fault diagnosis

Determination of the kind, size, location and time of detection of a fault. Follows fault detection and includes fault isolation and identification.

Fault identification

Determination of the size and time variant behaviour of a fault.

Fault isolation

Determination of the type and location of a fault

Innovation

A change in a characteristic property or parameter.

Performance validation

The final stages of the commissioning or re-commissioning of HVAC plants during which the equipment is tested to determine whether it is functioning correctly.

Performance monitoring

The detection of unsatisfactory performance by comparing current behaviour with that predicted by a reference model of the correctly operating plant.

Residual

The deviation between a measured and predicted value.

Sensor validation

The testing of the output from a sensor to check that the accuracy of the measurement is within specification (i.e. that the sensor is working correctly and has no faults).

Symptom

A change in an observable quantity from normal behaviour.

A.7 EFFECTS OF NEW TECHNOLOGIES ON FAULT DIAGNOSTIC SYSTEMS

Jouko Pakanen

One objective of the Annex has been to design and implement prototype FDD tools in real buildings. Less attention has been paid to transferring tools into FDD products. Designing a product usually means implementing the FDD tool or method on a BEMS or other building automation system. However, technology in this area is rapidly changing. This is due to the development of information technology and especially new communications systems. Many commercial building automation systems have already adopted some of these features. New technology will also have an effect on FDD product design, or even on FDD method design. The following is a brief summary of technological trends in this area and their possible effects on FDD design of HVAC systems.

- The Internet makes it possible to create decentralized building automation systems, where services can be retrieved from remote servers immediately they are needed. The user does not even need to know geographical origin of the information. These features will also benefit FDD design. One solution is to set-up a diagnostic help

desk for specific HVAC processes accessible to all customers. Another choice is to design large databases containing diagnostic information typical for specific products, for example, the products of an international company [Möttönen & Pakanen, 1997]. In this case measurement and status data about the HVAC system could be transferred to a remote server for FDD analysis.

- Brisk technical development is also evident in methods of communication inside buildings [Pakanen, 1998]. New technical systems and devices will utilise radio frequencies and the available infrastructures of electrical cables and phone lines as a transmission medium. It is probable that these new technologies will successfully compete with old approaches requiring custom wiring. Typical new products will be home LANs or home automation systems. They provide an easy access to the Internet for home and building automation equipment and products, and also new possibilities for creating diagnostic services for HVAC systems. Short-range wireless communication is becoming inexpensive and standard radio transceivers will soon be installed even in domestic appliances. In FDD applications this means easy and inexpensive installation and the possibility of getting more sensor data from the process.
- Mobile phones and systems are capable of transferring speech and data. The newest mobile phones, and also many pocket and hand-held computers, are equipped with wireless Internet access. These kinds of computers and phones can be taken anywhere, even close to a real HVAC process. For example, the user can apply his FDD tool while controlling or monitoring the HVAC process. Mobility is a benefit when new FDD tools are designed.
- An easy to learn and comprehensive user interface is essential when an FDD tool is designed. A conventional BEMS or a control device is rarely provided with such an interface. The Internet and its applications are rapidly replacing these old interfaces with new ones, based on www-technology [Webb, 2000, Nath, 1999]. WWW-pages are already used by many people and www-technology makes it possible to illustrate FDD methods by means of text, pictures, sound, video, animation and other multimedia effects. The result is that an FDD method or tool can be made comprehensive, and easy to learn and use, even for an ordinary user.

Pakanen, J. 1998. Rakennusten tiedonsiirtoteknologiat. Lähivuosien kehitysnäkymiä [Future communication technologies for buildings. A survey]. Espoo 1998, VTT Research Notes 1932. 48 p. + 1 p. app.

Webb, W. 2000. Designing Web Appliances on a Shoestring, EDN, April 13, 2000, pp. 89–96.

Nath, M. 1999. Low-cost techniques bring Internet connectivity to embedded devices, EDN, November 11, 1999, pp. 159–166.

Möttönen, V. and Pakanen, J. 1997. On-line fault diagnosis using Internet and WWW-pages. Computers in the Practice of Building and Civil Engineering. Worldwide ECCE Symposium. Lahti, Finland, 3–5 Sept. 1997, pp. 362–366.

A.8 AN OVERVIEW OF ARTIFICIAL INTELLIGENCE TECHNIQUES AND THEIR USE IN FAULT DETECTION AND DIAGNOSIS

A.8.1 Neural networks in fault detection and diagnosis

John M. House

Neural networks consist of large interconnected networks of relatively simple and typically non-linear units. Neural networks are often referred to as black boxes that are trained to learn the functional mapping of inputs to outputs using input/output training pairs. The output training data are referred to as the target output. The goal is to train the network until the output of the neural network is suitably close to the target output. When properly trained, neural networks faced with patterns similar to those used for training can generalize to produce meaningful outputs [Schalkoff, 1992]. A general introduction to neural networks can be found in the Annex 25 final report [IEA Annex 25, 1996].

Neural networks have been used for two purposes related to fault detection and diagnosis, namely, modelling of processes, and classification or discrimination of operating data as, for instance, normal or faulty. As a modelling tool, a neural network can be trained to represent complex functional relationships of a process. This functional relationship can then be used to predict the output of the process given the process inputs. The predicted output can be compared with the measured output and the difference can be used by any model-based classification technique to determine the operational status of the process. Neural networks are a popular modelling technique for several reasons. First, they can effectively model non-linear systems. Second, they are relatively straightforward to use and eliminate the need for detailed knowledge of the physics of the system. Third, they are robust to noise and can extract the underlying structure of a data set. Some of these same features that make neural networks a popular modelling technique also can be viewed as negative factors. Neural networks require vast amounts of training data to model effectively complex processes. Furthermore, it is difficult to gain any physical insight into the process being modelled from the parameters of the trained neural network. Like any regression technique, applying a neural network model to input data that are not well represented in the training data set can lead to erroneous output.

Neural networks can also be used to assign data to some operational classification. In this case the inputs to the neural network are typically a set of features that define the state of the system of interest. For instance, a feature could be the difference between a measured value of a temperature and the expected value of that temperature predicted by a model. The output(s) of the neural network is a status indicator, with different values of the output being associated with different states of operation. Hence, if sufficient data are available, input/output pairs consisting of patterns of features and labelled operating states (e.g., normal and faulty) can be used to train a neural network. Hence, when presented with an arbitrary pattern of features, the neural network will classify the operation based on the learned behaviour. Neural networks are highly effective for pattern recognition, and fault detection and diagnosis is essentially pattern recognition. The drawbacks of neural networks are the same as those cited above. Vast amounts of data are necessary to adequately train neural networks. Sufficient operating data representative of various types

of faulty operation may be particularly difficult to obtain. Even if such data are available, it may only be useful for the particular unit on which the data were collected. That is, because heating, ventilating and air-conditioning systems often have unique design features or control strategies, behaviour learned for one system may not be transferable to another. Another drawback is that because neural networks are black boxes, the reasoning behind decisions may be difficult to understand.

IEA Annex 25, 1996, *Building Optimization and Fault Diagnosis Source Book*, Eds. J. Hyvärinen and S. Kärki, Technical Research Centre of Finland.

Schalkoff, R.J. 1992. *Pattern recognition: statistical, structural, and neural approaches*, New York, New York: John Wiley & Sons.

A.8.2 Fuzzy Logic in fault detection and diagnosis

Arthur L. Dexter

Fuzzy methods of fault detection and diagnosis use fuzzy set theory to take account of the uncertainties associated with describing the behaviour of HVAC equipment [IEA Annex 25, 1996].

Fuzzy set theory is concerned with the uncertainty resulting from the imprecision or vagueness associated with the meaning of a concept expressed in the linguistic terms (For example, “the temperature is higher than usual”). The boundary of a fuzzy set is not sharp or precise and an element may be a member of a fuzzy set to a greater or less degree. For example, a temperature of 22 degrees C might be considered to have a 40% grade of membership of the fuzzy set “Higher than usual”. The variables in the antecedent and the conclusion of a fuzzy IF-THEN rule are described using fuzzy sets. A fuzzy model is a set of fuzzy rules that describe the relationship between a set of inputs and a set of outputs in qualitative terms.

Fuzzy FDD schemes have been proposed that use either implicit, shallow knowledge fuzzy models [Bourdouxhe and Seutin, 1998] or explicit, deep knowledge fuzzy models [Ngo and Dexter, 1999]. Implicit fuzzy models relate the observed symptoms to the faults. Explicit fuzzy models describe the behaviour of the system when it is operating correctly or when faults are present.

The main advantages of fuzzy FDD schemes are:

- Fuzzy models can take into account the highly uncertain, non-linear behaviour of HVAC equipment.
- Fuzzy FDD schemes are easier to commission because fuzzy rules are generic, to some extent.
- **Available expert knowledge about the symptoms of faults is easily combined with knowledge learnt from measured data.**
- Software implementation of fuzzy logic is computationally undemanding.

The main disadvantages of fuzzy FDD schemes are:

- Less precise results are generated in comparison with other approaches.
- Rule-based descriptions are often less concise than quantitative descriptions.

IEA Annex 25. 1996. *Building Optimisation and Fault Diagnosis Source Book* (Ed. Hyvärinen and Kärki), Section 4.6.2 ,VTT, Finland

Bourdouxhe, J-P. and H. Seutin. 1998. Fault Detection and Diagnosis of an Air-handling Unit of a Big Office Building, CD-ROM of Proc. SSB'98, Paper 44, Liege, Belgium.

Ngo, D. and A.L. Dexter. 1999. A Robust Model-based Approach to Diagnosing Faults in Air-handling Units, Trans. ASHRAE 105(1).

A.8.3 Expert and rule based systems for fault detection and diagnosis

Peter Gruber

The following definition of an expert system has been given by Professor Edward Feigenbaum of Stanford University [Harmon and King., 1987]:

“An expert system is an intelligent computer program, that uses knowledge and inference mechanisms in order to solve problems, which are at least of such a complexity, that for their solution substantial human expert knowledge is needed. The needed knowledge on this level together with the used inference mechanism can be viewed as a model for the expert knowledge of a human expert in the respective field”.

Any fault detection and diagnosis method, which applies rule-based knowledge, can be called an expert-system-based FDD method [Popovic and Bhaktar, 1994]. The number of rules and the complexity of the rule-base determine whether one speaks of an expert system or of a rule-based system for FDD. The difficulty of a rule-based method is to find a complete set of rules, especially in more complicated situations. Systems with a small number of rules can be implemented in a simple program language like C, more complex systems can be handled more efficiently by an expert system.

An expert system consists typically of the following five building blocks, which are usually embedded in an expert system shell [Gruber and Kaldorf, 1998].

Input data block

This block loads measured data from the process under supervision into an *archive database*. The measured data are sampled time-series of sensor signals and controller outputs. At the front end of the input data block these data have to be pre-processed in order to detect invalid or missing data. Invalid data are detected by comparing data with upper and lower bounds, missing data are interpolated. The stored time-series in the database are therefore regular time series.

Configuration block

This block provides a user interface where the user loads configuration information about the process under supervision (e.g. points, zones, plants, controllers). The configuration data are then stored in a *configuration database*. In the case of building supervision this database holds the following information:

- building topology (floors, zones)
- HVAC system (subsystem, equipment, design parameters)
- point definitions (read from the building energy management system BEMS)
- point functions (e.g. “zone temperature”)
- point locations
- operational and control parameters (setpoints, scheduler, ...)

Much of this information deals with relations among objects, so a relational database is a good choice for storing the data.

Knowledge block

This block contains the expert knowledge and is therefore the heart of the expert system. Fault Detection and Diagnostic knowledge is captured in rules and stored in a *knowledge database*. These rules can be expressed for instance by a simple list of IF-THEN rules, or by a decision tree. The rules represent relations between objects, their attributes and values. Rules can be characterised additionally by confidence factors in order to express uncertainty.

Inference and flow control block

This block processes the information stored in the archive, configuration and knowledge databases by an inference mechanism and a flow control strategy. The most widely used inference mechanism is the application of the logic rule called *modus ponens*. This rule is a deductive reasoning process and states that if the premises of a rule are true then its conclusions are also true. The rule parameters for this rule evaluation are the thresholds, which are needed in order to decide whether premises are true or false. The flow control strategy decides upon the processing of rules: where to begin (forward/backward chaining) and how to handle conflicts.

Output data block

This block handles the results of the inference block and displays them in a form that is adequate for the different users of the tool. It also stores the result in a *result database* for further analysis.

Generally the amount of information (configuration data, measurements) needed for diagnosis is of a magnitude higher than for detection only.

The advantages of an expert system over a simple rule-based system can be manifold:

- rule-handling, that means editing, adding and presentation of rules
- choice of flow control mechanisms, that means the way the rules are to be evaluated
- data handling of the input and resulting data
- error handling capabilities during rule editing and execution
- user interface

If an expert system is to be used successfully in practice, the user friendliness of the shell for the developer and the user is absolutely crucial. That includes the interface for editing rules, documenting rules, data input and result presentation. Another important factor is the ease by which it can be configured and set-up for a specific process and computer environment.

Harmon, P. and King, D. 1987. *Expertensysteme in der Praxis*, Oldenburg Verlag.

Popovic, D. and Bhaktar, V.P. 1994. *Methods and tools for artificial intelligence*, M. Dekker.

Gruber, P. and Kaldorf, S. 1998. *Performance Audit Tool PAT: ein Expertensystem zur Detektion und Diagnose von Fehlverhalten von HLK-Anlagen in realen Gebäuden*, 10 Status-Seminar energieforschung im Hochbau ETH Zürich.

A.8.4 Case-based reasoning in fault detection and diagnosis

Sipko Nannenbergh and Henk Peitsman

Case-Based Reasoning (CBR) is a methodology to model human reasoning and thinking, and a methodology for building intelligent computer systems [Bergmann]. CBR solves new problems using the following steps:

- Revise
Store previous experience (cases) in a database
- Retrieve
Retrieve experience about similar situations from the database
- Re-use
Re-use the experience in the context of the new situation: complete or partial reuse, or adaptation according to differences
- Retain
Store new experience in the database (learning)

Instead of relying on general knowledge of a problem domain, or making associations between problem premises, CBR is able to utilise the specific knowledge of previously experienced, concrete problem situations. These are called *cases*. A case is a description of a problem together with details of the actions that were taken to respond to the problem. Finding a similar past case and reusing it in the new problem situation solves the new problem. In the example given below, CBR works by selecting a case from a stored database of previous cases that best resembles the characteristics of the problem currently under investigation. An implementation of CBR is CBR-Works 4 [<http://www.cbr-web.org>]. It can be used to build a database of fault models and to determine a fault diagnosis. A fault model consists of the deviation between a good working system and an incorrectly operating system. More sensitivity can be obtained with this method by calculating the design-parameters and defining several performance indicators. These parameters can be calculated from the measurements by an equation

solver and appended to the fault spectra of the system. A simple mathematical model of the components in the system is still needed to be able to calculate these parameters.

Advantages

In the design phase of the CBR system, several faults are foreseen already and stored in the database as fault models. In practice, additional and unforeseen faults can occur. Being able to monitor unforeseen faults and transform them into new fault models in the database provides the user with the opportunity of getting a more reliable fault diagnosis system. The number of faults in the database increases and the system becomes more valuable and reliable in time. A good skilled maintenance engineer should be able to collect the monitoring data and derive new fault models.

Disadvantages

To get detailed and optimal information about the faults, a mathematical model of the system has to be derived to allow the performance parameters to be calculated from the measurements.

A.8.5 Bond Graphs and their use in fault detection and diagnosis

Sipko Nannenbergh and Henk Peitsman

Numerical modelling is the main tool for designing and analysing engineering systems. Nevertheless, engineers do not refer to systems exclusively in a quantitative manner; they often use qualitative relationships between variables, mainly for describing complex non-linear, time varying systems [Wang and Linkens, 1996]. The bond graph is a method for modelling mechanical, electrical, hydraulic, and thermal systems in a unified manner [Rosenberg and Karnopp, 1983]. Linear, non-linear or qualitative systems of equations can be derived from the bond graph model. Rosenberg and Karnopp give a detailed description of the bond graph method, and Wang and Linkens present the qualitative bond graphs. In thermodynamics no simple 'real' bond graphs can be used, therefore pseudo bond graphs have to be used [http://www.ece.arizona.edu/~cellier/bondgraph_2.html]. Ghiaus investigated the use of a qualitative bond graph for fault diagnosis in HVAC systems [Ghiaus, 1999].

The bond graph method represents a unified approach for modelling engineering systems. The main idea is that power transfer binds the components of a system. The bond graph model is the same for both a quantitative representation, in which parameters and variables have numerical values, and a qualitative approach, in which parameters and variables are classified qualitatively.

For example, bond graph modelling has been applied to a dynamic model of a chiller plant, consisting of several interconnected components. There are three connected subsystems: the Freon (the refrigerant) circuit, the water circuit and the air circuit. Every subsystem consists of several connected components. To get structure into the mathematical modelling process, Pseudo Bond graphs are used to define the connections between the components and between the subsystems.

With this methodology it is possible to reduce the overall complexity and to focus on every component. Mathematical equations for each component can be derived in detail and put together properly to describe the total system. An equation solver like EES32 [<http://www.fchart.com>] can be used to solve the mathematical model. With an equation solver of this type, there is no need to consider the causality of the set of equations. EES32 is therefore very helpful in solving the mathematical model derived from bond graphs. When considering individual components, a (simple) mathematical model can be derived using the mass, energy and impulse balances to answer questions about the global causality: what are the input signals and what is generated by the component. The latter is only used to gain more insight into the physical phenomenon of the process.

Advantages

- Structures the modelling process by dividing a complex physical system into subsystems.
- Physical interactions between subsystems become visible.
- Gives inside understanding of the physical processes.
- The mathematical model of a subsystem is easy to derive and can be solved by an equation solver.
- A simplified model followed by a more detailed model is common. There is no need to start with a complex model followed by model simplification.
- The use of bond graphs leads to a unified modelling process, capable of dealing with any situation.

Disadvantages

- A graphical language has to be learnt.
- Bond graphs can only be used for lumped parameter models.
- There are no simple “real” bond graphs in thermodynamics. Pseudo bond graphs have to be used.
- There is both strong belief in and strong opposition to the bond graph approach

Wang, H. and Linkens, D. 1996. Intelligent supervisory control, World Scientific series in Robotics and Intelligent Systems vol. 14, World Scientific Publishing.

Rosenberg, R. and Karnopp, D. 1983. Introduction to physical system dynamics, McGraw-Hill.

Cristian, Ghiaus C. 1999. Fault diagnosis of air conditioning systems based on qualitative bond graph, Energy and Buildings 30(1999), pp. 221–232.

A.8.6 Qualitative methods of fault detection and diagnosis

Peter Gruber

There are two possible reasons for using qualitative methods for fault detection and diagnosis [Glass, 1996; Tödtli, 1996]:

- The process under supervision cannot be described analytically in a satisfactory way. The behaviour of the process can only be described by general qualitative rules expressing the qualitative cause effect relationship between different measurable quantities of the process. The quantities can be known or measured inputs (control and disturbance), states, parameters or outputs of the process.
- The process under supervision is described by an analytical model whose complexity is either too high or whose parameters are hard to quantify. The change to a qualitative model reduces the dependency of the model on this complexity or on these parameters.

In both cases one tries to avoid either dependencies on parameters which are usually difficult to set or to identify, or on relationships that are hard to obtain. Knowledge about the internal structure of the process with the connections between the different subsystems of the process is however always preferable and is often used.

Qualitative methods eliminate exactly the dependency described above but this advantage must be weighed against two disadvantages:

- The fault detection capabilities are reduced in two ways: less types of faults can be detected than with quantitative methods and the fault level of detectable faults is coarsened.
- The parameters whose values are unknown are replaced by other parameters whose values must be tuned. Typical examples of these new parameters are the thresholds for transforming quantitative values into qualitative values.

Qualitative methods usually include a transformation phase where measured data are transformed into qualitative values, a knowledge base phase where the correct behaviour of the process is stored (rules, qualitative models) and an evaluation phase where violations of rules, or discrepancies between observed and correct behaviour, are checked.

There are several approaches of implementing a qualitative method:

- 1) The first is a pragmatic one, in which *general qualitative rules are derived from expert knowledge*, including analytic methods, and incorporated as built-in rules in the FDD system. In contrast to general expert-system-based approaches, where the knowledge is also expressed in rules, the rules formulated by the qualitative methods are purely qualitative.
- 2) The second approach makes use of formal *qualitative modelling methods to generate rules* that are suitable for incorporation in the FDD system, as in the first approach. In one variant the rules would be derived from information about the system layout (interconnections) and qualitative-physics models of the individual components.
- 3) A third approach is to *integrate qualitative methods into the FDD system itself without using qualitative rules*. Instead a programming method like PROLOG performs the detection and diagnosis using the system structure and qualitative models of the components directly.

Glass, A.S. 1996. Qualitative approaches to FDD, IEA Annex 25: Building Optimization and Fault Diagnosis, Source book, pp. 223–235, Editors: J. Hyvärinen and S. Kärki.

Tödtli, J. 1996. Configuration and parameter setting as a critical issue for practical applications, IEA Annex 25: Building Optimization and Fault Diagnosis, Source Book, pp. 314–318, Editors: J. Hyvärinen and S. Kärki.

A.9 BENEFITS OF INTRODUCING ADDITIONAL SENSORS

James E. Braun

Generally, there is a tradeoff between the number of sensors employed and the performance of an FDD method. Consider refrigerant leakage for a rooftop air conditioner having a fixed expansion device. Table A1 shows how temperature measurements change with refrigerant leakage. A system with low refrigerant charge has a lower evaporating and condensing temperature, higher suction superheat and discharge temperature, a lower air temperature differences for both the evaporator and condenser, and lower sub-cooling leaving the condenser. Although all of these measurements are sensitive to refrigerant leakage for the target system, not all of them are necessary for detecting and diagnosing this fault.

Table A1. Effect of refrigerant leakage on temperature measurements.

Fault	Evap. Temp. (T_{evap})	Suction Superheat (T_{sh})	Cond. Temp. (T_{cond})	Cond. Subcool (T_{sc})	Comp. Hot Gas Temp. (T_{hg})	Cond. Air Temp. Diff. (ΔT_{ca})	Evap. Air Temp. Diff. (ΔT_{ea})
Refrigerant leakage	decrease	increase	decrease	decrease	increase	decrease	decrease

Rossi and Braun (1997) considered the impact of the number of sensors on FDD sensitivity for refrigerant leakage from a rooftop air conditioner with a fixed orifice.

Figure A1 shows the minimum detectable charge reduction versus number of sensors determined from simulations. For each number of sensors, the combination providing the best sensitivity was used. The numbers above each bar indicate which sensors were selected (ordered according to column in Table A1). The results show that at least two measurements, T_{sh} and T_{sc} , are required to distinguish refrigerant leaks from the other four faults. However, adding a measurement of T_{hg} significantly improves sensitivity, while additional sensors do not provide much better performance. With three sensors (T_{sh} , T_{sc} , and T_{hg}), less than 2.0% reduction in charge was detectable. Similar trends were found through experiments for refrigerant leakage, but the sensitivity for refrigerant detection was around 5% reduction in charge.

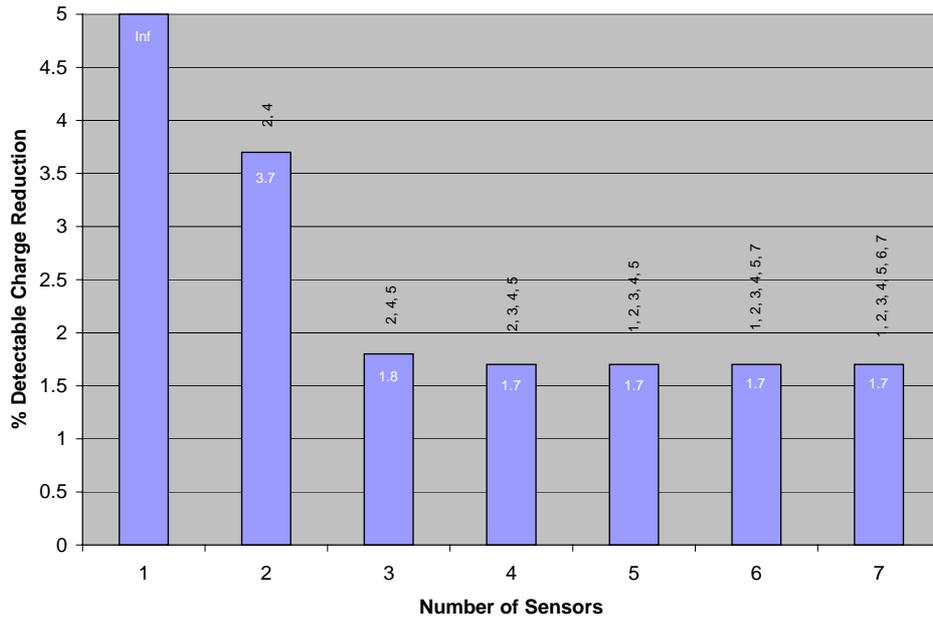


Figure A1. Refrigerant leak detection sensitivity (simulation results).

Rossi (1995) also considered the impact of the number of sensors on FDD sensitivity for condenser fouling. Figure A2 shows that at least condenser air temperature difference is necessary to distinguish condenser fouling from other faults. However, adding T_{sh} , T_{cond} , and T_{sc} significantly improves sensitivity, while the use of additional sensors does not lead to much better performance.

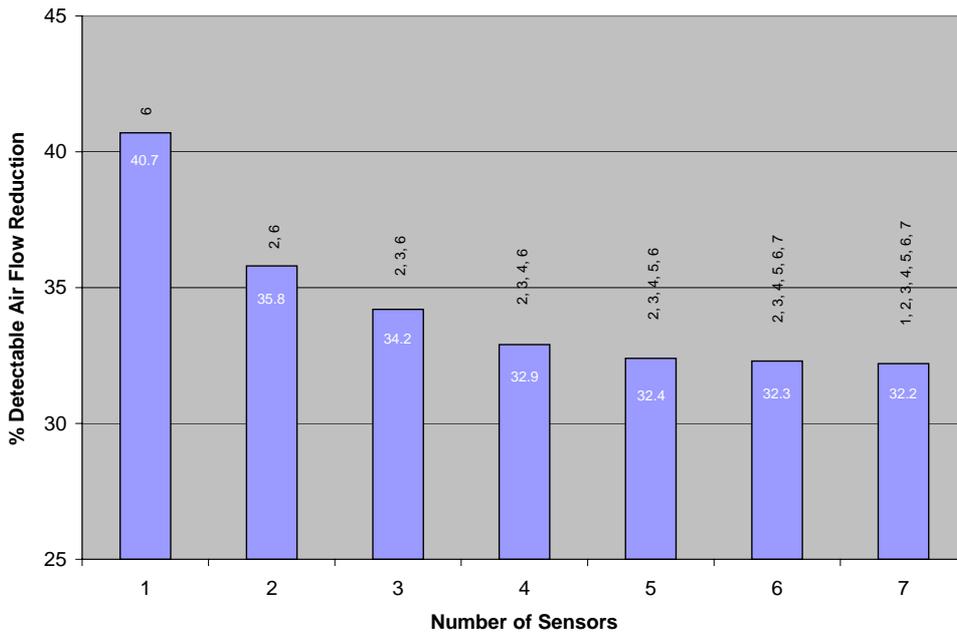


Figure A2. Condenser fouling detection sensitivity (simulation results).

The selection of sensors for a particular application will depend upon the cost of sensors and the potential improvement in FDD sensitivity.

Rossi, T.M. 1995. Detection, Diagnosis, and Evaluation of Faults in Vapor Compression Cycle Equipment, Ph.D. Thesis, School of Mechanical Engineering, Purdue University.

Rossi, T.M and Braun, J.E., A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners, International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research, Vol. 3, No. 1, pp. 19–37, 1997.

A.10 LIST OF ANNEX 34 PUBLICATIONS

Breuker, M.S. 1997. Evaluation of a Statistical, Rule-Based Fault Detection and Diagnostics Method for Vapor Compression Air Conditioners, Master's Thesis, School of Mechanical Engineering, Purdue University.

Breuker, M.S. 1997. Transient evaluation of a fault detection and diagnostics method – Analysis tools and experimental data. Technical Report HL97-29, Ray W. Herrick Laboratories, Purdue University, W. Lafayette, IN USA.

Breuker, M.S. and Braun, J.E. 1997. Demonstration of a Statistical, Rule-Based Fault Detection and Diagnostic Method on a Rooftop Air Conditioning Unit, Proc. Clima 2000, Brussels, Belgium.

Breuker, M.S. and Braun, J.E. 1998. Common Faults and Their Impacts for Rooftop Air Conditioners, International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research, 4(3), pp. 303–318.

Breuker, M.S. and Braun, J.E. 1998. Evaluating the performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment, International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research, 4(4), pp. 401–426.

Carling, P and Isakson, P. 1999. Temperature measurement accuracy in an air-handling unit mixing box. The 3rd International Symposium on HVAC, ISHVAC '99. Shenzhen, China.

Carling, P. and Isakson, P. 2000. Temperature efficiency to detect airside fouling of coils, submitted to the Int. J. of Building Services Engineering Research & Technology.

Castro, N.S. 2001. Application of Two Rule-based FDD Methods to a Reciprocating Chiller, to be submitted to Trans. ASHRAE.

Chen, B. 2000. Evaluating the Potential of On-Line Fault Detection and Diagnostics for Rooftop Air Conditioners, Master's Thesis, School of Mechanical Engineering, Purdue University.

Chen, B. and Braun, J.E. 2000. Simple Fault Detection And Diagnosis Methods for Packaged Air Conditioners, Proc. the 2000 International Refrigeration Conference, Purdue University, W. Lafayette, IN.

Chen, B. and Braun, J.E. 2001. Simple Rule-Based Methods for Fault Detection and Diagnostics Applied to Packaged Air Conditioners, to appear in Trans. ASHRAE.

Comstock, M.C. and Braun, J.E. 1999. Development of Analysis Tools for the Evaluation of Fault Detection and Diagnostics in Chillers, Purdue University, Ray W. Herrick Laboratories, Report # HL99-20.

Comstock, M.C. and Braun, J.E. 1999. Experimental Data from Fault Detection and Diagnostic Studies on a Centrifugal Chiller, Purdue University, Ray W. Herrick Laboratories, Report # HL99-18.

Comstock, M.C., Braun, J.E. and Chen, B. 1999. Literature Review for Application of Fault Detection and Diagnostic Methods to Vapor Compression Cooling Equipment, Purdue University, Ray W. Herrick Laboratories, Report # HL99-19.

Comstock, M.C., Braun, J.E., and Groll, E.A. 2000. Common Faults and Their Impacts on Chillers, submitted to the International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research.

Dexter, A.L. and Ngo, D. 2001. Fault Diagnosis in Air-conditioning Systems: a Multi-step Fuzzy Model-based Approach, accepted for publication in the International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research.

Gruber, P. and Kaldorf, S. 1998. Performance Audit Tool PAT: ein Expertensystem zur Detektion und Diagnose von Fehlverhalten von HLK-Anlagen in realen Gebäuden, 10. Schweizerisches Status-Seminar, Energieforschung im Hochbau, EMPA-KWH.

Gruber, P. 2000. Fehlerdetektor für zentrale Luftaufbereitungsanlagen, 11. Schweizerisches Status-Seminar Energie- und Umweltforschung im Hochbau, 14.–15. September 2000, ETH Zürich, Schweiz

Gruber, P. 2000. Fehlerdetektor für die Lüftung, Gebäudetechnik, 2. Jahrgang, Nr. 5/2000.

Gruber, P. and Kaldorf, S. 2001. Performance Audit Tool PAT: an expert system for the detection and diagnosis of building under-performance, to appear in ASHRAE Transactions.

House, J.M., Vaezi-Nejad, H. and Whitcomb, J. 2001. An expert rule set for fault detection of air-handling units, to appear in Trans. ASHRAE.

House, J.M., Lee, W.Y. and Shin, D.R. 1999. Classification Techniques for Fault Diagnosis of an Air-Handling Unit, Trans. ASHRAE 105(1).

Kärki, S. and Leskinen, M. 1999. A fault detection and diagnosis system as a tool in energy efficient building use. In: The 3rd International Symposium on Heating, Ventilation and Air Conditioning, Shenzhen, Kiina 17–19.11. Pp. 905–913. ISBN 962-367-255-1

Kärki, S. and Karjalainen, S. 1999. Performance factors as a basis of practical fault detection and diagnostic methods for air-handling units, Trans. ASHRAE, 105(1).

Li, X., Vaezi-Nejad, H. and Visier, J.C. 1997. Development of a Fault Diagnosis Method for Heating Systems using Neural Networks, Trans. ASHRAE, 102(1), pp. 607–614.

Luo, D., Norford, L.K., Shaw, S.R. and Leeb, S.B. 2000. Monitoring HVAC Equipment Electrical Loads from a Centralized Location – Methods and Field Test Results, accepted for publication in ASHRAE Transactions.

Miyasaka F., Yumoto, M., Yamasaki, T., Ohkawa, T. and Komoda, N. 1999. Real-Time Simulation for Fault Detection and Diagnosis using Stochastic Qualitative Reasoning”, Transaction of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, pp.11–21, No. 72.

Morisot, O. and Marchio, D. 1999. Fault detection and diagnosis on HVAC variable air volume system using artificial neural network. Proc. IBPSA Building Simulation '99, Kyoto, Japan.

Morisot, O. 2000. Modèle de batterie froide à eau glacée pour la maîtrise des consommations d'énergie en conception et en conduite d'installation. Thèse de doctorat EMP.

Möttönen, Veli & Pakanen, Jouko. 1997. On-line fault diagnosis using Internet and WWW-pages. Computers in the Practice of Building and Civil Engineering. Worldwide ECCE Symposium. Lahti, Finland, 3–5 Sept. 1997, pp. 362–366.

Ngo, D. and Dexter, A.L. 1998. Automatic Commissioning of Air-Conditioning Plant”, UKACC International Conference CONTROL'98, Vol. 2, pp.1694–1699.

Ngo, D. and Dexter, A.L. 1998. Fault Diagnosis in Air-Conditioning Systems using Generic Models of HVAC plant, SSB'98 System Simulation in Building Conference, Liege, Belgium.

Ngo, D. and Dexter, A.L. 1999. A Robust Model-based Approach to Diagnosing Faults in Air-handling Units, Trans. ASHRAE Vol. 105(1).

Norford, L.K., Wright, J.A., Buswell, R. and Luo, D. 2000. Demonstration of Fault Detection and Diagnosis Methods in a Real Building (ASHRAE 1020-RP). ASHRAE 1020-RP Final Report.

Norford, L.K., Wright, J.A., Buswell, R.A., Luo, D., Klaassen, C. and Suby, A. 2000. Demonstration of Fault Detection and Diagnosis Methods in a Real Building (ASHRAE 1020-RP), submitted for publication in Int. J. of HVAC&R Research.

Pakanen, Jouko. 2001. Demonstrating a fault diagnostic method in an automated, computer-controlled HVAC process. Espoo: VTT Publications 443. 50 p.

Pakanen, Jouko, Möttönen, Veli and Hyytinen, Mikko. 2001. WebDia – A WWW-based tool for diagnosing, servicing and operating heating systems. Information and Communication Technology (ICT) in the Practice of Building and Civil Engineering. 2nd Worldwide ECCE Symposium. Espoo, Finland, 6–8 June 2001. Association of Finnish Civil Engineers RIL. Pp. 175–178.

Pakanen, Jouko, Möttönen, Veli, Hyytinen, Mikko, Ruonansuu, Heikki and Törmäkangas, Kaija. 2001. Utilising dynamical HTML and multimedia techniques in diagnosing, servicing and operating HVAC systems (in Finnish). Espoo: VTT Research Notes 2100. 20 p. + app. 10 p. ISBN 951-38-5830-8.

Rossi, T.M. 2000. Commissioning HVAC Equipment with Portable Smart Tools, presented at 8th National Conference on Building Commissioning in Kansas City.

Ruud, S.H. 1997. Fault Detection Method Based on Steady-state Models and Statistical Residual Analysis, Licentiate Thesis, Building Services Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden.

Seem, J.E, House, J.M. and Monroe, R.H. 1997. On-line monitoring and fault detection of control system performance, Clima 2000, P76, Brussels, Belgium.

Seem, J.E. and House, J.M. and Monroe, R.H. 1999. On-Line Monitoring and Fault Detection, ASHRAE Journal, Vol. 41, No. 7, pp. 21-26.

Shaw, S.R., Luo, D., Norford, L.K. and Leeb, S.B. 2000. Detection of HVAC Faults via Electrical Load Monitoring, submitted for publication in Int. J. of HVAC&R Research.

Shiozaki, J. and Miyasaka, F. 1999. A Fault Diagnosis Tool for HVAC Systems Using Qualitative Reasoning Algorithm, *Building Simulation '99*, Kyoto, Japan.

Visier, J.C., Li, X., Corrales, P., Irigoien, M., Le Vannier, I., Lovetri, J., Le Men, M. and Picard, P. 1997. Fault Detection and Diagnosis Tool for Schools Heating Systems, C, Clima 2000, Brussels, Belgium.

Visier, J.C., Vaezi-Nejad, H. and Corrales, P. 1999. A fault detection and diagnosis tool for school buildings, Trans. ASHRAE, 105(1), pp. 543-554.

Wang, S.W., Wang, J.B. and Burnett, J. 1998. Sensor Fault Diagnosis and Estimation in BMS Commissioning, Proc. Fifth International Conference on Tall Buildings, Hong Kong.

Wang, S.W., Wang, J.B. and Burnett, J. 1998. FDD and Soft Fault Estimation in Commissioning BMS Monitoring Instruments of Central Chilling Plant, Proc. System Simulation in Buildings, Belgium.

Wang, S.W. and Wang, J.B. 1999. Law-Based Sensor Fault Diagnosis and Validation for Building Air-conditioning Systems, International Journal of HVAC&R Research, 5(4), pp. 353-378.

Wang, S.W. and Wang, J.B. 1999. Validation Of Time-Varying Sensor Faults In HVAC Systems, Proc. Int. Symp. on HVAC, Shenzhen, China, pp. 893-904.

Wang, S.W. and Wang, J.B. 2000. Robust Sensor Fault Diagnosis and Validation in HVAC Systems, in print, Trans. I.M.C.

Wang, S.W. and Wang, J.B. 2000. Automatic Sensor Evaluation in BMS Commissioning of Building Refrigeration Systems, under review by Automation in Construction.

Wang, S.W., Wang, J.B. and Burnett, J. 2000. Validating BMS Sensors for Chiller Condition Monitoring, under review by Trans. I.M.C

Wang, S.W., Wang, J.B. and Burnett, J. 2000. Diagnostics of Sensor Faults in Building Air-conditioning Systems – An Integrated Robust Strategy, to be submitted to International Journal of HVAC&R Research.

Yoshida, H. and Kumar, S. 1999. ARX and AFMM Model Based On-line Real-time Data Base Diagnosis of Sudden Fault in AHU of VAV system, Energy Conversion and Management, Vol. 40, pp. 1191–1206, 1999, Pergamon Press.

Yoshida, H. and Kumar, S. 1999. RARX Algorithm Based Model Development and Application to Real Time Data for On-line Fault Detection in VAV AHU Units, IBPSA Building Simulation '99, Kyoto, Japan, pp. 161–168.

Yoshida, H. and Kumar, S. 1999. Development of Model Based Automatic On-Line FDD Technique for AHU Investigation Using Real Data Set, Journal of Architecture, Planning and Environmental Engineering (Transaction of AIJ), No. 525, pp. 65–73.

Yoshida, H. and Kumar, S. 2000. Development of ARX Model Based Off-line FDD Technique for Energy Efficient Buildings, Renewable Energy, Vol. 00-4-1/3, pp. 1–7.

SECTION B: GENERAL TOPICS

B.1 CUSTOMER BENEFITS, USER NEEDS, AND USER INTERFACES

J-C Visier and K. Heinemeier

B.1.1 Introduction

The goal of the Annex 34 is "the practical application of fault detection and diagnosis techniques in real buildings". The terminology "fault detection and diagnosis" is probably clear to academics specialized in the field. Talking to different types of potential customers or users of the results of the Annex 34, it appears that they seldom use the words "fault detection and diagnosis". If progress is to be made in the practical application of FDD techniques, it is most important to bridge the gap between the academics, and customers or users.

The potential customers or users of the methods defined in Annex 34 are typically professional operators. Such professionals are able to define their goals. Firstly, they are looking for tools, which will enable them to detect differences between the goals they want to achieve and the reality. These tools are called by academics "fault detection tools". They are then looking for tools that will enable them to determine the reasons for these differences. These tools are called "diagnosis tools" by the academics.

Different users may have very different goals: "quality of service", "energy conservation", "indoor climate quality", "reliability of the system". A hotel manager may only be interested in the comfort of their clients; the service team in a computer centre may be mainly interested in the reliability of the HVAC system; a utility may only be interested in the peak power demanded by its customers. Fault detection and diagnosis techniques are potentially useful to all of them but they will be of no use:

- if the customers or users are not able to define their goals
- if the developer is not able to transform an FDD technique into an FDD tool that is adaptable to the users and their needs.

B.1.2 Users and customers

It is important to differentiate between the customers who will buy the FDD tools, the end users who will use them, and the service providers who will use the tools to improve the services offered to their clients.

B.1.2.1 Customers

The potential customers and their main goals are:

- BEMS manufacturers who want to (a) incorporate fault detection and diagnosis tools within future designs, and (b) provide fault detection and diagnosis services to their customers.
- Service companies who would like to (a) increase their productivity through energy and maintenance cost reduction, (b) provide better services including fault detection and diagnosis, and (c) better manage contracts with building owners.
- Building owners or facility managers who want to (a) maintain a comfortable environment in their buildings, (b) minimise energy and maintenance costs, (c) improve the management of the contracts they have with service companies, (d) reduce the number of employees involved in operation management, and (e) improve their overall understanding of the operation of the HVAC system.
- Commissioning engineers who want to (a) better understand the true operation of the equipment, (b) ensure that the building or system has no faults, and (c) establish a baseline for system performance.

The role of the different types of potential customers varies from one country to another. In some countries BEMS manufacturers are very involved in the operation of HVAC system and can be considered as service companies. In other countries BEMS manufacturers mainly provide a product and services linked to this product, but do not operate the HVAC system. Service companies are often more developed in these countries.

B.1.2.2 Users

Different users have different needs and it is important to adapt the tools to these needs.

"I want to be sure that my customers will never lack hot water" – Hotel manager in Meribel (France).

"I need to be woken up automatically if the boiler fails during the night in order to repair it before it freezes" – service worker in Montpellier (France).

"Every Monday morning we have a meeting with service people. I need a synthesis report on the behaviour of the 100 buildings we manage to define their work plan for the week" – Head of the energy department in the town of Montpellier (France).

If the client complains, the ESCO or maintenance company must identify the faulty system and send a person who is able to repair it – chiller manufacturer (Japan).

Utilities want to reduce peak demand and shift demand to night-time. A large number of buildings are monitored and sorted in two groups: good or bad – utility company (Japan).

A municipal building association owns a large number of community buildings and has to manage them. Their goal is to reduce the energy consumption of a large number of buildings e.g. 100 (The Netherlands).

Building associations give advice to tenants on energy consumption (The Netherlands).

Insurance companies verify the quality of maintenance and the energy consumption (The Netherlands).

We are two people paid by the city of Helsinki to manage energy in a school complex. We are under pressure from the building occupants, who are mostly interested in comfort, and we have a financial incentive to reduce energy consumption. We need tools to reach these two contradictory goals (Finland).

Utilities look at energy consumption, energy costs and deviations and also at peak demands (France).

Building owners can be split into two groups. Some maintain the buildings; others out source the maintenance. The appropriate FDD tool will be different in each case (France).

Different tools could be provided at different levels from overall performance evaluation down to the performance of an individual component (e.g. AHU) (Sweden).

All of these people can be users of an FDD tool. Some of them have a sound knowledge of HVAC plants, while some of them have mainly administrative or commercial duties. The needs of one group will be very different from the needs of the others. So one cannot define a "good" FDD tool, only an FDD tool adapted to the needs of its users.

The analysis of the users must be done before designing an FDD tool. In order to facilitate the analysis of user needs, different type of users are defined depending on the level and type of action that they must take.

The different levels of action can be classified as:

- multiple building level
- building level
- plant level.

The different types of action can be classified as:

- screening the performance of a large number of pieces of equipment
- detecting faults in a particular piece of equipment
- trouble-shooting a piece of equipment with known performance problems, and fixing it.

Examples of analyses of user needs can be found in [Kärki and Leskinen, 1999] and [Visier et al., 1999].

B.1.3 What is a good tool from the user and customer point of view?

From the users point of view a good FDD tool must have the followings qualities:

B.1.3.1 It must be adaptable to the needs of the users

As the same tool is often used by different users, it is important to adapt it to the particular needs of the users. Facility managers and technicians have different goals. A good tool will provide each of them with functions adapted to his/her needs. Although they might share the same FDD tool, the user interface should be different for, for example, the manager and the technician.

The tool must speak the language of the different users and be flexible enough to adapt to the time they have available.

A good tool will improve user skills or values: it will help users to improve the way they do their job and the quality of their work.

B.1.3.2 It must gain the confidence of the users

Very few people already know what fault detection and diagnosis is and most of them need to be convinced of the advantages of FDD tools. Moreover many people think that the BEMS should already provide diagnostic tools, even if currently they do not. They also feel that a lot of promises were made previously but not always with good results. The first step is therefore to make people confident about using the tools.

The tool must be presented correctly

FDD tools should not be presented as something revolutionary but as a tool that will help to transform the large amount of data which are stored in the BEMS, and which are not currently used effectively, into more useful knowledge.

The presentation of the tool must focus on users problems: “save time”, “save money”, “improve the occupants’ comfort” and not on its ability to "detect and diagnose faults”.

It is also important to be honest when describing what the system can and cannot do. For example, can the tool:

- automate simple tasks, which could be done manually but are time consuming?
- detect major faults?
- propose a plausible diagnosis?
- make the final diagnosis?

Few if any tools developed in the Annex can really do all of this. Most of them are probably able to perform the first tasks but not the final one.

The tool must help users not replace them

In some cases users may think that the tool will not help them but will replace them. This was experienced in the Annex when some fault detection tools were presented as fault detection and diagnosis tools. A fault detection tool was considered by the users as a way of automating the tedious task of looking at all of the raw data. A diagnosis tool was considered as a way of replacing the intelligence of the user, who has detailed knowledge of the installation. Users were quickly able to establish that the tool could detect faults but that it often generated the wrong diagnosis. The tool was then seen as a fault detection tool, which helped the users to focus on the important task of diagnosis. As a result, the user became more confident about the usefulness of the tool.

The tools must be easily customizable

Each potential user has specific problems. They want tools that they can customize. For example they might require a tool that could provide them with an automatic fault detection capability and a short list of possible causes, which they can modify and improve. It is also necessary to allow the user to define which faults are most important for him/her. A tool can, for example, propose a list of faults which can be detected and let the user choose the one he/she wants to detect.

The tool must be easy to understand and trust

It is much more difficult to be confident in a black-box than in a set of simple IF-THEN rules, which are easy to understand. Much more effort will be necessary to convince people to use a complex tool, which they have to trust, than a simpler tool that they can understand.

The tool must have been demonstrated in real buildings to make people more confident

The best way to make people confident is to enable them to talk with people who do the same job and already use the tool. Demonstration in real buildings is therefore a very important step towards the validation and dissemination of the tools. The demonstration projects described in Section C: Case Studies are a first step in building people's confidence.

B.1.3.3 It must do the job

The tool must be able to do what it promises to do. For example:

- reduce comfort complaints, energy costs, maintenance costs (manager, building level), CO₂ emission
- help to manage contracts with service companies, operators, users (manager, building level)
- lead to faults being fixed
- make early diagnoses to prevent damage (engineer: plant level)
- generate rough estimates of cost savings.

B.1.4 Designing a good user interface

For each method 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 user interface for commissioning the tool must enable the user to define: the type of HVAC plant to be monitored, the way in which the measurements are to be accessed, the design data, the thresholds etc. [These issues are discussed in more detail in Section B3: Commissioning of FDD Tools.]

The user interface for running the tool must give progressive access to the data. A synthesis report should be presented first but the user must also have easy access to more in depth analysis and possibly even to the raw data. The final diagnosis, a list of possible faults, the procedure for confirming the final diagnosis or a list of actions to be undertaken could also appear on the user interface.

An on-line FDD tool will issue an alarm in real time when a fault is detected. Off-line FDD tools will only operate when they are invoked by the user. This will lead to different types of user interfaces.

The following issues have to be considered in the design of a good user interface:

- The proper level of information must be provided for each type of user. It is therefore necessary to know the users: who they are; what is their level of understanding of HVAC systems; how much time they have to deal with the FDD tool; whether they will use the tool on-line or off-line and, in this case, how often it will be used (once a day, a week, a month).
- A simple adjustment of the alarm generation threshold(s) must be accessible from the user interface for running the tool. This will enable the user to choose the best balance between quick detection and the generation of false alarms. [This issue is discussed in more detail in Section B6: Threshold Selection]
- Designing a user interface is an iterative process. Prototypes have to be produced and presented to potential users for comments. Because the FDD tool used for prototyping must allow the user interface to be modified easily, it will often be different from the FDD tool used for the final implementation.

In addition it could also be useful to add information on operation costs, historical data and fault statistics. Finally a good user interface should also make the operator curious about the plant operation.

Examples of user interface design can be found in [Visier et al., 1999] and [Tessier and Vaezi-Nejad, 2001].

B.1.5 Cost benefit analysis

B.1.5.1 Main sources of cost

Installation and commissioning

The experience gained in the Annex has shown that a large part of the costs linked to implementing an FDD tool is linked to the installation and commissioning of the tool.

The time and money needed for installation and commissioning can vary greatly from one tool to another [more details on this issue are given in Section B3: Commissioning of FDD Tools]. Nevertheless for all tools a key difficulty is interfacing with existing databases to get access to measurements and other information which are needed by the tool. This point is not specific to FDD tools and is also important when one wants to implement new control functions in an existing BEMS.

The minimum prerequisite to lowering these costs is to have good documentation of existing databases and a good point naming convention. [This issue is discussed further in Section B4: Information Requirements and Data Access Issues.]

In order to reduce this cost one can

- reduce the amount of data needed during set-up and engineering
- re-use data which are already included in an existing data base.

In the short term, reducing the amount of data needed during set-up and engineering is probably necessary. In the longer term, there is a need for a common integrated database that will allow data to be reused. It should become more and more possible for buildings to have a lifecycle database that can be used for different purposes. The work of the International Alliance for Inter-operability has made some progress in this direction. Even today, access to the BEMS database is already possible in many cases.

For new buildings, the commissioning of the FDD tool must be done at the same time as the control commissioning so that the amount of additional data, which needs to be entered into the FDD tool, can be reduced. An attempt should also be made to develop the control functions and FDD schemes at the same time: control => reach the goal whereas FDD => verify that the goal is reached.

Hardware

The cost of the hardware (such as a PC) needed to implement the FDD tool is not a major issue. Such costs are very limited as FDD tools can usually be implemented in existing hardware. During the Annex FDD tools were often installed on dedicated hardware, though this was often to limit the risks associated with the malfunctioning of a prototype. As tools become more robust, the specific hardware requirements will become increasingly limited.

Extra sensors

The fault detection tools developed in the Annex required few or no extra sensors, and the cost of sensors for these tools will generally not be an issue.

Fault detection and **diagnosis** tools often do require extra sensors to avoid ambiguous diagnosis. For such tools, the cost of the extra sensors could represent a non-negligible cost. [This issue is discussed in more detail in Section B5: Sensor Validation.]

Standard Software

FDD tools rely partly on standard functions for

- data acquisition
- data handling
- the knowledge base: detection, diagnosis
- data presentation (graphics tools)
- data transfer

The associated costs will be significantly lower if the FDD tool uses existing software for these standard functions.

Training, operation and maintenance of the tool.

The Annex did not collect information on the costs associated with training, operation and maintenance. For training it appears necessary to differentiate between the cost of training end-users and the cost of training the installers of the FDD tools.

Cost of the FDD tool

FDD tools are mainly software and the selling price of the software itself is mainly a marketing issue, which cannot be discussed here.

B.1.5.2 Economic issues

Three factors have a key impact on cost benefit ratio of different tools.

Portability

Fault detection and diagnosis tools can be permanently installed in the building and connected to the BEMS. Portable tools can also be used to perform fault detection and diagnosis on specific components. These are of particular interest in the case of packaged units such as chillers.

Mass-production

A key difficulty in the design of fault detection and diagnosis tools is the diversity of the systems they have to deal with. For products that are mass-produced it is possible to develop FDD tools taking into account the exact characteristics of the products. These tools will be easy to commission on-site and will be able to detect and diagnose even small faults. For systems and buildings, which are not mass-produced, it is necessary to develop generic tools that can be used without the need for a long commissioning process. Such tools are usually only able to detect large faults and are, therefore, of less value to the user.

Detection or detection and diagnosis

Fault detection tools are today more robust and need fewer sensors than fault diagnosis tools. The cost benefit ratio is therefore better for fault detection tools.

The Annex was unable to produce an absolute economic assessment of the cost benefit ratio of different tools. Nevertheless there is now a consensus between the participants on the comparative assessment of the cost benefit ratio of different tools.

Portable fault detection and diagnosis tools for packaged units

In order to achieve reasonable cost-to-benefit ratios, FDD systems for packaged units are typically restricted to the use of low-cost sensors, such as temperatures and pressures. At the present time, better cost-to-benefit ratios are achieved for portable devices than for applications involving FDD that are permanently installed. Portable devices are used by service technicians in the course of maintaining and servicing

chillers or other vapor-compression cooling equipment. During “check ups”, the technician connects sensors to the equipment and provides some general description of the equipment being monitored. The measurements are compared with generic expectations for the specific type of equipment, so problems can be identified and diagnosed. Because of the generic nature of the methods embedded in these tools, only relatively large faults can be detected and diagnosed. Furthermore, problems are only detected and diagnosed after occupants have complained or during the course of a technician’s regular maintenance schedule. However, a single FDD tool can be used for many different pieces of equipment, which improves the cost-to-benefit ratio. This is a logical initial deployment of FDD for the HVAC&R industry.

Fault detection tools for subsystems

These tools focus on simple faults which occur often and which are today not detected. They can detect faults but are not designed to generate a final diagnosis. These tools are dedicated to simple subsystems: a single hydronic heating circuit, individual VAV boxes or air handlers. As they do not perform diagnosis, they need few or no extra sensors. Most of the time, the sensors used to control the subsystem are sufficient to enable fault detection.

The cost benefit ratio of such fault detection tools could be good in the near-term if they provide added functionality to the control system.

Fault detection and diagnosis tools for subsystems

These tools are the equivalent of the former tools but include a diagnosis module. It appears that they either have difficulties making the final diagnosis, and therefore have a low extra value for the user, or need many extra sensors or substantial additional effort to be commissioned, which leads to high cost. The deployment of such tools will come only after the deployment of fault detection tools.

It might be expected that, in the longer term, the FDD tools will be integrated into individual equipment controllers, provide continuous monitoring, fault detection and diagnostic outputs, and recommendations as to when servicing should be performed.

Fault detection tools for buildings

Some participants in the Annex developed simple tools that allow faults to be detected at a building level or at a multiple building level. These include tools capable of fault detection in similar or different subsystems and that provide their user with an adaptable user interface. The different simple fault detection tools are run in parallel without

coordination between them. Some of these tools have today a good cost benefit ratio, which could enable their deployment in the market in the near-term.

More general tools for use at the building level, which can coordinate information in a more structured way than the simple tools, still remain to be developed. [This issue is discussed further in the Section B8: Hierarchical FDD Schemes]. It is therefore still too early to assess their cost benefit ratio.

B.1.6 More about this topic

An overview of the issues that must be addressed in order to provide FDD tools that are commercially viable is given in [Heinemeier et al., 1999]. One of the central ideas is to address the marketing issues at the same time as the technology issues in order to ensure the successful development of FDD products. Potential users and customers of fault detection and diagnosis tools were interviewed in a very structured manner through focus groups. Two FDD tools were presented to them to determine if they were interested in the products and how these products should be marketed. Important issues were identified relating to problems to be solved in the marketing process.

B.2 CREATING ARTIFICIAL FAULTS FOR TESTING FDD TOOLS

H. Yoshida and J. Pakanen

B.2.1 Classification of faults

Faults can be classified into three different types by considering their nature: natural, artificial and simulated faults. A natural fault occurs in a real process and is a result of natural wear and/or deterioration, or human errors in either the design, operation or maintenance of the equipment. An artificial fault is an intentional man-made fault, typically implemented by replacing a component of the system with a faulty one or by changing process conditions or by manually introducing a faulty setting. An artificial fault can be introduced into a real or emulated process. A simulated fault is a man-made change to the system that reproduces the symptoms of a natural fault. Simulated faults are useful in situations where it is physically impossible or too expensive or too dangerous to introduce the actual fault.

B.2.2 An artificial fault – a practical choice for FDD tool testing

The best choice for testing an FDD tool would be to use natural faults occurring in real HVAC systems, but this is difficult to do in practice. Natural faults do not normally occur in a way and over a time scale that is convenient for testing FDD tools. If natural faults are used, their number should be large enough to allow all of the “typical cases” to be tested since every natural fault in a real process is unique and has unique symptoms. Therefore symptoms caused by faults that seem to be identical are only statistically similar. Ultimately this means that an FDD tool, designed to detect and diagnose one specific fault may not always be successful, even if all symptoms are clearly measurable. In addition some HVAC system faults, known as degradation faults, occur gradually. It is obvious that the implementation of realistic degradation faults is even more difficult. These limitations and difficulties mean that the introduction of artificial faults is the most practical, and in some cases the only, solution to the problem of testing an FDD tool in a real environment.

B.2.3 Natural faults occurring in real buildings

B.2.3.1 Faults due to human error

HVAC systems are designed, constructed and assembled by engineers and technicians, and operated and maintained by specialised technical staff. Throughout the life of the

system, man-made errors or mistakes can take place and faults may be embedded in systems or components. A feature of this type of fault is that its symptoms are not necessarily visible or directly measurable.

Design faults (HD)

The under-sizing of cooling or heating coils, the inappropriate location of sensors and the incorrect specification of the control logic are typical examples of design faults. This type of fault should be completely detected and eliminated during the commissioning process. However, it is difficult to find, and usually impossible to fix, all design faults. This is because all design conditions, such as outside weather and interior heating load variations, cannot be tested during commissioning. Thus, they are commonly detected only afterwards during the operation stage. Accordingly, even an FDD tool designed to deal with operational faults should be able to detect and diagnose design faults.

Construction and assembly faults (HC)

Erroneous wiring between sensors and local control devices, incorrect installation of water pumps and reverse rotational direction of fan motors are typical examples of construction and assembly faults. Usually these faults are detected and fixed during commissioning but some faults still remain undetected and are only found afterwards.

Operational and maintenance faults (HO)

After commissioning and hand-over, the HVAC system is maintained by operators, maintenance staff and building users, who sometimes interfere with the system. As a result a faulty input data, operational settings or other human mistakes can be made. A typical example of an operator error is setting the chilled water temperature set-point to a value that is too high or too low. Faulty manual closing or opening of a changeover valve following a mode change during spring or autumn is a typical error made by maintenance staff. Opening a window while an air-conditioning system is operating is an example of a fault that is generated by an occupant and causes energy to be wasted. Neglecting maintenance or poor servicing of equipment may cause a fault, either immediately or indirectly, or at least shorten the life of the HVAC system.

B.2.3.2 Control system faults

An automatic control system is an essential part of the HVAC system. It is equivalent to the brain and central nervous system of humans. In general the rate at which faults occur in the control system can be relatively high compared to other types of faults. This is mainly due to the sophisticated structure of the control system and its highly integrated

sub-systems, which include a variety of mechanical, electrical, and electronic components, as well as software embedded in microcircuits.

Most faults would be included in this category if we defined all faults related to automatic control as control system faults. Therefore, a simple hardware fault, such as control valve that has become stuck, should not be considered as a control system fault. Instead, only faults, which are closely related to the control system itself should be included in this category of faults. Only two fault types are therefore classified here as control system faults: a control software fault and a sensor fault. [A more specific description of control system faults is presented in Section B7 Control System Faults.]

Control software faults (CO)

Some examples of control software faults are inappropriate settings for the parameters of a controller, incorrect sequencing logic and errors in the decision-making logic of energy saving control strategies. This type of fault can be introduced by the commissioning engineer or by the plant/building operator, but in many cases the cause is a bug in the control system software that has not been detected by the manufacturer.

Sensor faults (CS)

Sensors are key components in the HVAC system as they provide the basic information upon which all decisions about the operation and control of the system are based. It is therefore very important that sensors operate accurately and reliably without any faults. Unfortunately this is often not the case in practice. Typical faults are loose or broken connections or external noise causing a sudden change in the measurement signal. Another example is drift in the sensor output caused by thermal ageing or changes in the ambient temperature that result in sensor offset and gain errors. [A more detailed description of sensor faults is presented in Section B5 Sensor Validation.]

B.2.3.3 Hardware faults

A hardware or equipment fault is generally regarded as the most common and typical type of fault in a mechanical system. Assuming that the original, installed product is fault-free (i.e. there are no manufacturing faults), hardware faults can be categorised as follows:

Abrupt faults (EA)

Abrupt faults are typically failures such as component malfunctions. Typical examples of physical defects that result in abrupt faults are a stuck valve, a broken fan belt and a burnt-out electric motor.

Degradation faults (ED)

Any component may deteriorate with time. This usually means that the performance of the component gets worse as it gets older. Degradation faults usually occur in moving parts or where fluid is passing a component. Typical examples are wear of ballbearings, fouling of a cooling or heating coil, and drift of the output of a pressure sensor.

[See also Section C: Belgium demonstration for examples of typical faults occurring in buildings.]

B.2.4 Introducing artificial faults

FDD methods and tools need to be tested before they can be made into commercial products. This is a central issue in developing FDD tools. Ultimately, it means that the FDD tool must be verified by testing it in the presence of all faults the tool is designed to handle. This should be done in a real process environment.

Because there are a great number of components and sub-systems in HVAC systems, there are so many possible faults that it is impossible to test them all. This means that selecting the most important faults and prioritizing them is essential (see Section B.3.4.4). Regarding this issue one should refer to a survey report of the Annex 25 source book [IEA Annex 25, 1996] where typical faults in HVAC systems are described. The article covers heating systems, chillers and heat pumps, VAV air handling units and thermal storage systems. Some important faults may be omitted in specific systems and the importance of faults may differ slightly from country to country due to local workmanship or other engineering conditions.

Basically there are two ways of introducing artificial faults. One is to replace the component under test with a faulty one, and the other is to create process conditions that produce similar symptoms to those associated with the fault. The first method is not usually chosen because it is difficult to find or make an appropriate faulty component; or, at least, to do so requires substantial work, and therefore unacceptable cost and time.

Some faults can be simulated by making minor modifications to existing components. Examples of such are faulty PID parameter settings, a stuck valve, and abnormal value of the chilled water temperature supplying the coil of an AHU coil. Examples of artificial faults that are difficult to introduce into an existing component are coil fouling, unstable data transfer behaviour through communication wiring, and bearing wearing resulting in vibration. In general, degradation faults are difficult to implement.

B.2.5 Examples of fault introduction

The following examples show how faults were introduced into real buildings or real plants by some of the participants of Annex 34.

B.2.5.1 Introducing faults into an AHU: Japanese case study

Twenty-two different faults were introduced into a VAV AHU system on the 7th floor of the R/D TEPCO (Tokyo Electric Power Company) building in Japan. [see Section C: Japan Demonstration 3 for details]. Data sets were collected through the BEMS with one minute sampling rate and the accumulated data were used to test FDD tools developed by Japanese researchers. All the data sets are available, on requested, for research use [see Appendix F].

The 22 faults are categorised into several types. The following list summarises fault type, the way the fault was introduced, and the abbreviated categorisation by the code defined in the Subsection B.2.3.

<u>Faults</u>	<u>Description of how fault was introduced</u>
1) wrong PID parameter setting	manual PID parameter change (HD, HC, CO)
2) fan speed decreasing (intended to simulate fan belt slipping)	manual inverter signal setting (HO, ED)
3) inappropriate sensor location	heating up a control thermostat (HD, HO, CS)
4) erroneous wiring of a sensor	reversed wiring (HC, CS)
5) control valve stuck	setting by forcing the control signal (EA)
6) VAV damper stuck	local manual setting (EA)
7) false AHU hatch opening	manual open (HO)

B.2.5.2 Introducing faults into an AHU: Finnish case study

The faults were introduced into an air-handling unit in a college building [see Section C: Finland Demonstration 1 for details]. The AHU was controlled by a BEMS, which gathered all the data for the demonstrations and FDD tests.

<u>Faults</u>	<u>Description of how fault was introduced</u>
1) sticking control valve	manually obstructing the control valve at open or close (EA)
2) faulty sensor	loosening a wire connector (EA, CS)
3) blocked coil or control valve	partially shutting a manually controlled valve installed close to the coil or control valve (EA)
4) partially opening valve	manually obstructing valve opening (EA)

B.2.5.3 Introducing faults into an AHU: Swedish case study

The Swedish group introduced a number of artificial faults into an AHU of an office building (the former Skanska HQ outside Stockholm, Sweden) [see Section C: Sweden for details]. The faults were implemented under different modes of operation and typically lasted for a few days. In total the field trials lasted for about half a year. The table lists, in groups, the different faults and how they were implemented.

<u>Faults</u>	<u>Description of how fault was introduced</u>
1) faulty water flow through coil	varying pump speed (EA)
2) stuck damper faults	mechanically constrained (EA)
3) coil valve leakage	introducing a by-pass pipe and valve (EA)
4) stuck valve faults	manually changing the control signal (EA)

B.2.5.4 Introducing faults in low-pressure chillers: Canadian case study

The Canadian team introduced faults into a low-pressure chiller [see Section C: Canada Demonstration 3 for details]. They first discussed the most natural ways of introducing faults with designers, maintenance staff, research technicians and engineers. The magnitude of each fault was analysed carefully to make sure that the faults were large enough to be detected but small enough to be realistic.

<u>Faults</u>	<u>Description of how fault was introduced</u>
1) condenser fouling	reducing water flow rate through the condenser (ED)
2) evaporator fouling	addition of oil to the refrigerant (ED)
3) refrigerant leak	removing refrigerant from the unit (EA, ED, HO)
4) refrigerant overcharge	adding refrigerant to the unit (HO)
5) air in the system	introducing nitrogen into the system (HO, EA, ED)

B.2.6 Conclusions

FDD methods and tools need to be tested before they can be converted into practical and commercial products. This should be done in a real process environment. The best choice is to use natural faults but this may be difficult in practice. Fortunately, many features of FDD systems can be tested and verified using artificial faults. A typical artificial HVAC fault is an abrupt or large abnormal change in the operation of the equipment or process. Examples include the installation of a temporary mechanical obstruction, a manually introduced perturbation to the process parameters, manual adjustment of the control signals applied to the process equipment, and a change in the electrical connections or a temporary modification of the software.

B.3 THE COMMISSIONING OF FDD TOOLS

P. Gruber and R. A. Buswell

B.3.1 Introduction

The process of commissioning FDD tools in many aspects resembles the commissioning process of a general piece of software interfaced to real measurements and equipped with a user interface. Therefore the definition of the commissioning of FDD tools can be given in the following way:

The Commissioning of FDD Tools is **the setting up, putting into operation, testing and maintaining of an FDD tool on a specific system, so that it can work according to its specification.**

This process includes both technical and organisational issues. The major factors that influence the technical part of commissioning process are:

- the level of design information required
- the level of data required and method used to extract the data from the system
- the sensors required
- the specific operations that need to be in place before data acquisition may take place
- the selection of model parameters, operational parameters and thresholds
- a knowledge of the control system and/or operational modes of the building
- a knowledge of the nature of fault conditions
- the required user settings.

Factors that influence the organisational part of the commissioning process are:

- the number and type of people involved
- the timing of interdependent tasks
- legal issues between partners
- boundary conditions dictated by partners involved in the construction and operation of the building
- the total cost of the FDD commissioning process.

Commissioning of FDD tools **does not** cover the following areas:

- optimisation of the performance of the FDD tool;
- the commissioning of the building, plant or control systems.

B.3.2 Commissioning phases

Commissioning starts when the FDD tool has been developed, tested and documented [Todd11, 1996]. During the commissioning process, there are four distinct phases, which run in the following sequence:

Setting-up ⇒ **Putting into operation** ⇒ **Testing** ⇒ **Maintenance**

Each phase should be terminated before the next is started. Each of the different phases deals with a number of issues, which can be classified as follows:

B.3.2.1 Setting-up

Description of the 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 for 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 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 fault 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 data processing
- Extent of data-base required.

Operator training

- Level of expertise assumed of the installer and/or user.

B.3.2.2 Putting into operation

Expert knowledge

- Who has to be present while the tool is put into operation?

Identification of parameters using training data

- List of fault-free 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 improvements resulting from continuous adaptation

Selection of thresholds 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

B.3.2.3 Testing

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

B.3.2.4 Maintenance

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

The above sequence must be embedded in an overall process covering the installation and commissioning of the whole HVAC system and its BEMS, which starts before and stops after the commissioning of the FDD tool. Therefore the required information listed in Section B.3.3 and the recommendations stated in Section B.3.4 also apply to phases before and after the process of commissioning the FDD tool.

B.3.3 Information classes

One of the more important issues, if not the most important issue, in the whole commissioning process of the FDD tool is the information that is required before the tool can be applied successfully. It must be clear what information is needed if the FDD tool is applied to a specific building, plant or component. Much of this information is also needed during the development of the FDD tool, and must also be provided with the description of the FDD method [see also Section B.4]. It is important that the FDD tool obtains the same information as the BEMS [Gruber and Kaldorf, 1998; Gruber and Kaldorf, 2001]. It is possible that not all of the listed classes of information are needed for the commissioning of a specific FDD tool. The required information can be classified as follows:

B.3.3.1 Design information

Building data

Physical characteristics of the building or zone, use of the building, location of the building

HVAC system design data

Installed power, manufacturers' 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.

B.3.3.2 Operational information

Mode of operation

Schedules, occupation profiles

Controller parameters

Set-points, types of controllers.

B.3.3.3 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.

B.3.3.4 Measurements

Type and number of sensors for detection

Additional sensors for diagnosis

Additional sensors for training

Sampling rate of data acquisition

Validation of measurements

B.3.4 Recommendations

Very different FDD tools were applied to widely different applications during the Annex. The background of the users was also very diverse. A comparison of the commissioning of the various tools is therefore extremely difficult. Nevertheless, a number of recommendations can be made which are essential to the successful commissioning of any FDD tool. In the following, the group of persons to which a particular recommendation is directed is indicated in brackets. Three different professions involved in the commissioning process are distinguished: the developer, the commissioning engineer and the user/operator.

1) Limit the commissioning of the FDD tool to the most important faults in the application under consideration

For each application, the commissioning (and/or application) engineer must provide a table of faults that should be checked during the commissioning phase. The selection and priority of faults to be detected will be application specific. It is essential that the inputs and other boundary conditions are also included in the table, so that the necessary fault conditions can be created artificially. The FDD tool should be tested at these conditions. The testing procedure must be such that a modular check of the tool is possible, starting with the most important features. [*developer, commissioning engineer, user/operator*]

2) Use of the BEMS

Before the FDD tool is commissioned, the BEMS/control system must be checked to ensure that it is running and is at least partly commissioned. The BEMS facilitates the testing of the FDD tool by allowing particular inputs to be applied to the HVAC system and data to be gathered. It can be especially well suited for keeping a history of the behaviour of the system. The history can, for example, be used to justify the usefulness of a FDD method, and for statistical purposes. If the BEMS is not yet in use, a data

acquisition system must be installed to facilitate the data exchange. [*commissioning engineer, user/operator*]

3) Additional Hardware

Before the FDD tool is commissioned, it is also essential to make sure that additional hardware that is needed such as sensors, communication links, wiring, etc., is working correctly. Some of this hardware will not stay with the application all the time but is only used during commissioning. If required, such hardware can be of higher quality as it can also be used in many other commissioning processes. [*commissioning engineer*]

4) User involvement

In many applications, it is desirable to enable the user to select the values of the thresholds for alarm generation during the commissioning of the FDD tool. It is also advisable to continue the adjustment of the thresholds for alarm generation into the operation phase, since experience of operating the tool will help the user to choose appropriate values for the thresholds. It is also important for the operator/user to become involved to better understand the main functions of the tool and to convince himself/herself of the value of the FDD tool. [*user/operator*]

5) Use of design data

The commissioning engineer must ensure the availability of all data, other than default data, needed to set-up the tool. This includes specific design data, configuration data, controller-related data, and possibly training data. If a training period is needed, this time has to be taken into account in the planning process [commissioning engineer].

6) Commissioning management

Commissioning always involves people and not only technology! Therefore a list of the partners (people, institutions, etc.) that are involved in the commissioning of the FDD tool is needed. The interaction and co-operation between these different parties must be co-ordinated in order to guarantee success. Before the commissioning starts, a co-ordinator has to identify where and when the different parties must become involved in the commissioning of the FDD tool. This involves technicians, software specialists, users/operators and commissioning engineers.

7) Re-commissioning

Re-commissioning of the tool might be necessary after some experience with the FDD tool has been gained. Re-commissioning is more difficult than commissioning because the BEMS will be operating normally and the necessary commissioning tests will not be easily performed. It may therefore be preferable to use a computer simulation of the HVAC system, which is based on mathematical models identified from measured data, to re-commission the FDD tool at some test conditions. [*commissioning engineer*]

B.4 INFORMATION REQUIREMENTS AND DATA ACCESS ISSUES

A. Legault, T. M. Rossi, R. A. Buswell, and J. M. House

B.4.1 Introduction

When trying to analyse the requirements of any “information” treating process it is useful to delineate as precisely as possible the boundaries between information, data, hardware, etc. An operator standing in a “stuffy” room will detect abnormal humidity levels, insufficient airflow and the like by processing information that one would not readily qualify as “data”. This operator is in fact operating as a fault detection and diagnostic (FDD) unit and this example shows how the “information requirements” definition transcends a reductive definition of data. The ensuing text will propose a few definitions that will help position the different data/information handling achievements and trials in this Annex in a unified context.

Information is stimulus that has meaning in some context for its receiver. For automated FDD tools, interest lies specifically in the types of information that can be converted into data and passed on to another receiver. Relative to the FDD tool, the relationship between information and data can be expressed as the following: Information is encoded into data, “transferred” to the FDD tool where it is stored and processed as data, and then output as data in some form that can be perceived as information.

Generally in science **data** are taken to mean a gathered body of facts about an event, process, etc. FDD tools require data that are digitally encoded or analogue encoded. It will be assumed that all of the information needed by an FDD tool can be encoded in this way.

A **data dictionary** is a collection of descriptions of the **data objects** or items in a data model for the benefit of FDD tool designers, programmers or users and others, who might need to refer to them. When developing FDD tools that use the data model, a data dictionary can be consulted to understand where a data item fits in the structure, what values it may contain, and basically what the data item means in real-world terms.

Data modelling is the analysis of data objects that are used in a specific context and the identification of the relationships among these data objects. Data modelling is a first step in designing an object-oriented program. As a result of data modelling, you can then define the classes that provide the templates for program objects.

A **relational database** is a collection of data items organised as a set of formally described tables from which data can be accessed or reassembled in many different ways without having to reorganise the database tables. The standard user and application program interface to a relational database is the *structured query language* (SQL). SQL statements are used both for interactive queries for information from a relational database and for gathering data for reports.

In this work “information” will be taken to include all the various types (design, measurement, configuration, control sequencing) and sources (design documentation, BEMS, etc.) of information that FDD tools need. Properly distinguishing “data” and “information” will help to identify limitations of FDD tools that may result from an inability to encode some “information” into accessible and processible “data”.

B.4.2 Information encoding attempts in Annex 34

The first explicit concerns over information encoding arose when attempts were made to exchange information between different Annex 34 participants for the purpose of testing and validating FDD tools beyond their “cradle”. These attempts brought to the forefront many unfounded assumptions about the level of effort necessary to configure an FDD tool and the information-handling capabilities of these tools. Seemingly simple matters such as identifying occupied and unoccupied periods and specifying design airflow rates became considerably more laborious when every data set presented this information differently. Other requirements included the need for information regarding sensor position and type (e.g., single point or averaging). To enable the sharing of data sets, a structured and comprehensive approach was needed.

The first step in standardising information encoding-decoding was a proposal for a standardised point-naming scheme (see Section F). A triplet-based point-naming convention was proposed that provided a standard basis for uniquely identifying “points” in a “building”. This first step addressed to various degrees some aspects of information encoding, data handling and data dictionaries.

Building on the standardised point-naming convention, a standard for documenting and transferring data sets was proposed. The proposed standard is referred to here as the UK standard. It was comprised of the following five sections: general description, plant information, general notes, miscellaneous notes, and diagrams. This effort recognised further aspects of encoding, data capture, information/data flow and processing. An HTML documentation template implementing the UK standard for documenting and transferring data sets was later compiled (see Section F). This was an attempt at a common physical vehicle for data archival and exchange.

As Annex 34 progressed, it became clear that providing data sets with time stamped columns of data was easier than providing documentation. That is, participants could readily provide information automatically encoded by the BEMS, but other relevant information needed by FDD tools was more difficult to obtain and provide. This is something the participants experienced even within the confines of their own experiments as FDD tools were applied to data from different buildings or different pieces of equipment in the same building.

Recognising the fact that “information” was somewhat more than “just data”, more pragmatic approaches were suggested. One that lessened the burden on the data providers was to provide an initial set of documentation and add to it as participants requested further information. At the Autumn 1999 meeting, Annex 34 decided to simply provide nominal or design values for each of the measurements in a data set as the most basic and important documentation.

Much has been learned about the data/information requirements of FDD tools and progress has been made toward enabling access to this information; however, considerable work lies ahead. Kaldorf and Gruber reported on experiences with an expert system deployed in a real building [Kaldorf and Gruber, 2001]. Each installation of the expert system required more than a day to extract the necessary configuration data from the BEMs or design documents and to manually enter this information into the expert system shell. One of the main conclusions was that information encoding (“data pre-processing”) and the extent of the data dictionaries and data model are key to a successful (and cost effective) FDD tool.

As indicated above, the method of conveying data and information evolved as participants gained a better understanding of the challenges of applying FDD tools to different data sets. This evolution resulted in a data set standard described in Section B.4.3. Throughout Annex 34, U.S. participants sought to simplify the task of sharing data sets through the development of the FDD Test Shell. The Test Shell provides a mechanism for accessing design and measurement data from data files and provides considerable configuration information. Standardised configuration templates developed for vapour-compression cycles and air-handling units (AHU) are described in Section 4.4. [Further details of the Test Shell are provided in Section F.]

B.4.3 Annex 34 data set standard

A data set standard was established according to 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 standards were accepted:
 - MM/DD/YY HH:MM:SS.SSSSSS
 - DD.MM.YY HH:MM:SS
 - YYMMDD HHMM
 - 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 (e.g. “,” delimiter makes a comma separated value (.csv) file easily interpreted by Microsoft Excel).
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 (e.g. measured value outside of sensor range).

In creating a relational database, normalisation is the process of organising the database into tables in such a way that the results of using the database are always unambiguous and as intended. This Annex 34 data set standard is in effect a **First normal form (1NF)**. This is the “basic” level of normalisation and generally corresponds to the definition of any database, namely:

- It contains two-dimensional tables with rows and columns;
- Each column corresponds to a sub-object or an attribute of the object represented by the entire table;
- Each row represents a unique instance of that sub-object or attribute and must be different in some way from any other row (that is, no duplicate rows are possible); and
- All entries in any column must be of the same kind.

B.4.4 FDD Test Shell and equipment templates

Annex 34 developed the FDD Test Shell as a way to use data sets and other data sources (e.g. equipment models) to test, compare, and evaluate FDD tools. The Test Shell is based on a Microsoft Windows DDE server program called the Co-ordinator, which accepts data from one of a variety of data source programs and serves it to DDE client programs implementing FDD methods. This architecture allows FDD tool developers and data source providers to develop applications in the environment of their choice (e.g. C++, Visual Basic, Pascal, MATLAB), provided the data source or FDD tool conforms to the DDE communication standard established by the Co-ordinator program. The basic Test Shell platform includes a File Data Source program that uses Annex 34

standard data files (see Section B.4.3) to push time series data through the Co-ordinator program.

The Co-ordinator program is comprised of data cells containing measurements at a specified time. Vapour-compression cycle and AHU templates have been established that specify the measurements and units associated with each cell (see Tables B1 and B2). The software implementations of the templates include a graphic that displays the time series data in the appropriate physical location. The File Data Source program provides a utility for mapping file columns to cells, converting units, and setting default cell values for data not included in the file. Every standard data file, which is contributed with the FDD Test Shell software, is accompanied by a File Data Source configuration file that maps its contents to the appropriate standard template.

Table B1: Vapor-compression cycle template.

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	Condenser Inlet Water/Air Temperature	C
9	Condenser Outlet Water/Air Temperature	C
10	Discharge Temperature	C
11	Evaporating Temperature	C
12	Condensing Temperature	C

Table B2: AHU template.

Cell	Measurement	Units
1	Time	HH :MM :SS
2	Occupancy	0/1 for unoccupied/occupied
3	Supply Air Setpoint Temperature	C
4	Supply Air Temperature	C
5	Return Air Temperature	C
6	Mixed Air Temperature	C
7	Outdoor Air Temperature	C
8	Cooling Coil Inlet Temperature	C
9	Heating Coil Inlet Temperature	C
10	Cooling Coil Discharge Temperature	C
11	Heating Coil Discharge Temperature	C
12	Chilled Water Supply Temperature	C
13	Hot Water Supply Temperature	C
14	Supply Air Relative Humidity	0–100%
15	Return Air Relative Humidity	0–100%
16	Outdoor Air Relative Humidity	0–100%
17	Cooling Coil Inlet Relative Humidity	0–100%
18	Cooling Coil Discharge Relative Humidity	0–100%
19	Supply Air Flow Rate	m ³ /s
20	Return Air Flow Rate	m ³ /s
21	Exhaust Air Flow Rate	m ³ /s
22	Outdoor Air Flow Rate	m ³ /s
23	Chilled Water Flow Rate (through coil)	m ³ /s
24	Hot Water Flow Rate (through coil)	m ³ /s
25	Humidifier Water Volume	L/s
26	Supply Air Pressure Setpoint	Pa
27	Supply Air Pressure	Pa
28	Cooling Coil Valve Control Signal	0–100%
29	Heating Coil Valve Control Signal	0–100%
30	Mixing Box Damper Control Signal	0–100%
31	Supply Fan Control Signal	0–100%
32	Return Fan Control Signal	0–100%
33	Power Consumption	kW
34–43	Room Air Relative Humidity	0–100%
44–53	Room Air Temperature	C

B.4.5 Conclusions

The exercise of gaining access to the data and information needed by FDD tools has proven quite challenging and quite enlightening. It is easy to under-appreciate the amount of information that is required (e.g., design, measurement, configuration, control sequencing, etc.), and the effort required to extract this information from its source and to insert it in the FDD tool. Annex 34 participants collaborated to identify ways to facilitate access to this information and ultimately established a data set standard and a tool for extracting data from data sets and presenting it to FDD tools (FDD Test Shell). This effort eased the burden of, for example, using data from other buildings. Ultimately the effort to configure FDD tools has demonstrated the need for an integrated database that is populated with the information needed by the tools. A new awareness of the need for careful “upstream” definition of data objects, data dictionary, data modelling issues (normalisation, etc.) emerged from our collective efforts. Furthermore, these efforts helped to highlight the need for a standard interface for accessing the integrated database, such as SQL. Finally, there is recognition that the information in the database must evolve over the lifetime of the building to reflect current characteristics of buildings (e.g., as built equipment/parameters may not be same as design).

B.5 SENSOR VALIDATION

P. Carling and R. Grob

B.5.1 Introduction

All fault detection and diagnosis methods used within the Annex rely on data measured by sensors that are installed within the HVAC systems. Therefore, the reliability of each method is strongly connected to the reliability of the measurements, which are – in principle – no more than relatively accurate estimates of the measured quantity. The performance of all fault detection and diagnosis methods applied in this Annex depends strongly on the quality and the reliability of measurements. Inaccurate or incorrect measurements will inevitably result in poor performance of the FDD methods in terms of

- total failure to detect faults
- high rate of false alarms
- inconsistent system monitoring.

The validation of sensors is therefore a critical first step in the installation or commissioning of FDD systems. Numerous publications [e.g. Building Controls Group, 1995] cover general aspects of validating and calibrating sensors for various applications and purposes. In this section the issues and difficulties that arise, especially in regard to the application of FDD methods during the sensor validation process, are described.

Different fault detection and diagnosis methods require different levels of sensor accuracy. It is crucial to decide the required sensor accuracy for each method and to ensure that the requirements are fulfilled by the measurement system. It is particularly important to use accurate measurements during the commissioning of an FDD-tool in order to obtain the correct reference state.

There is a strong correlation between accuracy and the cost of a measurement system. This becomes an important issue since FDD tools must be affordable in order to be accepted by the market [see also Section E]. The development of FDD methods will be greatly simplified if accurate measurements are available. The challenge is to produce a tool that can detect and diagnose faults with a level of measurement quality that is economically acceptable.

Basic definitions:

Here a sensor is defined as a device that receives energy from the measured medium, converts the energy to a signal, which is suitable for transmission to a place where data can be stored and processed.

A measurement system is defined as the sensor plus the devices used for data storage and data processing.

Sensor validation is the assessment of the measurement system performance including the assessment of disturbances during measurements.

B.5.2 General sensor faults

Many sensor faults are unrelated to the specific type of sensor, and can appear regardless of the measurement arrangement. In FDD applications, these sensor faults can be identified as general sensor faults and can be subdivided into three different categories. These subcategories and examples for each subcategory are described in the following. The issues mentioned under the various subcategories are further addressed in Section B.5.4 for different types of measured quantities.

B.5.2.1 Location faults

Location faults are probably the most common faults occurring in HVAC systems. In the case of improper positioning, the sensor itself is working properly. However, because of the sensor location or placement, the reading obtained from the sensor does not give a value representative of the conditions for which measurements are required. Commonly, this fault occurs when the physical boundary conditions are not properly considered during design and installation. An example of the source of a location fault is stratification within air ducts after devices like mixing dampers or heat exchangers [Carling and Isakson, 1999; Carling and Zou., 2001]. Another possible fault, which can be related to sensor location, is the influence of radiation from sources/sinks such as heating or cooling coils. A location related sensor fault can also occur if sensors are placed in dead-legs (e.g. in ducts with insufficient air flow) or without sufficient straight duct lengths upstream of the sensor (e.g. with flow measurements).

B.5.2.2 Electrical installation faults

The sensing device of measuring systems is usually connected to the control system through wires. Shortcomings within these electrical connections can also cause sensor and measurement faults. One example of this is bad or possibly incorrect wiring (bad

solder joint or exchange of two wires). Another reason for faults due to electrical installation can be the use of unshielded cables, which might result in increased amounts of noise in the measurement. Additionally, the use of an unsuitable power supply for the sensors (e.g. incorrect supply voltage) can also lead to measurement errors. Further faults, which could fall into this category, are grounding problems, improper scaling, or possibly conversion faults.

B.5.2.3 Sensor related faults

The faults which belong to this category occur within or more generally at the sensing device or its electronic components. Output drift and bias are the most common faults that can be related directly to the sensor. A broken sensor, which gives no signal or a completely wrong signal can be put into this category. Also the use of inappropriate or unsuitable sensors (e.g. a sensor with the wrong range or a time constant that is too long) is classified as a sensor related fault. Sensor related faults can often be traced back to improper design or to mistakes made during the installation. As a result, it should always be noted that the accuracy of a measurement system is limited by the accuracy of the worst element composing this system.

B.5.3 Methods for sensor validation

There are several possible methods of carrying out sensor validation. The most common ones, which have been used during the Annex, are briefly described in the following. Additionally, example rules and procedures are given for each of these methods.

B.5.3.1 Temporary and permanent physical redundancy

A simple way of validating sensors is to install several sensors that measure the same quantity. This is referred to as physical redundancy and has long been used in engineering systems, especially those with high security requirements.

Recommended procedure for sensor validation using redundant sensor, which are installed temporarily:

- The sensors need to be installed as close as possible to the location of the sensors to be used in the final system.
- The sensors need to stay within the system for a long period (i.e. several days).
- All sensors at a single location (e.g. at the supply outlet) should be validated simultaneously.

- Every sensor should be paired with a validation sensor of a similar type, adjacent to it, in order to determine if the sensor itself is working correctly or if any incorrect readings are related to improper placement of the sensor.
- The validation measurement must be synchronized with the clock of the control system to ensure that the values from the sensors of the final system are synchronized to those from the validation sensors.
- For temperature measurements, several sensors need to be installed across the duct so that an average value can be calculated and compared to the value measured by sensor in the final system (uncovering the effects of incorrect placement or stratification).
- The sensors should be checked over their entire measurement range (i.e. under different conditions).
- It is important to document every step of the sensor validation process.

Recommended procedure for sensor validation using redundant sensors, which are installed permanently

- Survey the system to determine what kind of sensors are installed and where the sensors are located.
- Determine (together with the plant operator) the locations where additional validation sensors can be placed.
- Determine how the validation sensors can be installed in the system without interfering with its operation.
- Prepare the validation sensors so that they can be installed easily and quickly in order to avoid long interruption of the system operation.
- Work out a validation plan by defining the sensors that should be validated together.
- Carry out the measurements by collecting synchronized data from the data acquisition system (the validation sensors) and the control system (the installed sensors).
- Evaluate the measured data in order to determine possible faults and the accuracy of the different sensors.
- Make recommendations for improving the sensors and eventually for carrying out any modifications to the final system. (scaling, correction factors, placement, ...).

B.5.3.2 Manual checking of the sensors

Calibrate the sensors using the data acquisition and processing system and a reference sensor of high quality or with a well-known reference state (e.g. an ice-bath reference). Check the installation with a heat source (e.g., hair dryer, body temperature).

Manual sensor checking is used to compare the measurement sensor reading to the reading of a calibrated reference sensor. In practice it is convenient to use the building

energy management system (BEMS) including the installed electrical wiring to collect data during the checking procedure. The obvious advantage of this approach is that possible errors in the sensor as well as possible errors in the wiring are contained in the reading, making them easier to detect. An ice bath or a fluid bath can be used to achieve the reference states required for checking temperature sensors.

Manual sensor checking is a method that lacks the advantages of automatic checking. However, some important advantages are still associated with manual calibration. Often it is not possible to carry out the manual checking on-site because the required reference states can only be generated within a laboratory environment.

B.5.3.3 Diagnostic tests

Another method of checking the sensors is to perform test cycles. An example of this is to turn a valve into its closed position and check if the temperatures at the inlets and outlets of the valve or the coil controlled by the valve are logical and plausible. This method assumes that the HVAC system in which the sensors are installed can be considered fault-free. Hence this method cannot be used for sensor validation if there are possibly faults within components (e.g. a stuck valve or damper, fouling of a heat exchanger).

B.5.3.4 Analytical redundancy

This kind of validation method is based, for example, on physical laws such as energy and mass balances which represent universal correlations between the different variables in a system. Violation of these laws indicates the existence of sensor faults. The difference between analytic and physical values can be used to detect, diagnose and evaluate faults within the measurement system [Wang and Wang, 1999]. This method is feasible when significant physical and analytical redundancies exist within the measurement system. Analytical redundancy can also be used to check a system for consistent measurements by operating it without load or by stopping the flow within it.

B.5.3.5 Automatic sensor validation

Automated validation includes sensors that use a micro-controller to generate information more accurately than with standard sensors. These types of sensors could, for example, deliver diagnostic information. Other examples are self-validating sensors that perform internal diagnostics, measurement correction and generate standard metrics describing the measurement quality [Henry, 1995]. These metrics, which are generic and include on-line uncertainty, allow standard control system responses to changes in measurement quality. Self-tuning sensors can also be categorized under automated sensor validation. Automated validation methods are not usually affected by plant faults.

B.5.4 Quantities used in FDD-tools

This section considers a selection of measured quantities in HVAC-systems. Principles for measuring the quantity are discussed, examples of sensors are given, and different types and causes of common faults are discussed. When available, information about the possible range of faults is also mentioned. Additionally some recommendations concerning how to check and how to place the sensors are given.

B.5.4.1 Air temperature

Air temperatures are measured in various locations under different conditions (i.e., within ducts, in rooms or outdoors) by either using single-point or averaging sensors. The most common principle used for air temperature measurements within HVAC applications is the “electrical resistance” principle.

Table B3. Specific faults regarding air temperature measurements.

Causes for faults	Description of the fault
Stratification in rooms in ducts	Temperature differences due to differing air densities Stratification due to insufficient mixing of the air after mixing boxes or heat exchangers
Radiation (heat sources) (solar)	Installation of sensors close to and unshielded from heat sources or sinks (e.g. heat exchanger or cold/hot duct walls) Solar radiation on an unshielded air temperature sensor
Conduction	Faults caused by conduction through walls (e.g. uninsulated sensor installed on a wall)
Convection	Measurement of an incorrect outside or room air temperature by locating the sensor above heat sources which cause convective flows across the sensor
Insufficient airflow	Temperature readings are wrong because of insufficient airflow around the sensor
Time constants	Sudden changes in the air temperature cannot be detected because sensor time constants are too long

Recommendations:

For air temperature measurements the generally accepted accuracy should be within $\pm 0.5^\circ \text{C}$. The most important constraints for temperature sensor installations are related

to their location. Hence, adequate protection from environmental disturbances (e.g. sun, heat sources, cold/hot surfaces) should be foreseen. Regarding the detection of faults it can be said that it is best to check for stratification by using several temporarily installed redundant validation sensors distributed across a cross-section of the duct. Radiation faults should be checked with shielded sensors. Generally the physical boundary conditions (e.g. possibility of radiation, convection, conduction or stratification influences) should be examined prior to validation.

Throughout validations carried out within the Annex, it was crucial to use averaging sensors for air temperature measurements within ducts at most locations, and especially after mixing devices, in order to obtain reasonable measurements. In severe cases it may not be possible to use the mixed air temperature at all. An alternative is to use the return and outside air temperatures in conjunction with the control signals to estimate the mixed air temperature [see also Section B.5.5].

The possible range of faults due to stratification can be under certain conditions up to $\pm 10^{\circ}\text{C}$ [Carling and Isakson, 1999]. Faults related to solar radiation range from 4°C to 7°C .

B.5.4.2 Water temperature

Water temperatures are usually measured within or on pipes using immersion or surface mounted sensors, respectively.

Table B4. Specific faults regarding water temperature measurements.

Causes for faults	Description of the fault
Conduction	Surface mounted sensors with poor thermal conductivity between sensor and surface Conduction from surroundings Poor conduction due to bad contact within the immersion pocket of an immersion sensor
Laminar flow	“Stratification” within the flow at very low flow rates (particularly with immersion sensors)
Bad mixing (non-homogenous state)	Sensor gets inaccurate readings because it is installed too close to mixing valves

Recommendations:

The accuracy of this type of sensor should usually match the accuracy range of the air temperature sensors (i.e. $\pm 0.5^{\circ}\text{C}$). For surface mounted sensors, good thermal

conductivity between sensor and surface must be ensured. For immersion sensors the correct measurement position (upstream or downstream) is important. Immersion sensors should always be oriented in the opposite direction of the flow.

B.5.4.3 Air flow in ducts

There are three main approaches for measuring airflow in ducts: velocity, volume flow rate and mass flow rate measurements. The most commonly used techniques are the single-point Pitot tube, the averaging Pitot tube and anemometers. The choice of measurement technique is dictated by the application.

Table B5. Specific faults regarding air flow measurements in ducts.

Causes for faults	Description of the fault
Variation in fluid properties	The flow rate measurements differ because density changes with temperature (e.g. after heat sources like fan motors). This fault comes into effect especially if conversions from volume to mass flow rate are necessary
Flow disturbances	Flow profiles are not uniform before or after an elbow, tee or other components
Incorrect orientation of the flow meter	Incorrect installation of the sensor causes erroneous readings
Fouling of the sensor	Proper function of the sensor is restricted because of interference from particles, dirt, etc.

Recommendations:

Air flow measurements should be carried out after a sufficient length of straight duct. If measurements are taken directly after components, the results are usually not very reliable. In the case of volume to mass flow rate conversions it is necessary to check whether the assumption of constant fluid properties is valid throughout the whole measurement range.

B.5.4.4 Water flow in pipes

The principles for measuring water flow in pipes can be divided into methods with equipment that needs to be installed within the pipes (turbine meters, displacement methods, obstruction meters) and methods that utilize devices which can be attached to the pipes (electromagnetic or inductive flow meters, ultrasonic flow meters).

Table B6. Specific faults regarding water flow measurements in pipes.

Causes for faults	Description of the fault
Variation in fluid properties	For example, changing the glycol content of the water flowing through a coil
Particles or dirt	Inductive or ultrasonic based measurement gives incorrect readings if there are too many particles within the measured fluid. Hardware may be susceptible to damage
Flow disturbances	See Section B.5.4.3, line restrictions could modify flow properties
Incorrect orientation of flow meter	See Section B.5.4.3

Recommendations:

See recommendations of Section B.5.4.3.

B.5.4.5 Air differential pressure

Differential air pressures can be measured across HVAC components such as filters, coils or fans in order to survey them. Also, differential pressure measurements are needed for the control of HVAC systems. The most common method of measurement is that based on elastic pressure transducers.

Table B7. Specific faults regarding air differential pressure measurements.

Causes for faults	Description of the fault
Inappropriate location or orientation of the sensor	Dynamic pressure is measured instead of the static differential pressure Too short or too long rubber tubing will change the pressure drop
Loose transducer connection	Measurement is influenced by ambient pressure or other pressure sources
Flow disturbance at the measurement point	Local turbulence around the measurement point causes variations in the measurement (dynamic pressure is possibly also measured)

Recommendations:

It is important to check the correct location and orientation of sensors for static differential pressure measurements within the airflow, so that dynamic pressure influences can be excluded.

B.5.4.6 Humidity

There are many different principles and sensors available for measuring humidity. In HVAC-systems, humidity sensors that are based on the capacitive principle usually dominate.

Table B8. Specific faults regarding humidity measurements.

Causes for faults	Description of the fault
Inappropriate location of the sensor	The absolute humidity cannot be obtained correctly if the humidity sensor is not located close to the related temperature sensor Positioning too close to a humidifier reduces accuracy because of water droplets
Sensor degradation	Long term drift of the sensor
Pollution	Decreased sensitivity of the sensor

Recommendations:

For humidity measurements it is important to take measurements of the relative humidity and the dry bulb temperature at the same time and location, since they are strongly related. The sensors should be calibrated regularly (ideally 1–2 years) since the sensor degradation can be up to 1% per year. The combined error taking into account linearity, hysteresis and repeatability is within a range of 5% for capacitive humidity sensors at 20°C [Fahlen, 1993].

B.5.4.7 Refrigerant temperature in pipes

In most refrigeration systems, temperature sensors are mounted externally and do not have direct contact with the fluid whose properties are being measured. This leads to a different type of system fault.

Table B9. Specific faults regarding refrigerant temperature measurements in pipes.

Causes for faults	Description of the fault
Poor sensor placement	Sensor reading is affected by convective and/or radiant heat from surroundings (e.g. in direct sunlight)
Non homogeneous state	Sensor gets inaccurate readings because the refrigerant is two-phase
Contact	False reading because surface mounted sensors have poor thermal conductivity between sensor and surface
Insulation	Sensor is not well insulated and is subject to the effects of convection, radiant heat, or other interference

Recommendations:

Install the temperature sensor on the underside of the pipe to measure the temperature of the liquid refrigerant. If some gas exists it will be away from the sensor. In addition, ensure good contact with the pipe surface, removing paint or other residues that may have insulating properties. Adhere the sensor with a non-insulating epoxy or attach it from above with strong tape. Metal tape is recommended to provide a greater conduction contact surface between the sensor and the pipe. Proper insulation is critical. Additionally, temperature and pressure measurements used to determine other quantities must be taken as close to the same time and location as physically possible.

B.5.4.8 Refrigerant flow in pipes

See Section B5.4.4.

Table B10. Specific faults regarding refrigerant flow measurements in pipes.

Causes for faults	Description of the fault
Variation in fluid properties	The flow rate measurements differ because density changes with temperature. A flow meter that is designed for liquid measurement will give erroneously high readings for two-phase flows
Flow disturbances	Flow profiles are not uniform before or after an elbow, tee or other components. A liquid line restriction can cause a significant pressure drop to cause flashing in the pipe segment
Incorrect orientation of the flow meter	Incorrect installation of the sensor causes erroneous readings
Fouling of the sensor	Proper function of the sensor is restricted because of interference from particles, dirt, etc.

Recommendations:

See recommendations of Ssection B.5.4.3.

B.5.4.9 Refrigerant pressure

Table B11. Specific faults regarding refrigerant pressure measurements.

Causes for faults	Description of the fault
Variation in fluid properties	The pressure measurements differ because density changes with temperature. A pressure sensor that is designed for liquid measurement will give erroneously high readings for two-phase flows
Fouling of the sensor	Proper function of the sensor is restricted because of interference from particles, dirt, etc.

Recommendations:

See recommendations of Section B.5.4.3.

B.5.4.10 Air quality

CO₂-sensors based on infrared absorption are commonly used to measure the indoor air quality.

Table B12. Specific faults regarding air quality measurements in pipes.

Causes for faults	Description of the fault
Sensor degradation	Sensitivity of the sensor decreases because of long term drift
Pollution	Dust limits the performance of the sensor
Time constants	Sudden changes in pollution rates cannot be detected because of long sensor response times

Recommendations:

The sensors should be installed at a representative set of locations, or ideally in the return air duct, in order to get the correct measurement of the actual indoor air quality. The sensors should be calibrated regularly [Cotic, 1992]. Sensor degradation faults are

within a range of 1% full scale per year for air quality sensors. The time constants of these sensors are on the order of 1 min to 10 min [Cotic, 1992; VAISALA, 1999].

B.5.5 Estimation errors

In many cases variables that are needed for an FDD system cannot be measured because the associated sensors are not available (e.g. the water flow rate to an individual coil), or the variables cannot be measured directly (e.g. the mass flow rate of the air flowing down a duct). In these cases the variables must be estimated on the basis of other measurements. The following section deals with the faults and errors that can occur if a variable is estimated using measurements from other sensors.

B.5.5.1 Model-based estimation of unmeasured variables

The unmeasured variable is estimated using knowledge of its relationship to the 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 will depend on the accuracy of the model used to describe the relationship between the measured and unmeasured variables, as well as the accuracy of the measurements.

B.5.5.2 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. A biased estimate of the average air temperature can result even though the sensor has been calibrated properly and is operating correctly. 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).

It should be noted that, because of the non-uniform velocity of the air over the cross-section, averaging sensors or sensor grids do not necessarily provide a true measurement of the spatial average of the temperature.

B.5.5.3 Estimating steady-state values

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

- 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 will depend on the value of the threshold used in the steady-state detector.
- 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.
- 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 will depend on the accuracy of the model assumed in the design of the pre-processor.

B.5.6 Conclusions

The installation and testing of FDD tools in real buildings has shown that validating the system sensors is a crucial step if the tools are to perform well. Sensor errors have a large impact on the FDD process and some form of sensor validation is always needed to prepare HVAC systems for the installation of FDD tools. Another important finding is that sensors are often faulty and frequently result in incorrect measurements, especially sensors used to measure quantities associated with the air in a duct or zone. Thorough system sensor validation is therefore a prerequisite to any successful FDD application.

B.6 THRESHOLD SELECTION

A. L. Dexter and H. Vaezi-Nejad

B.6.1 Use of thresholds in FDD schemes

Thresholds are required to prevent false alarms from being generated by uncertainties, such as modelling and measurement errors, and to adjust the fault sensitivity of the FDD tool. There are three basic types of thresholds used in FDD tools.

(i) 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.

(ii) Mode detection thresholds

This type of threshold is used to determine the mode of operation of the system. For example, the system is assumed to be in steady-state if measures of the variability of all the process variables are less than a given threshold; the system is assumed to be in heating mode if a particular process variable is above a certain threshold value.

(iii) Alarm generation thresholds

An alarm is generated whenever the probability of the fault being present exceeds the alarm threshold.

B.6.2 Causes of uncertainty

The main causes of uncertainty are measurement errors, modelling errors, and mode detection errors. Measurement errors are either sensor errors, which cannot be diagnosed and eliminated (see also Section B.5 Sensor Validation), or estimation errors, if the output of the sensor is noisy or the process variable cannot be measured directly. Calibration errors are unlikely to be significant but there may be large offset errors associated with estimating spatial averages from the output of a single-point sensor or with estimating steady-state values in the presence of time-varying disturbances.

There are two types of modelling errors. Structural errors arise from a mismatch between the structure of the mathematical model and the process to be modelled. One of the most important causes of structural errors is an unmodelled disturbance. Errors also arise from inaccurate estimation of the parameters of the mathematical model. The most common cause of parameter estimation errors is poor quality design information, or inadequate or incomplete calibration data.

When the model is in the form of a set of expert rules, rules may be incorrect, or may not have taken all factors into account and be incomplete, or they may be inconsistent and contradictory.

Mode detection errors arise because, in practice, it may be impossible for the mode to be specified precisely (For example, how should steady-state operation be defined in practice?). Mode detection errors may also be due to poor commissioning of the detector (For example, incorrect choice of a filter time constant).

It should be noted that the magnitude of these errors could vary with the operating conditions in non-linear HVAC plants.

B.6.3 Fault sensitivity and false alarm trade-offs

The choice of thresholds is a compromise between the sensitivity of the FDD tool and the number of false alarms that are generated. Too high a threshold can mean that only large faults are detected. Too low a threshold may result in an unacceptable number of false alarms.

The required fault sensitivity may depend on the type and size of the fault to be detected, or the economic cost of detection and non-detection [Dodier et al., 1998], or whether the end-user has time to deal with the fault once it has been detected.

A higher false alarm rate may be more acceptable for fault diagnosis than for fault detection.

B.6.4 Threshold selection

There are three basic ways of determining appropriate values for thresholds.

B.6.4.1 Heuristic methods of selecting thresholds

The default values of the thresholds are often based on expert/domain knowledge [Rossi and Braun, 1997]. The analysis of historical data collected from several similar HVAC systems [Seem et al., 1997; Glass and Todtli, 1996] or from the same system at different times [Carling and Isakson, 2000] is commonly used to generate the default values. To adjust the false alarm rate, these generic values can then be tuned by trial and error testing using training data from the actual system when it is assumed to be fault-free [Nakahara et al., 1997; Visier et al., 1999; Yoshida and Kumar, 1999; House et al., 2001]. This approach, which should only be used if the available data are thought to be

representative of all the possible operating conditions, is frequently used to determine suitable steady-state detection thresholds. The use of heuristic fuzzy thresholds has also been proposed [Bourdouxhe and Seutin, 1998].

B.6.4.2 Statistical methods of selecting thresholds

These thresholds are based on confidence intervals and hypothesis testing using estimates of the means or standard deviations of the residuals [House et al., 2001; Norford and Little, 1993] or parameters [Buswell et al., 1997]. The means and standard deviations are often estimated from the training data [Lee et al., 1996; Shiozaki and Miyachika, 1999]. It should be noted that a suitable threshold can only be determined in this way if representative fault-free data are available for the system under test.

The detection threshold of a particular fuzzy model-based FDD scheme is embedded within the fuzzy relational reference models it uses. The effective value of the threshold, which varies with operating conditions, depends on the size of the class of systems used to generate the generic reference models and the magnitude of the sensor offsets included in the training data [Ngo and Dexter, 1999].

B.6.4.3 User selection of the threshold

In many FDD tools, the end-user is allowed to adjust the default values of the thresholds [Kärki and Leskinen, 1999]. The alarm generation thresholds may be modified on-line by the end-user so as to achieve a false alarm rate and fault sensitivity that is appropriate to the application [Visier et al., 1999]. The main disadvantages of allowing the end-user to adjust the thresholds are:

- The end-user must personally benefit from the detection of a fault otherwise he or she may increase the threshold until no alarms are generated. For example, the building owner has an economic interest in detecting faults quickly if their presence means that energy is being wasted, whereas the detection of too many faults may simply stretch the resources of the maintenance personnel.
- Some faults may be more sensitive to uncertainties than others. The user may therefore adjust the threshold according to the most sensitive fault and cause the FDD tool to become too insensitive to other faults.

In practice, it is most likely that thresholds will need to be adjusted to achieve a manageable fault alarm rate, and not a particular fault sensitivity or rate of false alarms. One compromise is to allow the end-user to adjust the value of a single multiplying factor that adjusts the relative values of each of the individual thresholds [Ruud, 1997; House et al., 2001].

B.6.5 Methods of varying the threshold with operating point

The behaviour of HVAC systems is often non-linear and the thresholds may need to be varied as the operating conditions changes. Expert rules can be used to vary the threshold according to the observed operating conditions [Sauter et al., 1994]. Allowance must also be made for variations in the set-points and other disturbances if the reference models do not take these changes into account. It is often advantageous to smooth the changes in the threshold values using a low-pass filter [Ruud, 1997]. In some FDD schemes, fault isolation relies on each of the possible faults having a detection threshold that varies with operating conditions [Salsbury et al., 1995].

B.6.6 Accumulating evidence

Smaller alarm thresholds can be used if the alarm generation is based on a number of independent diagnoses. A simple approach is to set the alarm only if the fault has been detected continuously for a specified period of time [Glass and Todtli, 1996] or the number of times a fault has been detected in a specified period exceeds a user-specified value [Pape et al., 1991; Li et al., 1997; Peitsman and Soethout, 1997, Carling and Isakson, 2000], or to smooth the results of the diagnoses using a low-pass filter [House et al., 2001]. A more rigorous approach based on combing new evidence with old evidence using Dempster's rule has also been suggested [Dexter and Benouarets, 1997].

B.6.7 Recommendations and conclusions

- An appropriate fault sensitivity is difficult to specify since the cost of failing to detect a fault and the cost of having to deal with a false alarm is usually unknown.

Thresholds should only be tuned by trial and error if the available training data are thought to be representative of all the possible operating conditions.

- Estimation bias is usually the greatest source of uncertainty in air-conditioning systems. For example, the use of a single-point sensor, or even a commercial averaging sensor, to estimate the average temperature of the air flowing down a large duct can introduce significant errors.
- In most applications, the end-user must be able to adjust the thresholds so that the rate at which faults are correctly identified is no greater than the rate at which it is possible to deal with them.

Although many methods of threshold selection have been proposed, it is still difficult to choose suitable thresholds in practice.

B.7 CONTROL SYSTEM FAULTS

S. Wang and J. E. Seem

There are two main categories of faults that occur in building control: *hardware faults and software faults*. These faults might arise in all three phases of the control system life cycle: the *production*, *implementation* and *application* of control systems. The *production* phase includes the production and development of the hardware and standard software or “firmware”. The *implementation* phase includes the installation of the hardware, the development of application software, the initial commissioning of hardware and application software, and the tuning of control strategies (loops). The *application* phase is the period of normal operation after the initial commissioning phase. Unless they are eliminated, all of the faults eventually influence the control of the system control in the *application* phase.

B.7.1 Hardware faults

The hardware faults are actuator faults, interface failures, controller hardware faults and sensor faults. Since sensor faults are extensively discussed in Section B.5: Sensor Validation, they are not considered here.

B.7.1.1 Actuator faults

Actuators are used to drive the dampers or valves in an air-conditioning system and can be divided into three types: electromagnetic, pneumatic and motor-driven. Faults therefore include defects such as blocked or burnt-out electrical coils, elastic failure (e.g., broken damper linkage), etc. In VAV systems, damper and cooling/heating valve actuator defects results in temperatures or air flows that are higher or lower than the associated set-point.

B.7.1.2 Interface failure

Interface failure in the communication networks of building control systems is a complicated problem and the diagnosis and troubleshooting methods are different for different systems and problems. A hardware communication failure might be the result of physical connections (cabling) faults, faults in interface cards, or failure of the power supply (fluctuations).

B.7.1.3 Controller hardware faults

In modern building control systems, the controller is built from digital electronic devices. Controller hardware faults include short-circuits, broken circuits, degradation and burn-out of electronic components, and loose interface connections, battery failure, etc. These controller hardware faults can result in incorrect values of the control signal or no control signal to actuator.

Additionally, electronic controllers are susceptible to transient electromagnetic interference, which can cause functional errors, often without damaging any of the controllers components. This can also result in incorrect values of the control signal being sent to the actuators [Shin et al., 1985]. In this case, there are several possible outcomes:

- The controller can generate the wrong control signal due to erroneous computation
- The controller can fail to update the control signal until the failure is detected and handled properly (i.e. there will be a delay in the feedback control loop)
- Poorly designed anti-aliasing filters can cause the controller to oscillate in response to the high frequency electromagnetic interference

B.7.2 Software faults

Controller software faults include programming errors, execution failures and incorrect values of default parameters [Hartman, 1993].

B.7.2.1 Programming errors

Improper control action

The software must be checked to ensure that the control algorithm has been implemented correctly. The control action can also be affected by the transducer that translates the control command into actuator movement. Calibration of the transducer can be performed during routine testing of the controller-process interface. Feedback control can be direct acting or reverse acting [Hartman, 1993]. Selection of the wrong control action will cause the actuator to be driven in the wrong direction.

Incorrect initial values

Inappropriate initialisation of a parameter estimator in an adaptive controller can result in non-convergence or cause erroneous parameter estimates to be generated.

Improper range selection

The value of the control signal is checked to ensure that it is within a specified range. If the controller is to function correctly, an appropriate range needs to be determined prior to the software implementation of the control algorithm, in some cases, via computer simulation of the control loop. The input range for sensors must also be specified correctly.

Improper run-time

The control sampling interval time must be long enough to allow for time to sample measured data, perform necessary calculations and issue appropriate commands. A security timer is usually provided to check the execution time and switch in an alternate controller if a pre-specified time limit is exceeded. A suitable time limit has to be determined beforehand based on previous test runs.

Incorrect flags

Flags are used as switches that direct the program flow. The control strategy will not operate as it was designed if the flags are not set and reset correctly.

Improper step size

An appropriate step size must be selected for any control algorithm involving iteration. Too small a step size will result in unnecessarily long execution times. Too large a step size may result in poor convergence or convergence to the wrong result.

Scheduling errors

Scheduling errors include incorrect start-up or stop times of a plant, and incorrect sequencing of the different modes of operation of the control. These errors may be a result of an inappropriate choice for the parameters of the sequence controller or programming errors.

Errors in the control logic

Errors in the software implementation of the control logic will result in wrong decisions, incorrect logic inferences and unconsidered conditions and cases.

B.7.2.2 Execution failures

Improper input signals

The input signals to the controller must be received correctly. This will depend on the correct operation of the interface between the process and the controller. Since this mainly consists of hardware for converting and transmitting the signals, any problems can be mitigated by periodic testing.

Delayed inputs

There is a time interval within which the process should respond to a control command. Exceeding such a time period may be indicative of a malfunction in the control program.

Unavailability of information

Input information and stored data must be available for use by the controller when they are needed to execute the control program. Such data might be inadvertently deleted or corrupted, or interpreted incorrectly and this can result in improper control action. Corruption of historical data automatically stored in many digital controllers can also degrade the performance of the controller, although it should not result in any control errors.

Erratic control action

The change in the controller output, averaged over a given period of time, should be within predictable limits. Often erratic, or frequent abrupt, changes in the control signal can be indicative of a control system fault. Erratic behaviour can result from over-regulation and, hence, the process output may not reach a stable state. Such action can occur after initiating a shut-down or a start-up command. However, allowance should be made for some limited over-shooting or over-correction of system response. Thus, only persistence of erratic action should be checked.

Execution errors

Execution errors may include:

- computational errors, such as an attempt to compute the square root of a negative number, division by zero, etc., that could cause execution of the program to be interrupted.
- operational errors, such as attempting writing to a copy-protected area, assignment of a string to a numerical variable, etc.,
- algorithm errors resulting in computational instability,
- truncation and accumulation errors

B.7.2.3 Poor tuning

Inappropriate selection of the parameters of the control strategies can cause both local and supervisory control loops to oscillate [Seem et al. 1999; Seem, 1998]. The values of control parameters that result in stable control at one operating point can result in unstable control at another operating point. For example, poor tuning of the temperature and air flow rate controllers of a VAV box can cause both the temperature and the flow to oscillate about their set-points. Any change in the characteristics of the HVAC

equipment within a feedback control loop may also result in unstable or unsatisfactory behaviour of the control loop. On-line tuning of a local control loop is sometimes needed to fine-tune a controller during commissioning.

Building simulators and emulators provide an efficient method of testing control strategies and software during the development and commissioning stages. Dynamic simulation may be used to test a control algorithm at difficult operating conditions. Emulators can be used to check and commission the BEMS implementation of the control software in a simulated real-life environment.

B.7.3 The occurrence of faults during the lifecycle of the control system

Faults that occur in the *production* phase should be identified and eliminated by the product quality control processes. Faults that occur in the *implementation* phase should be diagnosed and resolved during commissioning. However, if this is not the case, faults that occurred during these two phases will need to be detected and eliminated during the *application* phase. Clearly, the behaviour of the control system during *application* phase will also be sensitive to faults that occur during this phase of the lifecycle.

Hardware faults generally occur in the *application* phase

B.7.3.1 Actuator failures

Actuator faults may be caused by thermal ageing of both the electrical and mechanical components, short-circuits or broken connections in the electronic components and motors, elastic and fatigue failures in the mechanical linkages, and worn-out moving parts.

B.7.3.2 Interface failures

Electrical connectors may become loose and result in short or open circuits. The contact resistance of switches may increase due to ageing. Both types of fault will lead to signal transmission errors.

B.7.3.3 Controller hardware faults

The thermal ageing of electric components, such as resistors and capacitors, over long periods of time can cause problems in analogue controllers. Digital controllers are more susceptible to the catastrophic failure of integrated circuits, such as memory chips, and power supply faults.

Software faults can occur in all three phases in the lifecycle

B.7.3.4 Programming errors

The effects of any programming errors in the system software or firmware should first be observed during the *production* phase.

B.7.3.5 Execution errors

Execution errors first occur during either the *production* or *implementation* phases. The effects of any programming errors in the applications software should be observed during the *implementation* phase.

Some execution errors occur during the *implementation* phase (for example: errors in the control logic and scheduling errors). Other execution errors may occur in the *application* phase (for example: improper input signals, delayed inputs, the unavailability of information, and erratic control action).

B.7.3.6 Poor tuning of the controller

The effects of poor tuning should first be observed during the *implementation* phase. They may also occur in the *application* phase if there are any subsequent changes in the behaviour of the HVAC system, or any of its components.

B.8 HIERARCHICAL FDD SCHEMES

J. M. House and P. André

B.8.1 Introduction

The development of automated fault detection and diagnostic (FDD) schemes for HVAC systems is still in its infancy; however, it is expected that FDD tools will one day be a standard feature of building energy management systems (BEMS). BEMS systems, especially those in “large” buildings, are already designed using a hierarchical approach. Not only is the hardware distributed throughout the building, but the system intelligence is as well. FDD tools will need to conform to this hierarchy. Current efforts of BEMS manufacturers, in addition to the incorporation of additional capabilities (like FDD), are orientated towards the standardization of the information exchange protocols. Information exchange will be a key to coordinating the output of multiple FDD tools.

Early development efforts of FDD tools have focused primarily on stand-alone software tools using a very pragmatic approach. These tools generally have some hierarchical structure to facilitate understanding. The tools will reside somewhere in the hierarchical structure of the distributed control system, whether embedded in local controllers or as a stand-alone software application that interfaces to work station software. These tools will someday be interfaced to other stand-alone FDD tools in a hierarchy that will integrate this distributed intelligence to produce a comprehensive and consistent description of the state of all HVAC equipment and systems in a building. As evidenced by this brief introduction, hierarchical structure is a pervasive aspect of FDD, whether it is manifested in the logic of an FDD algorithm or in physical structure of the control system in which these algorithms are (or will be) embedded. This section will explore hierarchical FDD schemes in greater depth, summarizing what has been learned to date and proposing how future challenges might be met.

B.8.2 What are hierarchical FDD schemes and why are they needed?

There is no commonly accepted definition of what constitutes a hierarchical FDD scheme. Hence, this subsection will describe some of the many meanings of the term.

Experience has demonstrated that reasoning associated with even simple diagnostic problems can be quite complex. A common approach to dealing with this inherent complexity is to decompose a problem into smaller sub-problems that use a subset of the inputs and that have fewer possible outcomes. Figure B1 provides an example of

this type of hierarchical approach with shaded rectangles and bold lines used to indicate the path followed. The AHU subsystem-level FDD classifier receives various input data and determines that the fault exists in the coil and filter section. The coil and filter section FDD classifier receives input data that may be a subset, a superset, or independent of the data used at the higher level. This classifier produces an output that identifies the cause of the fault – in this case a stuck valve. Lee et al. described an approach such as this for implementing a neural-network based FDD method for AHUs [Lee et al., 1997]. It can be argued that most, if not all, stand-alone FDD modules include an embedded hierarchy that simplifies the process of inferring the present state of operation of a system. Perhaps the single most compelling reason for developing “hierarchical FDD schemes” is that they help simplify the inference of faults in complex systems. Developers of FDD schemes for HVAC systems have seemingly accepted this notion by focusing their efforts on specific systems/subsystems rather than attempting to develop a single FDD algorithm that encompassed the details of all HVAC equipment in a building.

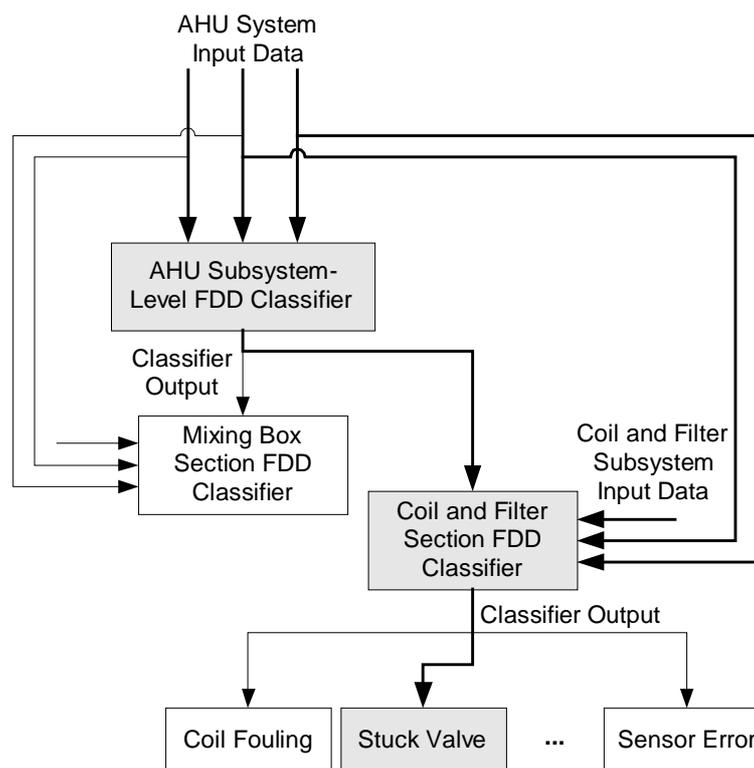


Figure B1. Stand-alone FDD tool with an embedded hierarchy to simplify the inference process.

Developers of stand-alone FDD tools have traditionally used one of two approaches for assessing the operation of HVAC equipment and systems. The first approach, termed the top-down (or whole-building) approach [IEA Annex 25, 1996], uses performance

measures from higher levels of the building/system/controller hierarchy to reason about possible lower-level causes of degradations to those higher level measures. For instance, if building energy use exceeds its expected value by an amount considered to be significant, top-down reasoning would be used to navigate down through the hierarchy and isolate the most probable explanation(s) for the excess energy use. An example of this approach is described by Dodier and Kreider [Dodier and Kreider, 1999]. The second approach, termed the bottom-up (or component level) approach, uses performance measures at lower levels of the hierarchy to isolate problems such as stuck valves and coil fouling. In theory, this information could be propagated up through the hierarchy to determine its impact on building performance. Katipamula et al. describe a rule-based method for AHUs that computes the energy cost of various faults associated with economizer operation [Katipamula et al., 1999]. This cost information can be used to prioritize maintenance.

Two basic questions have to be considered regarding the implementation of a hierarchical FDD scheme in the BEMS, namely,

Where in the BEMS hierarchy should the FDD scheme be located?

What type of architecture is needed to enable multiple FDD tools to work cooperatively?

Implementation of FDD schemes in BEMS clearly requires consideration of the physical hierarchy of distributed control systems. Much of the development of stand-alone FDD modules for HVAC systems has been performed by individuals outside private industry. For this reason, only limited attention has been given to implementation issues. Figure B2 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 primarily 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 would tend to be 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 depicted in Figure B2, 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.

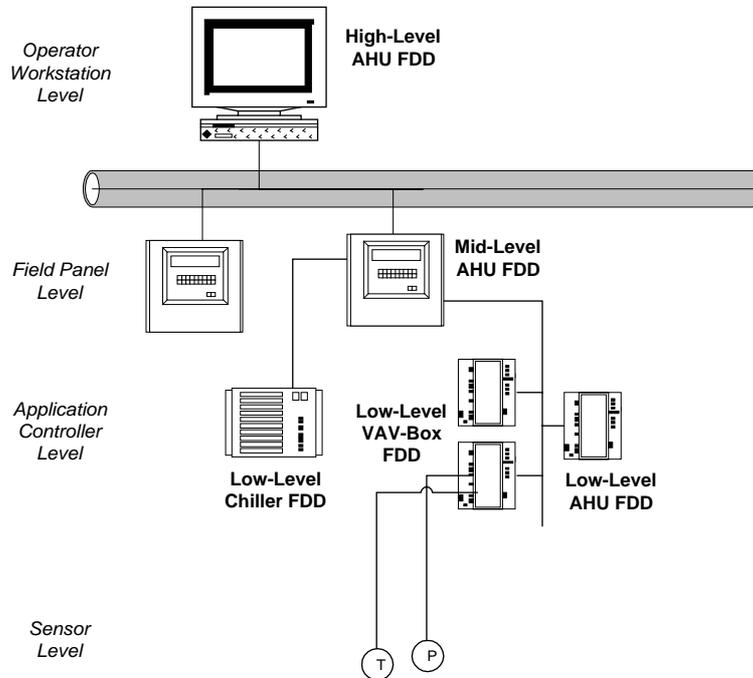


Figure B2. Distributed control system architecture showing stand-alone FDD tools embedded at different levels of the control system.

The development of stand-alone FDD tools was a logical starting point for improving the operation of HVAC systems. However, there is some danger in deploying numerous stand-alone FDD schemes that lack integration. First, building operators may become frustrated by seemingly conflicting information that may be produced. More importantly though, building operators do not have time to monitor numerous FDD modules. They need automated diagnostic capabilities that integrate and summarize the information provided by related FDD schemes. As the technology matures further, it is anticipated that FDD modules will one-day 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 will likely become 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.

B.8.3 Requirements for enabling integration of FDD schemes in a hierarchical structure

For many years, building owners and operators were plagued by the inability of HVAC control systems from different companies to communicate with one another. More recently, the standardization of open communication protocols such as BACnet™ has given building owners much greater flexibility in specifying control systems, and has simplified the task of monitoring operations when the control systems come from multiple vendors. Standardization of data exchange will also be necessary to enable the expansion of FDD from stand-alone tools to hierarchical FDD tools that integrate the information from these stand-alone tools in some higher-level reasoning scheme. At this point it is not clear what information will need to be exchanged to enable this integration. One could envision that various systems and pieces of equipment would have standardized fault lists. A stand-alone tool might produce an output of fault or no fault. In the fault case, a diagnosis and an associated confidence level or degree of belief would be produced from the standard fault list.

In addition to information about the operating status, the standardized data might include measurements and control signals directly linked to interfaces between different systems. This information may be necessary for resolving conflicting diagnoses. Conflict resolution of this nature will likely arise when integrating information obtained from two or more FDD schemes that act independently, but are linked in the sense that an interface exists between the systems they monitor, thereby allowing each to be influenced by the same physical effect. As an example, performance problems associated with a chiller may be detected by an FDD scheme dedicated to the chiller and by a second FDD scheme dedicated to an air-handling unit that receives chilled water from that chiller. A supervisory FDD scheme would use the information produced by each of the lower-level independent FDD schemes to reason about the most likely cause and/or location of the problem. Conflict resolution is similar to “command fusion”, where control actions suggested by various control algorithms are combined (or fused) to generate the control action that is implemented. Expert and fuzzy reasoning models are often used as the basis for fusing such information. Identifying appropriate interfaces and rules governing behavior on either side of the interface appear to be key aspects of developing higher-level FDD schemes that perform conflict resolution.

In addition to standardized data exchange between FDD tools, it is also envisioned that an architecture for implementing hierarchical FDD schemes will be needed. The architecture depicted in Figure B3 provides a structure for implementing higher-level reasoning, such as deciding the true source of an alarm when two or more lower-level FDD schemes indicate that the problem resides in the system they monitor. The primary components of a hierarchical FDD scheme are FDD modules and blackboards.

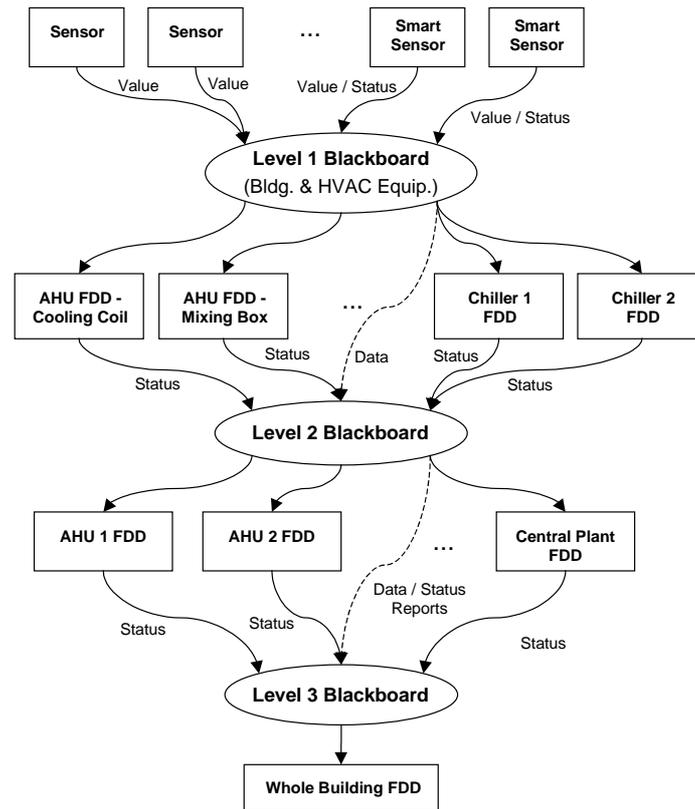


Figure B3. Hierarchical FDD structure for integrating information from stand-alone FDD tools.

Blackboards are essentially data repositories, and the adoption of the term “blackboard” is based on a desire to parallel the terminology used for a particular hierarchical structure used in some knowledge-based systems [De Silva and Lee, 1994]. FDD modules take information (e.g.; measurement and design data, FDD status reports from lower levels in the hierarchy) from blackboards, produce status reports, and pass these reports to the next higher blackboard (assuming one exists).

The building and HVAC equipment can be thought of as being the Level 1 blackboard. That is, because stand-alone FDD modules could very well be implemented in local controllers throughout the distributed control system, the information they require (design information and sensor data) would also need to be distributed. Examples of Level 1 stand-alone FDD modules include methods applied to subsystems of an AHU (e.g., cooling coil subsystem, mixing box subsystem), and methods applied to unitary equipment such as chillers. AHU FDD modules and whole building FDD modules that use only design data and sensor data would also reside at Level 1. Status reports from Level 1 FDD modules would be passed up through the distributed control system to the operator workstation, where they would be stored in the Level 2 blackboard. Examples of Level 2 FDD modules include methods for AHUs that combine information from the

AHU subsystem diagnostics at Level 1. Finally, at Level 3, whole building FDD might be performed. Blackboards and FDD modules for Levels 2 and 3 would likely reside in the operator workstation. Figure B3 gives the appearance that the blackboards at different levels would be a single repository for all information at that level. In fact, there could be multiple repositories at different levels distributed throughout the control system.

B.8.4 Examples of Annex 34 hierarchical FDD schemes

While most of the FDD tools implemented by Annex 34 participants are stand-alone tools, there are examples that can be described as hierarchical. A hierarchical FDD tool for VAV boxes was developed by the Canadian participants to the Annex. The system is integrated within the hierarchical organization of the BEMS. The FDD method is aimed at detecting faults at the lower level (VAV boxes) and performing some limited diagnosis functions. Only the diagnosis output and certain data are transferred to the central network where they are further processed. Thus, this tool has both functional hierarchy (i.e., the intelligence of the tool is divided in a hierarchical structure) and physical hierarchy (i.e., the intelligence of the tool is implemented at different physical levels of the BEMS hierarchy).

Seem et al. describe a similar type of tool for VAV boxes [Seem et al., 1999]. The tool consists of performance indices for control loops that are computed at the VAV box local controller to alleviate data traffic on the network. The performance indices may be used to quantify information about the amount of travel of an actuator, the difference between the desired process output and the actual output, saturation of a controller, etc. The performance indices of large numbers of VAV boxes can be accessed simultaneously from a central location in order to observe outliers in the data. As in the previous example, this tool has a functional hierarchy and a physical hierarchy. The functional hierarchy consists of first computing performance indices for individual VAV boxes and then comparing the performance indices with those of other VAV box controllers to detect outliers. The physical hierarchy consists of the performance indices being computed at the local controller level, and the comparison of the performance indices at a higher level of the BEMS hierarchy.

B.8.5 Conclusions

By focusing initial FDD tools on particular systems and subsystems rather than attempting to develop comprehensive tools addressing all possible faults, FDD tool developers have seemingly accepted the notion that a hierarchical structure is needed. Furthermore, stand-alone FDD tools are routinely designed with an embedded

hierarchical structure that helps simplify the inference of faults within the domain of application of that method. Implementation of FDD tools in BEMS requires consideration of the functional hierarchy of the tool and the physical hierarchy of distributed control systems. Ultimately there is a desire to integrate stand-alone FDD tools in a hierarchy that will utilize this distributed intelligence to produce a comprehensive and consistent description of the state of all HVAC equipment and systems in a building. To reach this goal, a standard for data exchange between FDD tools and a structure for handling the data flow is needed. These remain as challenges to the developers and implementers of FDD tools.

B.9 REFERENCES

Bourdouxhe, J-P. and Seutin, H. 1998. Fault detection and diagnosis of an air-handling unit of a big office building, Paper P44, Proc. System Simulation in Buildings SSB'98, Liege, Belgium.

Building Control Group, 1995. Control Sensor Installation.

Buswell, R., Haves, P. and Salsbury, T. I. 1997. A model-based approach to the commissioning of HVAC systems, CD-ROM of Proc. Clima 2000, Paper 237, Brussels, Belgium.

Carling, P. and Isakson, P. 1999. Temperature measurement accuracy in an air-handling unit mixing box, Proceedings of the International Symposium on HVAC 99, Shenzhen, November.

Carling, P. and Isakson, P. 2000. Temperature efficiency as a performance index to detect air-side fouling of coils, submitted for publication.

Carling, P. and Zou, Y. 2001. Comparison of CFD simulations and measurements of the stratification in a mixing box of an air handling unit, accepted for publication in the International Journal of Energy Research.

Costic 1992. Capteurs et Compteurs dans les bâtiments, PYC Edition, 1992.

Fahlen, P. 1993. Demand controlled ventilating systems-sensor tests, Air Infiltration Review, Vol. 14, No. 3, June.

De Silva, C. W. and Lee, T-H. 1994. Knowledge-based intelligent control, Measurements and Control, April.

Dexter, A. L. and Benouarets, M. 1997. Model-based fault diagnosis using fuzzy matching, Trans IEEE on Systems, Man, and Cybernetics – Part A, Vol. 27, No. 5, pp. 673–682.

Dodier, R. H., Curtiss, P. S. and Kreider, J. F. 1998. Small scale on-line diagnostics for an HVAC system, Trans. ASHRAE 104(1).

Dodier, R. H. and Kreider, J. F. 1999. Detecting whole building energy problems, Trans. ASHRAE, 105(1), pp. 579–589.

Glass, A.S. and Tödtli, J. 1996. Testing qualitative model-based fault detection for air-handling units using operational building data, Technical Papers of IEA Annex 25 (Ed. J. Hyvärinen), VTT Building Technology, Finland, pp. 227–247.

Gruber, P. and Kaldorf, S. 1998. Performance Audit Tool PAT: ein Expertensystem zur Detektion und Diagnose von Fehlverhalten von HLK-Anlagen in realen Gebäuden, 10. Schweizerisches Status-Seminar Energieforschung im Hochbau, EMPA-KWH.

Gruber, P. and Kaldorf, S. 2001. Performance Audit Tool PAT: an expert system for the detection and diagnosis of building under-performance, to appear in ASHRAE Transactions.

Hartman, T. B. 1993. Direct digital control for HVAC systems, New York: McGraw-Hill.

Heinemeier, K. H., Richardson, R. M. and Kulathumani, K. 1999. User and market factors that influence diagnostic tool development, published in Workshop Proceedings: "Diagnostics for Commercial Buildings: from Research to Practice". Pacific Energy Center, San Francisco CA. <http://poet.lbl.gov/diagworkshop/>

Henry, M. 1995. Sensor validation and fieldbus, Computing and Control Engineering Journal, December.

House, J. M., Vaezi-Nejad, H. and Whitcomb, J. M. 2001. An expert rule set for fault detection of air-handling units, to appear in ASHRAE Transactions.

IEA Annex 25, 1996. Building optimization and fault diagnosis source book, Eds. J. Hyvärinen and S. Kärki, Technical Research Centre of Finland.

Kärki, S. and Leskinen, M. 1999. A fault detection and diagnosis system as a tool in energy efficient building use, Proc. 3rd International Symposium on Heating, Ventilation and Air Conditioning, Shenzhen, China, pp. 905–913. ISBN 962-367-255-1.

Katipamula, S., Pratt, R. G., Chassin, D. P., Taylor, Z. T., Gowri, K. and Brambley, M. R. 1999. Automated fault detection and diagnosis for outdoor-air ventilation systems and economizers: methodology and results from field testing, Trans. ASHRAE, 105(1), pp. 555–567.

Lee, W. Y., House, J. M. and Shin, D. R. 1997. Fault diagnosis and temperature sensor recovery for an air-handling unit, Trans. ASHRAE, 103(1), pp. 621–633.

- Lee, W. Y., Park, C. and Kelly, G. E. 1996. Fault detection in an air-handling unit using residual and recursive parameter identification methods, *Trans. ASHRAE* 102(1).
- Li, X., Visier, J-C. and Vaezi-Nejad, H. 1997. A neural network prototype for fault detection and diagnosis of heating systems, *Trans. ASHRAE* 103(1).
- Nakahara, N., Zheng, M. and Nishitani, Y. 1997. Simulation and fault detection of thermal storage system, *Proc. IBPSA Conf. Building Simulation '97*, Prague.
- Ngo, D. and Dexter, A.L. 1999. A robust model-based approach to diagnosing faults in air-handling units, *Trans. ASHRAE*, Vol. 105(1).
- Norford, L. K. and Little, R. D. 1993. Fault detection and load monitoring in ventilation systems, *Trans. ASHRAE* 99(1).
- Pape, F. L. F., Mitchell, J. W. and Beckman, W. A. 1991. Optimal control and fault detection an heating, ventilating, and air-conditioning systems, *Trans. ASHRAE* 97(1).
- Peitsman, H. C. and Soethout, L. L. 1997. ARX models and real-time model-based diagnosis, *Trans. ASHRAE* 103(1).
- Rossi, T. M. and Braun, J. E. 1997. A statistical, rule-based fault detection and diagnostic method for vapor compression air conditioners, *IJHVAC&R Research* 3 (1).
- Ruud, S. H. 1997. Fault detection method based on steady-state models and statistical residual analysis, *Licentiate Thesis, Building Services Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden.*
- Salsbury, T. I., Haves, P. and Wright, J. A. 1995. A fault detection and diagnosis method based on first principles models and expert rules, *Proc. 1st Int. Symp. on HVAC*, Tsinghua.
- Sauter, D., Mary, N., Sirou, F. and Thieltgen, 1994. Fault diagnosis in systems using fuzzy logic, *CCA '94*, Glasgow, Scotland.
- Seem, J. E. 1998. A new pattern recognition adaptive controller with application to HVAC systems, *Automatica*, Vol. 34, pp. 969–982.
- Seem, J. E, House, J. M., and Monroe, R. H. 1997. On-line monitoring and fault detection of control system performance, *Clima 2000*, P76, Brussels.

Seem, J. E., House, J. M. and Monroe, R. H. 1999. On-line monitoring and fault detection, *ASHRAE Journal*, Vol. 41, No. 7, pp. 22–26.

Seem, J. E., Park, C. and House, J. M. 1999. A new sequencing control strategy for air-handling units, *HVAC&R Research*, 5(1), pp. 35–57.

Shin, K. G., Krishna, C. M. and Lee, Y. H. 1985. A unified method for evaluating real-time computer controller and its application. *IEEE Trans. on Automatic Control*, Vol. AC-30, No. 4, pp. 357–366.

Shiozaki, J. and Miyachika, F. 1999. A fault diagnosis tool for HVAC systems in using qualitative reasoning algorithm, *Proc. IBPSA Conf. Building Simulation '99*, Kyoto, Japan.

Tessier, P. and Vaezi-Nejad, H. 2001. Fault detection and diagnosis tool for swimming pool plant operation, submitted to *Trans. ASHRAE*.

Tödli, J. 1996. Configuration and parameter setting as a critical issue for practical application. *IEA Annex 25, Building Optimization and Fault Diagnosis Source Book*, pp. 314–318.

VAISALA 1999. GMW20 series CO₂ transmitters, Operating manual.

Visier, J. C., Vaezi-Nejad, H. and Corrales, P. 1999. A fault detection and diagnosis tool for school buildings, *Trans. ASHRAE*, 105(1).

Wang, S. W. and Wang, J. B. 1999. “Law based sensor fault diagnosis and validation for building air-conditioning systems”, *International Journal of HVAC&R Research*, 5(4), pp. 353–380.

Yoshida, H. and Kumar, S. 1999. RARX algorithm based model development and application to real time data for on-line fault detection in VAV AHU units, *Proc. IBPSA Conf. Building Simulation'99*, Kyoto, Japan.

SECTION C: CASE STUDIES

C.1 QG-MET BUILDING IN NAMUR

Patrick Lacôte, FUL, Belgium

C.1.1 FDD tool

Work reported below focus on performance validation during the first months of operation of the building on one hand (fault isolation by manual checking and diagnosis tests) and on the other hand, on a global approach of an automatic (rule-based) FDD tool which could be used during the whole operating phase. In a first step, this tool is intended to work off-line on data from the BEMS. In a second step, it could be embedded in the BEMS (this tool is not implemented yet).

C.1.2 Intended end-user

The intended end-user are building operators and operating maintenance team.

C.1.3 FDD method

Automatic FDD tools have to be developed in order to detect faults during the operating phase of the building. In this case, the operation of the building started during the period devoted to the research so that feedback on faults which would be worth to detect during the operation stage was not sufficient. Nevertheless, this performance validation is a very interesting approach on typical faults that occurred during the first months of the operation of the building. But for most of them, faults are issued from the design and construction phases and this poor performance doesn't allow to test an FDD tool. So, in order to reach this goal, the first step for implementing an FDD tool consisted in validating the measurement and the control systems. Typical faults were found (see Results of trial) and some rule-based laws were developed to detect some of them which are likely to occur again during the next years of the operation phase.

C.1.4 Test building, plant and control system

Building

The building is designed for a one thousand occupants and is made of 13 modules representing together 15 000 m² of gross floor area. Each module can be subdivided in three sections, from South to North:

1. The southern building
2. The atrium (or the interior street)
3. The northern building

The division appears different for the central module, which constitutes a "welcome area" for the whole building. Most of the useful area of the building consists in offices distributed on four rows (two in each building, separated by a corridor) and three to five levels.

HVAC plant

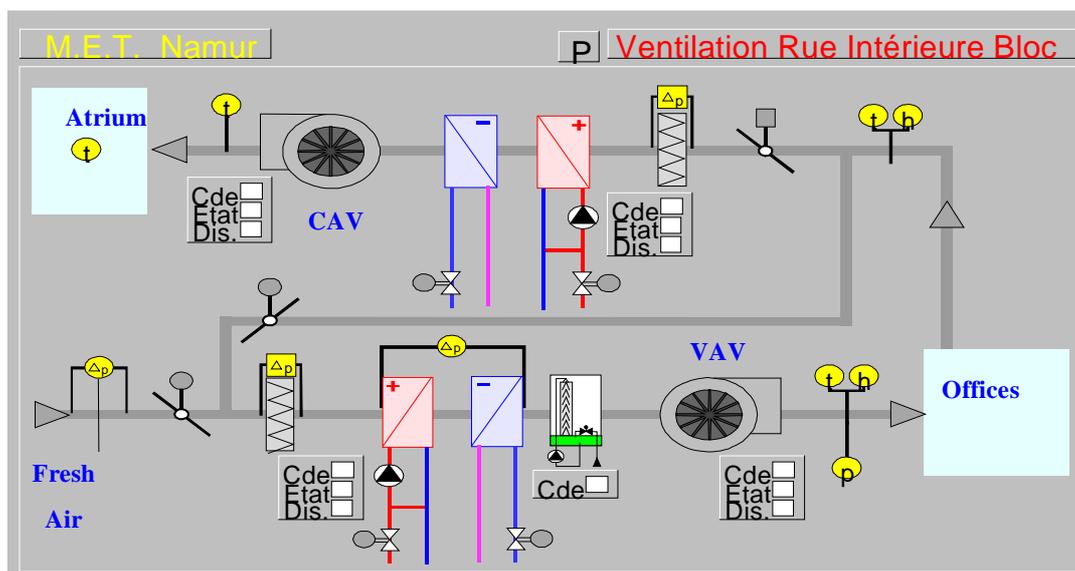


Fig. C1. Schematic of typical offices-atrium AHU's.

The QG-MET building is characterized by a complex HVAC plant made of the following components:

- Centralized production of heating and cooling using:
 - 3 boilers (operating in cascade)
 - 2 chillers (reciprocating compressors with air condensers).
- Heating and cooling power is distributed through collectors to 14 substations. Most of the substations, divided in northern and southern parts are feeding two building modules. In each substation, distribution of heat is organized from local collectors who are feeding the different entities connected thereto. In each substation, the AHU's feeding the offices and the atrium are connected to each other in that a fraction of the air extracted from the offices is ventilated in the atrium. The part that is not injected in the atrium AHU's is re-circulated in the offices or extracted through the toilets. Ventilation in the atrium is happening at constant flow rate (CAV system)

while ventilation in the offices is made through a VAV system. A constant fresh air flow rate is furthermore provided in the office. Figure C1 shows a schematic diagram of a coupled offices-atrium AHU. Some rooms (meeting-rooms) are provided with fan-coils which ventilate air, pre-heated at 20 °C.

- The Air Handling Units are made of the following components: mixing box, filter, heating coil, cooling coil (not present in the fan coils AHU's), humidifier, fan.
- Energy is distributed in the room by means of radiators (heating), fan-coils (heating and cooling) or VAV boxes (cooling and ventilation). Thermostatic valves or VAV terminals provide local control.

Control system

The Building Energy Management system is controlling both the Air Handling Units and the radiators heating circuits. For AHU's, the strategy consists in controlling the valve of the heating or cooling coil in order to modify the supply air temperature according to the return air and the outside air temperature conditions.

The control is thus performed following two steps:

- Return temperature setpoint calculation (including summer weather compensation)
- Supply air temperature set point calculation from the difference between return temperature measurement and its set point (including winter weather compensation).
- Valves signal control (by a classical PI algorithm).

For radiators heating circuits, control is changing the water supply temperature depending upon both the external conditions (temperature) and the internal climate (reflected by a room temperature sensor).

C.1.5 Faults to be identified

Different simple rules were developed to detect faults on:

- equipment and actuator: fan cut-off and heating/cooling coil valve stuck.

In that case, the rule-based methods compare measurements of temperatures, pressures, valves and fan modulation.

- sensors: drift and bias (concerned outside air temperature sensors (E, W and N/W), supply and return temperature sensors, supply pressure sensor and fresh air and heating/cooling coils pressure drop sensors).

Here the method proposed is based on cross-validation routines which could be run during the night when the AHU's are off.

- control system: improper controller input (concerned sensors connected to the electrical supervisory system).

The method proposed to detect noise on the measurement chains is based on the calculation of statistical indices.

C.1.6 Sensors used

The sensors used in the FDD rules are the following:

- fresh air and coils pressure drop sensors
- supply pressure sensor
- supply and return air temperature sensors
- zone temperature sensor (one room connected to the AHU)
- indoor air quality sensors (only in 6 testing offices: temperature, humidity and CO₂ concentration measurements)
- outside air temperature sensors (E, W, N/W)
- fan speed modulation and control signal
- water pump control signal
- cooling and heating coils valve modulation signal

C.1.7 Design data used

The following data were used to perform preliminary fault detection methods:

- static pressure, supply and return temperature set points.

C.1.8 Training data required

The FDD tool is not implemented yet, so no recommendation on required data.

C.1.9 User interface

The FDD tool is not implemented yet, so no user interface realized.

C.1.10 User selected parameters

The FDD tool is not implemented yet, so no recommendation on user selected parameters.

C.1.11 Threshold selection method

The FDD tool is not implemented yet, so no recommendation on threshold selection.

C.1.12 Results on trials

The automatic FDD tools expected to run during the whole operation life of the building is not implemented yet, no result can be illustrated.

On the other hand, the performance monitoring realized on the building during the first years of its operation allowed to isolate faults classified (according to B2, B5 and B7 sections) as:

Natural faults

- design faults: building (1), equipment's (3), sensors(2), actuator(1), control system (3)
- construction fault: equipment's (4), sensors (3), actuator (1), control system (6)
- operation stage faults: equipment's (3), sensors (5), control system (1), actuators (1)

Artificial faults

- equipment's (3)

Simulated faults

- equipment's (1)

The results of the performance validation are the following:

- First, most of the faults observed should have been detected and eliminated during the commissioning process (24/40, design and construction faults). This kind of faults does not require an automatic FDD tool.
- Nevertheless, some of the faults observed during the monitoring periods can also appear during the operation life of the building (operation stage faults). For these faults, the development of a preliminary FDD tool (described above) was initiated.
- Finally, some faults also occurring during the monitoring processes allow us to validate some simulation tool (artificial and simulated faults).

C.1.13 Satisfaction of user requirements

The FDD tool is not implemented yet, so no feed back on satisfaction of the users requirements.

C.2 FAULT DETECTION AND DIAGNOSIS TOOL FOR VAV BOXES

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C.2.1 FDD tool

The FDD tools developed uses the combined application of control loop indices and expert rules to detect and diagnose faults on Variable Air Volume (VAV) terminal boxes.

C.2.2 Intended end-user

The intended end-users of the described tool are building operators and service company personnel. The tool is embedded in each box controller and results are reported in graphic form on the Building Operating Station (BOS). The tool is a module of our Diagnostic Agent for Building Operators (DABO) which serves as the interface between the end-user, the energy management and control system or a database and the fault detection and diagnosis software.

C.2.3 FDD method

Fault Detection and Diagnostics (FDD) are based on the analysis of control point data. The implementation of FDD on this type of equipment requires the management and processing of many different points, hence the importance to find a method that minimises the use of points, data and DDC working memory.

The FDD method uses a combination of control loop performance indices with a set of expert rules. Control loop performance indices evaluate the stability of setpoints and controller outputs while rules filter transient state and provide other diagnostics.

Control loop performance indices use simple statistical functions and minimal historical data; this allows the direct implementation inside the DDC box controllers. This way, only residual output and results have to be transferred to a master panel or a central database to finalise a diagnosis and inform the user. This method reduces the traffic level on the building control network and ensures the data transfer required for other operations.

FDD is primarily intended to detect faults that are normally missed by conventional systems as well as provide a low-level diagnosis. To meet the objectives, the method must be able to analyse data in real time and at high frequency. When we combine this data requirement with the quantity of VAV boxes in a building, we chose to embed our

FDD tool directly in each box controller. Only diagnostic output and limited data need be transferred to the central network on a longer time interval. This significantly reduces traffic and the risk of traffic on the control network.

The FDD procedure begins with the filtering of input data, followed by the detection of unstable setpoints and control outputs. Verification is done to make sure that setpoints are satisfied before a diagnostic transmission is sent to the BOS. Values ranging from 0 to 4, where each represents a specific fault, are sent to the BOS. The value 0 indicates no fault, 1 unstable airflow setpoint, 2 airflow setpoint not satisfied, 3 unstable airflow, and 4 temperature setpoint not satisfied.

C.2.4 Test building, plant and control system

The test plant is the M3 AHU dedicated to conditioning the office space at the CEDRL located in Varennes, Québec, Canada.

The 5500 l/s air handling unit has outdoor, mixing and return air dampers, hydronic cooling and heating coils, an air filter section, a supply fan, a return fan, an air plenum section and an electronic humidifier. The supply air is ducted to 35 VAV boxes that supply air to 35 different office zones. Both supply and return fans are fitted with inlet vanes.

The air handler and VAV boxes are controlled by a direct digital control system (DDC). The unit uses a pressure independent VAV system and attempts to maintain a constant static pressure at the VAV box inlets by sensing and controlling pressure in the supply duct. A static pressure controller with a PID algorithm sends a control signal to an inlet vane actuator, which regulates the capacity of the supply fan. The supply airflow is measured and the desired return airflow is calculated (supply airflow minus both the airflow through the local exhaust fans and the amount of airflow required for building pressurisation). The desired return airflow rate is compared with the actual return rate and the difference is used in a PID algorithm to set the inlet vanes on the return fan.

Terminal boxes used for this project are the pressure independent VAV type and control the amount of airflow in local rooms in order to maintain a room temperature setpoint. The FDD algorithm was deployed on three of the 35 VAV boxes connected to the M3 AHU.

C.2.5 Faults to be identified

VAV boxes are relatively simple, but because of their huge quantities and their disparate locations in false ceiling areas, they benefit from almost no preventive maintenance. It is common to find more than 100 boxes in a simple medium sized building.

VAV box faults can produce occupant discomfort, equipment wear, energy waste, especially when equipped with terminal or remote reheat and a global reduction in ventilation system efficiency. Without an FDD tool, faults generating complete dysfunction are normally detected by occupant complaints or single alarm points from Building Energy Management Systems (BEMS). Faults causing equipment wear are rarely detected.

As FDD tool complexity is limited by the VAV box DDC memory, efforts were concentrated on developing a simple algorithm that particularly detects faults that are usually not detected by conventional alarms. Symptoms, faults and detection and/or diagnosis capability of the tool are listed in Table C1.

Table C1. VAV fault detection characteristics.

Symptoms	Potential Faults	Detection	Diagnosis
Setpoint instability	Poor tuning of temperature controller	X	X
Control output instability	Poor tuning of airflow controller Unstable AHU supply air	X	X
Temperature higher or lower than setpoint	Damper, actuator defect Heating valve or actuator defect Flow or temperature sensor defect	X	
Airflow set higher or lower than setpoint	Damper, actuator defect Flow or temperature sensor defect	X	

C.2.6 Sensors and control signals used

The following sensors and setpoints are used:

- Room temperature sensor
- Air velocity sensor
- Room temperature setpoint
- Airflow setpoint

C.2.7 Design data used

VAV box type and control strategies.

C.2.8 Training data required

No training data is required for this method.

C.2.9 User interface

The interface is divided into two parts, parameters that are configured in the OWS of the BEMS and graphical summary reports showing the behaviour of VAV boxes, which are generated in DABO.

C.2.10 User selected parameters

Airflow:

Threshold

Filter rate constant, setpoint, error

Threshold duration not satisfied

Maximum permitted variance

Number of permitted reversals

Temperature:

Threshold

Threshold duration not satisfied

Filter constant

C.2.11 Threshold selection method

Before implementing the algorithm in the VAV box controller, its capability was tested on a controller output simulator developed specifically for this application.

The simulator allowed the simulation of hypothetical standard output curves and the visualisation of their impact in real time on the variables of the algorithm. This allowed the method to be validated under controlled conditions.

This method considerably reduces implementation time and helps in the selection of the threshold value.

C.2.12 Results of trials

In field trials, the building operating station software "Delta Commander", which allows the user to communicate with the building control panels, has been used to verify sensors, introduce faults, calibrate thresholds, acquire data and report faults in real time. The graphical summary reports are generated through the DABO interface. Figures below show how the data is presented graphically in DABO and BEMS.

C.2.13 References

T.I. Salisbury. 1999. "A practical algorithm for diagnosing control loop problems", *Energy and Buildings* 29 (1999), pp. 217–227.

John E. Seem, John M. House, and Richard H. Monroe. "On line monitoring and fault detection of control system performance", *Clima 2000 Conference* (1997), Brussels, Belgium.

A.S. Glass, P. Gruber, M. Ross and J. Todtli. "Qualitative Model-Based Fault Detection in Air-Handling Units" *Control Systems Magazine*; Vol. 15, issue 4, pp. 11–22; August 1995.

C.3 FAULT DETECTION AND DIAGNOSIS TOOL FOR AHU

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C.3.1 FDD tool

The FDD tool was developed to detect and diagnose faults in HVAC air handling units, and is integrated in a software tool DABO (Diagnostic Agent for Building Operators).

The tool optimizes the detection process by applying methods that are custom designed for the component in question and by reducing data traffic on control networks. The tool is capable of detecting thirty faults that occur in an air-handling unit.

C.3.2 Intended end-user

The intended end-users of the tool are building operators and service company personnel. The tool is a module of our Diagnostic Agent for Building Operators (DABO) which serves as the interface between the end-user, the energy management and control system or a database and also the fault detection and diagnosis software.

C.3.3 FDD method

The FDD method consists primarily of expert rules that are grouped according to the operating mode of the air-handling unit. The general architecture of the FDD application is illustrated in Figure C2. The rules were grouped into 11 sets or modules. The modular structure of the application allows partial or full implementation of specific rule modules depending on the degree of sophistication of the building's BEMS and also facilitates manageability, modifications and reuse. The rules are integrated within DABO, which provides the communication link between the database of measured building data and the expert system's working memory.

A steady state detector is directly embedded in the system's control panel. The method is based on control loop performance indices that use statistical functions to determine the stability of controllers and set points. The stability of the controllers and set points is stored as a variable (0 for stable, 1 for unstable) in the SQL server database at the same frequency as all other measured building data.

The Data Module, which is an integral part of DABO, presently retrieves data required by the expert rules from the SQL database at a user-specified interval, filters the data to eliminate outliers (extreme values), and calculates the average of each point. A future version of DABO will allow data to be taken directly from the control panel via a DDE link, thus eliminating the need for the SQL database. Finally, the Data Module transfers

the averaged values to the working memory of the expert system and calls the expert rules.

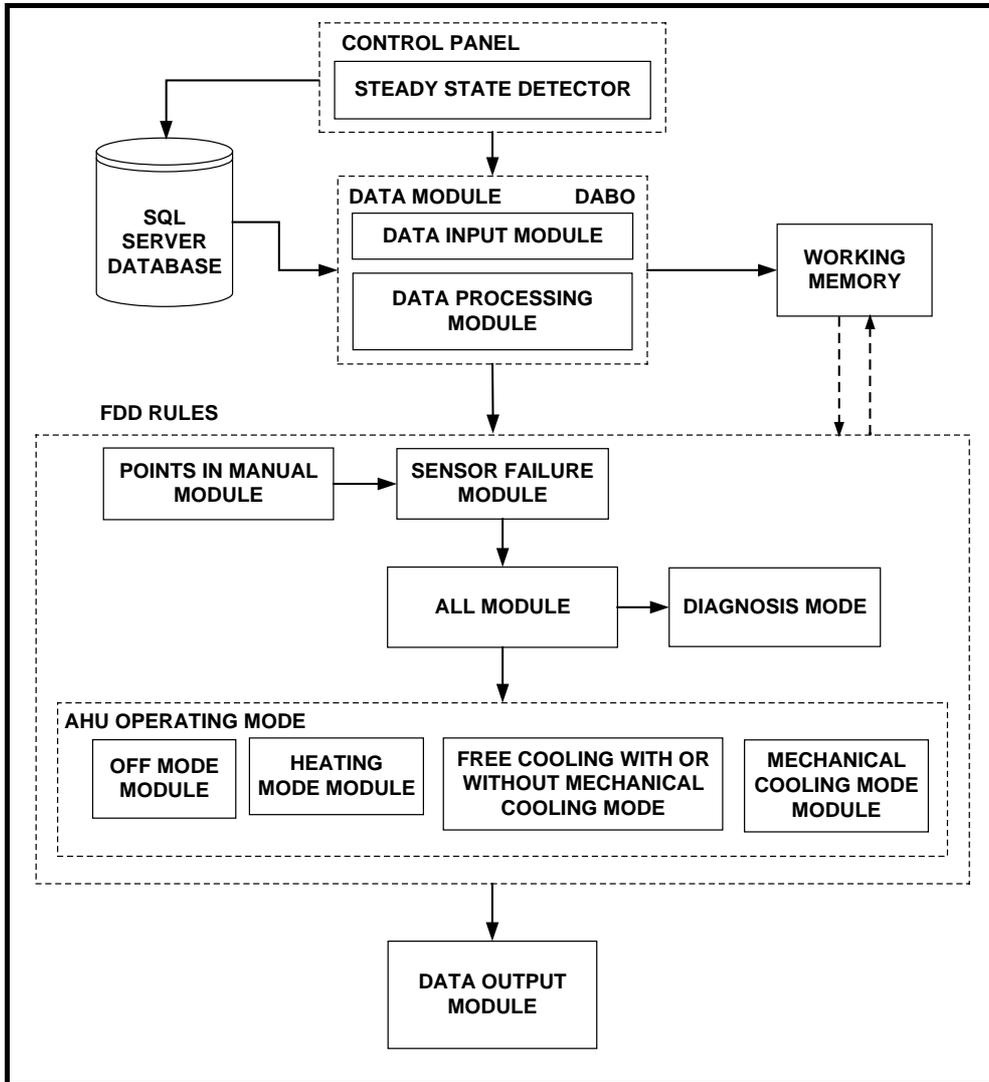


Figure C2. Modular architecture of the AHU FDD system implemented in DABO.

The Points in Manual Module consists of rules that determine whether a measured point is set in manual mode or in the default automatic mode on the control system. A fault is indicated when the point is in manual mode.

Rules in the Sensor Failure Module verify whether the measured signal of temperature, humidity and pressure sensors are within prescribed limits. If the measured signal does not fall within those limits, complete sensor failure is indicated, and its corresponding value is removed from the working memory to prevent false alarms.

The All Module contains rules that are run prior to the remaining rule modules. This module verifies whether the controllers and supply air temperature set point are stable, and also verifies control signals for dampers and coils against feedback values. Rules in this module identify single faults such as stuck or faulty indication of damper position,

stuck or faulty indication of valve position, improper controller tuning, and software fault.

The Diagnosis Mode consists of a system test in which the AHU is operated in recirculation mode; this module allows the expert system to identify faults primarily associated with sensor calibration.

Remaining rule modules are called depending on the operating mode of the AHU: off mode, heating mode, free cooling mode, and mechanical cooling mode. With the exception of the off mode, the remaining modes are determined based on outdoor air temperature.

C.3.4 Test building, plant and control system

The test building is the CEDRL energy research laboratory located in Varennes, Québec, Canada. The M3 AHU serving the office space has been selected for the field test.

The 5500 l/s air handling unit has outdoor, mixing and return air dampers, hydronic cooling and heating coils, an air filter section, a supply fan, a return fan, an air plenum section and an electronic humidifier. The supply air is ducted to 35 VAV boxes that supply air to 35 different office zones. Both supply and return fans are fitted with inlet vanes. The air handler and VAV boxes are controlled by a direct digital control system (DDC). The unit is a pressure independent VAV system and attempts to maintain a constant static pressure at the VAV box inlets by sensing and controlling pressure in the supply duct. A static pressure controller with a PID algorithm sends a control signal to an inlet vane actuator controlling the capacity of the supply fan. The supply air flow is measured and the desired return air flow is calculated (supply air flow minus both the air flow through the local exhaust fan and the amount of airflow required for building pressurisation). The desired return air flow rate is compared with the actual return rate and the difference is used in a PID algorithm to set the inlet vanes on the return fan. The unit is sequenced during the occupied period to provide heating, cooling, and ventilation based upon control of the discharge air temperature to meet the return air setpoint. An enthalpy control economiser allows cooling with cooler air, and humidification is provided to maintain a minimum setpoint of the relative humidity in the return air during winter.

C.3.5 Faults to be identified

The FDD method described is intended to detect symptoms that can be used to diagnose 30 possible faults. Faults include:

- 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
- Pump failure.

C.3.6 Sensors and control signals 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 temp. 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 temp. set point unstable
 Supply air temp. unstable
 Fault code
 Diagnosis mode
 Current transmitter pump 10, 11.

C.3.7 Design data used

Information from design data is needed to set the following configuration parameters in the FDD tool:

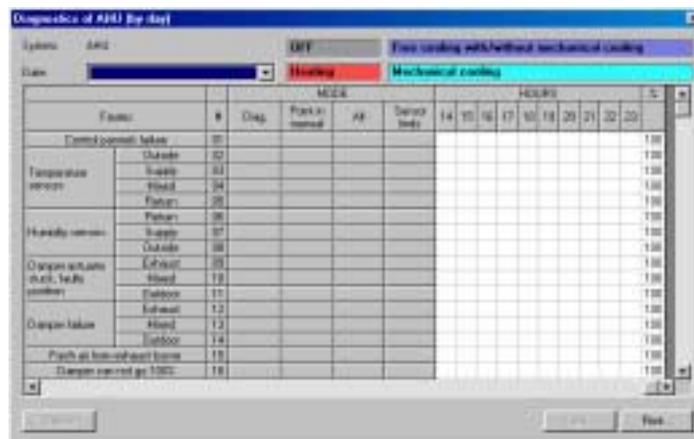
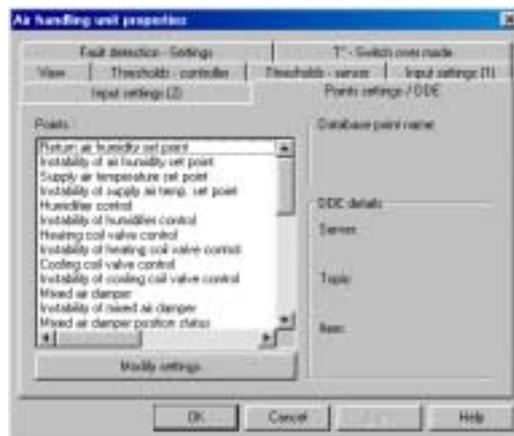
- Air handling system configuration and Control strategies
- Setpoint values (temperature, humidity and Outdoor air airflow rate)
- Winter and summer design temperatures.

C.3.8 Training data required

No training data is needed with this method.

C.3.9 User interface

The Figures below show the user interface for the current version of the AHU FDD.



The interface allows the configuration of the system, and the invoking of various detection modes. It can also ensure data communication and management between the building control system, database and expert shell as well as generate reports.

C.3.10 User selected parameters

Numerous configuration inputs are required to ensure the proper operation of the AHU FDD. In addition to the design data, the AHU FDD requires the following parameters:

- Minimum and maximum return air temperatures during winter and summer
- Temperature rise across supply and return fans

- Fresh air damper position at minimum ventilation
- Threshold on control values and sensor inputs.

C.3.11 Threshold selection method

Threshold levels are a function of the quality of the installed equipment and that of the commissioning procedures (if any) used during their installation. In the case of quality equipment, low thresholds allow the AHU FDD to perform early detection of faults. However, standard installation practices would require higher thresholds to avoid false alarms. As it is very difficult to evaluate the condition of the HVAC system prior to the FDD system implementation, thresholds are easily modifiable. In our case, thresholds have been manually selected after analysis of normal operating data.

C.3.12 Results of field trials

The building operating workstation software "Delta Commander" has been used to verify sensors and introduce faults on the AHU for the field trials. An SQL database is link to the building control system and is used for data acquisition and archiving. It is linked to DABO which is the user interface for the AHU FDD.

Data acquisition has been going on for a full year to test the validity and robustness of the FDD system under all controlled conditions. Table C2 summarises the tests done and methods used to introduce faults.

The tests carried out to date were meant to test the performance of the modules "diagnosis mode", "all mode" and "heating mode." Problems have been encountered in the filtering of the monitored data, consequently additional work will be required before a full report of the field trials can be presented.

C.4 DIAGNOSTIC AGENT FOR BUILDING OPERATION – CHILLER DIAGNOSTIC MODULE

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C.4.1 FDD tool

The Diagnostic Agent for Building Operators (DABO) is the environment in which fault detection and diagnosis of a number of HVAC equipment is carried out. It uses a number of methods to predict the energy performance of the building, detect problems as they occur and signal the operator when maintenance is required.

Architecture of diagnostic agent for building operators

The Diagnostic Agent for Building Operators is comprised of three interlocking modules: The building energy agent, the fault detection and diagnostic agent and the condition-based maintenance agent. The three modules interact with the Building Energy Management System (BEMS) through a database that holds the information from the BEMS (data, sequence of operations) and the reports from the Diagnostic Agent.

The Diagnostic Agent is configured by the specialized service person of the controls vendor and is completely transparent to the operator. The only interaction with the operator will be when the operator receives a message about a problem. At that point he/she can interact with the database to obtain more information about the problem and inquire whether it will be cost-effective to repair it.

Fault detection and diagnosis agent

Significant amounts of energy are wasted each year in commercial buildings due to inefficient operation of heating, cooling and ventilation equipment. Malfunction of these equipment that include chillers, boilers and air handling units, are estimated to increase energy consumption in commercial buildings by 10–35%, while many of these problems contribute to increased HVAC system electrical demand. Increased levels of demand on the order of 0.5–1.5 W/sqft are common. Often routine maintenance procedures do not recognize or correct these problems, and may, in some cases, cause them.

Since each HVAC system is somewhat different, the methods used to diagnose the performance of HVAC systems must be flexible enough to accommodate variations in system configuration, yet structured enough to ensure that the data and diagnostic procedures will sufficiently indicate any problems within the operation of the HVAC system.

The approach that has been used in the software development is to provide a method for a user to describe the HVAC system as a set of functional blocks. The operator will be

informed of problems using the report generator that is part of the Diagnostic Agent. The report will present the results of the diagnosis in a combination of graphs, facilitate the identification of problems and of diagnostic messages that indicate the probable cause of the fault.

C.4.2 Intended user

The intended user for DABO, and by extension, the chiller module is the building operator and facilities manager.

C.4.3 FDD method

Researchers have used a number of methods for detecting faults in vapour compression units. Although the available literature relating to fault detection and diagnosis applied to vapour compression equipment is limited, contributions have been made by Wagner and Shoureshi (1), Grimmelius et al. (2), Stylianou and Nikanpour (3), Rossi and Braun (4), and Stylianou (5).

The approach used for the detection of faults in vapour compression units is described in Stylianou (5), and is a combination of statistical modelling and pattern recognition that was used to develop a fault detection and diagnosis module for a chiller. This method was chosen because the vapour compression unit's performance is dependent on a limited number of variables, namely the condition of the air at the condenser and evaporator.

The method used is based on regression models. The monitored parameters are predicted by the model, and are based on the entering water temperatures at the evaporator and condenser.

The data is filtered and a model is developed for each of the monitored parameters. The model is then used to predict these parameters, which are subsequently compared to the measured ones. Differences between measured and predicted parameters are generated and used to plot graphs. The operator uses these graphs to detect the problem, based on the presence of the differences. Diagnosis of the fault is made based on the pattern of these differences.

C.4.4 Test building, plant and control system

The chiller serves the National Film Board Complex with an area of over 321,000 ft² located in Montreal, Canada.

The chilled water plant is composed of three low-pressure centrifugal chillers working with R123 and three cross-flow water towers. The three chillers are rated at 700, 670

and 500 tons. The 500-ton chiller, which is used for the purposes of the project, is the most energy efficient chiller and is used as the priority chiller working 12 months per year. During the winter months it is the only one, operating while in the summer months it satisfies the first 500 tons of load. Chiller #2 is also operable during the winter months and is used as stand-by for chiller #3. During the winter months, chiller #1 is off-line and cooling tower 1 is emptied.

The chiller used is a low-pressure, water cooled, centrifugal liquid chiller. It is manufactured by Trane (model CVHE). The chiller is composed of five basic components: the evaporator, a 3-stage compressor, a water-cooled condenser, a 2-stage economiser and interconnecting piping.

C.4.5 Faults to be identified

The faults to be identified are:

1. Condenser fouling
2. Evaporator fouling
3. Refrigerant Overcharge/Leak
4. Air in the system.

C.4.6 Sensors and control signals used

The monitored points are shown in Table C2, and the location of the sensors are shown in Figure C3. Data acquisition is carried out through the use of the TRACER BEMS.

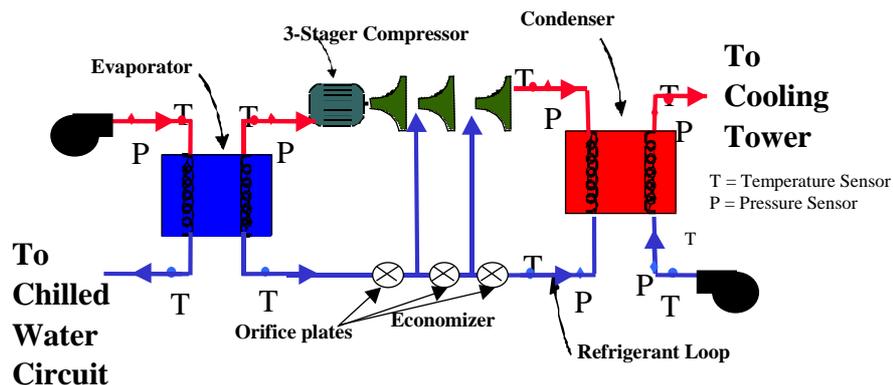


Figure C3. Sensor location for chiller.

Table C2. Monitored variables.

Water side	Compressor
Evaporator entering water temperature (EWT)	Differential oil pressure
Evaporator leaving water temperature (LWT)	Oil temperature
	Compressor speed command
Condenser entering water temperature	Discharge oil pressure
Condenser leaving water temperature	Oil tank pressure
	Compressor winding temperatures
	Inlet guide vane position
	Bearing temperatures
Refrigerant side	
Evaporator pressure	Electrical
Saturated evaporator temperature	Compressor Phase currents %RLA
Condenser pressure	Compressor Phase currents Amps
Saturated condenser temperature	Compressor phase voltages
Discharge temperature	Compressor power factor
	Compressor kW

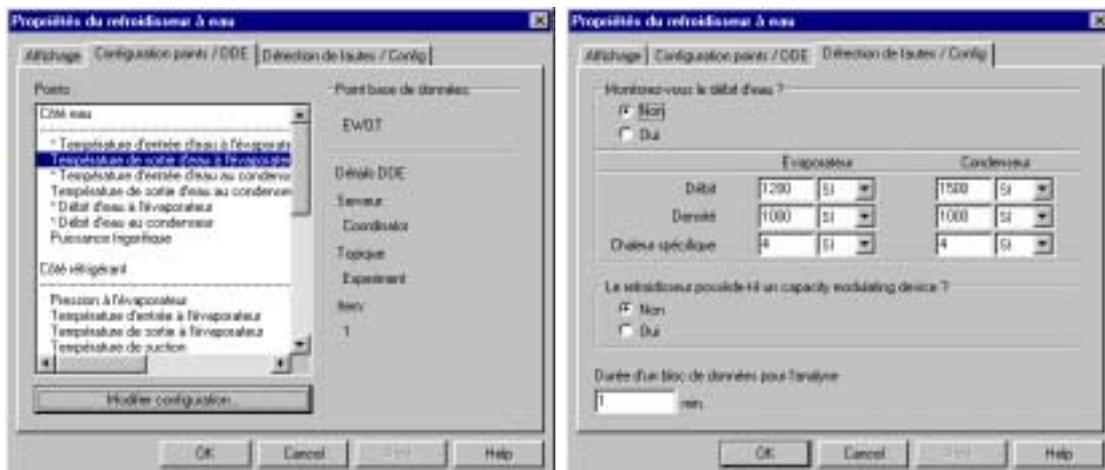
C.4.7 Design data used

No design parameters were used.

C.4.8 Training data required

Training data is required to develop the regression models.

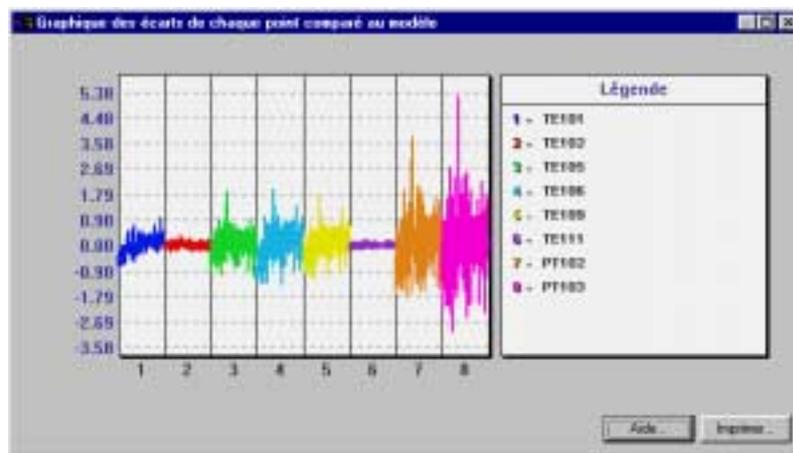
C.4.9 User interface



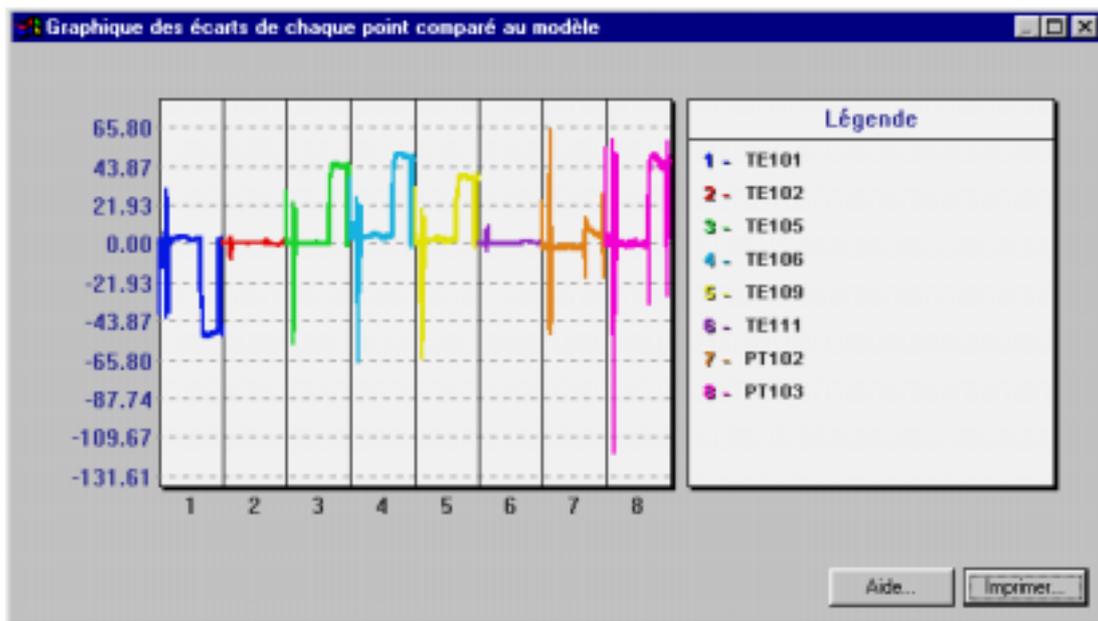
The figures above show the user interface for this first version of the chiller module in DABO. The interface allows the operator to configure the module such that data from the chiller are easily accessed, and allows for inputs that cannot be obtained from the monitoring system.

C.4.10 Results of field trials

The chiller data collected were used to test the module. The figure below shows the results for the normal operation of the chiller. As can be seen there is noise in the results, however it is quite obvious that the diagnosis for this situation is for normally operating conditions.



The figure below is obtained when the chiller is operating in a faulty manner.



The differences between the predicted and measured values indicate the presents of faults.

The module is still not equipped with a diagnostic ability, consequently it is used exclusively for fault detection.

C.4.11 References

1. Wagner, J. and R. Shoureshi. 1992. Failure Detection Diagnostics for Thermofluid Systems, *Journal of Dynamic Systems, Measurement, and Control*, 114 (4): pp. 699–706.
2. Grimmeliuss, H. T., J. Klein Woud, and G. Been. 1995. On-Line Failure Diagnosis for Compression Refrigeration Plants, *International Journal of Refrigeration*, 18 (1): pp. 31–41.
3. Stylianou, M. and D. Nikanpour. 1996. Performance Monitoring, Fault Detection, and Diagnosis of Reciprocating Chillers. *ASHRAE Transactions* 102(2): pp. 615–627.
4. Rossi, T.M. and J.E. Braun. 1997. A statistical, Rule-Based Fault Detection and Diagnostic Method for Vapour Compression Air Conditioners, *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research*, 3(1): pp. 19–37.
5. Stylianou, M. 1997. Application of Classification Functions to Chiller Fault Detection and Diagnosis. *ASHRAE Transactions* 103(2): pp. 433–445.

C.5 DEMONSTRATING ON-LINE DIAGNOSTIC TESTS IN A COLLEGE BUILDING

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C.5.1 FDD tool

The FDD tool consists of a computer program embedded in a building energy management system (BEMS). The user interface, measurements, controls and some script programming procedures of the BEMS are utilized in the FDD tool.

C.5.2 Intended end-user

The system is designed for building operators or servicemen. The user must be familiar with the BEMS in which the FDD tool is embedded.

C.5.3 FDD method

The employed FDD method is on-line diagnostic tests (ODT) (Pakanen, 1996). ODTs are series of control and monitoring actions applied to a process, which try to reveal possible faults of the process. Performing an on-line diagnostic test involves activating an automated process by means of prescribed input signals, disturbances or loads, supervising responses and comparing results with a process model. In this demonstration system, only input signal activation was considered. If abnormal responses are generated, the process is faulty (Figure C4). The final decision is the result of a statistical test. An ODT is focused on one process at a time. When the entire process consists of several subprocesses, faults are isolated by testing each subprocess separately.

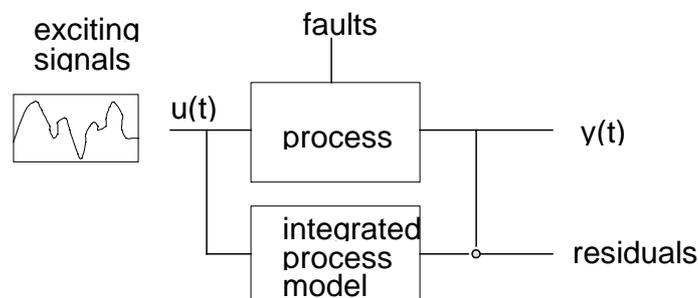


Figure C4. Principle of fault diagnosis using on-line diagnostic tests.

C.5.4 Test building, plant and control system

The demonstration system for on-line diagnostic tests is installed in a college building in Oulu, Finland. The three story building was constructed during the seventies. The volume of the whole building is 60,000 cubic meters, but only part of it is controlled by the demonstration system (Figure C5). The zone under control of the demonstration system consists of a few laboratories and staff facilities. The building is occupied by students and officials during the day between 8:00 and 20:00 five days a week.



Figure C5. An overview of the demonstration system. The air-handling unit is on the left and the BEMS is on the right.

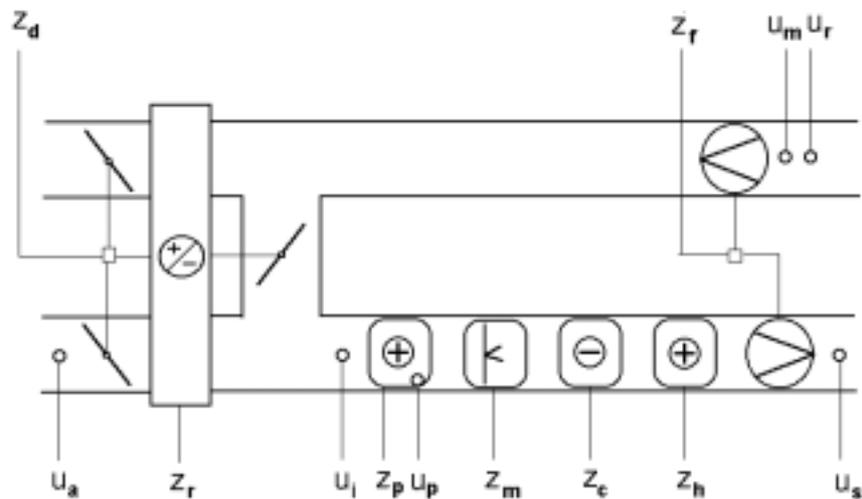


Figure C6. Simplified schematic of the air-handling unit.

The demonstration system consists of a BEMS interfaced to an air handling process. Figure C6 represents a schematic of the AHU. It contains a heat recovery unit, mixing dampers, and preheating, humidifying, cooling and heating processes. The heat recovery unit, dampers, heating and cooling need continuous control signals (z_r, z_d, z_p, z_h, z_c), but the humidifier is controlled by an on-off signal (z_m). The dampers are connected to a single control signal z_d . Supply and return fans can be driven at two different speeds, controlled by signal z_f . In addition, there are temperature measurements of the outdoor air (u_a), mixed air (u_i), supply air (u_s), return air (u_r), leaving water of the preheating coil (u_p) and the humidity of the return air (u_m). Usually, the set point temperature of the zone is maintained using a cascade control algorithm, but during the ODTs each subprocess is controlled separately.

A building energy management system (BEMS) controls the AHU. The BEMS is applied only for one air-handling unit although its capacity is enough to control several AHUs and zone areas. The reason for this is that the AHU and the BEMS consist a teaching system. By means of the system students of the college study operation of automation equipment and air handling processes. The AHU and the BEMS are designed for air handling of some laboratories, and facilities for the staff. The rest of the building and its zone areas are controlled by another building energy management system.

The BEMS is made by a commercial building automation company. The user interface is based on Intouch -real time operating system. InTouch controls all operations concerning the air handling process. Interface to the process equipment is implemented using a separate sub-control unit. The operating system enables the user to add new features into the original process control by writing his/her own computer programs using a special script language. All the extra operations needed for controlling the on-line diagnostic tests are programmed using the script language but analysis of the results needed also other programming tools.

C.5.5 Faults to be identified

- 1) A blocked coil or valve; the coil and/or pipes in a preheating process are partially blocked, causing a 30 % decrease in water flow. The fault is made artificially by partly shutting a manually controlled valve.
- 2) A sticking valve; the control valve of the heating coil is sticking in the opening phase. The controller is eventually able to steer the valve to a fully open position, but opening is delayed when compared to a no-fault case. The fault is artificial and it is made by mechanically hindering valve opening.
- 3) A partially opening valve; the control valve of the heating coil opens only partly. The valve does not reach a fully open position. The fault is made by mechanically hindering valve opening.
- 4) A faulty sensor; the electric cable connecting a temperature sensor to a controller is faulty. The fault is made artificially.

C.5.6 Sensors used

The BEMS provides on-line diagnostic tests using the following measurements:

- Supply air temperature
- Return air temperature
- Channel air temperature after preheating coil
- Outgoing water temperature of the preheating coil
- Water temperature entering the heating processes
- Valve position feedback (optional)

C.5.7 Design data used

No design data is needed.

C.5.8 Training data required

Data of different sensors are recorded several times before the system is ready for fault detection (identification period). It is necessary that the process is in good condition during recording. The processed data is saved and used later in the ODT procedure.

C.5.9 User interface

The BEMS user interface was applied (InTouch real-time operating system).

C.5.10 User-selected parameters

Initialization of the FDD tool in a new process environment requires selection of several parameters. The suggested procedure is to have a contractor or system designer perform the initialization right after commissioning. He or she selects the parameters requiring good knowledge of the FDD system operation, and then the user selects the rest of the parameters.

C.5.11 Threshold selection method

The final decision concerning a fault is the result of statistical tests (t-test). Usually, a fault decision and an alarm message is based on not one, but several tests, which compare old and new recorded data from different sensors. The user has to set a probability limit for these statistical test.

C.5.12 Results of trials

The main objective of the trials was fault detection, although the recorded data also provided features for fault isolation. All four of the above-mentioned faults could be detected. However, the trials pointed out some possible problems in practical applications.

- 1) The BEMS must be able to control all the HVAC processes of the building with influence on the ODT and the test environment. The conditions must be the same during the identification and test periods.
- 2) Temperature control of the heating water must be in good condition. Large fluctuation in temperature or difficulties in achieving the targeted operating point may cause problems in performing on-line diagnostic tests or at least degrade the results. So, degrading or poor temperature control may prevent performing the ODT.

C.5.12 Satisfaction of user requirements

Not tested.

C.5.13 References

Pakanen, Jouko. Detecting and isolating faults of an air-handling unit using on-line diagnostic tests. Espoo 1996, Technical Research Centre of Finland, VTT Publications 284. 52 p.

Broman, Jouni. Ilmastointikoneen vikadiagnoosimenetelmän testaus. (Testing of a fault detection method). Oulun Teknillinen oppilaitos, Sähköosasto 1998. 35 p. + app. 8 p.

C.6 PROTOTYPING A WWW-BASED DIAGNOSTIC TOOL

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C.6.1 FDD tool

The basic configuration of the diagnostic tool consists of a web server, PCs or PDAs with an Internet connection or WAP mobile phones. The idea is that the server computer shares its resources and knowledge with the user. Due to its central role in the network, the server can continuously deliver essential, updated information to a large number of customers. The prototype system, called WebDia (URL: <http://webdia.vtt.fi>), is constructed for diagnosis of district heating substations and oil heating systems. Besides diagnosis, other essential topics include instructions for service, maintenance and use of the plant. The main difference between WebDia and conventional FDD approaches is that the former is not directly interfaced to any building or plant. This means the user must provide necessary information to WebDia. Diagnostic decisions are made interactively and they are based on observations made by the user (Pakanen 1994). However, this makes the tool flexible and easy to apply without any FDD installations in the building. Multimedia representation makes interaction comprehensive. The diagnostic system and its alternatives have been outlined by Möttönen & Pakanen (1997).

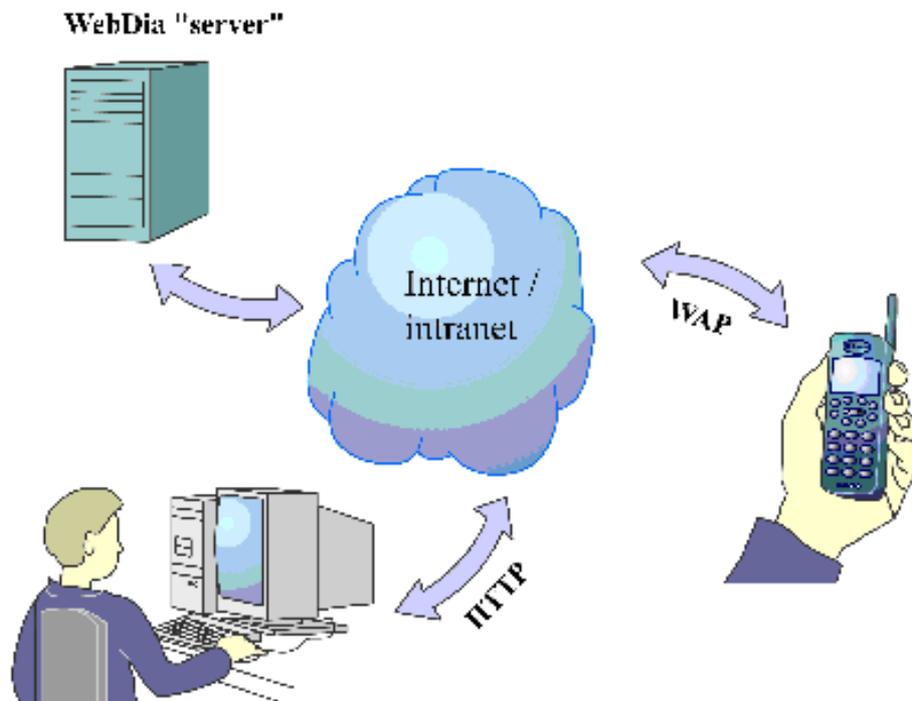


Figure C7. Principle of the WebDia diagnostic tool on the Internet.

The third technique of WebDia is a conventional fault tree, which uses dynamical HTML page techniques. Implementation of the fault tree is based on Java applets, which is one web architecture for building an Internet Transaction Processing (ITP) system (Möttönen & Pakanen, 1997). Java applets are embedded in the HTML code of a Web page and executed on the clients browser.

C.6.4 Test building, plant and control system

The designed system is suitable for all kinds of buildings equipped with a district heating substation or oil heating system.

C.6.5 Faults to be identified

All typical faults of a district heating substation belong to this category.

C.6.6 Sensors used

The diagnostic system has no direct interface to the sensors of the district heating substation. The FDD method does, however, benefit information from the process instruments. The idea is that the user makes observations, reads process instruments and then follows instructions given by the diagnostic system.

C.6.7 Design data used

No design data is needed.

C.6.8 Training data required

No training data is needed.

C.6.9 User interface

The demonstration system contains a web-based user interface. Customers have access to WebDia through a PC, PDA or WAP browser (Figure C9). Perhaps the best way to apply WebDia is to use a PDA or WAP equipped with a wireless link to the Internet. This permits using the WebDia system at the site of the process.

The web-based user interface is flexible. Presented information consists of not only readable text but also pictures, photographs, video recordings, and animations. Thus, the

information can be made comprehensive and easy to understand even for unskilled persons.



Figure C9. Accessing WebDia from a WAP mobile phone.

C.6.10 User selected parameters

No user selected parameters are necessary.

C.6.11 Threshold selection method

WebDia is designed for fault isolation only. Thresholds for fault detection are not needed.

C.6.12 Results of trials

The system has been publicly available on the Internet since the beginning of 2000, although the site is not yet finished. The number of visitors to the web site has not been registered. Later, after the development project is over, it is assumed that links to the WebDia site will be made by many HVAC, automation and energy companies from their own web site.

C.6.13 Satisfaction of user requirements

The diagnostic procedures of WebDia have been developed together with professional servicemen and representatives of HVAC, building automation and energy companies.

C.6.14 References

Pakanen, Jouko. 1994. Interactive Fault tree reasoning of a District Heating Substation – A Practical Approach for Fault Location. Service Life Prediction and Maintenance of Building. 2nd Joint Finland-Japan Workshop. Oulu, 6th to 10th of June. Oulu VTT Building Technology. Pp. 81–92.

Möttönen, Veli & Pakanen, Jouko. 1997. On-line fault diagnosis using Internet and WWW-pages. Computers in the Practice of Building and Civil Engineering. Worldwide ECCE Symposium. Lahti, Finland, 3–5 Sept. 1997, pp. 362–366.

C.7 A PERFORMANCE MONITORING TOOL FOR ENERGY-EFFICIENT BUILDING USE

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C.7.1 Test building, plant and control system

The test building is the Roihuvuori vocational school in Helsinki. About 700 students are studying a profession there. In the school, there are working about 70 teachers and about 30 other employees.

There is a water radiator heat distribution network in the building. District heating subdistribution systems include four heat exchangers of which two heat the water radiator network, one heats the water of the heating coils of the air-handling units, and one heats the hot water. In the building, there are 14 kitchens for education which are connected to 60 coldrooms.

In addition to the radiator network, air-conditioning is also used for heating. In the building, there are 13 central air-handling units which include liquid circulated heat recovery units. The air-handling units are operating mainly during weekdays between 7 and 16. The supply air temperature setpoint is determined based on exhaust air temperature.

The building automation system includes one management unit and five automation devices. There are 450 I/O points of which 273 are digital inputs, 47 digital outputs, 102 analog inputs and 28 analog outputs.

C.7.2 Intended end-user

The intended end-user of the FDD-system of Roihuvuori vocational school is mainly the foreman. The foreman takes care of the operation and maintenance of the technical systems and devices including heating, ventilation, air-conditioning, plumbing, and drainage systems as well as sewing machines, refrigeration devices, and kitchen systems. Also the janitor and the deputies will use the system.

C.7.3 Faults to be identified

The purpose of the building level fault diagnostics is to ensure that energy consumptions are kept in their target values in a way that suitable indoor conditions are met. The three major elements of the building level fault detection are:

- monitoring the energy consumptions,
- monitoring indoor conditions in relation to main control actions,
- monitoring control loop performance.

The FDD system utilizes the data collected by the building automation system in monitoring the energy consumptions, indoor conditions, and control loop performances. When deviations are detected, they are diagnosed with fault-symptom trees.

C.7.4 Sensors used

The energy consumption monitoring block uses the following sensors:

- total heating energy consumption (kWh)
- water consumption (m³)
- heating water consumption (m³)
- total electricity consumption (kWh)
- electricity consumptions from nine submeters (kWh).

In the first stage, the indoor conditions monitoring and the control loop performance monitoring block are implemented so that only a part of the building is covered. So, all the spaces and control loops are not monitored which influences to the amount of sensors required.

The indoor conditions monitoring block uses the following sensors:

- four room temperatures
- two inlet water temperatures of the radiator networks (southern and northern network)
- supply air temperature.

The control loop performance monitoring block uses the following sensors:

- one supply air temperature
- inlet water temperature of the southern water radiator network
- inlet water temperature of the northern water radiator network
- the hot water temperature.

The fault-symptom tree does not need any sensors itself.

C.7.5 FDD method

The FDD system contains four blocks. Three blocks are for fault detection, namely energy consumption monitoring, indoor conditions monitoring, and control loop performance monitoring. The fourth block is for fault diagnosis. There fault-symptom trees are utilized for locating fault causes (Kärki & Karjalainen 1999).

The fault-symptom trees for the Roihuvuori vocational school were done by Helsinki construction bureau (HKR). Utilized fault-symptom trees for top events of building services are:

- the heating energy consumption is too high/low
- the electrical energy consumption is too high/low

- the water consumption is too high
- control loops do not operate acceptably
- the electricity consumption of the cold rooms is too high.

C.7.6 Design data used

The system uses very little design data. These are mainly related to setting of target values of energy consumptions (e.g., design air flow rates, and operation times).

C.7.7 Training data required

The system does not need any training data.

C.7.8 User interface

The user interface was developed using Visual Basic 6. From the main window (Figure C10) different blocks (energy consumption monitoring, indoor conditions monitoring, control loop performance monitoring, and fault locating) are opened by clicking a certain picture.

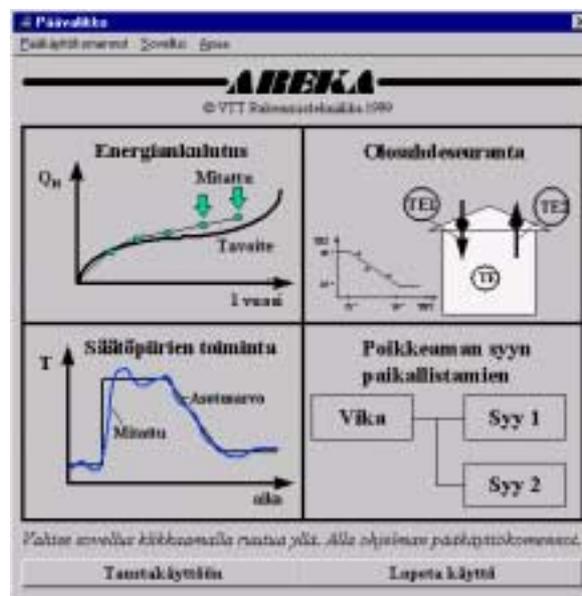


Figure C10. The main window of the AREKA FDD-system.

C.7.9 User selected parameters

User selected parameters are not required but the user may change the thresholds.

C.7.10 Selection of thresholds

The user may select the thresholds but the system has some default values. For example, if the normalised heating energy consumption deviate 10 % of its target value, the system alarms.

C.7.11 Results of trials

The system has been implemented to the test building. However, testing phase has just started.

C.7.12 Satisfaction of user requirements

The first version of the application has been demonstrated to the users. The feedback so far has been positive. Suggestions have been made to improve the application.

C.7.13 References

Kärki, S. & Karjalainen, S. 1999. Performance factors as a basis of practical fault detection and diagnostic methods for air-handling units, *Trans. ASHRAE*, 105(1).

Kärki, S. & Leskinen, M. A fault detection and diagnosis system as a tool in energy efficient building use. In: *The 3rd International Symposium on Heating, Ventilation and Air Conditioning*, Shenzhen, China 17.–19.11.1999. Pp. 905–913. ISBN 962-367-255-1

C.8 EMMA FOR SCHOOL

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C.8.1 Test buildings, plant and control system

The test buildings consist of school or nursery school buildings with average size of 2000 m². The buildings are located in the towns of Montpellier and Limoges, South and West part of France.

The building heating system consists generally of one to three boilers producing hot water that is distributed to one to five hydronic heating circuits. The hydronics heating circuits supply hot water to the radiators in the rooms.

Supply water in each circuit is controlled according to outdoor temperature. Intermittent heating is obtained by a night and weekend setback and an optimal start/stop controller.

As compared to large air conditioning systems, school heating systems can be considered simple. The main difficulty encountered by the service teams is linked to the number of buildings to manage. The service team manages tens or hundreds of buildings. In order to facilitate the management of such large number of buildings, remote Energy Management and Control System (EMCS) system have often been installed in buildings and are connected to a central supervisor (a PC with supervision software) through the public switched telephone network. The EMCS are used to control the HVAC plants, to trigger alarms and to log and transfer data to the central supervisor.

C.8.2 Intended end-user

The FDD software (EMMA: Energy Management at Municipal level) implemented is aimed as being used by municipality service teams (experimented building and plant control operators). The current version (version 3.6) of the software can be used with most EMCS database (ASCII format with rows and columns data) and the user interface has been adapted to the user needs (easy to use, synthetic information, easy to understand,...).

C.8.3 Faults to be identified

Questionnaires answered by 46 experts and the evaluation of the tools with the town of Montpellier and Limoges have helped to define the faults to be identified.

The questionnaire includes a list of components in a hydronic heating system. For each of these components, a list of possible faults was given. The experts ranked the faults

based on the following: frequency of occurrence, degree of difficulty for the operating team to detect the fault, impact on users' comfort, impact on energy consumption.

The faults to be detected are the following 5 faults: Too early boost, Overheating at beginning of occupancy, Underheating at beginning of occupancy, Overheating during occupied period, Underheating during occupied period, Heating during unoccupied period.

C.8.4 Sensors used

The sensors used here are typical HVAC system grade sensors commonly used in hydronic space heating systems (Table C3). No extra sensor is required to use the FD tool.

Table C3. Sensors used.

Measurement	Unit	Comments
Indoor air temperature	°C	Point sensor, one sensor per network
Supply water temperature	°C	Point sensor, one sensor per network
Outdoor air temperature	°C	Point sensor, one sensor per building
Gas or oil meter (optional)	m ³	Pulse generator, one sensor per building

C.8.5 FDD method

Our approach involves trying to detect the main symptoms of faults that can lead to an increase in energy consumption or to comfort degradation. We focused our work on the symptoms of faults that can be determined by the indoor temperature and the water departure temperature. The idea was no more to diagnose the primary cause of a fault, but to detect symptoms and to let service men find the primary cause by themselves.

The method developed includes:

- The measurement every hour of indoor temperature, supply water temperature and outdoor temperature (measurement are performed by the EMCS with its standard sensors)
- A pre-processor which transforms the information contained in the hourly measurement into 5 indices: 1) Daily mean of outdoor temperature, 2) Mean value during occupancy of indoor temperature, 3) Value of indoor temperature 2 Hours before occupancy, 4) Value of indoor temperature at the beginning of occupancy, 5) Mean value of water departure temperature in the middle of vacancy period
- A classifier which diagnoses 5 faults from these indices.

The pre-processor calculates 5 daily values from the hourly measurement. Its role is to divide the information up from 72 (24*3) measurements into 5 indices only which are then transferred to the classifier. The pre-processor functions can be easily performed by any database management system using simple query. The only requirement is knowledge of the occupancy schedules.

The classifier includes a set of "if/then rules". For each decision a condition has been set in order to reduce the false alarms.

C.8.6 Design data used

None.

C.8.7 Training data required

No need of training data.

C.8.8 User interface

The user interface has developed in close collaboration with municipality service teams. It has 3 levels (3 windows, see Figures C11 and C12).

The 1st window is based on 3 main ideas:

- To give to the user an overview of all the buildings he has to manage
- To present the results on weekly based period (schools building are running on weekly based period)
- To give to the user the possibility to prioritise its maintenance tasks (operate gradually for solving important to low level faults).

The 2nd window is a set of standard graphs (one graph per type of fault) that help end-user to better understand how faults have been detected.

The 3rd window is again a standard graph with trend measurement that can help end-user to make its own diagnostic about the fault.

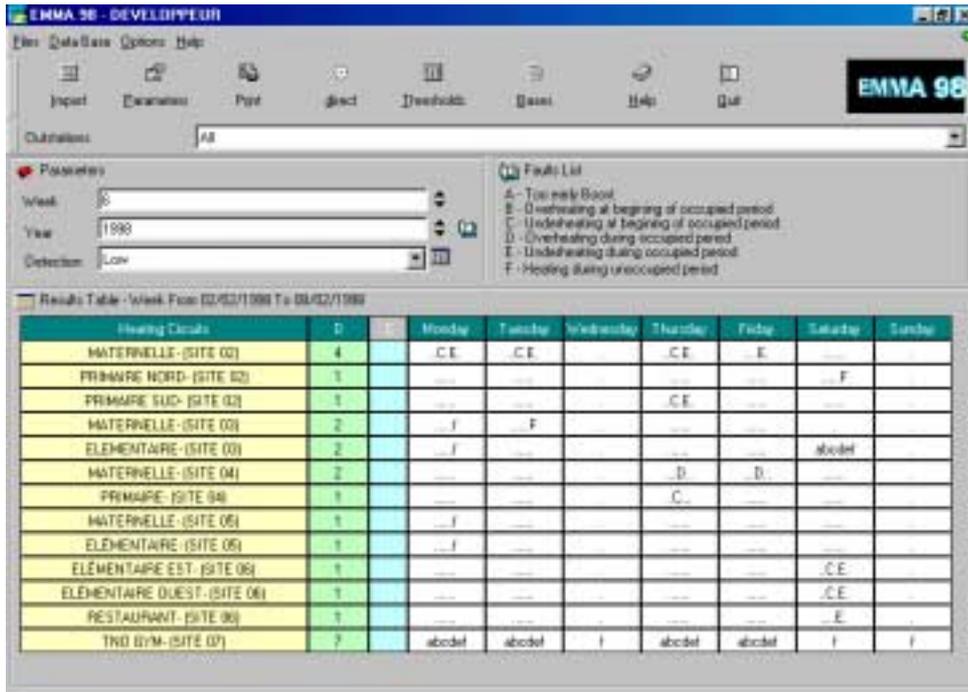


Figure C11. User interface, first window.

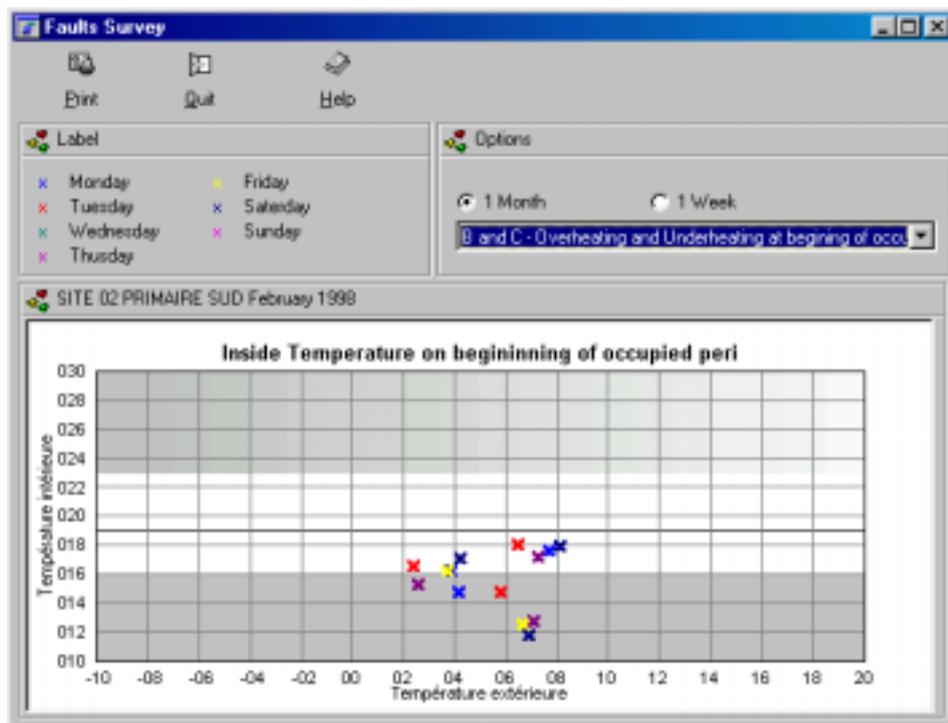


Figure C12. User interface, second window.

C.8.9 User selected parameters

The user needs to define the indoor temperature set-point and the occupancy schedules.

C.8.10 Threshold selection method

The if/then rules of the classifier use thresholds. All thresholds are physical values that are defined according to expert rules.

Threshold can be easily adjusted or adapted by end-user by using qualitative approach: choosing between High, Normal or Low sensitivity or with sliders to increase or decrease the sensitivity of detection. In order to simplify the end-user task, the adjustment processes modify all the thresholds of the software in one operation.

C.8.11 Results of trials

The testing and validation procedure has followed 6 main steps.

1st step: the method has been evaluated with simulated data.

2nd step: a first software has been tested off-line with the data of Montpellier municipality.

3rd step: the software has been validated on-line in Montpellier.

4th step: the software has been improved with Limoges service team (increasing the robustness and the easiness of dissemination)

5th step: the municipality of Limoges constantly uses the software since 1997

6th step: Dissemination to other towns is going on in co-operation with EMCS manufacturers and the association of engineers of French towns.

C.8.12 Satisfaction of user requirements

The EMMA software has been evaluated first with the service team of Montpellier during one heating season (one year) and then it has been validated with the service team of Limoges.

The EMMA software is today supported by the Association of French Town Engineers and 4 others municipality have asked to use the software.

C.9 FDD FOR HOTEL

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C.9.1 Test building, plant and control system

The test building consists of a middle size hotel with 44 rooms, a dining room and a hall. The hotel is located in the mountains in the French Alps.

The main feature of our building in term of HVAC system is the use of electricity for heating rooms (electric convectors and electrical floor heating system) and for producing domestic hot water (electrical hot water tanks).

The hotel is equipped with an Energy Management Control System (EMCS) that controls the heating systems, the hot water production, the lighting of the shopping center, the restaurant ventilation and the load shedding. The EMCS is also used to trigger alarms, to log data and to follow the comfort in each room and the electric consumption.

The electric floor heating systems and the hot water tanks run during low tariff hours of electricity .The convectors, equipped with intelligent room controllers, run to provide individual comfort. They have 2 different set-points (comfort and economy) that can be adjusted by occupant in the room or by the hotel manager from the supervision PC.

C.9.2 Intended end-user

The FDD Hotel software implemented in the site is aimed as being used by the hotel manager who has little knowledge of technical equipment in the hotel. The current version (version 2.0) of the software can work only with the EMCS database of the hotel. The user interface has been adapted to the user needs (synthetic information, easy to understand, easy to use, ...).

C.9.3 Faults to be identified

Interviews of different hotel managers and discussion with a group of EMCS expert have helped us to define the list of faults to be detected for this type of building.

We have ranked the faults based on the following: degree of difficulty for the operating team to detect the fault, impact on users' comfort, impact on operating costs (energy and damaging equipment costs). This study has led us to select twelve significant faults to be detected.

C.9.4 Sensors used

The sensors used here are typical HVAC system grade sensors commonly used in electrical heating system and water heating tank (Table C4).

Table C4. Sensors used.

Measurement	Unit	Comments
Indoor air temperature (in each room)	°C	Point sensor
Outdoor air temperature	°C	Point sensor
Hot water tank temperature (4 tanks)	°C	Point sensor
Water meter	m ³	Pulse generator
Electric meter	kW	Pulse generator

C.9.5 FDD method

Our approach involves trying to detect the main symptoms of faults that can lead to an increase in operative costs or to comfort degradation. We focused our work on the symptoms of faults that can be determined by using the data available on the EMCS. The idea was no more to diagnose the primary cause of a fault, but to detect symptoms and to let service men find the primary cause by themselves.

The method developed includes the following procedures:

- The measurement every 10 minutes of indoor air temperatures and temperature set-points in all rooms of the hotel (measurements are performed by the EMCS with its standard sensors), outdoor air temperature, hot water tanks temperatures, water meter index, electric meter index, powers subscribe in different time slot and the periods of the day (off-peak hours, peak hours, ...).
- The measurements are filtered: elimination of inconsistent values, filtering data with a moving average window and estimation of slopes.
- The estimation of operating modes such as heating mode, occupied or unoccupied mode, ...
- The estimation of thresholds for the FDD rules.
- The detection of faults: application of FDD rules (if/then rules).
- The suggestion of likely fault causes.

C.9.6 Design data used

None.

C.9.7 Training data required

No need of training data.

C.9.8 User interface

The user interface has been developed in close collaboration with the hotel manager. It has 3 levels (3 windows, see Figures C13 and C14).

The 1st window is based on 3 main ideas:

- To give to the user an overview of all the rooms and main equipment of the hotel.
- To present the results on monthly based period (hotel managers need long term performance results and can't devote too much time to FDD tools).
- To give to the user the possibility to prioritize its maintenance tasks (operate gradually for solving important to low level faults).

The 2nd window is more detailed view and the results are based on weekly period.

The 3rd window is fault oriented graph with trend measurements that can help end-user to make its own diagnostic about the fault.

The interface was developed in MS Excel environment.

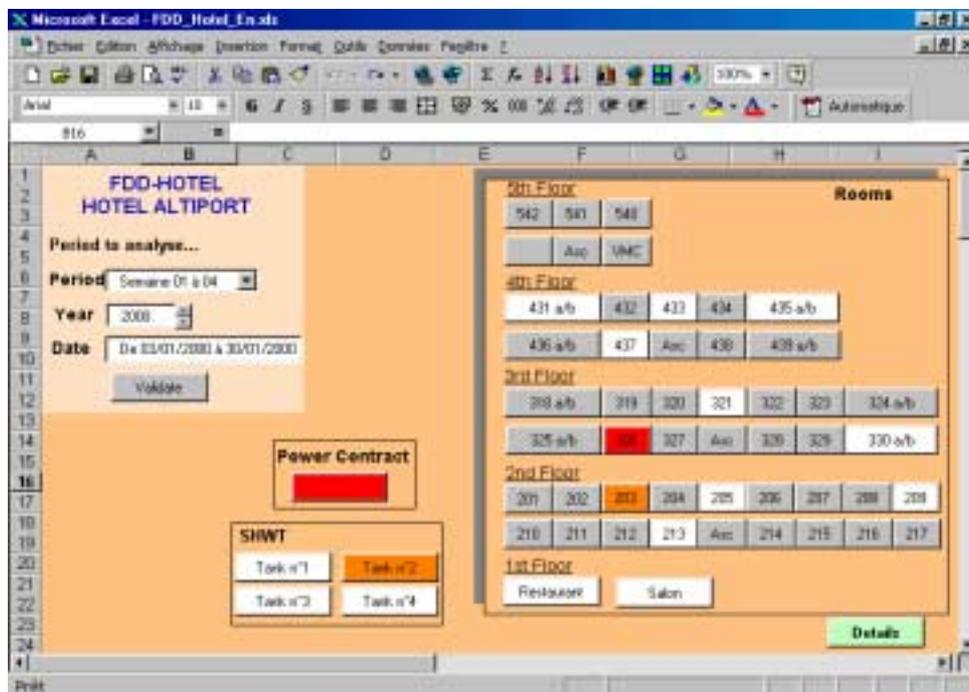


Figure C13. User interface, first window.

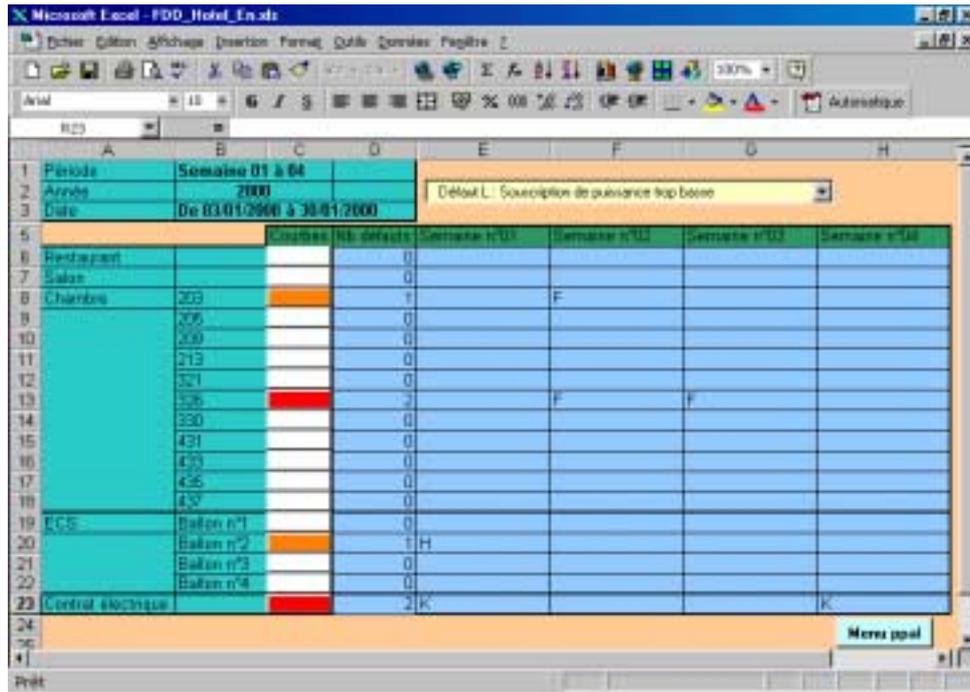


Figure C14. User interface, second window.

C.9.9 User selected parameters

The user needs to define the indoor temperature set-points, the normal occupancy schedules, the number, the capacity and the minimum temperature of the hot water tanks.

C.9.10 Threshold selection method

The thresholds are estimated automatically according to set-points or user selected parameters.

Threshold can be easily adjusted or adapted by end-user by using qualitative approach: choosing between High, Normal or Low. In order to simplify the end-user task, the adjustment processes modify all the thresholds of the software in one operation.

C.9.11 Results of trials

The testing and validation procedure has followed 3 main steps.

1st step: the method has been evaluated with simulated data.

2nd step: a first software has been tested off-line with the data of the hotel.

3rd step: the software has been validated on-line in the hotel.

C.9.12 Satisfaction of user requirements

The hotel manager shows its satisfaction of the results (the use of the tool has helped to detect several major faults). and asks us some additional functionality in order to facilitate its task of using the software.

C.10 FDD FOR OFFICE

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C.10.1 Test buildings, plant and control system

The test building consists of an office building of 4522 m² with 240 offices (270 employees work in it). The building is divided into 2 parts: A, B. The Building is located in the town of Strasbourg (in the Northeast part of France).

The main feature of our buildings in term of HVAC system is the use of electricity as the main source of energy for the air-conditioning of the rooms. A heat pump and an electric hot water tank produce hot water during cold season and the same heat pump with a chiller produce cold water during hot season. An Air Handling Unit (AHU) equipped with a cooling coil, heating coil and 2 additional electrical coil (for preheating and for supporting the heating coil) supplies hygienic conditioned air to the offices. Two others smaller AHU supply air to two conference rooms.

In the offices, Fan-Coil Units (FCU) equipped with intelligent room controller run to provide individual comfort. The fan coils have a reversible water coil and an electrical coil.

The Buildings is equipped with an EMCS that controls the plants, the AHU, the FCU, the lighting and the load shading. The EMCS is also used to trigger alarms, to log data, to follow the comfort in each room and to survey the electric consumption of the building.

The plants are stopped during night and only the electric hot water tank run during low tariff hours of electricity. The plants and AHU start at fixed time but each office get into occupied set-point according to optimal start/stop controller. The heating pump changeover and the AHU supply air set-point are controlled according to the outside temperature.

C.10.2 Intended end-user

The FDD Office software implemented in the site is aimed as being used by an experienced building and plant control operative. The user interface has been adapted to the user needs (synthetic information, easy to understand, easy to use,...).

C.10.3 Faults to be identified

Interviews of different office building managers and discussion with a group of EMCS expert have helped us to define the list of faults to detect for this type of building.

We have ranked the faults based on the following: degree of difficulty for the operating team to detect the fault, impact on users' comfort, impact on operating costs (energy and damaging equipment costs). This study leads us to select thirteen faults significant to detect.

C.10.4 Sensors used

The sensors used here are typical HVAC system grade sensors commonly used in FCU, AHU and Heat Pump system (Table C5).

Table C5. Sensors used.

Measurement	Unit	Comments
Indoor air temperature (in each room)	°C	Point sensor
Change Over water temperature (in each room)	°C	Point sensor
Outdoor air temperature	°C	Point sensor
AHU supply air temperature	°C	Point sensor
Heat Pump supply water meter	°C	Point sensor
Electric meter	kW	Pulse generator

C.10.5 FDD method

Our approach involves trying to detect the main symptoms of faults that can lead to an increase in operative costs or to comfort degradation. We focused our work on the symptoms of faults that can be determined by using the data available on the EMCS. The idea was no more to diagnose the primary cause of a fault, but to detect symptoms and to let service men find the primary cause by themselves.

The method developed includes the following procedures:

- The measurement every 10 minutes of indoor air temperatures, temperature set-points, heating/cooling demands, fan speeds, FCU on/off state, FCU change-over state in all rooms of the building (measurement are performed by the EMCS with its standard sensors), outdoor air temperature, AHU supply air temperature, heat pump supply water temperature, electric meter index, powers subscribe in different time slot and the periods of the day (off-peak hours, peak hours, ...).
- The measurements are filtered: elimination of inconsistent values, filtering data with a moving average window and estimation of slopes.
- The estimation of operating modes: heating mode, occupied or unoccupied mode, ...
- The estimation of thresholds for the FDD rules.

- The detection of faults: application of FDD rules (if/then rules)
- The diagnostic: suggestion of likely fault causes

C.10.6 Design data used

None.

C.10.7 Training data required

No need of training data.

C.10.8 User interface

The user interface has developed in close collaboration with the office building operating contractor. It has 3 levels (3 windows, see Figures C15 and C16).

The 1st window is based on 3 main ideas:

- To give to the user an overview of all the rooms and main equipment of the office building.
- To present the results on monthly based period (building operating operator need long term performance results and can't devote too much time to FDD tools and for short term information, he use the EMCS).
- To give to the user the possibility to prioritise its maintenance tasks (operate gradually for solving important to low level faults).

The 2nd window is more detailed view and the results are based on daily period.

The 3rd window is fault oriented graph with trend measurement that can help end-user to make its own diagnostic about the fault.

The interface was developed in MS Excel environment.

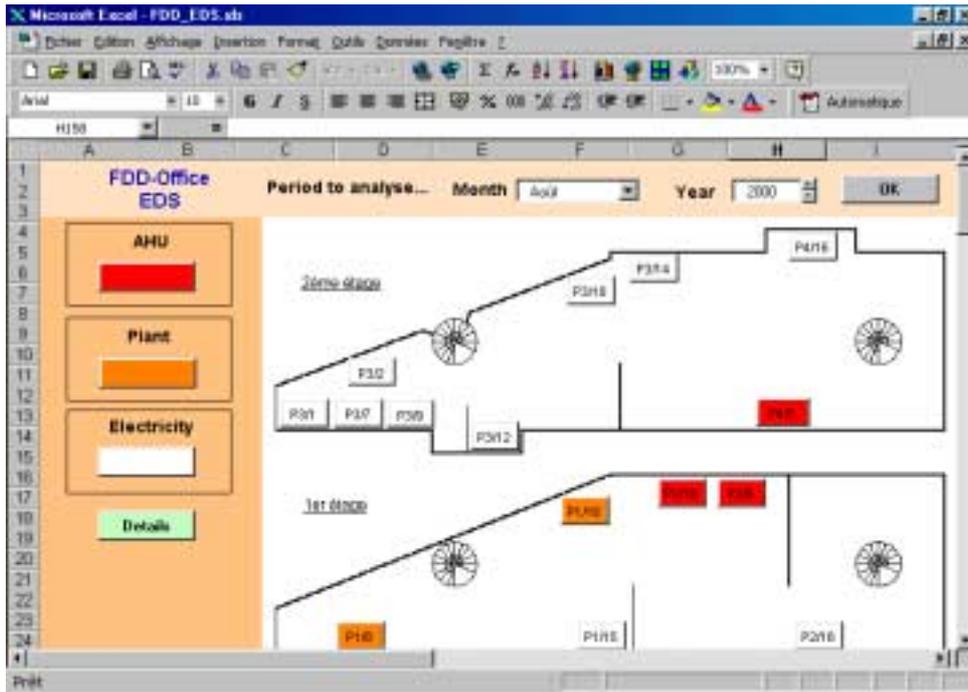


Figure C15. User interface, first window.

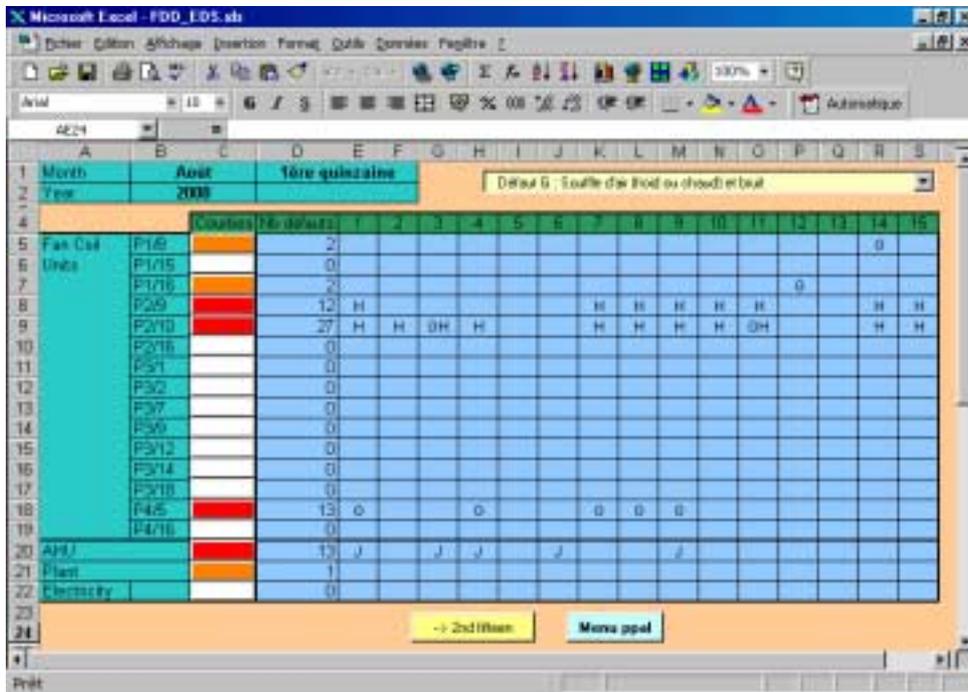


Figure C16. User interface, second window.

C.10.9 User selected parameters

The user need to define the indoor temperature set-points and the normal occupancy schedules.

C.10.10 Threshold selection method

The thresholds are estimated automatically according to set-points or user selected parameters.

Threshold can be easily adjusted or adapted by end-user by using qualitative approach: choosing between High, Normal or Low. In order to simplify the end-user task, the adjustment processes modify all the thresholds of the software in one operation.

C.10.11 Results of trials

The testing and validation procedure will follow 3 main steps.

1st step: the method has been evaluated with simulated data.

2nd step: a first software has been tested off-line with the data of the office building.

3rd step: the software has been validated on-line with the help of the building operating contractor.

At this level we have validated the software off-line.

C.10.12 Satisfaction of user requirements

Will be assessed at the next step.

C.11 EMMA FOR SWIMMING POOL

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C.11.1 Test buildings, plant and control system

The test building is a swimming pool (piscine des Casseaux) located in the town of Limoges that depends on the Sports Department and is managed jointly with the municipal technical centre for the heating plant and Energy Management Control System (EMCS).

This is an indoor swimming pool with one pool that was commissioned in 1972.

This establishment was refurbished and the heating system, the air treatment, water treatment and hydraulic configuration of the pool were renovated.

The pool has the following dimensions: length: 25 m, width: 10 m, volume: 300 m³, shallow end depth: 0.8 m, maximum depth: 2 m.

The water circuit configuration is of inverted hydraulic type: suction from the bottom (recuperation of "heavy" elements or driven by flocculation to the bottom), and surface suction using peripheral channels (recuperation of the pollution film caused by swimmers: surface pollution), supply through side grilles.

Three boilers supply a primary loop. On the water header, there are the following outlets: three outlets for the heating battery of the air handling units treating the pool hall, changing room and sports hall areas, one outlet for the Hot Water System (HWS) exchanger, one outlet for the pool exchanger.

The HWS loop is also connected to an exchanger supplied by a hot water circuit from the refrigeration system condensers of the ice rink located in the vicinity of the swimming pool. This exchanger supplies two 1500 litres HWS storage tanks that are in addition to the existing 1500 litre tank.

Dehumidification is performed by fresh air modulation.

The local EMCS unit retrieves information via the local network (Mod-Bus). The local unit mainly deals with the heating (air and water). As for water treatment, it retrieves the reading of chlorine and pH measurements in 4–20 mA.

Everyday, technical centre of the town of Limoges retrieves the data onto a PC, fitted with Modem and supervision software. The EMCS is used to control the HVAC plants, to trigger alarms and to log and transfer data to the central supervisor.

C.11.2 Intended end-user

The FDD software (EMMA Pool) implemented is aimed as being used by municipality service teams (experimented building and plant control operators). The current version (version 1.0) of the software can be used with most EMCS database (ASCII format with rows and columns data) and the user interface has been adapted to the user needs (synthetic information, easy to understand, easy to use,...).

C.11.3 Faults to be identified

Interviews of experts, visits of 6 different swimming pools and the collaboration with the town of Limoges have helped to define the faults to be identified.

Thus, a list of identified faults was set up and validated with experts. The experts ranked the faults based on the following: frequency of occurrence, degree of difficulty for the operating team to detect the fault, impact on users' comfort, impact on water quality and impact on fluid (electricity, gas and water) consumption.

The faults to be detected are divided into 2 groups: air side faults and water side faults.

Air side faults are: deviation of hall temperature from set-point during occupancy, hall temperature below set-point at the beginning of occupancy, heating during unoccupied periods, hall humidity out of range.

Water side faults are: deviation of pool water temperature from set-point during occupancy, pool temperature below set-point at the beginning of occupancy, heating water during unoccupied periods, water quality out of range (pH, chlorine).

C.11.4 Sensors used

The sensors used here are typical HVAC system grade sensors commonly used in HVAC and water treatment systems of swimming pool (Table C6). No extra sensor is required to use the FDD tool.

Table C6. Sensors used.

Measurement	Unit	Comments
Indoor air temperature (hall)	°C	Point sensor
Supply water temperature	°C	Point sensor, one sensor per network
Pool water temperature	°C	Point sensor
Outdoor air temperature	°C	Point sensor
pH meter	pH	Point sensor
Free chlorine	mg/l	Point sensor

C.11.5 FDD method

Our approach involves trying to detect the main symptoms of faults that can lead to an increase in fluid consumption, to comfort or water quality degradations. We focused our work on the symptoms of faults that can be determined by the indoor temperature and the water characteristics. The idea was no more to diagnose the primary cause of a fault, but to detect symptoms and to let service men find the primary cause by themselves.

The method is based on a fault detection and diagnosis method using “if/then” rules with thresholds. The structure includes a pre-processor and a classifier. The pre-processor is fed by the data extracted from the EMCS and outputs values averaged on relevant time periods depending of the entry variable processed. The classifier is fed by the pre-processor and combines these variables using “if/then” rules to detect the different faults.

C.11.6 Design data used

None.

C.11.7 Training data required

No need of training data.

C.11.8 User interface

The user interface has developed in close collaboration with municipality service teams. It has 3 levels (3 windows, see Figures C17 and C18).

The 1st window is based on 3 main ideas:

- To give to the user an overview of the swimming pool faults
- To present the results on weekly based period (swimming pool in municipalities are running on weekly based period) and
- To give to the user the possibility to prioritise its maintenance tasks (operate gradually for solving important to low level faults).

The 2nd window is a set of standard graphs (one graph per type of fault) that help end-user to better understand how faults have been detected.

The 3rd window is again a standard graph with trend measurement that can help end-user to make its own diagnostic about the fault.

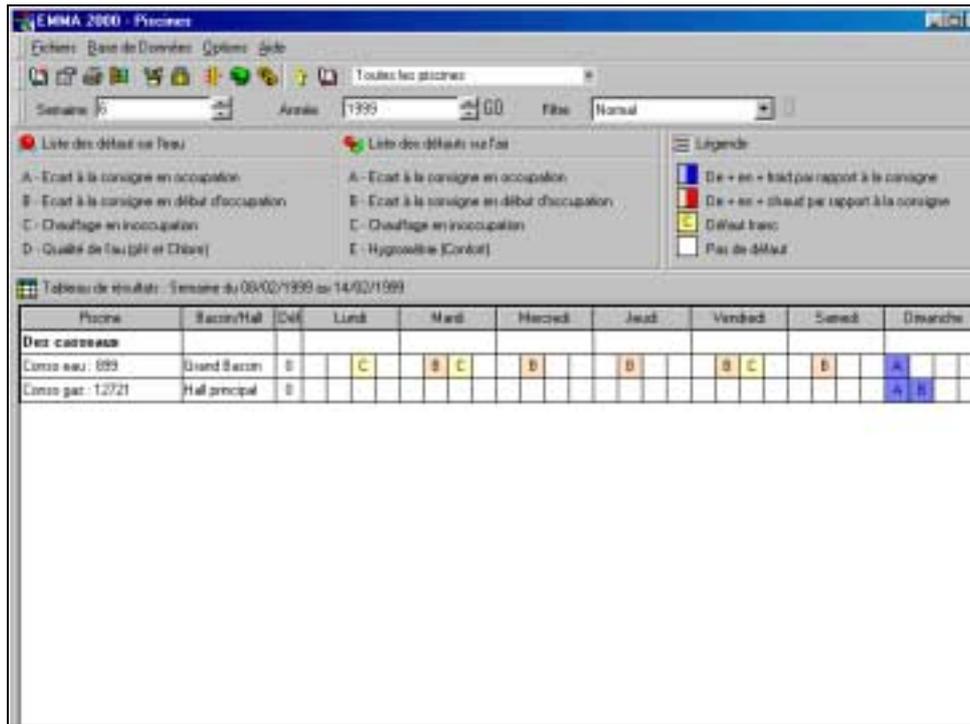


Figure C17. User Interface, first window.

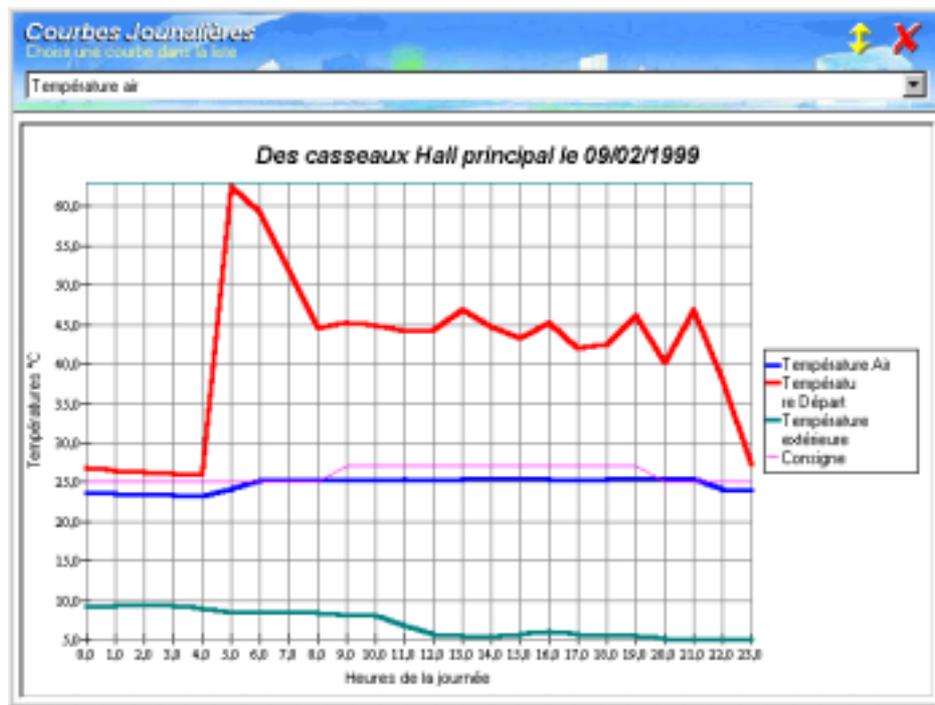


Figure C18. User Interface, third window.

C.11.9 User selected parameters

The user need to define the indoor and water temperature set-points and the occupancy schedules.

C.11.10 Threshold selection method

The if/then rules of the classifier use thresholds. All thresholds are physical values that are defined according to expert rules.

Threshold can be easily adjusted or adapted by end-user by using qualitative approach: choosing between High, Normal or Low sensitivity or with sliders to increase or decrease the sensitivity of detection. In order to simplify the end-user task, the adjustment processes modify all the thresholds of the software in one operation.

C.11.11 Results of trials

The testing and validation procedures follow 3 main steps.

1st step: a first software has been tested off-line with the data of Limoges municipality.

2nd step: the software will be validated on-line in Limoges.

3rd step: the software will be validated on-line with different municipalities (to increase the robustness and the easiness of dissemination).

C.11.12 Satisfaction of user requirements

Will be assessed at the next step.

C.12 AN ARTIFICIAL NEURAL NETWORK -BASED FAULT DETECTION DIAGNOSTIC TOOL

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C.12.1 Test building, plant and control system

The test building consists of experiment test hall. The building is located in Paris suburbs, FR and was first constructed in 1995. The hall is used by students coming for experimental activities. The heat rejection of the plant is used to heat the underground parking.

The system is a variable volume air handling unit (1000–4000 m³/h) represented on Figure C19. The air is extracted from the basement room. Air from the space is returned and mixed with outside air via a mixing box in the AHU. The flow of outside air which is controlled by dampers. The AHU's provide cooling (rating power 9 kW) and heating to the occupied space. The air distribution is completed by fan coils (heating and cooling). The primary plant is made of reversible heat pump.

The AHU monitored in this work stands horizontally and is approximately 5.0 m long by 1 m². The "mixed air" passes through a filter, the cooling coil, the heating coil and the supply fan. The air is humidified before passing over the supply air sensor and then being supplied to the space.

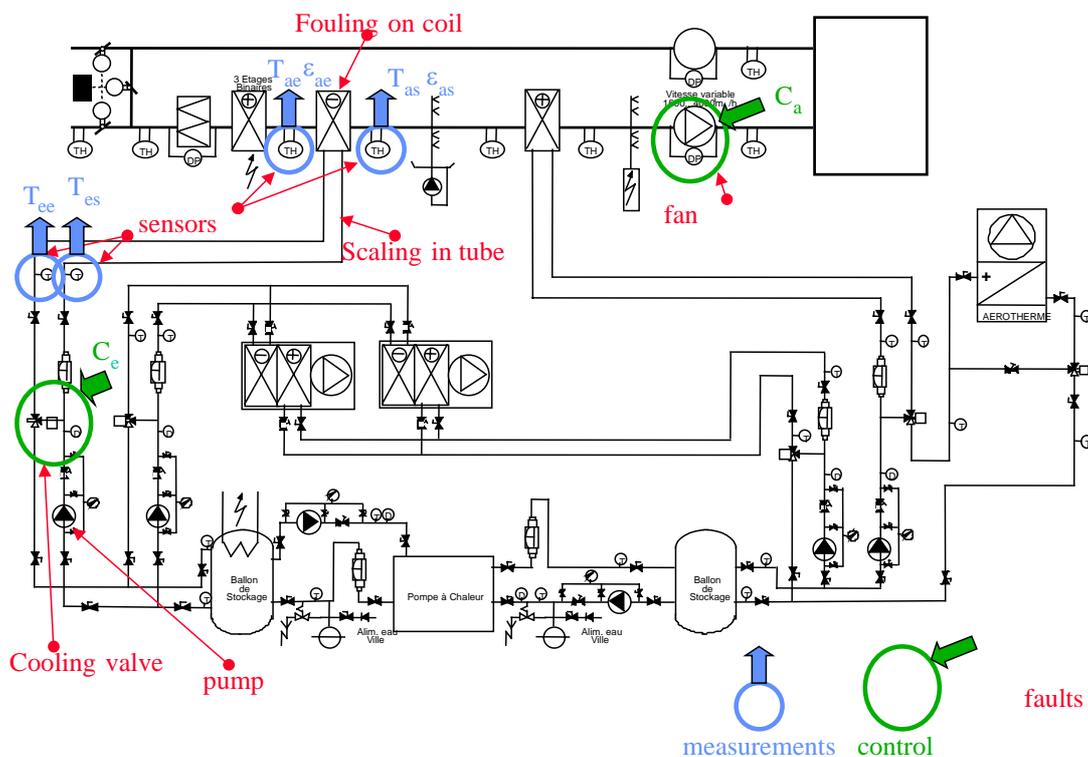


Figure C19. Experimental VAV system.

C.12.2 Intended end-user

Two different FDD software were implemented and tested in this study. One is prototype of Landis Siemens FELDER using logical tests, the other is an experimental ANN algorithm.

C.12.3 Faults to be identified

The faults relate to

- the cooling coil, mainly: fouling side air and fouling side water,
- the fan (relaxation of belt, displacement of the pulleys)
- the valve
- faulty sensors.

C.12.4 Sensors used

The informations concerning the cooling coil are the following:

- inlet and outlet air humidity (ε_{ai} ε_{ao} in %) and temperature (T_{ai} T_{ao} in °C),
- inlet and outlet water temperature (T_{wi} T_{wo} in °C),
- fan signal control (C_a in %),
- chilled water valve signal control (C_w in %).

The sensors used are typical from an industrial plant, and their accuracies are respectively $\pm 0.5^\circ\text{C}$ on temperature sensor and $\pm 5\%$ on relative humidity. Those values must be taken into account to determine the threshold of fault detection.

Commonly, there are no sensor inside the air handling unit but this add is easy and not too expensive (around 2,000 FF for 4 sensors, 300 €).

Data acquisition is realized with common BEMS product. The sensors are from Landis & Staefa and the supervisor is a PRV commonly used in such VAV systems. At the stage of the project, all algorithms (training of ANN and FDD) are processed off line.

C.12.5 FDD method

Model method consists in comparing real behavior of the HVAC plant to a normal behavior given by ANN trained during a preliminary phase (see Figure C20).

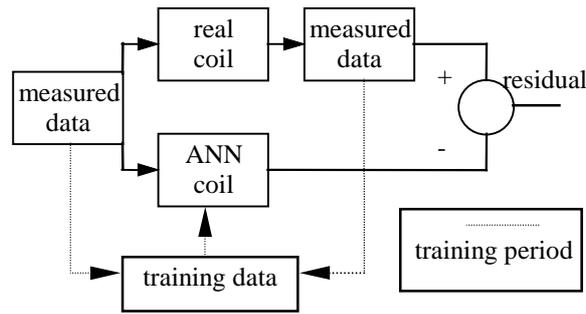


Figure C20. Fault detection process – training with real data.

The residual on air temperature and humidity are calculated as following

$$r(T_{ao}) = T_{ao}^{ANN} - T_{ao}^{mes}$$

$$r(\epsilon_{ao}) = \epsilon_{ao}^{ANN} - \epsilon_{ao}^{mes}$$

The main advantage of the ANN is the adaptability to all kind of information of the data. Indeed, it is not necessary to evaluate the absolute value of airflow rate. The control signal is enough because the ANN includes in the training the relationship between signal and absolute value.

The previous work on data simulation leads to an optimal architecture of the network with an hidden layer with 4 neurons as shown by Figure C21. This architecture is a compromise between performance on training set and performance on test set to prevent from over-fitting and under-fitting.

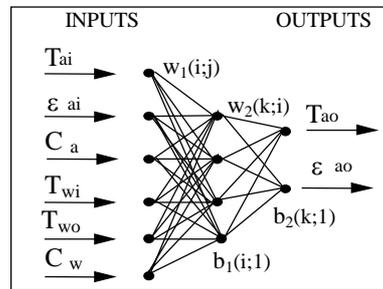


Figure C21. Architecture of the ANN.

The ANN described above is characterized by 2 biases vectors $b_1(i;1)$ and $b_2(k;1)$ and two weights matrix $w_1(i;j)$, $w_2(k;1)$. j is the number of inputs neurons, i is the number of neurons in the hidden layer and k is the number of outputs neurons.

The neural network toolbox of MATLAB [MathWorks, 1994] provides the ANN used. The training algorithm used is back propagation algorithm with Levenberg-Marquardt approximation.

C.12.6 Design data used

No design data is required for the cooling coil subsystem model.

C.12.7 Training data required

The performance of an ANN as an FDD tools is directly linked to the training data; which leads to 3 main difficulties. Indeed, the network learns the phenomenon occurring in training data. These difficulties are:

- first, if the training data are collected on a faulty air handling unit, the detector will never detect the fault. A commissioning is necessary to produce training data.
- Second, if the training data file is not exhaustive, the new configuration will appears as a faulty operation. For instance, if the training data includes no condensation, when condensation will appear, the ANN will detect a fault.
- Third, the ANN cannot extrapolate values, all the range of variation of each inputs must be in the training data.

So, it is necessary for the training data to be the most exhaustive as possible. The procedure of using real data obtained after a recommissioning is really difficult and restricting:

- because of the time and staff required,
- because all the system operation layout have to be included in the training data.

An alternative way of producing training data is to use simulation. To be plug and play, this model could be parameterized from measurements and then used for training the ANN.

C.12.8 User interface

Off line experiment. Software is developed inside MATLAB library.

C.12.9 User selected parameters

None, other than the method "thresholds".

C.12.10 Threshold selection method

There are a number of thresholds and operational parameters associated with the operation of the FDD software (Table C7).

Table C7. Method thresholds and operating parameters.

Applies to	Operational Parameter or Threshold
Models	Steady state detector time constant
Models	Steady state detector threshold
RPE	Forgetting factor
Exp. Rules	Significant innovation level
Exp. Rules	Bin demarcation, low-middle and middle-high
Exp. Rules	Forgetting factor

The steady state detector time constant represents the maximum time constant that would be expected from the system and can be obtained from the test data used to calibrate the models. The steady state threshold varies little from one system to the next and can be taken as to be constant (in the order of 0.75). The forgetting factors are tuned to give stable performance of the methods; the RPE forgetting factor is tuned such that the "fault parameters" just move in value for "normal operation". The expert rules forgetting factor is tuned to ensure that innovations that occurred a significant period in the past do not over influence the current diagnosis. Although there are six parameters listed, it is not envisaged that they will need adjustment for different applications to the same subsystem type. The thresholds associated with the bin demarcation and innovation significance would need resetting, but this could be easily automated from the calibration tests.

C.12.11 Results of trials

The ANN detects the faults. The progressive increasing in the fault appears on the residual variation on temperature (Figure C22) and relative humidity (Figure C23). The 1°C threshold for temperature and 0.05 for relative humidity seem to be optimal in this case.

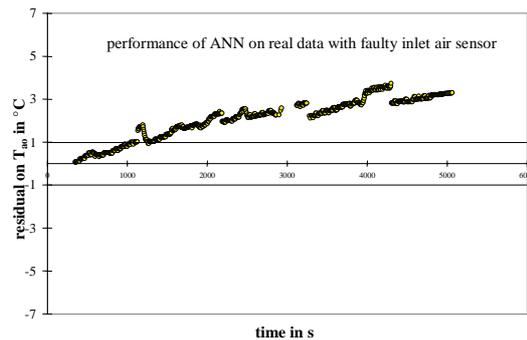


Figure C22. Residual values on indoor temperature.

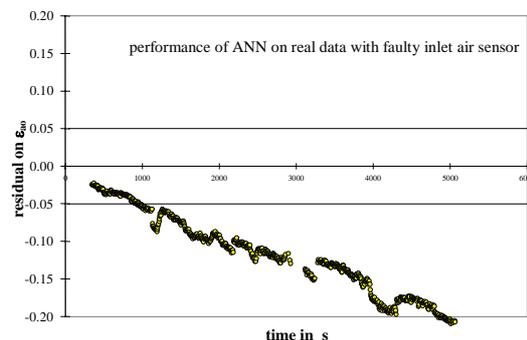


Figure C23. Residual values on relative humidity.

C.12.12 Satisfaction of user requirements

Not tested.

C.13 AN FDD TOOL BASED ON A LIFE CYCLE APPROACH

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C.13.1 FDD tool

The FDD Tool which has been developed in the IEA Annex 25 (Bach et al. 1997) is based on expert knowledge about possible faults and their related measurable symptoms. The symptoms are determined by comparing the results of a simulated reference model with the actual measured system behavior. The reference model is obtained from the life cycle approach for building and HVAC system simulation (Bach et al., 1992). The FDD-tool can be used as a standalone program. But it is also possible to integrate the tool into an existing building energy management system in the future. All data which are collected throughout the FDD process as well as the data which result from it are stored in a data base so that they can be evaluated and processed at any time.

C.13.2 Intended end-user

The intended end-users for the applied FDD tool are mainly operators who are responsible for the maintenance and the operation of building and HVAC systems. The tool can also be used by service companies which provide maintenance services.

C.13.3 FDD method

The fault and diagnosis method is based on the comparison of two data streams which are obtained from the simulation and by measurements within the considered building and the therein installed plants. The FDD method can be divided into two processes (Bach et al., 1997). During the fault detection process performance indices (PI) are generated from the two data streams. The PIs can consist of a single value from each data stream, but they can also combine different values based on mathematical or physical relations. The PIs are used to extract information from data which do not become obvious from single values (e.g. calculation of heat exchanger efficiencies) as well as for condensing the data for an easier handling and evaluation within the fault diagnosis process. The PIs from the simulated and measured data are compared by using predefined thresholds. A fault occurs when the difference between both PIs is greater than the according threshold. The detection of one or more threshold violations initiates the diagnosis process. The threshold violations are basically the measurable result of faults and are also called fault symptoms. In order to avoid wrong fault alarms it is also possible within the PI-generation to calculate a floating average of the measured or

simulated data in order to filter random peaks (e.g. caused by measurement errors) from the data.

At the beginning of the diagnosis process all symptoms (i.e. threshold violations) which have been detected up to the current time are collected. This collection of symptoms is then processed using a knowledge base within the FDD-tool. The knowledge base basically contains information about possible faults and the symptoms which are related to them. This includes information about the topology of the components and the control system of the considered HVAC system as well as about the resulting connections and influences of the single components on each other. During the diagnosis process it is checked if the detected symptoms match the symptom pattern of any fault which is described in the knowledge base.

C.13.4 Test building, plant and control system

The demonstration or test side for the application of the described FDD method is an HVAC system which is installed at a large industrial hall with a floor area of about 34000 m². The hall is divided into different – constructional separated – sections. A section with a floor area of 7400 m² is used for the assembly of computer systems from per-manufactured components whereas the other sections serve as storage and shipping areas of the assembled computer systems. The test building is built as a sheet metal construction with mineral wool as insulation. It complies with the German energy saving act of 1995. The FDD tool is set up and used for the HVAC plant which is used for the air conditioning of the assembly area. The demonstration plant consists of two identical air handling units with components for heating, cooling and humidification. The AHUs can also be operated in an economizer mode. They are connected to a common supply and return duct system. The conditioned air is distributed by a VAV-system. Therefore the supply and return fans of both AHUs are speed-controlled. There is no heat recovery installed. The AHUs have a maximum volume flow rate of 70 000 m³/h each. Both air handling units are controlled by one DDC-controller which is connected to a central building energy management system. The data which are measured during the system operation can be stored in a database which is supplied by the control system manufacturer.

C.13.5 Faults to be identified

The faults which are to be identified with the FDD-tool can be divided into two the categories component and sensor related faults.

Component related faults:

Stuck valves/dampers

Wrong positioned valves/dampers

Leaky valves/dampers

Heat exchanger fouling.

Sensor related faults:

Sensor offset

Sensor drift.

C.13.6 Sensors used

The use of sensors for the fault detection and diagnosis at the demonstration system is mainly restricted to the sensors which are installed in the system.

- Outside air temperature
- Outside air humidity
- Supply air temperature
- Supply air humidity
- Supply air differential pressure
- Return air temperature
- Return air humidity
- Return air differential pressure
- Mixed air temperature
- Return water temperature (cooling coil)
- Return water temperature (heating coil)
- Room temperature.

Additionally to the sensor readings the control signals for damper and valve positions are used within the FDD tool. The only figure which is measured additionally is air volume flow rate.

C.13.7 Design data used

Data from the design stage are mainly used for the generation of the simulation model which is used as a reference for the fault free operation. These data contain information about the building (construction and materials) as well as about the design of the HVAC system. The data for the characteristic curves of the fans are taken from manufactures data.

C.13.8 Training data required

Measured training data from the demonstration system are required for adjusting and calibrating the simulation model. The characteristic curves for the heat exchangers within the simulation model are generated from data which are measured within the system. The training data area also needed for the threshold selection.

C.13.9 User interface

The configuration of the FDD-tool is done with a graphical user interface. Within this interface the data which are needed for the fault detection and diagnosis can be defined regarding the type of data (measured or simulated) and origin (input channel). The interface is also used to set up the PI generation and to set the thresholds. Based on the PI the possible symptoms are defined. Finally the faults are connected to the symptoms by using logical expressions which are also entered within the graphical user interface. The evaluation is done by using Excel macros which extract and display the data about the possible occurrence of faults from the data base in which all data that are calculated within the detection and diagnosis process are stored.

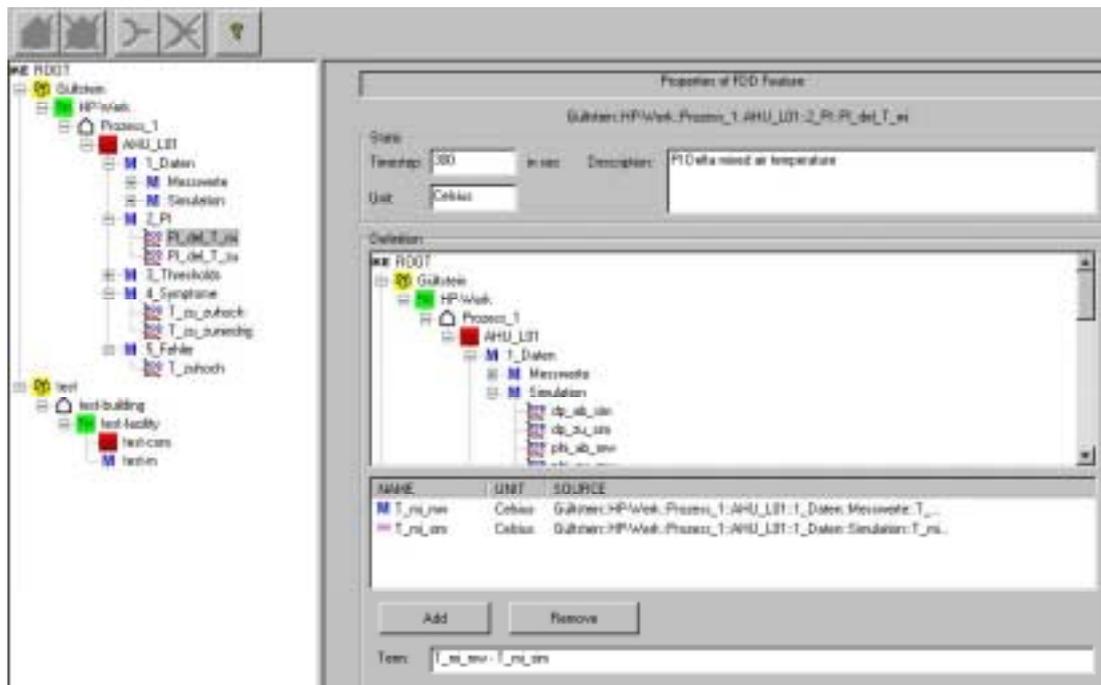


Figure C24. Graphical user interface for the configuration of the FDD tool.

C.13.10 User selected parameters

The FDD tool is set up by an expert who decides on the thresholds and the required information. It is not foreseen to allow the user to change the FDD configuration.

C.13.11 Threshold selection method

The thresholds which are used within the system are obtained by evaluating the accuracy of the simulation as well as of the measurements within the demonstration system. For this purpose training data are acquired. Also the data from a validation which is carried out for all sensors within the system, are used for the determination of the thresholds.

C.13.12 Results of trials

Results are not available yet since the German project started with one year delay. The project will be finished one year after the end of the Annex

C.13.13 Satisfaction of user requirements

See above

C.13.14 References

Bach, H., Hinkelmann, M., Madjidi, M. & Schmidt, F. Optimierung von Anlagen der technischen Gebäudeausrüstung durch Integration von Planung, Computersimulation und Betrieb. IKE 4-134, Universität Stuttgart, 1992.

Bach, H., Baer, K., Bauer, M., Grob, R.F. & Madjidi, M. Entwicklung eines Systems zur Erkennung und Diagnose von Fehlern beim Betrieb von HLK-Anlagen, Final Report, IKE 7-27, Stuttgart, 1997.

C.14 AUTOMATIC SENSOR EVALUATION OF CHILLING SYSTEM

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C.14.1 Summary on FDD tool

A FDD tool is developed to automatically diagnose and evaluate the BMS sensors of building chilling systems during commissioning or periodical check. This sensor FDD&E strategy is based on the fundamental mass and (steady state) energy conservation (balance) relationships. These relationships are easy to build and their validity is absolute and independent of plant performance degradations and change of working conditions. Sensor bias values are estimated basically by minimizing the weighted sum of the squares of the corrected residuals of each of the involved balances. On this basis, a software package in prototype is developed to evaluate the BMS sensors automatically on a personal computer using the measurements recorded in a period, downloaded from BMS, during BMS sensor commissioning or periodical check.

C.14.2 Intended end-user

The sensor validation method can be used both in on-line and off-line application. The FDD tool developed is for offline application only. It can be used in stage of BMS commissioning and the periodical check on sensors (measurements) during normal operation. The data can be downloaded from local BMS or from remote BMS via Modem and Internet. The intended end-users are the BMS suppliers, commissioning engineers, maintenance engineers and operators chilling systems.

C.14.3 FDD method

The FDD method is based on the statistics heat balance and mass balance exist in each control volume in statistics over a period [1]. Using the measurements from the sensors shown in Figure C25, the residuals (unbalances) of the mass and heat balances for the control volumes are calculated. Minimization of these balance residuals achieves the estimation of sensor biases by introducing a set of bias estimates to correct these measurements. Two schemes are developed, namely basic scheme and robust scheme. The basic scheme is illustrated by Figure C26. It is actually minimize the sum of balance residuals of individual control volume sequentially.

As the mass and heat balance residuals for the control volumes are minimized individually in the basic scheme, and outputs of estimators are used as the known parameters of the other estimators. The uncertainty of the estimation might be accumulated. The estimation errors of an estimator used earlier might be amplified by

the other estimators used later. To overcome this problem, a robust scheme is developed, which minimizes systematically the heat balance residuals of the control volume A and B. The robust scheme employs the basic FDD&E scheme and a robust GA Estimator [2]. The basic scheme determines the condition of unique estimation results and obtain the initial estimates of biases. The GA estimator estimates the biases based on the robust minimization objective function.

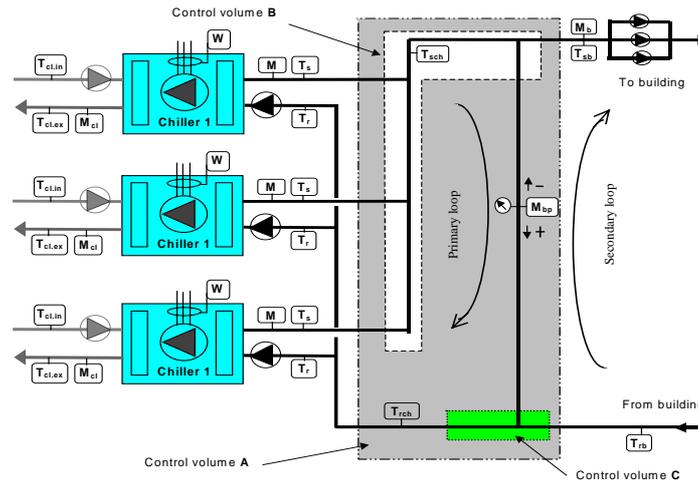


Figure C25. Schematic of chilling system.

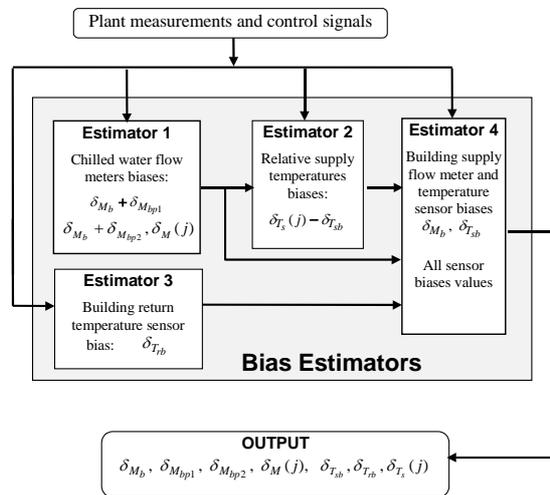


Figure C26. Basic FDD&E scheme.

C.14.4 Test building, plant and control system

An example of applying the software to an existing building refrigeration system of five chillers is presented. The FDD tool is applied to the central chilling system in a

forty-six stores office building with a useful area of about 74,000 m². The system has the same configuration and the BMS sensor instrumentation as the system in Figure C25 except that the common return water temperature measurement (T_{rch}) is not available. An integrated Building Management System is installed to monitor and control the central chilling plant and the air-conditioning system. The measurement data from the monitoring sensors are recorded in BMS, which are then retrieved from the central computer station.

C.14.5 Faults to be identified

Faults to be identified are the sensor faults of temperature sensors, flow meters in the chilling plant. The main objective of the FDD tool is to diagnose the soft sensor faults and estimate the biases of the sensors. However, complete sensor faults can be detected and diagnosed by the tool also.

C.14.6 Sensor used

The sensors used and examined are the temperature sensors and flow meters (see Figure C25), which include the building supply flow meter (M_b), building supply and return temperature sensors (T_{sb} , T_{rb}), chilled water flow meter and supply and return temperature sensors associated to each chiller ($M(j)$, $T_s(j)$, T_{rch}), cooling water flow meter (M_{cl}) and temperature at condenser inlet and outlet of each chiller ($T_{cl,in}$, $T_{cl,ex}$), and bypass flow meter (M_{bp}).

C.14.7 Design data used

The design cooling capacities of chillers are the only design data used.

C.14.8 Training data required

The FDD tool does not require specific training. However, experience about the characteristics of the measurements in real sites from analyzing the measurements is needed to determine some threshold values, which do not vary in different systems.

C.14.9 User interface

The software consists of three modes: *Preparation*, *FDD&E programs*, and *Presentation*. The *Preparation* mode is designed for users to input necessary information for configuring and running the FDD&E programs. The FDD&E programs are a series of sensor bias estimators, the corresponding confidence estimators, and the

routines for generating data for presenting the results. Execution (*Running* mode) of those programs is the core of the package. The *Presentation* mode allows users to review the FDD&E results. The results include the estimates of the sensor biases, the confidence intervals for the estimates, and the statistics of the balance residuals based on the raw and corrected measurement data. Graphic user interface is developed for all the modes. Figure C27 shows an example of user interface for preparation mode and Figure C28 shows an example for presentation mode.

C.14.10 User selected parameters

As the parameters or threshold values are independent from specific chilling systems, users do not need to select parameters for their own applications. However, experienced users might fine-tune those values to adjust the sensitivity of the steady-state detector.

C.14.11 Threshold selection method

Two kinds of thresholds are used in the strategy, which include the threshold for detecting sensor fault existence (or occurrence) and those used in steady-state detection. In general, 3δ of the normalized balance residual variance is selected as sensor fault detection and steady-state threshold. For the cooling water meter FDD, a threshold of characteristic quality is selected so as to trigger fault alarm when given percentage of relative bias is exceeded.

C.14.12 Results of trails

Sensor faults (biases) are introduced to three of the chilled water temperature sensors (T_{sb} , $T_s(2)$, and $T_s(3)$) through changing the definitions of the relevant temperature sensors in the BMS outstations. The values of the introduced biases are given in Table C8. Prior to introducing these faults, check and calibration of the temperature sensors in the refrigeration plant are conducted. The output of the robust FDD&E scheme is presented in Table C8 also. The biases introduced to the three temperature sensors (T_{sb} , $T_s(2)$, $T_s(3)$) are successfully diagnosed. The largest error of the three estimates is 0.25°C . Besides the confidence interval of each estimate, the balance residuals (Figure C28) are also presented for users to inspect the reliability of estimates.

Tests show that the balance residuals are sensitive indicators of the existence of flow meter and temperature sensor biases. Analysis of the residuals under various operating conditions of the refrigeration plants and minimization of the sum of the squares of the corrected balance residuals allows locating biased sensors and to estimate the magnitudes of the biases.

Table C8. Introduced and estimated biases in the BMS sensors.

<i>Biases Introduced</i>								
Temperature sensor	T_{sb}	$T_s(2)$			$T_s(3)$			
Fault - bias (°C)	1.5	-1.0			1.5			
<i>Biases Estimated</i>								
Sensor	$M(1)$	$M(2)$	$M(3)$	$M(4)$	$M(5)$	M_b	M_{bp1}	M_{bp2}
Bias Estimate (L/s)	3.2	17.9	17.7	6.8	17.0	-4.9	-2.2	16.8
Sensor	$T_s(1)$	$T_s(2)$	$T_s(3)$	$T_s(4)$	$T_s(5)$	T_{sb}		
Bias Estimate (°C)	-0.08	1.10	-1.47	0.14	0.27	1.75		
Sensor	$T_r(1)$	$T_r(2)$	$T_r(3)$	$T_r(4)$	$T_r(5)$			
Bias Estimate (°C)	-0.24	-0.11	0.04	0.24	0.08			

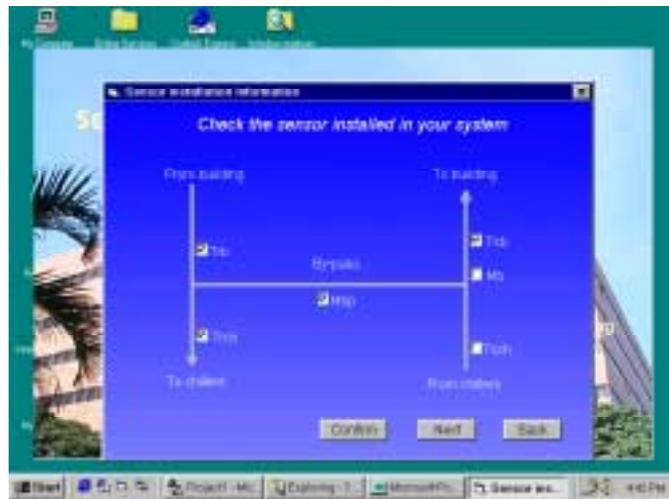


Figure C27. Example of interface in preparation mode.

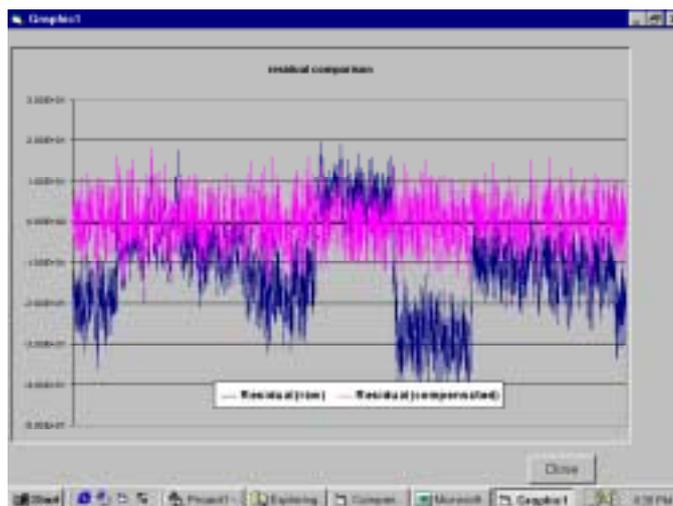


Figure C28. Interface showing the raw and corrected Flow Balance residuals (presentation mode).

C.14.13 Satisfaction of user requirement

In offline application, the FDD tool is very convenient to be used. The users do not need to know how the tool work except the use of the user-interface. However, to well interpret the outputs of the FDD tool, basic understanding on chilling system and the measurement is needed.

C.14.14 References

1. Wang, S.W. and Wang, J.B. “Law-Based Sensor Fault Diagnosis and Validation for Building Air-conditioning Systems”, *International Journal of HVAC&R Research*, Vol. 5 (4), pp. 353–378, October, 1999.
2. Wang, J.B., Wang, S.W. and Burnett, J. “Diagnostics of Sensor Faults in Building Chilling Systems – An Integrated Robust Strategy”, submitted to *International Journal of HVAC&R Research*.

C.15 REAL-TIME SIMULATION FOR FAULT DETECTION & DIAGNOSIS USING STOCHASTIC QUALITATIVE REASONING

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C.15.1 Test building, plant and control system

The tests were performed on a variable-air-volume air-conditioning system in a commercial office building. The building is located in Kawasaki, Japan. The tested system includes 1 AHU and 8 VAV units.

C.15.2 Intended end-user

The intended end-users are the HVAC system operators, engineers in the building and the engineers in the remote maintenance company.

C.15.3 Faults to be identified

Actuator failures (water valve failures, damper failures, fan malfunctions), Sensor failures, Controller failures,

C.15.4 Sensors used

VAV Room Temperature Set Point []
VAV Room Temperature []
Supply Air Temperature Set Point []
Supply Air Temperature []
VAV Air Volume [m³/h]
Supply Air Volume [m³/h]
VAV Full Open Signal

C.15.5 FDD method

The SQR model (shown in Fig. C29) is composed of nodes, arcs with propagation rules and functions. Each node is characterized with some of the qualitative values (shown in Fig. C30) such as "A", "B", "C", "D" and "E". The nodes are classified into two kinds of type. One type represents a component that is measured by a sensor or set point. These qualitative values must correspond to the measured ones. Other type is a component that is not measured. An arc connects two nodes and the direction of the arc shows the direction of influence propagation. Propagation rules are attached to an arc. A function

(shown in Table C9) receives the qualitative values of nodes as input, and gives the change in direction and their probabilities as output.

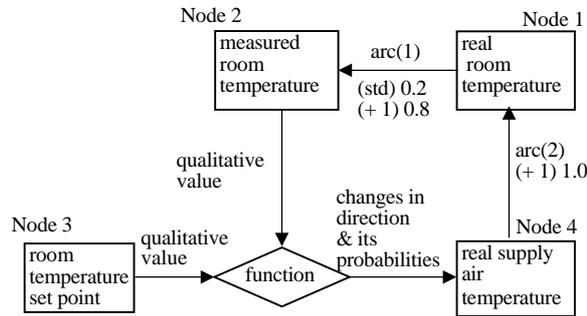


Figure C29. A stochastic qualitative model.

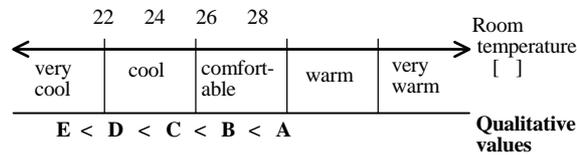


Figure C30. An example of the relationship between threshold limit values and qualitative values of room temperature.

Table C9. An example of a definition of a function.

Qualitative value of measured room temperature	Change in directions	Qualitative value of room temperature set point				
		High	←————→			Low
		A	B	C	D	E
A	up	0	0	0	0	0
	const.	1.0	1.4	0	0	0
	down	0	0.6	1.0	1.0	1.0
B	up	0.6	0	0	0	0
	const.	0.4	1.0	0.4	0	0
	down	0	0	0.6	1.0	1.0
C	up	1.0	0.6	0	0	0
	const.	0	0.4	1.0	0.4	0
	down	0	0	0	0.6	1.0
D	up	1.0	1.0	0.6	0	0
	const.	0	0	0.4	1.0	0.4
	down	0	0	0	0	0.6
E	up	1.0	1.0	1.0	0.6	0
	const.	0	0	0	0.4	1.0
	down	0	0	0	0	0

The procedure of the SQR simulation is shown in Fig. C31.

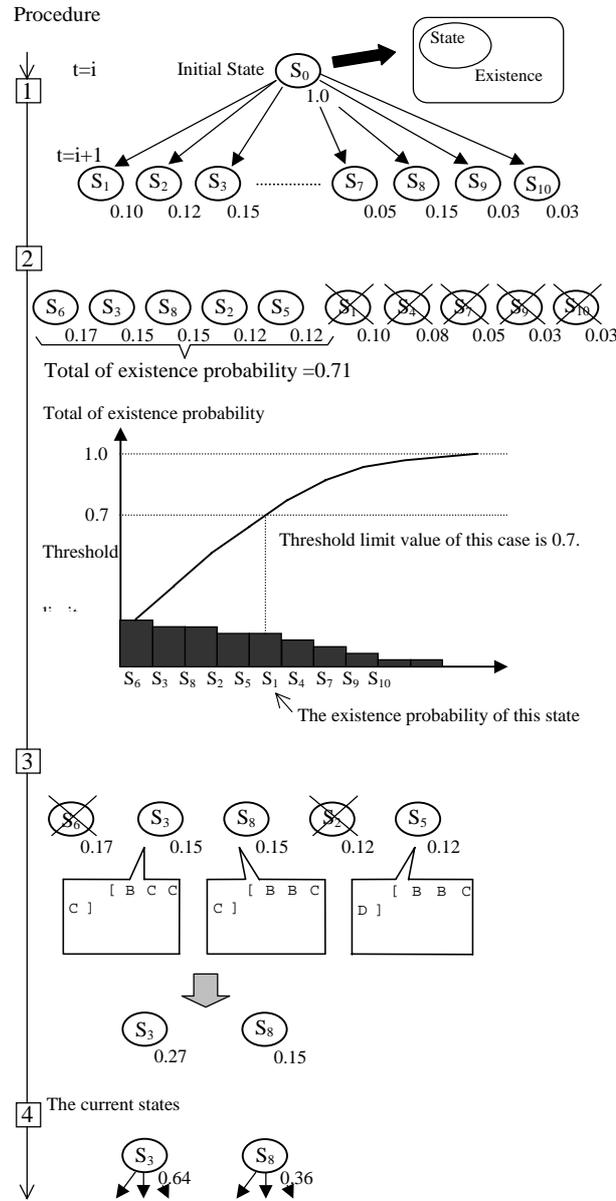


Figure C31. Simulation process.

- (1) All propagation rules and functions are applied to the current state, and then all possible states are generated and the existence probabilities of them are calculated.
- (2) The states are sorted in order of the existence probabilities. Each of the probability is added in order until the sum arrives at the predefined threshold. Then, all of remaining states are eliminated.
- (3) If the qualitative value of the measured node in a new state is different from the actual measurement, the state is discarded.
- (4) The existence probability of remaining states is normalized to make the total of the existence probability equal to 1.0. The normalized state is recognized as a new current state of the next stage and the same operations from (1) to (4) is repeated until final stage.

The important process of making the SQR models is the generation of functions. Characteristic parameter expression is a way to standardize the generation of functions. However, to decide the characteristic parameter values directly from experiential knowledges is difficult. The generation of functions by giving the qualitative informations are effective and easy.

Real-time processing of the SQR is necessary for the FDD applications. The real-time processing synchronizes the on-line system such as Building Automation Systems(BAS), completes the processing of measurement data immediately and specifies the fault state. The operators of the air-conditioning systems judge the system state from trend graphs of various processing data on the CRT of the BAS or other process computer. The real-time processing of the SQR realizes a way of replacing or supporting the operator's behaviors.

As a practical application, the processes and results of the FDD real-time simulation of an actual VAV system are explained. First, the control informations of the VAV System and the details of fault state data are shown. Next, the SQR models are generated by their informations. Finally, the results of the FDD real-time simulation are shown.

C.15.6 Design data used

Not used.

C.15.7 Training data required

The algorithm requires sensor values in normal state with no failure.

C.15.8 User interface

The diagnosis reasoning programs works every 5 minutes. Users can watch the results using the results window. All operation parameters can be set using another window.

C.15.9 User selected parameters

Thresholds using standard deviation of normal state, the diagnosis cycle time,

C.15.10 Results of trials

In Conclusion (shown in Table C10), the SQR simulation is an effective way for complex systems such as air-conditioning systems. However, several subjects remain to

be solved. For example, some algorithm that cuts too short the cpu time of simulation and tuning process of the large systems is necessary. And more easy methods that generate the functions of the normal and abnormal qualitative models must be developed.

Table C10. List of detection results.

Experiment \ Season	Summer season experiment	Intermediate season experiment
VAV-6 full open	4/6	6/9
VAV-6 full closed	7/10	4/13
Supply air volume decreasing experiment	9/13	9/12
Chilled water flow rate decreasing experiment	14/20	8/14

C.15.11 Satisfaction of user requirements

Not evaluated.

C.15.12 Reference

F. Miyasaka, M. Yumoto, T. Yamasaki, T. Ohkawa & N. Komoda: "Real-Time Simulation for Fault Detection and Diagnosis using Stochastic Qualitative Reasoning", Transaction of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, pp. 11–21, No. 72, Apr., 1999.

C.16 HVAC SYSTEM FAULTS DIAGNOSIS BY QUALITATIVE CAUSAL REASONING USING SIGNED DIRECTED GRAPHS

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C.16.1 Test building, plant and control system

The tests were performed on a variable-air-volume air-conditioning system in a commercial office building. The building is located in Kawasaki, Japan. The tested system includes 1 AHU and 8 VAV units.

C.16.2 Intended end-user

The intended end-users are the HVAC system operators, engineers in the building and the engineers in the remote maintenance company.

C.16.3 Faults to be identified

Actuator failures (water valve failures, damper failures, fan malfunctions), Sensor failures, Controller failures,

Sensors Used

Fi	Air flow rate of VAV unit [m ³ /min]
Ti	Room Temperature of the VAV area [C]
Ci	Output of temperature controller [-]
CCi	Output of flow rate controller [-]
Di	Damper full open switch (ON/OFF) [-]
FAHU	AHU air flow rate [m ³ /min]
CAHU	AHU air flow rate controller output value
TAHU	AHU air temperature [C]
CTAHU	AHU air temperature controller output
FW	Water flow rate [m ³ /min]
TWIN	Water temperature [C]

C.16.4 FDD method

We used a signed directed graph(SDG) of the HVAC system and the causality-based diagnosis algorithm. By use of the SDG, we could minimize engineering efforts for customizing a diagnosis system for a specific HVAC system. The SDG model is so compact model, compared with the usual IF-THEN rule model, that the required man-hours are very small.

SDG Model

We used an SDG (Signed Directed Graph) to represent the model of the system. $SDG = (G, f)$ is the composite concept consisting of the directed graph G and a set f of signs of branches. The node of the SDG represents the state variable. The branch represents the direct influence between state variables, and its branch is assigned sign "+" if it represents positive influence (reinforcement) and sign "-" if it represents negative influence (suppression).

The value of the state variable being normal, higher than the normal value, or lower than the normal value is represented as "0", "+" or "-" respectively. The combination of the signs assigned to the nodes of the SDG is defined as a "pattern" and represents the state of the system.

In the tank system (Fig. C32) F_0 , F_1 , and F_2 represent the flow rate, and L_1 represents the liquid levels in the tanks. The SDG of this system is shown in Fig. C33. The arrow with the solid line represents the branch with "+" whereas the arrow with the broken line indicates the branch with "-". The branch with "+" from node F_0 to node L_1 indicates that when F_0 is increased (decreased), L_1 is also increased(decreased). The branch with "-" from node F_1 to node L_1 indicates that when F_1 is increased (decreased), L_1 is decreased(increased). For instance, if blockage occurs in the pipeline between Tank1 and Tank 2, it may generate the pattern that is shown in Fig. C33.

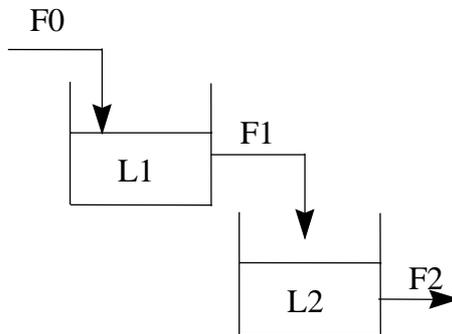


Fig. C32. Tank system.

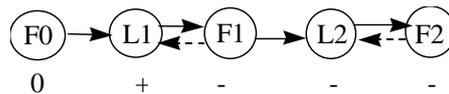


Fig. C33. Signed directed graph of the tank system.

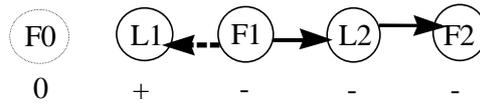


Fig. C34. A CE graph corresponding to the cause 'F1 close'.

Reasoning

When an SDG and a pattern on it are given, a branch b is said to be consistent if its sign coincides with the product of signs of initial and terminal nodes, and a node whose sign is not "0" is called a valid node. The partial graph G consisting of all the valid nodes and all the consistent branches is called a CE(Cause Effect)-graph.

If a CE-graph is given, it is not difficult to find the cause of the failure. There exists the cause of the failure in the most upstream nodes of the CE-graph. An example of CE-graph is shown in Fig. C34. The most upstream node of the CE-graph is F1. In the above explanation of CE-graph, we assumed all signs of nodes are given. However, there are few cases where all nodes with their signs. Usually, some nodes are measured by sensors, but the others are not measured. In such cases, we assume all the signs of the unmeasured nodes. If we test all possibility of the combination of all unmeasured nodes' signs, and if we could find the CE-graph, the most upstream node can be a cause candidate of the failure. We made an effective algorithm to find the all candidate causes. The algorithm uses an assumption; "There is only one cause (origin) of the failure." This assumption is used in many fault diagnosis systems, because the probability that two (or more) causes occur simultaneously is very small.

Symptom Detection

The sign of the measured node is determined by comparing the value of the state variable with corresponding thresholds. There are two types of thresholds. A sign of a node corresponding to state variable x is determined to be "+" if $x > a1$, "0" if $a2 < x \leq a1$, and "-" if $x < a1$. The thresholds $a1$, $a2$ are determined by using the standard deviation value in the normal state.

C.16.5 Design data used

Not used.

C.16.6 Training data required

The algorithm requires sensor values in normal state with no failure.

C.16.7 User interface

The diagnosis reasoning programs works every 5 minutes. Users can watch the results using the results window. All operation parameters can be set using another window.

C.16.8 User selected parameters

Thresholds using standard deviation of normal state, the diagnosis cycle time,

C.16.9 Results of trials

We did experiments for 4 cases. Followings are the cause candidates output from diagnosis the system.

Case 1. + FAHU, + CAHU, SD6, + D6 true cause , + CC6, + C6

Case 2. – D6 (true cause), – CC6, – C6

Case 3. – FAHU (true cause), – CAHU

Case 4. – FW (true cause), – VAHU, – CAHU

The cause candidates included the true cause in all four cases. Each computing time of the diagnosis was less than one second. The number of cause candidates was from 3 to 6. This accuracy seems to be good.

C.16.10 Satisfaction of user requirements

Not evaluated.

C.16.11 References

Shiozaki, J., Miyasaka, F. 1999. "A Fault Diagnosis Tool for HVAC Systems Using Qualitative Reasoning Algorithm", Building Simulation '99, Kyoto, Japan.

Shiozaki, J., Shibata, B., Matsuyama, H. and O'Shima, E. 1989. "Fault Diagnosis Processes Utilizing Signed Directed Graphs – Improvement by Using Temporal Information", IEEE Transactions on Industrial Electronics, Vol. 36, No. 4, pp. 469–474.

C.17 AN FDD TOOL FOR VAV TERMINAL BOXES

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C.17.1 Test building, plant and control system

Research & Development Center (38,000 m² gross and 11 story) of Tokyo Electric Power Co. is located in Yokohama Japan and was completed in 1994. Most of the building is used as office space and each typical floor has two VAV air-handling units for the south and north zone. Using the south zone AHU a series of several typical faults introduction tests was performed for 8 weeks period just after building completion. The capacity of AHU is; supply air fan capacity 12,000 m³/h, 65mmAq, cooling capacity 83,200 kcal/h, heating capacity 37,200 kcal/h, design outside air intake 1,725 m³/h, and the capacity of each VAV Unit is; max air flow rate 1,500 m³/h, min. air flow rate 375 m³/h with PID Controller.

The configuration of VAV AHU control is sophisticated equipped with four sub-control systems: 1) indoor air temperature control, 2) supply air temperature control, 3) reset control of supply air temperature, and 4) speed control of fan-inverter. The supply air temperature set-point and power supply to fan-inverters are controlled based on thermal load calculated from air-flow and temperature difference at the AHU.

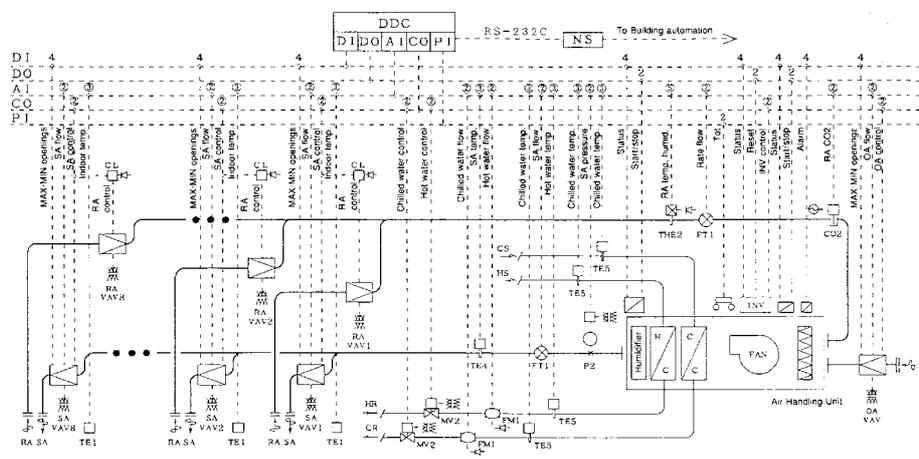


Fig. C35. VAV system components and distribution diagram.

C.17.2 Intended end-users

The intended end-users of this prototype are building operators and product suppliers. The tool could be embedded in Building Energy Management System (BEMS), however, it would rather be embedded in a local controller attached to a VAV unit, or in an outstation for the group control of multiple VAV units. Although this tool was

developed for a simple objective to detect and diagnose VAV unit faults there is substantial need in real fields because HVAC operators often suffer from VAV troubles which are very difficult to be detected due to the inconvenient VAV location in ceiling space for maintenance. At present the tool was only tested on the software level implemented on a personal computer.

C.17.3 Faults to be identified

Three types of artificial faults and their simultaneous combinations were introduced such a way that one type or combination fault occurs at 14:00 on each day. The three types of faults and their simultaneous combinations used are stuck damper at 1) fully opened position, 2) fully closed position and 3) half opened position.

C.17.4 Sensor used

The sensors used are 1) air flowmeter through a VAV unit and 2) room temperature sensor. Both are commonly used as typical VAV AHU system grade sensors and the signals are transmitted to the local outstation where digital signals are available.

C.17.5 FDD method

A Single Input / Single Output (SISO) Recursive Auto Regressive Exogenous (RARX) system identification methodology with forgetting factor is used and the dynamic performance of VAV sub-systems are modeled using the normal data base accumulated for 16 days before the fault introduction. A typical difference equation black box model algorithm can be expressed as,

$$y_n = -\sum_{i=1}^p a_{n-i} y_{n-i} + \sum_{j=0}^q b_j z_{n-j} + e_n$$

where,

y = output to be predicted,

z = inputs which influences the output,

e = random variables (normally distributed),

a = autoregressive parameters,

p = autoregressive parameter order,

b = exogenous parameters and

q = exogenous parameter order.

The model represents the causality between the input and output. In the present analysis, deviation of room air temperature from the set point is used as input variable, and

change in airflow rate between each sample time is considered output variable as explained.

Recursive Parameter Estimation: The above method is modified to discount old measurements so that the model adopts the changing situation dynamically. An observation that is τ samples old carries a weight that is R^τ of the weight of the most recent observation. Here, R is called the forgetting factor. A typical choice of R is in the range of 0.97–0.995 which amounts to approximately remembering 33–200 last observations respectively.

Frequency Response: n-Point complex frequency response $H(f)$ of the model can be computed from the Autoregressive and Exogenous parameters. The following variable is computed by subtracting the average mean value of the amplitude $\overline{A(f)}$ corresponding to each frequency response $A(f)$ for last five normal days and dividing it by standard deviation $\sigma(f)$,

$$P_{av} = (A(f) - \overline{A(f)}) / \sigma(f)$$

The methodology keeps the average magnitude near to zero of all the parameters. P_{av} are analyzed for fault detection and diagnosis application.

C.17.6 Design data used

No specific design data are used.

C.17.7 Training data required

Although minimum requirement of training data length was not well analyzed, the tool requires approximately one week long training data corresponding to normal operation.

C.17.8 User interface

The tool was developed to detect simple VAV unit faults without sophisticated user interface. Since VAV units are usually installed in a ceiling space where providing appropriate and regular maintenance work is very difficult due to poor accessibility, maintenance staffs require a simple automatic FDD tool which at least can make report of abnormal operation even without diagnosis.

C.17.9 User selected parameters

No specific parameter defined by users is required.

C.17.10 Threshold selection method

As P_{av} are normalized by standard deviation threshold selection is easy. According to our test threshold value of 10 is the present compromise.

C.17.11 Results of trials

Present study shows that the frequency response of the model can be a good tool in diagnosing the fault besides detecting. Sixteen normal days are used for training the model and optimizing number of parameters, forgetting factor and sampling time. Faulty day data is used in succession. Besides, the methodology is based upon frequency response of all the Autoregressive and Exogenous parameters and preserves their properties.

The data points are filtered and sampled at five minutes' interval. Therefore, 102 data points represent one day of operation. The faults include, 1) stuck damper at fully opened position, 2) fully closed position and 3) half opened position; and their simultaneous combinations.

Figure C36 shows the instantaneous frequency response of the model for all the VAVs before and after the fault (No. 6) is implemented. It was concluded that the fault can be detected and the response of the fault remains approximately the same even after nearly two hours after the fault was introduced. Most other faults were also detected by the same analysis. A soft fault like damper stuck between fully opened and fully closed position was difficult to detect, however, the temperature variation inside the room due to this fault is very small and remains near to the set point temperature. Since temperature remains near to the set point, it may not be considered fault from performance of HVAC point of view.

A few frequencies can be identified both for activating warning signals and identifying faults. In the present case, five such frequencies ($f_1 = 18/128$, $f_2 = 23/128$, $f_3 = 25/128$, $f_4 = 27/128$ & $f_5 = 30/128$) are identified out of 64 frequencies considered initially between 0 and 0.5. These frequencies lie in the range 0.1–0.3, where the fault responses are clearer. A fault corresponding to closing of damper has signature at all the frequencies, a fault of damper opening has signature at no more than two frequencies. The method can be further refined after accumulating experiences and adjusting the threshold value.

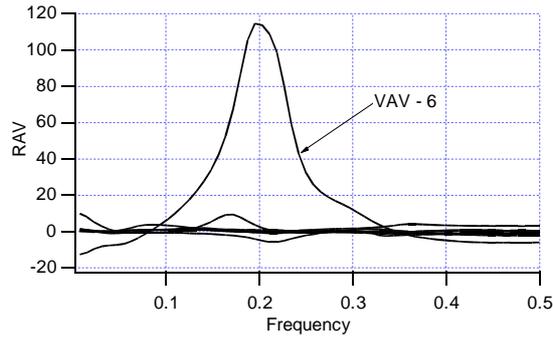


Fig. C36. Frequency response of models.

C.17.12 Satisfaction of user requirements

Engineers of a control product company is interested in this tool because the requirement of VAV FDD is substantial among maintenance staffs, however, no commercialization is planned at present.

C.17.13 References

1. Yoshida, H. & Kumar, S. ARX and AFMM Model Based On-line Real-time Data Base Diagnosis of Sudden Fault in AHU of VAV system, Energy Conversion and Management, Vol. 40, pp. 1191–1206, 1999, Pergamon Press 1999.
2. Yoshida, H. & Kumar, S. RARX Algorithm Based Model Development and Application to Real Time Data for On-line Fault Detection in VAV AHU Units, IBPSA Building Simulation '99, pp. 161–168, 1999.
3. Yoshida, H. & Kumar, S. Development of ARX Model Based Off-line FDD Technique for Energy Efficient Buildings, Renewable Energy, Vol. 00-4-1/3, pp. 1–7, 2000.

C.18 REMOTE MONITORING, FAULT DETECTION AND FAULT DIAGNOSIS ON A LABORATORY CHILLER TEST BENCH

Sipko Nannenbergh, Hogeschool Windesheim, Technology Faculty, Zwolle, The Netherlands,
Henk Peitsman, TNO Bouw, Delft, The Netherlands

C.18.1 FDD tool

The FDD tool was developed to assess the performance of a chiller by developing an automatic diagnosis system.

C.18.2 Intended end-user

The intended end-users are students of universities and politechnical schools and Service Company personnel.

C.18.3 FDD method

The FDD method is based on Case-Based Reasoning (CBR).

Instead of relying on general knowledge of a problem domain, or making associations between problem premises, CBR is able to utilise the specific knowledge of previously experienced, concrete problem situations. These are called cases. A case is a description of a problem together with details of actions that were taken to respond to the problem. Finding a similar past case and reusing it in the new problem situation solves the new problem.

In this example, CBR works by selecting a case from a stored database of previous cases that best resembles the characteristics of the problem currently under investigation.

An implementation of CBR is CBR-Works 4 [1]. It can be used to build a database of fault models and to determine a fault diagnosis.

A fault model consists of the deviation between a good working system and an incorrectly operating system.

More sensitivity with this method can be obtained by calculating the design-parameters and defining several performance indicators. These parameters can be calculated by an equation solver out of the measurements and appended to the fault spectra of the system. To be able to calculate these parameters a simple mathematical model of the components in the system is still needed.

C.18.4 Test building, plant and control system

The chiller test bench is situated at the “Faculteit Techniek” of “Hogeschool Windesheim”, Zwolle, the Netherlands. The test bench was developed with support of TNO-Bouw (Delft) and TRANE (Soest) and sponsored by the Dutch government.

The goal for starting a test bench was to apply all theory taught to students to a real process. The basis of the test bench is a TRANE CGAB 027P Air-cooled Reciprocating Liquid Chiller. The chiller was modified in order to make it suitable for research, and it was necessary to build additional parts: air ducts for cooling its condenser, a closed water circuit to heat its evaporator, a regenerator to exchange the heat from the air to the water, etc. Besides, analogue sensors were strategically located all over the plant to get measurements of the main parameters involved in the physical behaviour of the plant (flows, pressures and temperatures). Data-acquisition and man-machine interaction systems were designed and built. Software for remote monitoring/control and fault detection/diagnoses was designed and built. Sensors were calibrated and tested. For fault detection, a mathematical component model of the chiller was developed and parameters were fitted. A sensibility investigation for fault detection was made and a reliable fault spectrum was chosen. For diagnoses, an expert system operating according to the Case Base Reasoning (CBR) method was chosen and tested.

For testing the fault detection system, the air flow as well as the water flow can be modified by acting on the air fans and air dampers, the speed rotation of the water pump, and the water circuit valves. Besides, faults can be introduced in the system easily.

The control of the test bench, originally made by relays when it was just a Chiller, was transferred to a PLC that offered an effective and safe way to control the process in automatic or manual mode.

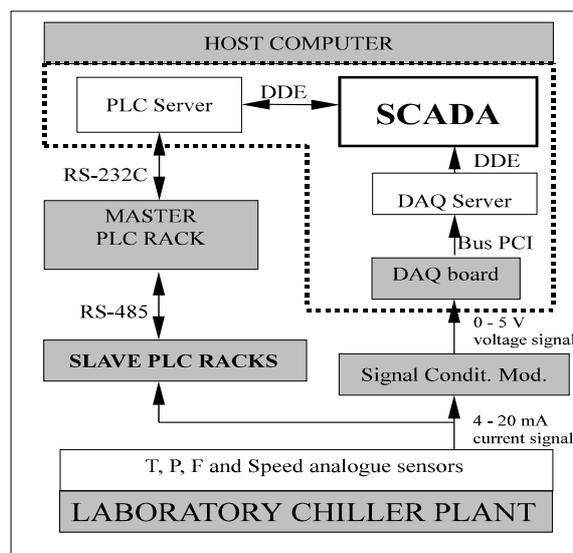


Figure C37.

A hard-wired Operator Interface was developed to make it possible to interact with the PLC and get basic information about and control over of the test bench. The test bench could run stand alone, reaching a steady state for different loads. A personal computer supports the Data Acquisition (DAQ) System and the Plant Control System (through the PLC). The first one, the DAQ System consists of the analogue sensors, signal conditioning modules (purposes: electrical isolation, multiplexing, filtering and amplification), a plug-in DAQ board and the “DAQ Server application” developed in Lab Windows /CVI. The other, the Plant Control System consisted of an SCADA (Supervisory, Control and Data Acquisition) application developed in Intouch that was connected to the “PLC DDE server application” and to the “DAQ Server Application”. Figure C37 presents the different hardware and software modules commented above and show the communication channels and methods.

C.18.5 Faults to be identified

Specific sets of fault that can be identified are (1) Water-side fouling and (2) Airside fouling.

C.18.6 Sensors used

For the detection and fault diagnosis the following signals are used:

Symbol	Condenser:	Symbol	Pump:
FQ_3	Flow of Freon	WP_1	Water pressure before the evaporator
FP_1	Pressure Freon before Condenser	WP_2	Water pressure after the evaporator
FT_1	Temperature Freon before Condenser	SS_1	Water pump rotation speed
FP_2	Pressure Freon after Condenser	WQ_3	Water flow in the water circuit
FT_2	Temperature Freon after Condenser		Evaporator:
AP_2	Pressure of the cooling air before evaporator	FQ_3	Flow of Freon
AT_2	Temperature of the cooling air before evaporator	FP_2	Pressure before Thermostatic Expansion Valve (TEV)
AP_6	Pressure of the cooling air after evaporator heat exchanger	FT_2	Temperature Freon before TEV
AT_6	Temperature of the cooling air after evaporator heat exchanger	FP_4	Pressure Freon after TEV
AQ_1	Flow in the cooling air in the air circuit	FT_5	Temperature Freon after Evaporator (overheating)
		WP_1	Water pressure before evaporator
		WT_1	Water temperature before evaporator
		WP_2	Water pressure after evaporator
		WT_2	Water temperature after evaporator.

C.18.7 Model identification

For model identification, the following system coefficients are calculated:

- Heat conductivity between Chilled liquid and wall;
- Chilled water flow conductivity in Evaporator;
- Heat conductivity between Cooling air and wall Condenser;
- Cooling airflow conductivity in Condenser.

C.18.8 Training data required

The fault detection approach is based on a classification technique. Classification is only possible with training data. In the design phase of the CBR system, several faults are foreseen already and stored in the database as fault models. In practice, additional and unforeseen faults can occur. Being able to monitor unforeseen faults and transform them into new fault models in the databank creates the opportunity to get a more reliable fault diagnosis system. The number of faults in the databank increases and the system becomes more valuable and reliable in time.

C.18.9 User interface

Two user interfaces are developed; one for local control and monitoring and one for remote control and monitoring through Internet. Every measured signal mentioned in 8.1.6 can be shown on command. There is a fault-detecting interface too. Crucial faults can be monitored. At this moment only in the water circuit. By monitoring the signals under various fault conditions, now we have the knowledge to implement the fault spectra on the interface supported by Fault messages.

C.18.10 User selected parameters

There are no explicit selected parameters except the waterpump rotation speed.

C.18.11 Threshold selection method

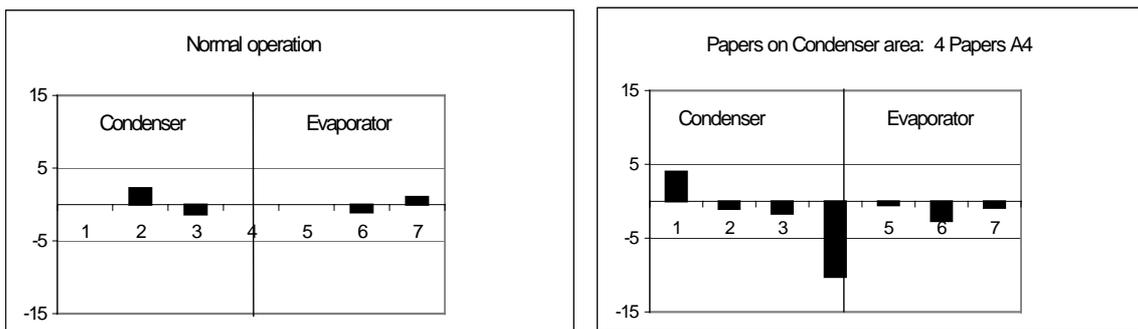
There are no explicit thresholds.

C.18.12 Result of trials

Fault detection

Model based fault detection using a component reference system

Give the mathematical model the same input values as in the real system and compare the model outcome with the outcome of the real system. The model, developed in EES [2], is used to calculate the theoretical results. The result is present in Figure C38. It presents the results of the model based residual generation. The figure presents clearly that there when the condenser is fouled (simulated by covering it with paper) are no effects except for a rise of the pressure in the condenser. When four paper sheets are put on the condenser area, the deviation is outside the threshold of 5%. The pressure difference between model and measurement is continuously increasing. A similar behaviour is observed for the temperature in the evaporator, when a fault is introduced in the by-pass valve of the evaporator. The pressure in the evaporator is hardly effected.



Legend:

1 = AT_6 5 = FP_4 KAawc = heatcond. between cooling air and wall condenser
 2 = FT_2 6 = FT_5 KAclwe = heatcond. waterside between liquid and wall evaporator
 3 = AT_4 7 = WT_2 4 = FP_2

Figure C38. Model based residual generation.

Performance-based fault detection using parameter estimates and signatures.

The next possibility can be based on signatures of the Chiller. In this case the heat transfer coefficients in the evaporator and condenser and the flow resistance in the pipes and used.

Because the high fidelity of several small measurement fluctuations, the item NTU (Number of Transfer Units) is not used.

In Figure C39 the result of the number of papers on the heat exchanger area is shown.

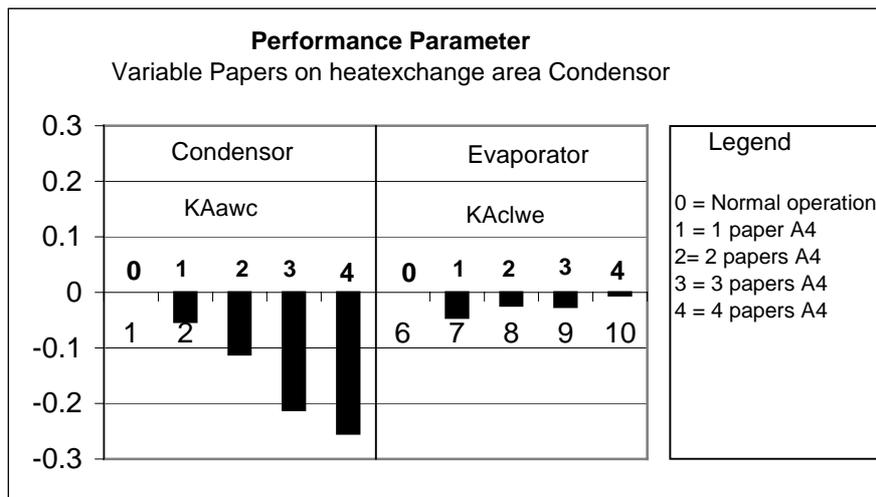


Figure C39. Fault detection based on performance parameters.

There is no influence on the flow resistance in the pipe, no influence on the heat exchange coefficient in the evaporator. Only the heat transfer coefficient in the condenser is affected.

Experiments have shown that there are two possibilities to give the diagnosis program reliable data: Model-based and Performance-based fault detection. For both methods of fault detection a reference model of the Chiller is needed. The performance-based fault detection gives the best result. This fault is foreseen and programmed. There are a lot of other faults possible, even not foreseen faults. The best way to be flexible in fault detection and diagnosis is to give a spectrum of measured pressures and temperatures differences with a reference model consisting of fitted components.

The basic model can be developed and fitted easily with EES [2]. In changing the input variables for each component a linear regression model can be derived. These regression components can be programmed and incorporated into the main program.

Fault diagnosis

The next step is to test the possibility of making a diagnosis. For the fault model, a combination of measured pressures, temperatures and design parameters of heat conductivity (mentioned in 8.1.7) is chosen.

The first step is to 'load' a fault model, e.g. the example of 3 sheets of paper on the evaporator heat-exchanger area as a query.

The next step is to do a query. The results gave a similarity of 0.676 with the stored diagnosis for 2 sheets of paper and a similarity of 0.668 with the stored situation of 3 sheets of paper on the heat-exchanger area.

Another test consisted of a measurement of a partially closed valve (position 25) in the mainline of the chilled water circuit. The result is a diagnosis pointing a closed valve in position 30 or 20.

CBR provide a great stability in detecting the correct fault.

Although there is a lot of fine-tuning to do and preliminary experiments show that the method of CBR is working in fault diagnosis, if we can define a suitable additional fault spectrum (included performance parameters) and not only using measured signals like temperature and pressure.

C.18.13 Satisfaction of user requirements

To date, intended end-users have not fully tested the test bench. Such tests are scheduled for the next year.

C.18.14 References

[1] TECINNO GmbH, kaiserslautern, Germany. (<http://www.cbr-web.org>)

[2] EES: F_Chart Software, Middleton, Wisconsin, USA. (<http://www.fchart.com>)

C.19 A TOOL TO IMPROVE ENERGY EFFICIENCY AND PERFORMANCE OF SWIMMING POOLS BY FAULT DETECTION AND DIAGNOSIS

Wim Kornaat and Henk Peitsman, TNO Bouw, Delft, The Netherlands

C.19.1 FDD tool

The FDD-tool is set up for diagnosis of the functioning/ performance of the energy production (electricity and heat) – and the energy consumption in swimming pools.

C.19.2 Intended end-user

The intended end-users are swimming pool operators and service companies.

C.19.3 FDD method

The fault detection and diagnostic method is based on expert rules. The rules examine the measured heat production in relation to the expected heat demand. Control signals like heating curves are also used to identify the particular mode of operation of the CHP, Boilers and Heat pump, thereby identifying a subset of the rules that are applicable for the current operation. Relationships are derived between the heat demand of different energy consumers in the swimming pool and the outside air temperature. The relationships are also used for identification of the expert rules.

C.19.4 Test building, plant and control system

The activities are executed in the swimming pool “the Banakker” in the city of Etten-Leur, The Netherlands. The swimming pool is equipped with two indoor swimming pools, namely: a 25 m pool (25 m x 12,5 m x 15/3,5 m) and an instruction pool (17,5 m x 8 m x 0,6/1,2 m).

From origin the swimming pool was equipped with a small and large outdoor pool. These outdoor pools were however hard to exploit successfully. Therefore in 1993 was decided to convert the small outdoor pool into an ice skating rink for use in the winter period. The heat subtracted from the ice skating rink in the winter period should be used to heat up the indoor swimming pools (heat pump function of the chiller). In the summer period the pipes in the ice-skating rink should function as a solar collector thus heating the indoor pools. At the moment however this solar collector function is no longer in use. Besides heating the indoor pools, the heat from the chiller/heat pump is also used for the preparation of hot water for showers, etc. The remaining (not useful to

use) heat from the chiller/heat pump is put into the outdoor pool. The installation dates from 1995.

For heat and electricity production the Banakker is equipped with a combined heat and power installation with gas engine (CHP). The motor heat, extracted from the CHP, is supplied to the central heating system. On this central heating system the heat exchanger for the swimming pools are connected and furthermore the room heating facilities (radiator groups, air heaters, etc). With a heat exchanger in the exhaust air of the motor, heat is supplied to the tap water system. The installation dates from 1996.

Besides the CHP, two gas boiler are available for the heat production. These boilers have an improved efficiency. Furthermore are they equipped with exhaust gas exchangers. They date from 1996.

In 1996 the Banakker is equipped with a Energy Management and Control System (EMCS) from the Dutch manufacturer PRIVA. With this EMCS system the control of the installation takes place. Within this EMCS system the threshold values of various items, time schedules etc can be set while furthermore a large amount of parameters concerning the functioning and energy consumption of the installation are monitored. The complexity and extensiveness of the installation is illustrated by the fact that the EMCS system consists of 4 substations (4 separate control units), while in total about 250 pages (windows) are available with settings, readings of parameters, etc.

For minimum primary energy consumption a good use of the combined heat and power plant (CHP) is needed. The CHP is together with the boilers regulated on the heating demand of the complex. A scheme of the heating system is given in Figure C40. The CHP and the two boilers are put parallel to one another. On the distributor/collector placed in the boiler room are connected:

- the heat exchanger for the 25 m pool;
- the heaters for the boiler room;
- the transport pipes to the main distributor/collector (located in a separate distribution room) for the rest of the complex.

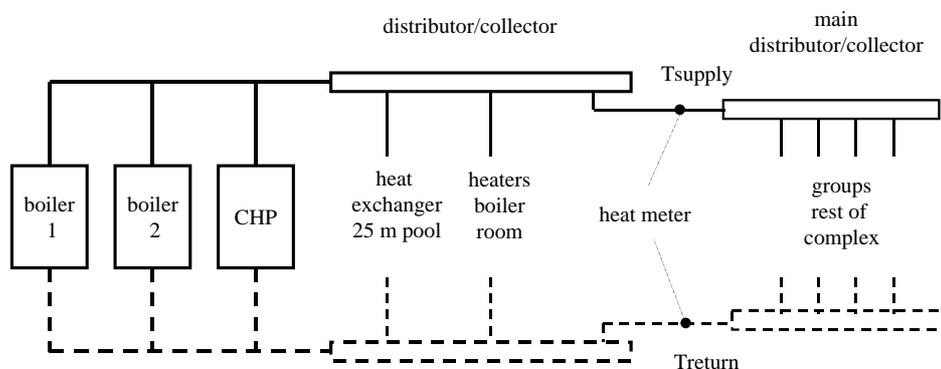


Figure C40. Scheme of the heating system.

The control of CHP and boilers takes place on the heat demand of the groups connected to the main distributor/collector. For that purpose a heat meter is placed in the transport pipes to the main distributor/collector. This heat meter calculates the heat demand on the supply to and return temperature from the main distributor/collector and the water flow.

The wanted supply water temperature to the main distributor/collector is set in the EMCS system with a heating curve.

The control is realised as follows:

- with the heat meter, the actual momentary heat output to the system (main distributor/collector) is measured. This is called the actual heat power (P_{actual});
- based on the wanted supply water temperature (depending on the outside air temperature according to the heating curve) plus the measured water flow and measured return water temperature with the heat meter, the wanted heat power (P_{wanted}) is calculated;
- upon the difference between the wanted (P_{wanted}) and actual heat power (P_{actual}), the control unit in the EMCS system determines the needed heating capacity. This is called the power according to the controller ($P_{\text{controller}}$).

In the controller of the EMCS system the time constants for the increase and decrease of $P_{\text{controller}}$ can be set;

- based upon $P_{\text{controller}}$ the heating components are switched on.

C.19.5 Faults to be identified

Based upon the analysis of the functioning of the installations the following items are selected for faults to be identified:

- Performance and correct functioning of the control of the heating installations (combined heat and power plant, CHP, and boilers);
- Monitoring of the use of the heating energy from the heat pump for the heating of the indoor swimming pools;
- Efficiency of the separate installations (CHP, heat pump and boilers).

C.19.6 Sensors used

In relation to the mentioned items in 8.2.5, the following sensors and control signals are monitored and used:

(1) Performance:

- outside air temperature;
- water temperatures of the swimming pools, heating systems, hot water systems, etc;
- P-controller (Pin);
- P-actual;
- P-wanted.

(2) Use of the heating energy:

- outside air temperature;
- water temperatures of the swimming pools, heating systems, hot water systems, etc;
- air temperatures within the complex;
- position of control valves;
- heat meter from chiller/heat pump to the swimming pools;
- heat meter from chiller/heat pump to the tap water system.

(3) Efficiency:

- outside air temperature;
- gas consumption of CHP and Boilers;
- heat meter from CHP to the heating system;
- heat meter from CHP to the tap water system;
- heat meter from ice-skating rink to chiller/heat pump;
- heat meter from chiller/heat pump to the swimming pools;
- heat meter from chiller/heat pump to the tap water system;
- electricity consumption of the Heat pump;
- electricity production of the CHP
- water temperatures of the swimming pools, heating systems, hot water systems, etc.

C.19.7 Design data used

The following design data are used to implement the rules:

The main specifications of the **Chiller/ Heat pump** are:

- electrical input 20 kWe
- evaporator 320 kW
- condensor 440 kW
- C.O.P. 3.7

The main specifications of the **CHP** are: electrical output 60 kW

- thermal output motor cooler to heating system 140 kW (minimum 70 kW)
- thermal output to tap water system 25 kW

The main specifications of each of these **Boilers** are:

- nominal output 690 kW (minimum 225 kW)
- nominal load 747 kW
- full load efficiency 92 %.

Furthermore, set points are used of controllers as well as the heating curve of the heating production.

In case of heat demand at first the CHP is regulated to maximum capacity and than the first and second boiler.

The switched on heating capacity (P_{in}) is thus related to the $P_{controller}$ as shown in Figure C41.

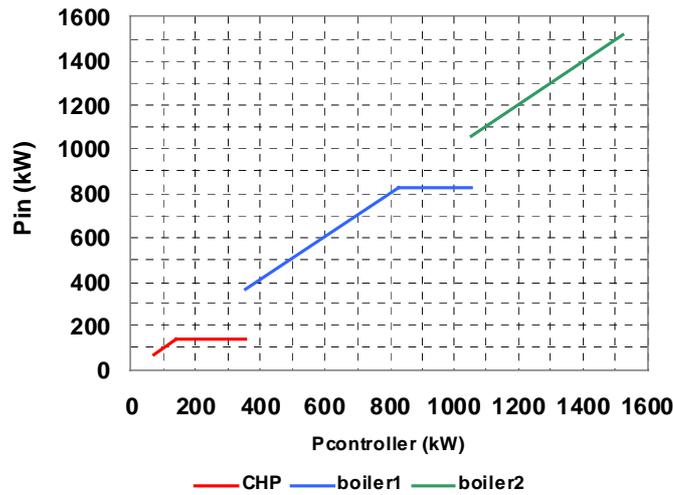


Figure C41. Relation between switched on heating capacity (P_{in}) and needed capacity according to the controller ($P_{controller}$).

C.19.8 Training data required

The first training data is used for manual checking of the functioning and performance of the whole swimming pool installation. After solving of faults and optimising of the installation no new training data is required.

C.19.9 User interface

An off-line user interface is developed.

C.19.10 User selected parameters

The rules include an amount of parameters that must be specified by the user. Those parameters are:

- maximum number of times that the operating mode of the CHP can change without considering the operation unstable;
- the power production in the different operating modes of the CHP and Boilers;
- pool water setpoints.

C.19.11 Threshold selection method

There are no explicit thresholds.

C.19.12 Result of trials

Detected fault

An fault example is present in the context of the control of the heat generation (combined heat and power plant + boilers). The detected fault is:

The combined heat and power plant (CHP) was not controlled optimal during about 75% of the monitoring period. This corresponds to a period of about 15 months. The fault was that the CHP was not set at maximum capacity when this was possible, but was kept as minimum capacity.

Analysis of the fault

The fault was that the CHP was not switched to maximum capacity when Pcontroller was increases to 140 kW. Instead of that the CHP kept running at the minimum capacity of 70 kW.

Several possible causes for this fault are investigated, such as:

- the incorrect functioning of the flow meter from the heat meter for the control;
- a too long start up cycle of the CHP after switching off due to a too high return water temperature. It was believe that perhaps signals being sent from the controller to the CHP (when the CHP was switched off), were not processed correctly by the CHP.

The fault concerns the return signal from the CHP to the controller. The signal from the CHP that it is fully switched on, was given in situations that this in fact was not the case. When the controller than reached a threshold value (e.g. Pcontroller = 365 kW) at which an boiler needed to be switched on additional, the capacity of the CHP was automatically also increased (because it actually was not switched on to full capacity yet).

The fact that the CHP is not used to its maximum capacity of course results in a higher primary energy consumption of the complex.

Fault detection

From the analysis before, can be concluded that the best check for the control of the heating installations can be performed based upon the relation between:

- the switched on heating capacity (P_{in});
- and the needed heating capacity according to the controller ($P_{controller}$).

Using the history option, these capacities will be collected from the EMCS system every 8 minutes and will be put in a separate file together with a time-axis. The FDD-tool will, using if-then-rules, analyse these 8 minutes-data and will, in case applicable, place a code of a fault in a separate column of this file.

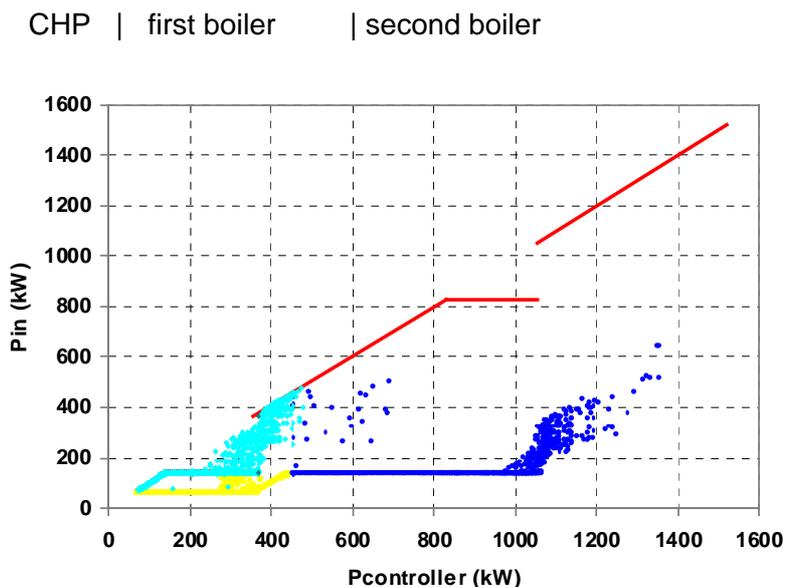
For instance:

- if the CHP is not switched to maximum capacity. This is the case when $P_{in} < 140$ kW while $P_{controller} > 140$ kW;
- if the boilers are switched on at the right moment. This is not the case when P_{in} stays 140 kW or less, when $P_{controller}$ exceeds 365 kW.

With a graphical presentation the control can best be interpreted. An example of this is given in Figure C42.

In Figure C42 with:

- a red line the relation between P_{in} and $P_{controller}$ according to the actual control strategy is given (see also Figure C41). Below the figure is indicated which installation (CHP, first and second boiler) should be in use;
- with cyan points, a situation with correct control is presented. Due to transitional effects these points scatter around the red line. Points that occur outside this cyan area indicate a faulty functioning;
- faulty functioning is presented with different colours in this figure and described below the figure:
 - with yellow a situation in which the CHP is not switched on to its maximum capacity of 140 kW is indicated;
 - with bleu a situation in which a boiler is switched on too late is indicated.



- occurred faults:
- (a) CHP switches not to maximum capacity (yellow)
 - (b) first boiler does not switch on (bleu)

Figure C42. Monitoring of the control of the heating installations in the FDD-tool.

A presentation of the control according to Figure C42 will default be given for the last week (7 days) or the current day. In this way an early and easy detection of faults is made possible.

Furthermore it will be made possible to choose the time interval for this figure so that over a longer period or a certain period in the past information about the functioning can be obtained.

C.19.13 Satisfaction of user requirements

The FDD tool is in process.

C.20 AN FDD TOOL FOR AIR-HANDLING UNITS

Per Isakson, Pär Carling, KTH and Svein Ruud, SP, Sweden

C.20.1 FDD tool

The prototype tool can be embedded in a building management and control system (BMS) or operate as a stand-alone module that interfaces to the BMS.

C.20.2 Intended end-user

The intended end-users are building operators and service company personnel.

C.20.3 FDD method

The fault detection method used in this project is based on steady state models of subsystems of the air-handling unit (AHU), e.g. the mixing box, the heating coil, the mixing valve, etc (see Ruud, 1997 and Ruud, 2000). The models are based on the principles of mass and energy conservation; relationships between control signals and the actual values, etc. Controls signals and occupancy status are used to identify the current mode of operation. Filtered residuals between modelled and measured values for half a dozen quantities (e.g. heating coil return temperature and supply air temperature) are compared to threshold values and when exceeding its threshold it indicates a fault. Furthermore, the standard deviation of these residuals are calculated and compared to thresholds. Hence, 12 residuals are used in total.

The method deals with transient conditions in three ways. First, during a period succeeding a start-up, the method rejects data. Second, a floating mean value of the residual instead of its momentary value is used in the comparison. The same applies to the standard deviations. Third, the threshold is also a floating mean value that increases during periods with transient conditions.

A diagnosis routine based on the concept of fault direction space (FDS) (Jiang et. al, 1995) have been preliminary tested and will in the future complete the method.

C.20.4 Test building, plant and control system

The method was tested on one air-handling unit (AHU) in a seven-story office building close to Stockholm, Sweden. The building, which was erected in the late sixties, served as the head quarter of the building company SKANSKA. The AHU is a constant volume system, which supplies the south facing rooms in the building with heated or cooled air. In each room there is an additional convector.

The original BMS including sensors and actuators, which controls the AHU was replaced in the beginning of the nineties, by a modern PC-based system. The system was built with separate heating and cooling coils. However, now the cooling coil, which has five tube rows, serves both heating and cooling which results in an oversized heating coil. The operator manually changes from heating to cooling mode and vice versa a few times a year.

The control system of the plant maintains the exhaust air temperature at +21°C by governing the mixing box dampers and the heating/cooling coil valve in sequence. When the exhaust air temperature is lower than +21°C the supply air set-point temperature is +21°C. When the exhaust air temperature is equal to or higher than +21°C the supply air set-point is a function of the outside air temperature. When the outside temperature is -15°C or below the set-point is +20°C and when it is +15°C or above the set-point is +16°C. In between it depends linearly on the outside temperature. In heating mode the supply water temperature varies in the range of +20°C to +45°C depending on the ambient temperature. To satisfy the ventilation requirements the outdoor air damper can only be closed to a minimum position, which normally is set to 45% open. However, this limiting value was changed manually to values as low as 25% during periods with low ambient temperature. The reason is concern for insufficient heating capacity, since the heat is supplied by a number of rooftop air-to-water heat pumps.

To support the test of the fault detection method we installed ten additional sensors. The accuracy of all sensors used were checked at two occasions. The additional sensors measured three airflow rates, some water temperatures, and the pressure drop over the coil on the waterside, and the average temperature downstream the mixing box. They were all standard sensors delivered by a control manufacturer and they were connected to the BMS.

In the preliminary stages of the project some faults in the plant were detected. Of these the temperature stratification in the air downstream the mixing box was especially analysed, see Carling and Isakson (1999) and Carling and Zou (2001).

We introduced a number of artificial faults in the AHU, as listed in Table C11. These faults, each with duration of typical a couple of days, affected the operation during ordinary use of the building. Thus, there were a number of restriction to the faults that could be implemented.

Table C11. The faults implemented in the AHU during heating and cooling mode respectively.

Faults implemented (heating mode)		Faults implemented (cooling mode)	
H1	Low water flow through coil	C1	Low water flow through coil
H2	High water flow through coil	C2	High water flow through coil
H3	Outside damper stuck fully open	C3	Outside damper stuck fully open
H4	Return damper stuck 55% open	C4	Return damper stuck fully closed. Outside damper stuck fully open
H5	Return damper stuck fully closed. Outside damper stuck fully open	C5	Return damper stuck 55% opened. Outside damper stuck 45% open
H6	Return damper stuck 55% opened. Outside damper 45% open	C6	Return damper stuck fully opened. Outside damper stuck fully closed.
H7	Outside damper stuck 45% open	C7	Outside damper stuck 45% open
H8	Three-way valve leakage by opening an additional by-pass valve.	C8	Three-way valve stuck fully open
H9	Low supply water temperature.	C9	Three-way valve stuck mid way open

C.20.5 Faults to be identified

A specific set of fault to be identified is not established in the method. Faults that could be detected include:

1. Stuck and leaking mixing box dampers.
2. Stuck and leaking heating and cooling coil valves.
3. Sequencing logic errors.
4. Deviations in supply air temperature.
5. Deviations in supply air flow rate.
6. Deviations in exhaust air temperature.

C.20.6 Sensors used

The method is based on commonly measured quantities. They are:

1. Supply air flow rate
2. Outside air temperature
3. Return air temperature
4. Supply air temperature
5. Supply water temperature
6. Heating/cooling coil return water temperature
7. Exhaust air temperature
8. Heating/cooling coil valve position
9. Mixing air damper position

C.20.7 Design data used

The following design data is used:

1. Set-point of the supply air flow rate,
2. Set-point of supply air temperature,
3. Set-point of exhaust mean air temperature
4. Temperature rise through the supply fan
5. Temperature rise through the pump
6. Heating/cooling coil water flow rate
7. Temperature efficiency of heating/cooling coil
8. Minimum mixing air damper position

C.20.8 Training data required

The thresholds setting method requires some training data from fault-free operation. Furthermore, the method depends on correlation functions for valves and dampers. These could be acquired from the manufacturer, from laboratory measurements, or they need to be established from measured data on site.

C.20.9 User interface

A user interface (UI) was developed in the programming environment DELPHI. The UI had the capability to supervise several subsystems in a building. However in the prototype the FDD method was only fully implemented for one subsystem. The UI could give an alarm on a building level, and the operator could then have a closer look at tables and diagrams for the particular subsystem that had alarmed. Tables and diagrams gave both actual and historic values for several residuals as well as a diagnosis of the most likely faults to have occurred.

As the tool never was tested by an end-user, the final development of the tool, in interaction with end-users, has not been made.

The user interface was developed with help of the industrial partners ÅF VVS-Projekt and TAC.

C.20.10 End-user selected parameters

The user can adjust the overall sensitivity of the method by adjusting the "General threshold limit adjustment" (GTA).

C.20.11 Threshold selection method

The threshold values, which depend on the mode of operation, are chosen in an interactive procedure that uses training data. First, one sets a high overall sensitivity of the method, $GTA = 0.5$, and adjusts the threshold values for each mode until the method yields a 50 percent alarm-rate with data from fault-free operation. Second, one lowers the sensitivity, $GTA = 1.0$, and no alarms should be triggered. The end-user may vary GTA in the range 1.0 to 2.0.

C.20.12 Results of trials

The trials were made with the GTA set to 1.5.

In heating mode the results were not conclusive. The faulty conditions H3, H5, H8, and H9 were detected, but H1, H2, H4, H6, and H7 were not. The oversized heating coil in combination with the modest change in flow-rate (plus and minus approx. 10%) explains the failure of detecting H1, and H2. During H4, H6, and H7 the position of the damper did not deviate much from its correct value. Only faulty condition H8 was correctly diagnosed as the most likely fault. Faulty condition H5 was however diagnosed as the second most likely fault when it occurred. Faulty conditions H3 and H7 could not be diagnosed, as they were not included in the fault library.

In cooling mode all the faulty conditions were detected. However, in the "fault-free periods" there was an, at first sight, unacceptable frequency of "false" alarms. A closer study showed that many of these faults were caused by not artificial faults, see Table C12. Table C12 shows the ratio for false alarms. The largest ratio has the residual dQ_{SA} , which alarms were caused by varying airflow rate, i.e. a fault. The alarms caused by dT_{EA} are due to that the temperature in the building zone, served by the AHU, is too high, i.e. also a fault. For the alarms caused by dT_{RWC} we have not been able to establish the cause. The residual dU_C depends on 17 different parameters, which makes analysis difficult. One conclusion is that residuals depending on few parameters should be preferred. Faulty conditions C1, C2, C5 and C8 were also correctly diagnosed as the most likely faults. Faulty condition C4 was only diagnosed as the second most likely fault. The other faults could not be diagnosed, as they were not included in the fault library.

Both air and water flow rates in the AHU deviates substantially from the design values, on which the fault detection method is based and it is obvious that the result is greatly influenced by this.

During the work, a tool, based on visual data inspection, was developed in Matlab (see Isakson, 2000). Many faults could easily be detected with this tool. Examples are incorrect operation schedule and reversed airflow in the mixing box during non-operating periods.

Table C12. Alarm rates during periods of no artificial faults.

Residual	Alarm rate	Description of residual
dQ_{SA}	0.15	Difference between measured and nominal airflow rate
dT_{EA}	0.06	Difference between measured exhaust air temperature and set-point
dT_{RWC}	0.01	Difference between measured and modelled return water temperature
dU_C	0.07	Difference between measured and modelled control signal to the valve
STD of dU_C	0.01	Standard deviation for dU_C

C.20.13 Satisfaction of end-user requirements

Not tested.

C.20.14 References

Carling, P. and Isakson, P. 1999. Temperature measurement accuracy in an air-handling unit mixing box. The 3rd international symposium on HVAC, ISHVAC '99. Shenzhen, China.

Carling, P. and Zou, Y. 2001. A comparison of CFD-simulations and measurements of the temperature stratification in a mixing box of an air-handling unit. Accepted for publication in the International Journal of Energy Research.

Isakson, P. 2000. A visualisation tool for performance analysis in HVAC systems. Submitted for publication.

Jiang, Y., Li, J. and Yang, X. 1995. Fault direction space method for on-line fault detection, ASHRAE Transactions, 101(2), 219–228.

Ruud, S. 1997. Fault detection method based on steady state models and statistical residual analysis. Bulletin no 44, Building Services Engineering, KTH, Stockholm, Sweden.

Ruud, S. 2000. Description of the FDD method applied on an AHU at the SKANSKA head quarters in Sweden. SP AR 2000:21, SP Swedish National Testing and Research Institute, Sweden.

C.21 QMBFD: A QUALITATIVE FAULT DETECTION METHOD APPLIED TO A CENTRAL AIR HANDLING UNIT IN A LABORATORY ENVIRONMENT

P. Gruber, Siemens Building Technology, L & S Division, Zug, Switzerland

This demonstration describes a **qualitative model based fault detection method (QMBFD) applied to a central air handling unit in a laboratory environment.**

C.21.1 Test Building, Plant and Control System

The **FDD method (QMBFD)** was tested in a **laboratory environment**, consisting of one central air handling unit (CAHU) with constant air volume supplying conditioned air to two rooms. The laboratory is located at the **University de Cergy-Pontoise** near Paris, France. The air handling unit has heat recovery by **damper controlled recirculated return air**, an electrical preheater, a cooling and a heating coil. As the unit is used in a laboratory environment, several applications can be configured including humidity control. For the tested method the humidity control was not a topic of investigation, only supply air temperature control is examined. The unit is rather small sized. The laboratory environment however allowed to introduce several artificial faults without having to convince operators or users.

C.21.2 Intended end-user

The qualitative model based fault detection method (QMBFD) is intended to be implemented as an on-line supervision function in commercially available controllers. The QMBFD has been programmed in the proprietary COLBAS language of the commercially available PRV substation of the VISONIK BEMS system of Landis & Stäfa, which controls the CAHU at Cergy. Alarms and trend plots can displayed on a PC. The intended end-user is a building operator.

C.21.3 Faults to be identified

The QMBFD is a method which is primarily designed to detect faulty behaviour without diagnosing the cause of the fault. The following faults can be identified: damper, heating and cooling control valve blocked midway or in extreme positions; damper, heating and cooling valves cannot open and/or close fully, sensor offsets in outdoor air return air and supply air temperature. Extensive oscillations of the command signals can also be detected.

C.21.4 Sensors used

No additional sensors are needed beside the ones that are used for the control anyway. These are outdoor air, return air and supply air temperature sensors

C.21.5 FDD method

The qualitative model based fault detector method (QMBFD) has been developed in the Annex 25 project and has been described in the Annex 24 Technical report extensively [1], [2], [3]. The detector consists of the following function blocks: steady state detector, transformation, model based prediction and discrepancy evaluation block. The different blocks carry out the following tasks:

- As the method is applied to steady state conditions of the command signals and some temperatures, a **steady state detector** is used, which supervises the variances of the said variables.
- The **transformation block** reduces the command signals for the heating and the cooling valve and the heat recovery to a few qualitative values: The qualitative commands for the heating and cooling valve can be either “on” or “off”, the heat recovery command can be either in “minimum”, “between” or “maximum” position. This transformation to qualitative values reduces the dependency of the method to plant specific parameters like volume flows or geometrical data.
- The method uses a model of the correct behaviour of the controlled system in steady state. This model can be represented graphically in a plane, can be programmed logically or can be expressed by rules. It provides for each measured temperature triple (supply temperature, return temperature, outdoor temperature) the possible correct qualitative control commands for heating, cooling and heat recovery. It is assumed that the controller can attain the set point of the supply temperature. The supervision of the control error is done by another supervisory software. The **model based predictor** uses the the plane representation for the correct behaviour. The plane representing the temperatures of the CAHU in steady state can be divided into different zones or regions for each of which a list of possible correct control command triples can be generated.
- Thus at a given time, when the control system is in steady state, the transformed qualitative control commands of the controller are compared with the possible qualitative control commands generated by the model based predictor, which belong to the zone in which the measured temperature triple lies. If a discrepancy is detected by the **discrepancy evaluation block** in one or more control commands, the detector generates an alarm signal if this situation persists for a certain time.
- The method has two more characteristics which might defer from alternative approaches:
 - 1) The faults that are detectable are not detectable in all steady states. Depending on the size of a specific fault, the steady states in which this fault is detectable, is

varying. The larger the fault is, the more steady states are feasible for possible detection.

- 2) The method has the ability to detect faults, that the control system is compensating, that means these faults are not visible by inspecting the supply temperature alone. In a way the control loop is fault tolerant to these faults and treats them as disturbances. The fault detector however can detect these faults with the additional knowledge of the control commands and some temperatures.
- 3) The method can not detect capacity faults (fouling, sizing, ...). These faults however can be detected by supervision of the control error in extreme temperature situations (for example very hot or cold outdoor air temperatures or large internal loads).

C.21.6 Design data used

Few design data are used. They are:

- configuration knowledge (fan positions in relation to supply and return air temperature measurements, damper or heat recovery wheel, minimum damper position, temperature rise across fan, addresses of all data points needed)
- operation knowledge (mode of operation, heating and cooling set point, dead zone for economy changeover)
- maximal installed heating and cooling power or maximal temperature rise or drop across the emitters are useful information. They are however only needed in extreme cases.

C.21.7 Training data required

No training data of a specific site are required. Default parameters (forgetting factor for steady state detection, ...) were chosen after off-line training and simulation.

C.21.8 User interface

As the method is running on-line in a substation with a high sampling rate of e.g. 10 sec, data was stored in larger time intervals for displaying the trend plots of the variables of interest over a time window of a given length. Steady state and fault conditions as well as control commands discrepancies in the case of fault can also be retrieved.

C.21.9 User selected parameters

The user can choose between recirculating damper or heat recovery wheel. Also the temperature across the fans can be chosen. Both parameters have to be edited at the moment in the COLBAS code of the substation directly.

C.21.10 Threshold selection method

Different thresholds have to be selected. They can be divided into the following classes:

- Thresholds for the quantization of the control commands. The default values are chosen as 1% over or under the min/max or off limits.
- Thresholds for steady state detection. These values correspond to the limits of the standard deviations of the temperature and command signals and are set to default values
- Thresholds dx,dy and dz in the temperature plane for the definition and separation of the different zones. These values depend on three kind of errors which have to be taken into account:
 - measurement errors (sensor errors ± 0.1 °K)
 - steady state errors (dependent on the limits of the standard deviations of temperature and command values)
 - modeling errors (these include uncertainties of temperature rise across fan, sensor placement,...)
- Thresholds in time for steady state (default value: some minutes) and fault persistence for alarm generation (default value: 5 minutes to 30 minutes).

The last threshold for alarm generation is user dependent, the other thresholds were chosen as default values.

C.21.11 Results of trials

The trials covered mainly the ability of the method to detect faults. The detector was tested in several daily trials. First the behaviour under correct operation was investigated. After that several tests were carried out with different positions of the blocked heating valve. Under the environmental conditions (outdoor temperature could not be influenced) a blockage of 30% or bigger could be detected. Return air sensor offsets and outdoor air temperature offsets were also injected as faults and could be detected. The more the value of the outdoor air temperature differ from the value of supply air temperature, the larger the offset of the outdoor temperature sensor has to be in order to be detectable. If on the other hand, the two temperatures are too close to each other, the qualitative method of finding control command discrepancies fails.

The results of trials confirmed the expectations of simulation results. It demonstrated nicely the dependency of detecting faulty behaviour on the operating conditions. Care must be also given to the fact that different kind of valve characteristics or damper characteristics might alter the detection level of faults.

C.21.12 Satisfaction of user requirements

It was demonstrated that the method can be implemented and commissioned without great effort at a new site and that different kind of faults could be detected. The satisfaction of the user cannot be judged from these trials because only the commissioning engineer was present at the site. His feedback however was very positive, especially because few design and site data had to be known for the commissioning.

C.21.13 References

[1] IEA Annex 25 on “Real Time Simulation of HVAC Systems for Building Optimization, Fault Detection and Diagnosis, Technical papers, editor: J. Hyvärinen, Nov. 1996, pp. 203–247.

[2] A.S. Glass, P. Gruber & J. Tödtli. Qualitative approaches to fault detection and diagnosis, *Building Services Engineering Research and Technology*, Vol. 17, No. 3, (1996), B24–B27.

[3] A.S. Glass, P. Gruber & J. Tödtli. Automatische Erkennung von Fehlern in einer zentralen Luftaufbereitungsanlage mit qualitativen Methoden, 8. Schweizerisches Status Seminar 1994 Energieforschung im Hochbau, 15./16. September 1994, pp. 189–196.

C.22 QMBFD: A QUALITATIVE FAULT DETECTION METHOD APPLIED TO A CENTRAL AIR HANDLING UNIT IN AN OFFICE BUILDING

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This demonstration applies the same **FDD method (QMBFD)** as was used in Switzerland Demonstration 1 to **another building**. So only differences to the points listed in the Demonstration 1 case will be reported here.

C.22.1 Test Building, Plant and Control System

The FDD method (QMBFD) was tested in an **office building**, consisting of one central air handling unit (CAHU) with constant air volume supplying conditioned air to a medium sized office building.. The building is located in Steinhausen, Switzerland and is the office building “**Sennweid**” of Siemens L & S Switzerland. The air handling unit has a heat recovery by a **heat recovery wheel**, an electrical preheater, a cooling and a heating coil. For the tested method the humidity control was not a topic of investigation, only supply air temperature control is examined. The office environment made it however difficult to introduce artificial faults because operators or users had to be convinced.

C.22.2 User interface

As the method is running on-line in a substation which is connected to a central BEMS station, data could be stored in a large data base. From that data base it is possible to retrieve any data for displaying the trend plots of the variables of interest over a time window of a given length. All relevant temperatures and control commands can be plotted. Steady state and fault conditions as well as control commands discrepancies in the case of fault can also be retrieved. Additionally the alarms that are generated during the whole time span of operation are stored in a special file.

C.22.3 Results of trials

The aim of these trials was the behaviour of the detection method with regards to false alarms. The detector was tested over a very long period from 1997 until 2000. During this time period several improved versions have been implemented and tested. The major changes were connected to lowering the false alarm rate. An important parameter that influences the alarm and false alarm rate is the minimum time interval during which a fault has to persist, before it is acknowledged as an alarm. This time interval should be a user selected parameter. By putting this time interval to a half an hour, hardly any false alarm was generated. This result means on the other hand that the chance of detecting faults of short duration is decreasing.

An important result of these trials was that most thresholds and other parameters of the method had not be altered at all when the method was transferred from one site to another. That gives hope that generic default parameters can be used in many cases.

During short periods some faults could be introduced like blocking the cooling or the heating valve. The result of these fault injection was not as representative as in the first demonstration case because the faulty situation could often not be persistent enough. In cases however where the steady state was reached the result was comparable to the one obtained in demonstration case 1 under similar operating conditions.

C.22.4 Satisfaction of user requirements

Two “faults” in the control system could be identified, where the control strategy differed from the optimal one. Both occurred not during the heating season. They were concerned with the energy free zone (no heating or cooling required) and with the economy change over. So the method proved to be effective and pointed out some “faulty” behaviour which required an explanation from the operator. The operator welcomed this kind of supervision. It is highly probable that the method will be exploited commercially as an add on to existing BEMS.

C.23 PERFORMANCE AUDIT TOOL PAT: AN EXPERT SYSTEM BASED FDD TOOL FOR THE DETECTION AND DIAGNOSIS OF BUILDING UNDERPERFORMANCE

P. Gruber, Siemens Building Technology, L & S Division, Zug, Switzerland

The **expert system based FDD tool (PAT)** was applied to the same building as the one which was used in Switzerland demonstration 2.

C.23.1 Test Building, Plant and Control System

The FDD tool (PAT) was tested in an **office building**, consisting of one central air handling unit (CAHU) with constant air volume supplying conditioned air to a medium sized office building.. The building is located in Steinhausen, Switzerland and is the office building “**Sennweid**” of Siemens L & S Switzerland. The tool was applied to the central air handling unit and three individual zones with additional radiator heating and chilled ceiling facilities.. The air handling unit has a heat recovery by a **heat recovery wheel**, an electrical preheater, a cooling and a heating coil. For the tested method the humidity control was not a topic of investigation, only supply air temperature control is examined. The office environment made it however difficult to introduce artificial faults because operators or users had to be convinced.

C.23.2 Intended end-user

The Performance Audit Tool (PAT) will be used to automatically supervise building performance. In its final state it will be installed in Landis & Stäfa branch offices or maybe at big customers’ offices. It will be run over night as a batch job having (remotely) automatic access to building data and producing a printed report of its findings. It is thought to be used as a service tool supporting the building operator. The operator himself is only confronted with findings in the printed reports but not with the commissioning of the tool.

C.23.3 Faults to be identified

The PAT is a tool which is designed to detect and diagnose faulty behaviour. As the tool can be applied to zones, central air handling units and chillers, the faults that can be identified are classified into these three categories. Tests with the chiller module were not carried out.

The faults or underperformance types to be detected include comfort issues like zone temperature and exceeded energy consumption as well. Their causes may be among others total or partial component failure, wrong parameter settings, operators’ errors, undersized system capacity, changes of usage. As the PAT will not get any user input

during the audit it will in most cases not be able to indicate the exact cause of an underperformance it has detected. Instead it will produce a list of possible causes.

The number and type of detectable faults are given in Table C13 for each application.

Table C13.

	Zone	CAHU	Chiller
number and type of detectable faults total number: 36	11 for zone 1 for building <ul style="list-style-type: none"> • too hot/too cold (2) • too much heating/cooling (2) • sensor defect/offset (4) • cooling/heating ineffective (2) • higher energy consumption (2) 	21 for CAHU 1 for building (same as for zone) <ul style="list-style-type: none"> • supply too hot/ cold (2) • too humid/ dry (8) • simultaneous heating/cooling (1) • wrong control combinations (2) • sensor error/ offset (5) • exceeded energy consumption (2) • pressure too high/low (2) 	2 <ul style="list-style-type: none"> • evaporator pressure too low (1) • condenser pressure too high (1)

C.23.4 Sensors used

If the number of sensors is considered, one has to distinguish between number of sensors needed for the detection and the number of additional sensors needed for the diagnosis. For both, detection and diagnosis, not only measured quantities have to be acquired by sensors, but also on-line information about certain states and signals of the controllers are necessary. In Table C14 both types of on-line information are put under the label point information.

Table C14.

	Zone	CAHU	Chiller
number and type of points needed for detection	9 temperatures control signals operation mode	12 temperatures control signals operation mode humidity pressure, speed	4 status pressure load
additional number and type of points needed for localisation and diagnosis	12 temperatures local commands CO2	14 temperatures operation modes alarms control signals	9 temperatures pressures

As can be seen from the table, a large number of data points are required. If one restricts the detection and the diagnosis on a specific fault, this number is of course heavily reduced.

C.23.5 FDD method

The expert system based tool called **PAT (Performance Audit Tool)** for the detection and diagnosis of building underperformance or faults has been described in [1] and [2] extensively. Prior to the Annex 34 a first prototype was finished, which was improved and tested in more realistic situations during this Annex. In contrast to the FDD method (QMBFD) applied in the Switzerland demonstration 1 and 2, PAT is much more general and complex and is not restricted to steady state conditions. The main features of this method can be summarized as follows:

System structure of PAT:

The system structure is shown in Fig. C43.

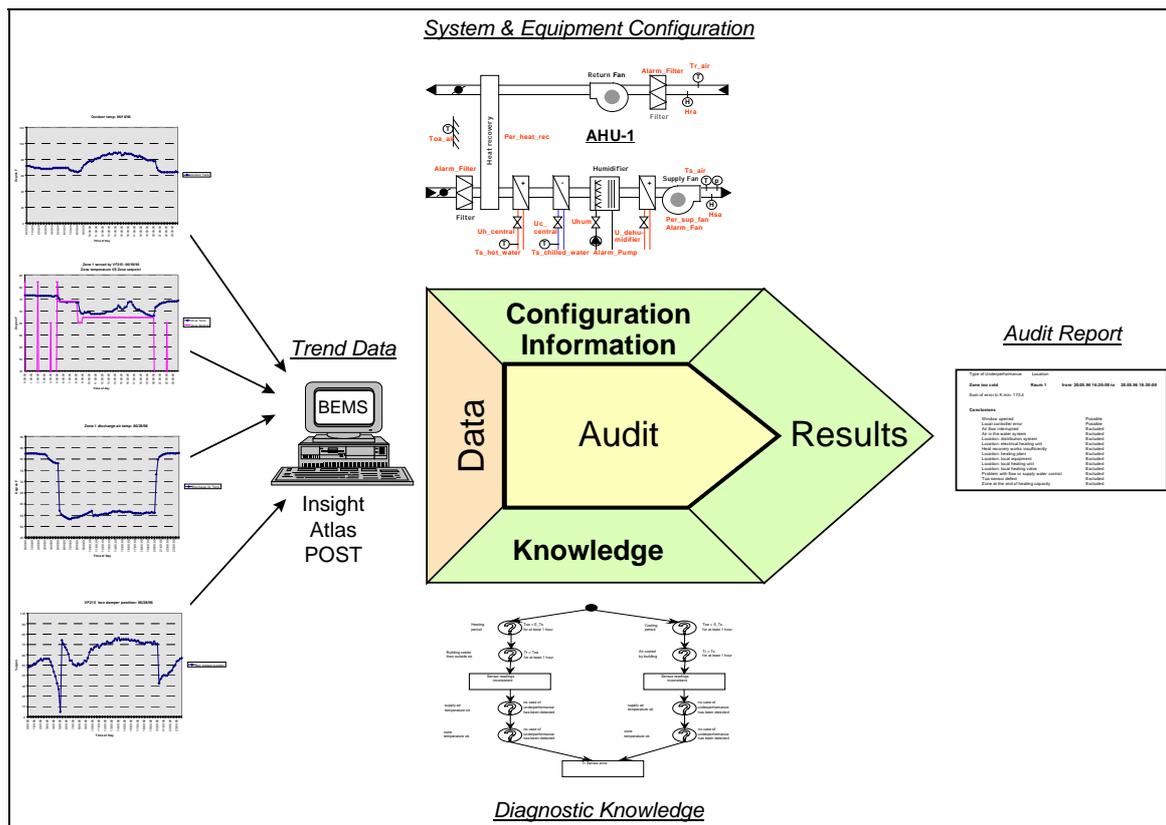


Figure C43. PAT system structure.

- The “Data” component loads trend data from the BEMS into the PAT trend data archive database using existing packages like. Existing data management tools for the different BEMS are integrated at the front end of the data acquisition process. Invalid data are detected by comparing the data with upper and lower boundaries and missing data are handled.
- The “Configuration Information” component provides a user interface to enter configuration information (e.g., points, plants, zones) into the **configuration database**. Part of this “set-up” module are the “point parsers” that try to extract automatically information from point names and descriptions. The configuration data are stored in a relational **configuration data base** holding data for each installation about:
 - building topology (floors, zones)
 - HVAC system (subsystem, equipment, design parameters)
 - point definitions (read from the BEMS)
 - point functions (e.g. “zone temperature”)
 - connections between points and their setpoints
 - point locations (minimum: buildings, floors and zones under consideration)
 - operating schedule and holidays
 - some fixed operational and design parameters (e.g., design temperatures)
 - data storage.
- The “Knowledge” component contains expert knowledge on improving building performance. Diagnostic knowledge is captured in rules forming decision trees. It is stored in a **knowledge base**. A knowledge-based system was used to capture and store the expertise on improving building performance. This knowledge-based system realised with a commercially available expert system shell was embedded into “conventional” relational databases. Users will only see the database interface. Only those people maintaining the knowledge base will have to deal with the proprietary technology of the “expert system shell”. Knowledge bases exist for zone, central air handling unit and chiller underperformance. The knowledge for each type of underperformance is captured in fault or decision trees. 28 such trees exist with approx. 250 diagnostic rules and approx. 85 conclusions.
- The “Audit” component combines knowledge and configuration information to interpret and evaluate trend data. Cases of underperformance and their likely causes are exported into the result database.
- The “Results” component consists of a **result database** holding cases of underperformance and diagnostic results. It is automatically filled by the Audit component. The block transforms also the results of the audit into easy to understand audit reports.

The prototype uses MS Access as database for the trend data archive, the configuration and the results. Modules handling trend and configuration data are written in Visual Basic. In order to enable the exchange of the database system with little effort those modules that are meant to run as batch jobs use ODBC access to the database. The user interface for the configuration entry was written as modules inside the MS Access database for cost reasons.

Structure of the configuration base

The data modelling that led to the chosen data structure was based on an entity-relationship model. The main structure of the overall configuration data base consists of seven major blocks. Each block may consist of several subblocks. Each subblock on its part may contain several tables which are connected via relations. Each table has from a few up to 50 entries with a typical number of approx. 10. The data base is implemented in MS Access. The different tables can have a 1:1-, 1:max 1 (is a), 1:N or a N:N relations. Every N:N relation can be further broken down by an additional table into two 1:N relations.

Structure of the knowledge base

The knowledge that is used during the audit, is divided in two type of rule groups:

- detection rules for each underperformance
- diagnostic rules for localization and identification of underperformance or fault cause.

The rules are written in a generic way, that means that specific data points are not used for the knowledge presentation in the rules. If a rule is used during the audit, the corresponding identifiers of the needed data points and parameters are filled in in order to evaluate the rules for every item.

Underperformance detection

The underperformance or fault detection component consists of three connected loops which are executed periodically:

- time loop activated at predefined intervals (e.g. 10 min)
- type of underperformance (all underperformances which apply to a specific item like zone, CAHU, sensor,...)
- item (all zones and CAHU's, equipment,...)

For every type of underperformance there exists a **detection rule** describing the conditions for this underperformance to be detected. These detection rules refer to a time t_0 , the start time of the underperformance. The rules are executed for every item they can be applied to (zones, equipment etc.) and for every time interval. Some types of underperformance are checked just once a day. Whenever all conditions come true at the same time an "underperformance" record is created and stored for diagnosis. The detection is done by **forward chaining**, starting from the data and facts and then proceed along all rules until the underperformance is detected.

If the information needed to evaluate a condition is not available because of missing sensors, interruption of data transmission etc. rule execution is stopped.

Underperformance diagnosis

For every type of underperformance there exists a decision tree containing the part of the system, where the cause might be located and the conditions necessary to blame a certain equipment, controller,.... In order to structure the diagnosis better, the decision tree is divided into **localization** and **proper diagnosis** or **identification**. Has the state “underperformance detection” been reached, then the search is continued by backward chaining. One starts from three possible “problem location” states (goals) and checks upwards, whether all conditions (rules) can be fulfilled by the given facts until one reaches the state “underperformance detection” by at least one path. If such a “problem location” has been found, then one starts from all diagnosis (goal) which can be reached via the found “problem location” and checks again in a **backward chaining** way if the found “problem location” state can be reached. If the information needed to evaluate a condition is not available because of missing sensors, interruption of data transmission etc. the corresponding cause must not be excluded. Therefore the condition is passed as if it were true but the conclusion is marked to be less reliable.

C.23.6 Design data used

These parameters are derived from plans and should change little over time. Typical configuration parameter classes are:

- Design parameters (e.g. minimal cooling setpoint, maximal outdoor air temperature)
- Identifiers (e.g. point name)
- Configuration parameters (e.g. central/local cooling).

All these data are kept in the configuration data base described before. It is also clear, that due to the complexity of the rules, especially for the diagnostic part a lot of information is needed.

C.23.7 Training data required

No training data of a specific site are required. As the rules depend more on qualitative knowledge capturing cause effect relationships detailed knowledge about plant dynamics or plant parameters are not needed. Default parameters were chosen on reliable expert knowledge.

C.23.8 User interface

The user interface is divided in a commissioning and set up interface and an on-line user interface. The commissioning interface allows to load from the configuration data base all the needed information in order to set up the Audit. For instance, for each CAHU and zone the correct identifiers have to be matched with the corresponding equipment.

The on-line user interface itself deals directly with the on-line handling of the tool. PAT is installed on a PC. By starting the program, the user is guided through a simple graphical inter-face, where he has to enter or acknowledge certain inputs.

C.23.9 User selected parameters

The user can choose the site and the time period, for which the Audit is done. The results of the Audit are stored in MS Access tables. From these tables the user can obtain reports with the findings.

C.23.10 Threshold selection method

Different thresholds have to be selected. The values of these parameters are captured by expert knowledge and are of a generic nature. Normally they are not changed for a specific application. Typical parameters are:

- Thresholds for deviations and integrated deviations
- Thresholds for sensor offsets, set point changes, actuator positions etc.
- Thresholds for number of missing or invalid data
- Time thresholds for persistency of faulty behaviour.

C.23.11 Results of trials

First a prototype was built with a full framework but with limited diagnostic capabilities. This prototype was used in the audited building. No faults had been injected during the trials. The tool was just passively analysing the recorded data by using PAT. Several faults could be found, which were related to zones and to the central air handling unit. Wrong room temperature set points, slow reaction time of the zone controller (too cold for too long a time) and unnecessary heating during some short periods were found for the zones. Due to incomplete information, no accurate diagnosis could be made and the list of possible causes was quite long. The audit for the central air handling unit a wrong control command combination for the heat recovery wheel and the heating valve was detected. The cause for this faulty behaviour could be a degradation of the heat transfer of the heat recovery wheel.

The trials in the office building proved that such a tool can fulfil its job. The periodic auditing was only applied during a short time. Most of the audits were done by inspecting data after they have been recorded for several weeks.

C.23.12 Satisfaction of user requirements

It was demonstrated that the tool can be implemented and commissioned at a new site and that different kind of faults could be detected. It was however clear that the time it needs to commission and set up the tool to a specific site was much too high. The main reason for that was the amount of configuration and design information that is needed for the tool. As most of this information could not be retrieved automatically from other data bases, they had to be entered manually. This was due to the fact that the tool was connected to a BEMS installed a long time before. Other points that could not fulfil the user requirements were:

1. Stability of the PC environment, including the communication with the BEMS, which proved to be not all the time as reliable as expected.
2. Updating the knowledge base by modifying existing or adding new rules. The used expert system shell had not all the capabilities that the user requested for a comfortable handling of an update. There was no graphical user interface for entering rules and the graphical documentation of the rules had to be done by another software.

Due to the difficulties covered in the above issues, PAT is not the success it could be. The prototype version will not be further developed to a full product. The lessons learned will be used to avoid similar difficulties with a new version. The core of PAT, the knowledge base, which was acquired during the development of PAT, however, will be of high value and can easily be reused.

C.23.13 References

[1] P. Gruber & S. Kaldorf. Performance Audit Tool PAT: ein Expertensystem zur Detektion und Diagnose von Fehlverhalten von HLK-Anlagen in realen Gebäuden, 10. Schweizerisches Status-Seminar 1998, Energieforschung im Hochbau, EMPA-KWH.

[2] P. Gruber & S. Kaldorf. Performance Audit Tool PAT: an expert system for the detection and diagnosis of building underperformnace, to appear in ASHRAE Transaction.

C.24 STUDY OF A PHYSICAL MODEL APPROACH TO FDD ON A COOLING COIL

R. A. Buswell, J. A. Wright and P. Haves, Loughborough University, U.K.

C.24.1 Test building, plant and control system

Building Description: Open plan office (each floor = 2500m²) constructed in 1970's located in Essex, UK. Refurbishment carried out on the building and the HVAC plant in 1994–1995. Approximately, 330 staff occupy the building between 06:00 and 22:00, 5 days a week, although there is limited occupancy for twenty-four hours a day, seven days a week.

Plant Description: The open plan areas are served by twelve constant volume, air handling units. Of these, nine are of similar construction, six serving one of the open plan spaces. The air is extracted through the light fittings into a common plenum formed by the suspended ceiling. Air from the space is returned and mixed with outside air via a mixing box common to all AHUs. The supply air for all the AHUs is fed from the mixing box, which formed by the plant room itself. The outside air, controlled by dampers, enters the plantroom via a number of louvered openings in the external façade. The AHUs provide cooling, heating and humidity control to the occupied space. The central plant has a cooling capacity of 660kW and 600kW heating capacity.

The AHU monitored in this work stands vertically and is approximately 4m high by 0.8m square. The mixed air inlet is at floor level in each unit. Air entering the unit passes through a filter, the cooling coil, the heating coil and the supply fan. The air is humidified before passing over the supply air sensor and being supplied to the space. The cooling coil is inclined at approximately 45° to the walls of the unit.

C.24.2 Intended end-user

Aimed at the experienced building and plant control operative, although product-state is largely that of a research tool. No end user evaluation carried out to date.

C.24.3 Faults to be identified

Demonstration system had no “deliberate” or intended faults implemented. The study largely reviewed the operational characteristics of a cooling coil over a completed load cycle (summer through to winter). However, the FDD schemes have been designed for three faults: leakage through the control port of a three port control valve; fouling of the cooling coil; and sensor offset.

C.24.4 Sensors used

The sensors used here are typical HVAC grade sensors commonly found in AHUs. In this particular instance, the atypical mixing box arrangement necessitated the installation of an additional air humidity sensor to measure the relative humidity of the air entering the AHU.

Table C15.

Measurement	Unit	Comments
Inlet air temperature	°C	Point sensor
Off cooling coil air temperature	°C	Averaging sensor
Heating and cooling demand control signal	%	+100% to -100%
Fan running indication	0/1	From flow switch
Chilled water supply temperature	°C	Located at discharge from chiller
Mixed air temperature	°C	Measured in front of the filter on the AHU.
Mixed air relative humidity	%	Measured in front of the filter on the AHU.

Table C15 gives the measurements that were used by the condition monitoring procedures. An indication of whether the fan is running is required to determine when the plant is operational and hence allow the application of the condition monitoring procedures. The off coil air temperature was used to generate the innovation between the model prediction and measured system operation. The other data are model inputs.

C.24.5 FDD method

Detection: Both methods described here are based on an innovations approach to FDD. Predictions from a “first-principles” steady state reference model of the system are used to model “correct operation”. The models are only valid when the plant is in steady state. A steady state detector is employed to filter out the unwanted transient data. The current system condition is compared to the reference, and the difference, an “innovation”, is generated. A significant innovation is evidence that the system operation has changed. Two techniques are presented here that address the diagnosis of the system condition, the first is based on recursive parameter estimation (RPE) and the second is based on expert rules. Both methods use the innovations generated from the steady state reference models. The recursive parameter estimator continuously re-estimates the model parameters in an attempt to reduce the innovations to zero, the selected parameters then tend to represent the current condition of the system. The expert rules approach, known as the “Bin Method”, uses the model innovations to track changes in the performance over specified portions of the operating range. Both methods require no more input data (sensor measurements and control signals) than are available from a typical HVAC control system.

Diagnosis using Expert Rules – the "Bin Method": The operating range of a subsystem is split into three “bins” that represent “high”, “mid” and “low” regions of

operation. The division is based on engineering judgement once the characteristics of the subsystem are established from the calibration tests. Innovations passed to each bin are recursively averaged with the greater weighting being assigned to the most recent innovations. The expert rules base consists of simple “IF-THEN” rules, which are applied to the contents of the bins to ascertain the region of operation that is affected by the change in plant condition and to provide possible diagnoses.

Diagnosis by Parameter Estimation: The steady state innovations are passed directly to the parameter estimator which recursively re-estimates the parameter values such that the innovation tends to zero. A change in parameter value from the model calibration value indicates a change in system condition. For instance, the three port valve model includes a parameter that represents the leakage of the valve; assuming that the model structure allows a good representation of valve leakage, then an increase in the leakage parameter indicates directly that the leakage has increased.

C.24.6 Design data used

The HVAC subsystem models developed in this work are generic in structure. They are applied to a specific system by identifying the model parameters from measured system input and output data. Design data required are: design water flow rate; design air-flow rate; face area of coil; type of coil (high/low efficiency; i.e. high efficiency may have turbulators on the water side and a high fin density); internal diameter of coil tubes; and number of parallel circuits.

C.24.7 Training data required

The subsystem model is required to represent the real system over the whole range of operation. To this end, steady state calibration data are collected from the cooling subsystem using a systematic test procedure:

1. Set to open loop control.
2. Divide the control signal range into a number of discrete points (e.g. eleven for 10% steps).
3. Starting from 0% demand, the data are collected until a period of steady state ensues. The stepwise increments are continued until steady state at 100% demand is reached.
4. The same sequence is repeated returning to 0% demand, although limitations on test time may necessitate a reduced number of test points in returning to 0%, but at least one point in the mid range is required.

It should be noted that this process is repeated for at least two air-flow rates in VAV systems and would be carried out for any other subsystems that require the application of these FDD tools. The following parameters are batch estimated from the data using a non-linear optimisation technique: valve actuator hysteresis; valve actuator low

activation point; valve actuator high activation point; installed valve curvature characteristic; valve control port leakage; coil resistance scaling factor (scales UA); and supply air sensor offset.

C.24.8 User interface

Command line.

C.24.9 User selected parameters

None, Method let as-is after set-up.

C.24.10 Satisfaction of user requirements

Not tested.

C.24.11 Threshold selection method

There are a number of thresholds and operational parameters associated with the operation of the FDD software. Table C16 lists these parameters and their values.

Table C16.

Applies to	Operational Parameter or Threshold
Models	Steady state detector time constant
Models	Steady state detector threshold
RPE	Forgetting factor
Exp. Rules	Significant innovation level
Exp. Rules	Bin demarcation, low-middle and middle-high
Exp. Rules	Forgetting factor

The steady state detector time constant represents the maximum time constant that would be expected from the system. This is unlikely to require adjustment for other HVAC thermal subsystems. The steady state threshold selection is somewhat arbitrary, but again, it is not expected to require re-tuning at each implementation. The authors are involved in current work that supports this statement. The level is set based on the training data, typically 0.75°C. The selection of the forgetting factor controls the sensitivity of the methods. Although there are six parameters listed, it is not envisaged that they will need adjustment for different applications to the same subsystem type. The thresholds associated with the bin demarcation and innovation significance would need resetting, but this could be easily automated from the calibration tests.

C.24.12 Results of trials

Characterisation of the target system can be time consuming where the collection of special data is required, although better model precision is achieved as a result. The selection of the method parameters and thresholds are simpler and appear to be more robust for the bin method whereas the performance of the RPE method is sensitive to these values.

Both methods demonstrate that diagnosis of the fault conditions is possible. The visibility some fault conditions is restricted to distinct regions of the operating space. This can aid the diagnosis of the system condition, although some fault conditions remain hidden until the system moves to an operating region where they have some effect. The methods implemented were configured to provide diagnosis of a single fault condition, although the recursive parameter estimation method has the potential to diagnosis multiple faults, provided that the faults are independent as regards their effect on the system operation, and do not mask each other. The bin method proved to be much simpler to set up and understand than the parameter estimation method. The performance of both schemes proved to be similar in that they produced the same trend in diagnosis of the system condition.

Figures C44 to C46 demonstrate some of the findings of the work.

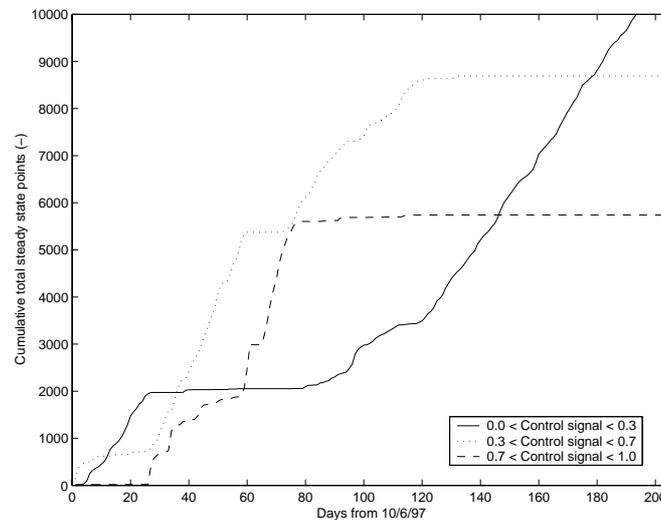


Figure C44. The accumulation of one-minute steady state samples over the test period where the system operated under normal control conditions, driven by changes in ambient conditions. The operating space of the monitored cooling coil is partitioned into three distinct regions by control signal relating the low, medium and high duty. Day 0 indicates the start of the monitored period (10th June), approximately 30 days before the commencement of the peak system loads. The system loads have decreasing significantly by day 80 and by day 120 the cooling coil is not in operation.

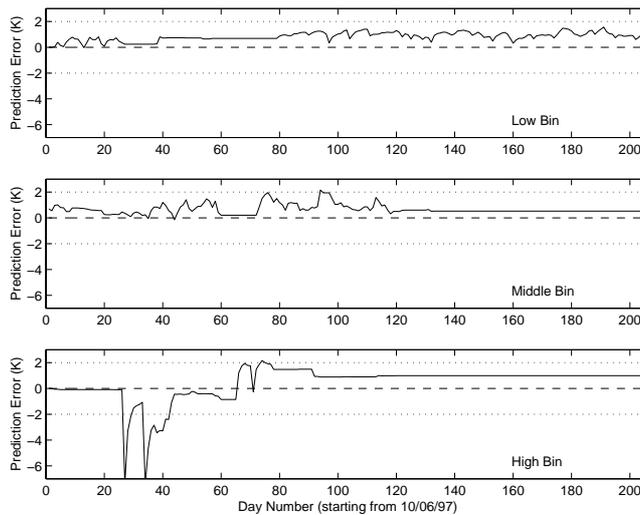


Figure C45. Shows the end-of-day bin values. The bin method output is given for the same operating regions as in Figure C44. The dotted lines show an estimation of uncertainty for each prediction error. The principle features are the large negative errors in the high bin around day 30, attributed to a failure in the chilled water supply system, and the persistent offset occurring after day 60, attributed to a change in one of the sensors used for acquiring the input data for the FDD tool.

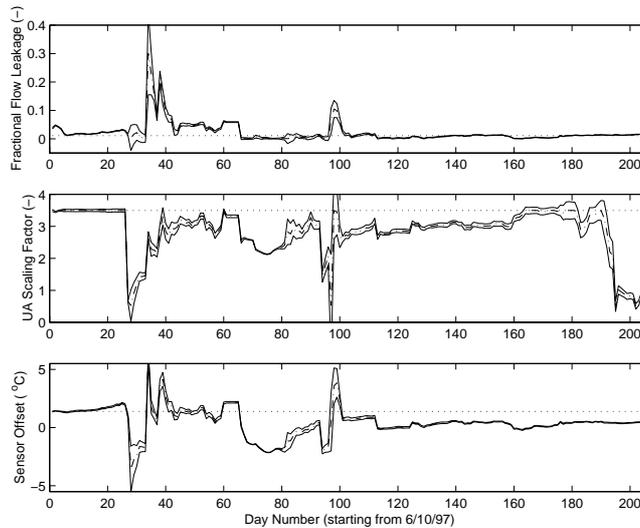


Figure C46. Shows the end-of-day recursively estimated fault parameter values. The parameter estimates describe the state of the system in terms of valve leakage, a scaling factor representing coil capacity and sensor offset. The behaviour is most sensitive to leakage in the low region of operation, is most sensitive to the UA scaling factor in the high regions and is equally sensitive to the sensor offset over the whole operating region. The principle features discussed in Figure C45 are visible here also. However, there are two other significant changes in the estimates of the parameters at day 100 and day 170. These events demonstrate the sensitivity of the approach. Disturbances can cause parameters to wander but the method is able to recover, as shown after day 100. The test period is not long enough to allow the method to correct the disturbance at day 170.

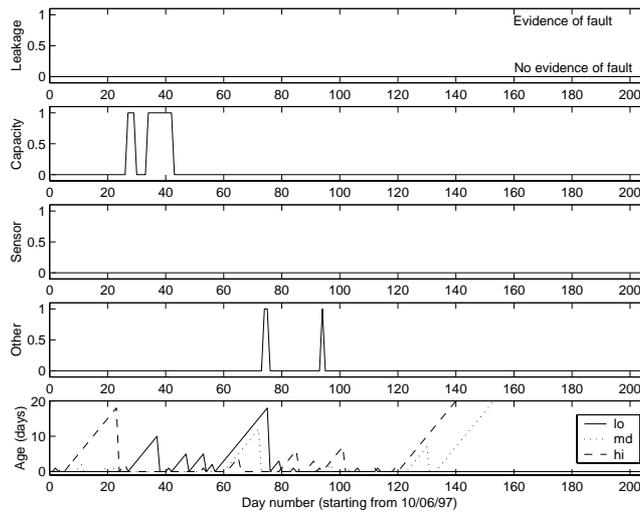


Figure C47. Shows the crisp rule diagnosis of the system condition based on the bin method. The rule set is of the form: **IF low bin prediction error is not significant AND middle bin prediction error is not significant AND high bin prediction error is significantly negative THEN the fault is “coil under capacity”**. “Other” was fired when the evidence (i.e. significant error) did not meet any of the pre-described rule set. The bottom plot shows the age of the information in each of the three bins in days. It can be seen that the scheme interpreted the evidence around day 30 as “under capacity”.

C.25 PMAC: A PERFORMANCE MONITORING AND AUTOMATED COMMISSIONING TOOL

Arthur Dexter, Xiong Fu Liu and Darius Ngo, University of Oxford, United Kingdom

C.25.1 FDD tool

Performance monitoring and automated commissioning tool.

C.25.2 Intended end-user

The Performance Monitoring and Automated Commissioning (PMAC) tool is designed to monitor the performance of control loops and automate the commissioning of air-handling units (AHU) [Ngo and Dexter, 1998a]. The PMAC tool resides in the PC-based supervisor and, as shown in Figure C48, communicates with the building energy management system (BEMS) in a remote building via a modem link. The intended end-user is a commissioning engineer employed by either the building operator or the manufacturer of the BEMS.

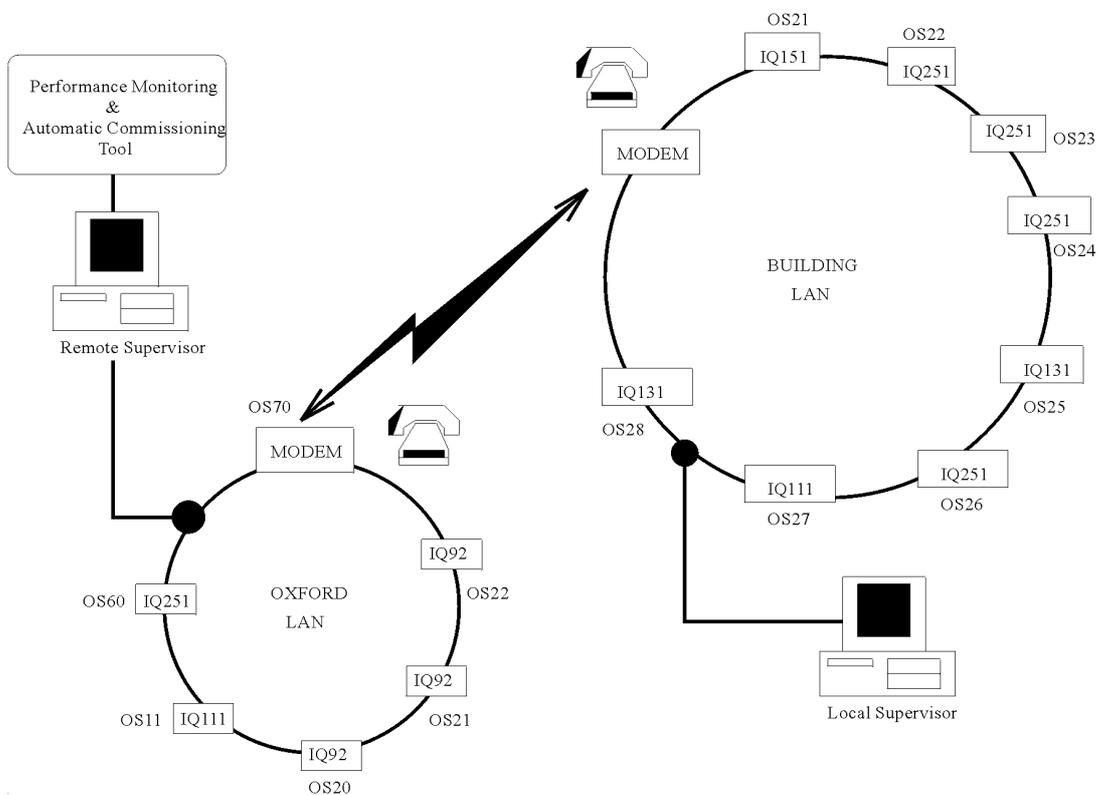


Figure C48. Communication with the BEMS in a remote building.

C.25.3 FDD method

The performance monitor undertakes the daily task of logging data from the BEMS and of assessing the subsystem's control performance based on the calculation of various performance indices from this data. The performance indices that have been used in the prototype tool are activity and transgression [Ngo and Dexter, 1998a]. Both indices are estimated recursively from the sampled measurements. The performance monitor also decides whether the performance is unacceptable or not. In each case, expert fuzzy rules are used to determine the outcome. The use of a fuzzy rule base allows the tool to interpret the performance indices and evaluate the control performance qualitatively. The linguistic approach simplifies the otherwise complicated task of analysing multi-dimensional data. If the performance is found to be unacceptable (e.g. the control signal is oscillating or the controlled variable is saturated) the operating point, at which the worst performance has been observed, is identified and the software switches to the loop tuner block, so that the controller can be retuned at this operating point. Another set of fuzzy rules is used to analyse qualitatively the result of retuning. If the retuning result is acceptable, the controller's parameters are updated using the new parameters obtained from the retuning process; otherwise, the tool automatically switches to the open-loop commissioning block to check if there is a fault in the HVAC plant associated with the subsystem under test. Before the software switches between the performance monitor and the loop tuner, or between the loop tuner and open-loop commissioning block, reconfiguration commands are sent out to the relevant outstation(s) of the BEMS to reconfigure the control strategy for loop tuning or subsystem commissioning. Such temporary changes to the outstation control strategy are automatically reset after the tuning or commissioning has been completed. The BEMS is set up to retrieve the necessary sensor data every day at a time when the building becomes unoccupied. The choice of such a time prevents the generation of additional traffic over the BEMS network during occupancy, and also avoids any complaints from the occupants that might result from changes to the control strategies introduced by the PMAC tool.

The open-loop commissioning block automatically reconfigures the control strategy in the outstation(s), produces the test sequence needed to generate the required commissioning data, analyses the data and displays the appropriate alarm messages. The control valve or damper is moved to several pre-designed positions (from fully closed to fully open). At each position, a transient detector is used to determine when the subsystem is sufficiently close to steady-state and, if steady-state is achieved within a predefined period of time, the steady-state values of the variables are then stored in a file for later diagnosis. The diagnosis is based on a semi-qualitative analysis of the measured data [Dexter and Ngo, 2001]. Each set of data from the commissioning test is used to identify a partial fuzzy model that describes the steady-state behaviour of the equipment at that particular operating point. The partial model is compared to a set of generic reference models that describe the behaviour of the subsystem when there are no faults and when each of a predefined set of faults is present. The training data used to generate the reference models are obtained off-line by simulating a number of different examples of the type of the equipment under test [Ngo and Dexter, 1998b]. Positive and negative offsets are then added to the training data produced by the simulations to account for bias on the output of the sensors [Ngo and Dexter, 1999]. A fuzzy matching scheme to determine the degree of similarity of the partial model and the reference

models. The final diagnosis is produced by combining the evidence obtained at one test condition with the evidence obtained at the other test conditions, using Dempster's rule [Dexter and Ngo, 2001]. The matching scheme accounts for any ambiguity that may result from fault-free and faulty operation, or different faults, having similar symptoms at some test conditions. No false alarms will be generated if the equipment under test is a member of the class of designs used to generate the training data, the test data are collected at operating conditions used to generate the training data, and the actual sensor bias is less than the sensor offset included in the training data.

C.25.4 Test building, plant and control system

The tests were performed on a constant-air-volume air-conditioning system in a commercial office building (see UK Demonstration 1 for details). The system has eight air-handling units of widely differing size and uses the plant room as a common mixing plenum. The cooling coil in one particular air-handling unit was used for the demonstration. This air-handling unit was chosen for the tests because the associated zone was unoccupied in the evenings and the design specification of the coil is within the class of designs that were used to produce the reference models used in the diagnosis.

C.25.5 Faults to be identified

The open-loop commissioning system is designed to identify the following five faults: coil under-capacity, leaky control valve, control valve stuck closed, stuck midway and stuck fully open.

C.25.6 Sensors used

The tool used single-point measurements of the cooling coil inlet and supply air temperatures and the relative humidity of the mixed air.

C.25.7 Design data used

The configuration information needed by the performance monitor (the address of the associated outstation and the addresses of the sensors to be used in the diagnosis) is predefined in a data file that is specific to each subsystem of each air-handling unit in each building. The design values are also specified in the file. In this case, the only design value used was that for the unmeasured supply airflow rate.

C.25.8 Training data required

The tool requires no training data to be collected from the HVAC system under test.

C.25.9 User interface

The PMAC tool consists of three basic function blocks: a performance monitor, an on-line open-loop commissioning system, and a loop tuner developed by the BEMS manufacturer. The end-user can initiate operation of each function block individually or allow the tool to generate automatic links between the function blocks. For example, if the performance monitor detects unacceptable performance, the PMAC tool automatically requests the loop tuner to re-tune the loop. If the proposed re-tuning of the controller's parameters is judged to be unacceptable, the tool automatically initiates open-loop commissioning to check if there is a fault in the associated subsystem under test. All of the monitoring information, including all of the commands that have been executed and the monitoring results, are written into a log file, so that it can be examined by the building maintenance personnel at a later date. The tool displays the measured data throughout the commissioning test.

The result of the diagnosis is a belief value in the range 0% to 100%, where 0% indicates no belief and 100% indicates complete belief, for each of the possible operating states of the subsystem under test. Alarms are generated in either of two ways:

1. The largest non-zero value of belief in a single fault condition determines the alarm message. If all the single state beliefs are zero, the largest non-zero value of belief in either of two fault conditions determines the alarm message, and so on.
2. The user sets a belief threshold and specifies a maximum number of alarm messages. First the alarm messages associated with values of belief in a single fault condition, which are greater than the threshold, are displayed in rank order according to the relative size of the beliefs. Then the alarm messages associated with values of belief in one of two fault conditions, which exceed the single fault beliefs by more than the threshold, are displayed. Then those for one of three fault conditions etc. are displayed, until the user specified maximum number of alarm messages has been displayed.

C.25.10 User selected parameters

The user must select the appropriate building, supply the number of the air-handling unit and specify the subsystem (cooling coil, heating coil, mixing box) to be commissioned.

C.25.11 Threshold selection method

The fault detection threshold is determined by the magnitude of the sensor offsets used to generate the robust generic reference models (in this case it was assumed that both the coil inlet and supply air temperature sensors could have a sensor bias in the range ± 1.0 K), and the size of the class of cooling coil subsystems to be represented by the reference models (in this case, coils designed for chilled water supply temperatures in the range 5.0 to 9.0 degC, and air flow rates in the range 1.0 to 5.0 kg/s).

The threshold for the transient detector is calculated by assuming that a first-order dynamic model can be used to describe the time variations of the measurements, and specifying a maximum acceptable prediction error.

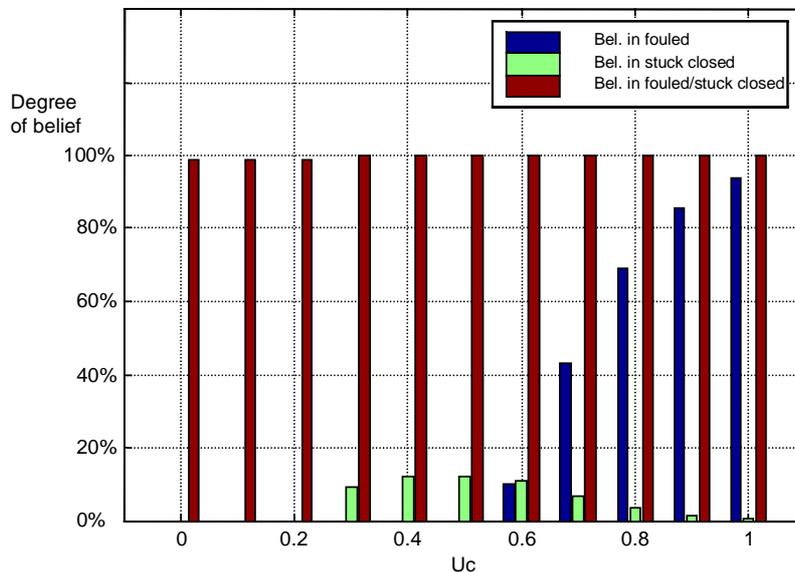


Figure C49. Results of diagnosis based on the fouled and valve stuck closed reference models.

C.25.12 Results of trials

Encouraging results (see Figure C49) have been obtained with the prototype performance monitoring and automated commissioning tool [Dexter and Ngo, 2001]. However there are a number of practical issues that require further consideration. Automated commissioning takes a significant amount time (up to one or two hours per subsystem). The tool requires a significant amount of detailed, application dependent, configuration information to be entered manually. The expert rules used to evaluate the closed-loop performance of the HVAC system need to be chosen with care to suit the particular application. Also, faults can only be detected if they have a greater effect on the observed behaviour than the sensor bias, and the accuracy of current sensors means that it is unlikely that small degradation faults can be detected in practice.

C.25.13 Satisfaction of user requirements

The tool has been demonstrated to a number of building operators and building controls manufacturers. The feedback has been extremely positive (particularly from building owners and operators) although, to date, no interest has been expressed in its commercial exploitation.

C.25.14 References

Ngo, D. and Dexter, A.L. 1998a. Automatic Commissioning of Air-Conditioning Plant, UKACC International Conference CONTROL'98, Vol. 2, pp. 1694–1699.

Ngo, D. and Dexter, A.L. 1998b. Fault Diagnosis in Air-Conditioning Systems using Generic Models of HVAC plant, SSB'98 System Simulation in Building Conference, Liege, Belgium.

Ngo, D. and Dexter, A.L. 1999. A Robust Model-based Approach to Diagnosing Faults in Air-handling Units, Trans. ASHRAE, 105(1).

Dexter, A.L. and Ngo, D. 2001. Fault Diagnosis in Air-conditioning Systems: a Multi-step Fuzzy Model-based Approach, Int. J. of HVAC&R Research, 7(1).

C.26 A FIRST PRINCIPLES MODEL-BASED FDD TOOL

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C26.1 FDD tool

Performance monitoring tool.

C26.2 Intended end-user

The FDD software implemented in this study is aimed at use by an experienced building and plant control engineer. However, the current version of the software is largely a research tool and only suitable for use by the experienced user.

C26.3 FDD method

The FDD method relies on the use of "first principle" models to act a reference for correct operation. Separate reference models were implemented for the economizer, cooling coil, and fan duct system. The economizer and cooling coil models were coupled by the mixed air relative humidity predicted from the economizer model. This was necessary, as no mixed air humidity measurement was available. All models are steady state, and therefore all transient data was filtered and discarded by a "transient detector". Fault detection was achieved when the difference between the measured and the modelled reference conditions exceeded a predefined threshold.

Two methods were implemented to diagnose the cause of the faults. The first was based on the recursive re-estimation of selected model parameters. The subsystem models were designed to include parameters that represent the fault conditions. The recursive parameter estimation (RPE) method continuously re-estimates the selected fault parameters such that the "innovation" or difference in the modelled and measured reference condition tends to zero. A change in the value of a parameter from the "correct operation" (calibrated) value indicates that system condition has changed. Since the re-estimated parameters are design to reflect particular fault conditions, a change in any one parameter indicates directly an increase the level of that particular fault. For instance, the three port valve model includes a parameter that represents the leakage of the valve; an increase in the value of the leakage parameter would indicate directly that the leakage had increased.

The second method of diagnosis was through the use on "crisp set" expert rules that draw a conclusion as to the nature of a fault through analysing the regions of subsystem operation for which the fault is visible through an "innovation" in the reference condition. The range of each subsystem operation was divided into three regions to represent the "low", "middle", and "high" loads. The innovations apparent in each

operating region were recursively averaged for steady state data sample in the region of operation (with the greatest weight being assigned to the most recent innovations). A conclusive diagnosis is only possible by the method when the system has spanned its complete range of operation; until then, the diagnosis is likely to remain ambiguous.

C26.4 Test building, plant and control system

The study was conducted at the Energy Resource Station (ERS) which is located Des Moines, Iowa, USA. The ERS is a unique building combining laboratory standard testing facility with real building characteristics. The building houses two identical full-scale variable air volume (VAV) systems that can be simultaneously tested with identical thermal loading. The two systems (AHU-A and AHU-B), each serve four test rooms. Of the four test rooms, one faces east, one faces south, one faces west, and one is an interior room. The building is oriented to have a true north-south solar alignment so that the pairs of test rooms have identical exposures to the external thermal loads. The test rooms are unoccupied although the capability to impose false loads on the rooms exists. A third VAV system (AHU 1), serves the general areas of the building including offices, reception space, a two classrooms, a computer centre, a display room, service spaces, and the media centre. Since AHU-1 serves the occupied part of the building it is subject to variable occupant, lighting, and external and internal loads.

Chilled water can be supplied from an independent two-stage reciprocating chiller (with thermal store) or the sites central chiller (both were used during the study). Heating is supplied from an independent boiler. The systems are controlled by commercially available digital control systems.

C26.5 Faults to be identified

Artificial faults were implemented on the two identical test systems (AHU A and B) over a two week period in each of the summer, spring, and winter seasons. During the second week of testing in each season, the faults were implemented blind to the investigators (Table C17). In addition, blind faults were implemented on the third system (AHU 1) during a summer operating period (Table C17).

Table C17. Faults implemented and to be identified.

Fault	AHU A and B			AHU 1
	Summer	Winter	Spring	Summer
Economizer section				
Recirculation damper stuck closed.	X	X		X
Leaking recirculation damper.		X	X	
Outside air damper stuck open.				X
Cooling Coil				
Leaking control valve.		X	X	
Reduced chilled water flow rate.	X		X	
Air side fouling.				X
Heating Coil				
Leaking control valve.				X
Supply Fan				
Static pressure sensor offset.	X	X	X	X
Oscillatory control action.	X	X	X	
Slipping fan belt.	X	X		
Loss of control.				X

C26.6 Sensors used

The sensors used here are typical HVAC system grade sensors commonly used in AHU's (Table C17). Three "reference" conditions for fault detection were the mixed air temperature (economizer faults), the supply air temperature (cooling and heating coil faults), and the supply air static pressure (supply fan-duct system faults).

Table C18. Sensors used.

Measurement	Unit
Inlet (or ambient) air temperature	°C
Inlet (or ambient) air relative humidity	%
Mixed air temperature	°C
Supply air temperature	°C
Supply air flow rate	m ³ /s
Return air temperature	°C
Return air relative humidity	%
Chilled water flow temperature to the coil	°C
Economizer control signal	–
Cooling coil control signal	–
Supply fan control signal	–
Return fan control signal	–

C26.7 Design data used

The design data required for use in the first principle models are: design chilled water flow rate; face area of cooling coil; type of coil (high/low effectiveness); internal diameter of cooling coil tubes; the number of parallel circuits in the coil; and the maximum and minimum speeds of the supply and return fans.

C26.8 Training data required

Training data is required for each subsystem (economizer, cooling coil, and supply fan-duct system). Data is required from across the full range of each subsystem operation. These data were acquired via a sequence of open loop steps in the control signal of each subsystem. The steps begin with the zero system output (0% signal) and continue with a sequence evenly spaced increments in control signal, until the maximum output of the subsystem is reached (100% signal). The reverse sequence in control signal is then applied (100% to 0%), although fewer than increments are required (saving time in testing). At each step, it is necessary to wait for the system to reach steady state before proceeding to the next step. The reverse sequence in control signal is necessary in order to be able to identify any hysteresis in the subsystem operation. This process must be repeated for at least two air flow rates in VAV systems. Following the step tests, the non-design model parameters are estimated from the data using a non-linear optimisation method. The identified parameters are, valve and damper actuator hysteresis; valve and damper actuator low activation points; valve and damper actuator high activation points; valve and damper curvature; damper asymmetry; valve and damper leakage; coil thermal resistance scaling "UA" factor; valve authority; and supply air sensor offset; supply and return fan temperature rises.

C26.9 User interface

A simple "command line" interface.

C26.10 User selected parameters

None, other than the method "thresholds".

C26.11 Threshold selection method

Table C19, indicates the thresholds and operational parameters associated with the operation of the FDD software.

Table C19. Method thresholds and operating parameters.

Applies to	Operational Parameter or Threshold
Models	Steady state detector time constant
Models	Steady state detector threshold
RPE	Forgetting factor
Exp. Rules	Significant innovation level
Exp. Rules	Bin demarcation, low-middle and middle-high
Exp. Rules	Forgetting factor

The steady state detector time constant represents the maximum time constant that would be expected from the system and can be obtained from the test data used to calibrate the models. The steady state threshold varies little from one system to the next and can be taken as to be constant. The forgetting factors are tuned to give stable performance of the methods; the RPE forgetting factor is tuned such that the "fault parameters" only just move in value for "normal operation". The expert rules forgetting factor is tuned to ensure that innovations that occurred a significant period in the past do not over influence the current diagnosis. Although there are six parameters listed, it is not envisaged that they will need adjustment for different applications to the same subsystem type. The thresholds associated with the bin demarcation and innovation significance would need resetting, but this could be easily automated from the calibration tests.

C26.12 Results of trials

Conclusions were drawn as to the time required to obtain calibration data, the effectiveness of the first principle models in fault detection, and the effectiveness of the two methods of diagnosis. The total time taken to obtain the calibration data for one AHU when each subsystem was tested separately was over 23 hours. This led to the potential for the simultaneous testing of all subsystems (economizer, coil, and fan) in one AHU to be tested. When the ambient conditions permit this, the time taken to obtain the calibration data was reduced to 14 hours. The results also indicated that the first principle model were somewhat over-parameterized and as such, the simultaneous identification of all the parameters associated with one subsystem could lead to poor parameter values. This deficiency in the approach was corrected by the implementation of a calibration procedure in which selected parameters were identified from a subset of the calibration data (for instance, the leakage parameters were identified separately from the other parameters using data for the control elements being closed).

In general, faults leading to the larger changes in system operation were detected. The more subtle faults due to low levels of leakage and slightly slipping fan belts were not detected however. In some instances, the effectiveness of the approach was limited by the occurrence of non-ideal (and unmodelled) system behaviour, which led to wide fault thresholds having to be set. However, the extent to which subtle faults, such as low

levels of leakage, can be detected using first principles reference models is likely to remain limited because of the high uncertainty in sensor measurements common in all HVAC systems. It was concluded that first principle models currently have the potential for use in AHU fault detection, but that low levels of fault may not be detectable due to the uncertainty in the system measurements.

Consistent diagnosis of faults by the both the "expert rules" approach and through recursive parameter estimation proved to be difficult. The "expert rules" approach requires considerable effort to formulate a rule base covering all fault possible fault conditions. Further, conclusive diagnosis with expert-rules was limited by the need for data to be available across the range of operation of the faulty sub-system. During most of the tests implemented in this study, the systems remained in a narrow region of operation, which restricted the extent to which a conclusive diagnosis could be made. In practice, it would be possible to wait for the system to move across its range of operation before a diagnosis was made. However, for the more significant levels of fault, a prolonged period of further system operation could result in excessive energy use or the development of addition faults. This suggests that the methodology should be extended to include the injection of test signals to exercise the system across its range of operation following a fault alarm.

The effectiveness of fault diagnosis by recursive re-estimation of the model parameters was limited, in some instances, by the over-parameterization of the models. This implies that it may not be possible to include fault parameters to represent all fault conditions. In general however, it was concluded that the recursive parameter estimation algorithm had some potential fault diagnosis, but that the method required careful tuning. It is also necessary to ensure that the models are not over-parameterized (especially when the fault data is not rich enough to excite the correct fault parameters).

C26.13 Satisfaction of user requirements

Not tested.

C.27 APAR: AHU PERFORMANCE ASSESSMENT RULES

J. M. House and H. Vaezi-Nejad

C.27.1 FDD tool

The tool was developed to assess the performance of air-handling units (AHUs) and is referred to as APAR (AHU Performance Assessment Rules). APAR is a fault detection tool only.

C.27.2 Intended end-user

The intended end-users of APAR are building operators and service company personnel. APAR could be embedded in an energy management and control system (EMCS) or operate as a stand-alone module that interfaces to the EMCS. The aim of the tool is to detect faults that can produce significant energy waste, occupant discomfort, and equipment wear and are difficult to detect with single point alarming that is standard in today's EMCS.

C.27.3 FDD method

APAR is based on expert rules for AHUs. APAR uses control signals and occupancy information to identify the particular mode of operation of the AHU, thereby identifying a subset of the rules that specify temperature relationships that are applicable for that mode. The two main mode classifications are occupied and unoccupied. For occupied periods, the mode is further identified based on how the setpoint value of the supply air temperature is achieved (heating, cooling with outdoor air, mechanical cooling with 100% outdoor air, mechanical cooling with minimum outdoor air, or unknown). As an example of the rule formulation, normal operation in the mechanical cooling mode with 100% outdoor air dictates that the outdoor and mixed air temperatures must be approximately the same. Rules are written such that if they are satisfied or true, a fault is presumed to have occurred. In the example above, the rule states that the outdoor and mixed air temperatures are not the same (i.e., if true, a fault has occurred). A thorough description of the method is provided in House et al. (2001).

C.27.4 Test building, plant and control system

Montgomery College is located in Montgomery County Maryland. The High Technology Science Center (75,000 ft² gross) is located on the Germantown Campus and was completed in 1996. Five AHUs that serve this building have been continuously monitored for a 39-week period for this project. The AHUs range in capacity (maximum) from 6100 CFM to 17000 CFM. AHUs 1 to 4 are standard rooftop air

handlers with variable frequency drive (VFD) controlled supply air fans, VFD controlled return air fans in the exhaust position, hydronic heating and cooling coils, a minimum outdoor air damper, a maximum outdoor air damper, a return air damper and an exhaust air damper. AHU 5 is similar; however, it has only a single outdoor air damper with a minimum open position established to satisfy ventilation requirements.

The AHUs are controlled by a direct digital control system. Each unit is sequenced on during the occupied period to provide heating, ventilation and air conditioning based on control of the supply air temperature to meet the space setpoint. Each unit can provide free cooling using either a temperature-based (AHUs 1, 2 and 5) or an enthalpy-based (AHUs 3 and 4) economizer.

C.27.5 Faults to be identified

A specific set of faults that can be identified has not been established. Rather, any fault that causes a rule to be satisfied (recall that rules are formulated such that if they are true, a fault has occurred) would be detected and additional effort would be necessary to isolate the cause of the problem. Faults that could potentially cause a rule to be satisfied include:

- Stuck or leaking heating coil and cooling coil valves
- Temperature sensor faults
- Design faults such as undersized coils
- Sequencing logic errors
- Heating and cooling plant faults that affect the hot or chilled water supply temperature conditions at the AHU coils
- Inappropriate operator intervention.

The operating point and severity of the fault will influence whether or not rules are satisfied. Possible explanations for the satisfaction of a rule (or rules) are provided to assist end-users with the diagnosis of the fault.

C.27.6 Sensors used

The following sensors are used:

- Supply air temperature
- Return air temperature
- Mixed air temperature
- Outdoor air temperature
- Return air relative humidity (for enthalpy-based economizers only)
- Outdoor air relative humidity (for enthalpy-based economizers only).

The method also uses the control signals to the cooling coil valve, the heating coil valve, and the mixing box dampers, as well as the occupancy status and the setpoint value of the supply air temperature.

C.27.7 Design data used

The following design data are used to implement the rules:

- Minimum and maximum values of control signals for the heating coil control valve, cooling coil control valve and mixing box dampers,
- Percentage outdoor air necessary to satisfy ventilation requirements,
- Changeover temperature from mechanical cooling with 100% outdoor air to mechanical cooling with minimum outdoor air (or corresponding condition for enthalpy-based economizer), and
- Description of sequencing/economizer cycle strategy.

The description of the sequencing/economizer cycle strategy is used to verify that the rules are suitable to a particular AHU installation.

C.27.8 Training data required

No training data are needed with this method.

C.27.9 User interface

A first generation user interface was developed, but it has not been evaluated by any end users.

C.27.10 User selected parameters

The rules include numerous parameters that must be specified by the user. Those parameters are:

- Rule thresholds associated with temperatures, flow rates, control signals, and enthalpies (if an enthalpy-based economizer is utilized),
- Temperature rise across the supply fan,
- Temperature rise across the return fan,

- Minimum difference between the outdoor and return air temperatures for assessing ventilation rates, and
- Maximum number of times that the operating mode can change without considering the operation unstable.

Values of these parameters are currently selected heuristically.

C.27.11 Threshold selection method

As indicated above, the rule threshold parameters are currently determined heuristically. In the future the intent is to define a process through which robust default values of the threshold parameters can be determined. This process would involve determining the error associated with each temperature measurement and then combining the error terms to produce the most conservative representation of each rule. Such an approach would tend to produce rules that combine sensitivity to faults and robustness against false alarms.

C.27.12 Results of trials

The results of the field trials at Montgomery College are encouraging. APAR successfully identified control performance problems that plagued most of the AHUs. Control problems observed were well known to the building operators and had resulted in the failure and replacement of numerous damper motors in recent months. A typical example of the observed control problems are seen in Figure C50. The supply air temperature and its setpoint value for AHU 2 are plotted in Figure C50a for a 12-hour period beginning at 6:00 AM on February 2, 2000. The control signals to the heating coil valve (100% corresponds to closed) and mixing box dampers (100% corresponds to a fully open outdoor air damper) are plotted in Figure C50b for the same time period. Figure C50a shows that the supply air temperature setpoint changes frequently and by rather large amounts. The set point is determined by an aggressive reset schedule based on the return air temperature. Because of the resolution of the analog to digital converter, relatively small changes in the return air temperature of approximately 0.32°F (0.18°C) result in a change in the supply air temperature set point of approximately 2.5°F (1.4°C). This leads to the highly oscillatory behavior observed in this case for the mixing box dampers. At other operating points, similar behavior has been observed for the cooling and heating coil valves.

APAR also successfully identified several occurrences of faults with the mixing box dampers, including a stuck damper, a manual override of a control signal that was not returned to automatic operation, and improper sequencing of the exhaust fan and the dampers. Detailed results are contained in House et al. (2001).

Further field testing of the rules is needed to identify appropriate values of user-selected parameters and to ensure the validity of the rules. This study did not attempt to assess

the false alarm rate of APAR. This remains as a task for future work. A more detailed consideration of the rule thresholds is also needed.

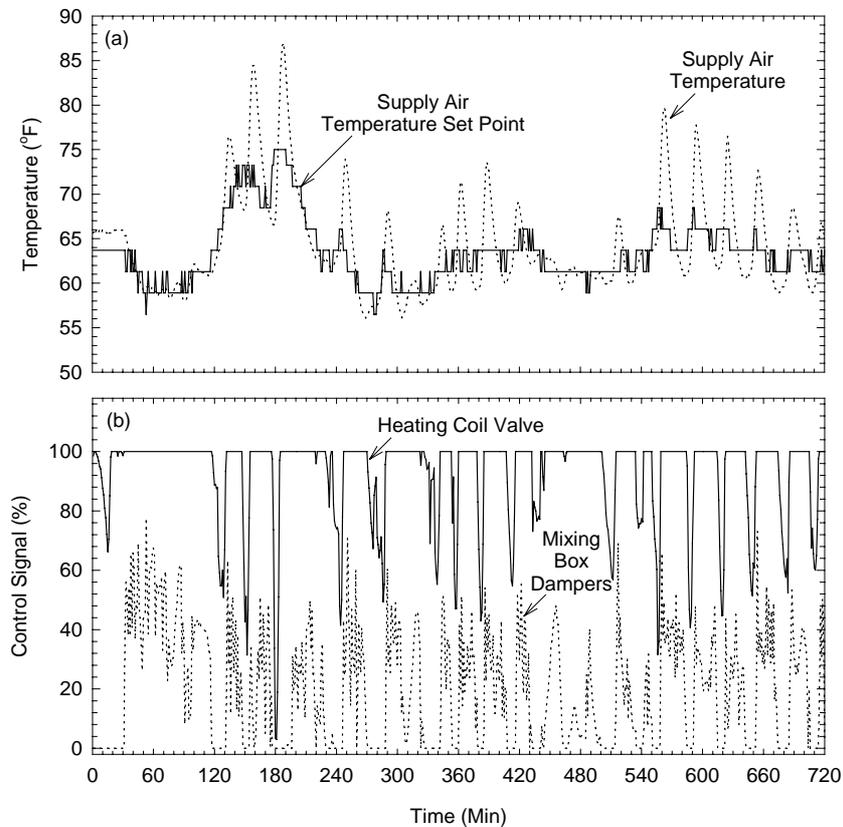


Figure C50. Typical control performance problem observed at Montgomery College.

C.27.13 Satisfaction of user requirements

To date, APAR has not been tested by the intended end-users. Demonstrations of APAR have involved batch processing of data followed by discussions of the results with the maintenance staff at Montgomery College. The staff is interested in the tool; however, in its present form the output is not readily understood by individuals unfamiliar with the details of the FDD method.

C.27.14 References

House, J. M., Vaezi-Nejad, H. and Whitcomb, J. M. 2001. "An Expert Rule Set for Fault Detection in Air-Handling Units." Accepted for ASHRAE Transactions.

C.28 AUTOMATED DIAGNOSTICS FOR PACKAGED ROOFTOP AIR CONDITIONERS

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C.28.1 FDD tool

The intended application is automated diagnostics for packaged rooftop air conditioners.

C.28.2 Intended end-user

It is intended that the diagnostic tool be integrated within the controller of packaged air conditioners and sold with either the original equipment or as a field installed retrofit. Ultimately, the intended end-users are building operators and service company personnel. The aim of the tool is to detect faults that can lead to occupant discomfort, equipment wear, environmental hazard, and excessive energy consumption.

C.28.3 FDD methods

Three different methods have been developed and evaluated: 1) statistical, rule-based method, 2) sensitivity ratio method, and 3) simple rule-based method. The statistical, rule-based method utilizes models for expected values of refrigerant and air states under normal operation. The differences between the model predictions and measurements (residuals) are used within statistical classifiers that detect and diagnose faults under steady-state operation. The sensitivity ratio method also uses residuals for fault detection and diagnosis. However, the classification is simplified by defining ratios of residuals that are uniquely sensitive to individual faults. The simple rule-based method does not use a model. However, performance indices are calculated that are relatively insensitive to changes in operating conditions, but are sensitive to faults.

C.28.4 Test building, plant and control system

Three different rooftop units have or are being evaluated: 1) a 5-ton unit system with a fixed orifice expansion device, 2) a 5-ton system with a thermal expansion valve (TxV), and 3) a 7.5-ton unit with a TxV. Experiments have been conducted in a laboratory setting under both transient and steady-state conditions where faults could be introduced at known levels and under reproducible conditions.

C.28.5 Faults to be identified

The following faults have been considered:

- Refrigerant leakage
- Refrigerant overcharge
- Fouled condenser coil or malfunctioning condenser fan
- Fouled evaporator filter or malfunctioning evaporator fan
- Compressor wear
- Non-condensables in the refrigerant
- Liquid refrigerant line restriction.

C.28.6 Sensors and control signals used

The following sensors and control signals are used by the statistical rule-based and residual ratio method:

- Supply air temperature
- Mixed air temperature
- Mixed air humidity
- Evaporating temperature
- Condensing temperature
- Compressor inlet temperature
- Compressor outlet temperature
- Condensor refrigerant outlet temperature
- Condensor air inlet temperature
- Condenser air outlet temperature.

The simple rule-based method doesn't require a measurement of the mixed air humidity.

C.28.7 Design data used

No design data are required

C.28.8 Training data required

Both the statistical rule-based and residual ratio methods require steady-state data for a normally operating unit for a range of operating conditions. The simple rule-based method requires data for the design rating condition.

C.28.9 User interface

A demonstration program was developed in a MatLab environment.

C.28.10 User selected parameters

There are a number of parameters that can be specified by the user. These include thresholds for the steady-state detector, fault detector, and diagnostic classifier. However, reasonable defaults have been established for these parameters.

C.28.11 Threshold selection method

Through analysis of laboratory test data, reasonable default values for threshold parameters have been established.

C.28.12 Results of trials

The methods have been tested extensively in the laboratory. Table C20 gives results from the evaluations of Breuker and Braun (1998) for a 5-ton unit with a fixed orifice device. The table gives FDD sensitivity quantified by fault level and its corresponding effect on system performance for five faults. The performance effects of the different faults at the point of detection are quantified in terms of changes in cooling capacity (affects comfort), efficiency (affects energy consumption), and compressor superheat and discharge temperature (affects compressor life). Tests were run over a wide range of operating conditions with the unit cycling on and off in response to different loads. The columns labeled “1st” and “All” give FDD sensitivities associated with correctly diagnosing the fault for a single point within the data set and all steady-state points within the data set. In general, the technique was able to correctly detect and diagnose faults before there was a loss of about 5% in cooling capacity and efficiency. This is undoubtedly before the unit would need any service.

Chen and Braun (2000) evaluated the performance of the sensitivity ratio and simple rule-based methods for a 5-ton unit with a TxV. Figures C51 and C52 present the sensitivities of the sensitivity ratio and simple rule-based methods determined from tests in the laboratory with the unit cycling on and off to maintain the zone temperature setpoint under different load conditions. The results are presented in terms of the fault level where an alarm was set for each fault type. The methods were able to correctly diagnose faults at all three load levels with reasonable sensitivity. The presence of non-condensables was only tested at the full load conditions.

Table C20. Performance of Statistical, Rule-Based FDD Prototype.

Performance index	Refrigerant		Liquid Line		Compressor		Condenser		Evaporator	
	Leakage (% Leakage)		Restriction (% ΔP)		Valve leak (% $\Delta \eta_v$)		Fouling (% lost area)		Fouling (% lost flow)	
	1st	All	1st	All	1st	All	1st	All	1st	All
Fault level (%)	5.4	Max	2.1	4.1	3.6	7.0	11.2	17.4	9.7	20.3
% Loss capacity	3.4	> 8	1.8	3.4	3.7	7.3	2.5	3.5	5.4	11.5
% Loss COP	2.8	> 4.6	1.3	2.5	3.9	7.9	3.4	5.1	4.9	10.3
ΔT_{sh}	5.4	> 11	2.3	4.8	-1.8	-3.6	-0.6	-1.6	-1.7	-2.7
ΔT_{hg}	4.8	> 10	2.4	4.8	0.0	0.0	1.8	2.3	-1.2	-2.7

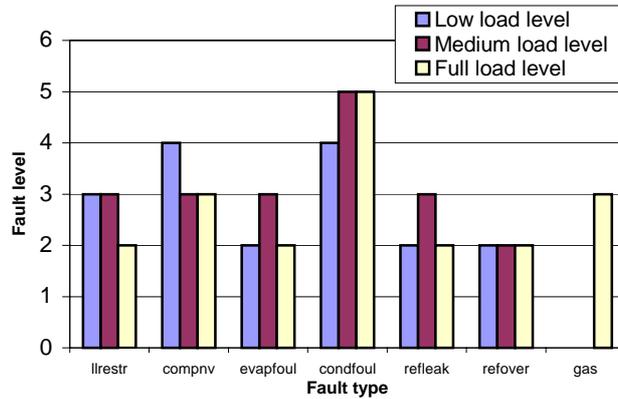


Figure C51. Sensitivity Ratio Method sensitivity

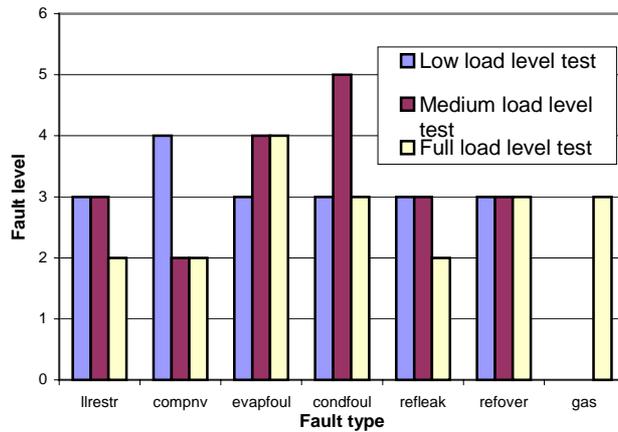


Figure C52. Simple Rule-Based Method sensitivity.

All three methods give good performance and are fairly easy to implement. The statistical rule-based method performs best but requires nine temperature measurements and one humidity measurement. The sensitivity ratio method requires six temperature measurements and one relative humidity sensor. The simple rule-based method only requires six temperature measurements. Since the simple rule-based method does not use a model (normally developed on a specified unit), it is more general and could significantly reduce the cost of engineering FDD systems for specific units.

C.28.13 References

Breuker, M.S. and Braun, J.E., "Evaluating the performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment," *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research*, Vol. 4, No. 4, pp. 401–426, 1998.

Rossi, T.M and Braun, J.E., "A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners," *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research*, Vol. 3, No. 1, pp. 19–37, 1997.

Chen, B. and Braun, J.E. "Simple Fault Detection And Diagnosis Methods for Packaged Air Conditioners" *Proceedings of the 2000 International Refrigeration Conference*, Purdue University, W. Lafayette, IN, 2000.

C.29 MATCH: MODEL-BASED ASSESSMENT TOOL FOR CHILLERS

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C.29.1 FDD tool

The FDD tool was developed to assess the performance of chillers and is referred to as MATCH (Model-based Assessment Tool for Chillers).

C.29.2 Intended end-user

This FDD tool could be incorporated into a building energy management system or used as a stand alone tool to be used by building operators, technicians, or service personnel.

C.29.3 FDD method

A two-step FDD method was developed for the NIST chiller using a k-nearest neighbor classifier and a rule-based fault diagnostic algorithm. A physical model, ACmodel [Rossi, 1999], is used to generate residuals between the measured experimental value for the test case and the predicted model value that define the distinct characteristics for normal operation and each fault case. Steady state training data is run through a clustering algorithm which serves to group the data points into clusters having the same values or properties, assigning a membership function. The k-nearest neighbor classifier calculates the Euclidean distance from the test data point to each of the training data points. The k closest neighbors are selected and the average values of their membership functions are calculated. The test data point classification is the class with the highest membership. Faulty data is then classified into specific fault types using rules based on the dominant residuals extracted from training data.

C.29.4 Test building, plant and control system

The test facility is located at NIST in Gaithersburg, MD. In 1994, NIST built a Temperature Control Module to test and verify the performance of the HVAC and control system. The chiller selected for this application was specifically designed for low temperature operation (return glycol -23 °C). It is a 12-ton air-cooled liquid chiller with a constant speed two-stage reciprocating compressor (Continental Model MBA-30FPTK) and is located outdoors at NIST adjacent to Building 226.

C.29.5 Faults to be identified

Five faults were selected: 1) Air-side condenser fouling, 2) Water-side evaporator fouling, 3) Liquid line restriction, 4) Refrigerant overcharge, 5) Refrigerant undercharge.

C.29.6 Sensors used

For model validation, a large number of sensors were used. However a study was conducted to determine the critical measurements required for good detection and diagnostic capabilities. The goal is to reduce the number of sensors needed and correspondingly the cost of implementing the FDD method.

Table C21.

MEASUREMENT LOCATION	DESCRIPTION	UNITS
Compressor outlet temp (R22)	Type T Thermocouple	deg. C
Condenser inlet fan1 temp (air)	Type T Thermocouple	deg. C
Condenser outlet fan1 temp (air)	Type T Thermocouple	deg. C
Subcooler outlet to evaporator temp (R22)	Type T Thermocouple	deg. C
Compressor inlet temp (R22)	Type T Thermocouple	deg. C
Subcooler expansion valve inlet temp (R22)	Type T Thermocouple	deg. C
Evaporator outlet temp (water)	Type T Thermocouple	deg. C
Evaporator inlet temp (water)	Type T Thermocouple	deg. C
Condenser inlet (R22)	Pressure Transducer (0-500)	psia
Compressor low stage inlet (R22)	Pressure Transducer (0-300)	psia
Flowrate to evaporator (R22)	Turbine Flowmeter (1.0-10.0)	gpm
Flowrate to subcooler (R22)	Turbine Flowmeter (0.5-5.0)	gpm

C.29.7 Design data used

Model input parameters include the heat transfer coefficients, geometry of the heat exchangers, and flow rates and system temperatures for refrigerant, air, and glycol.

C.29.8 Training data required

Data is needed under normal and fault modes. This data includes natural variations in outdoor conditions, temperature and humidity. For fault mode, the following conditions were simulated experimentally: 1) 10%, 20%, 30%, 40%, and 50% condenser fouling, 2) 10%, 20%, 30%, and 40% evaporator fouling, 3) 5%, 10%, 15%, 20%, and 25% liquid line restriction, 45#, 50#, 55#, 60#, 65#, 70#, 75#, 80#, 85#, 90#, 95#, 100#, 105#, 110#, 120#, 125#, 130# refrigerant charge.

C.29.9 User interface

Currently a “command line” interface under the Matlab software package.

C.29.10 User selected parameters

Users intended to select alarm threshold parameters.

C.29.11 Threshold selection method

In processing, the steady state detector calculates an exponentially weighted moving average over a specified time that must be selected, along with the threshold value for the ratio of the standard deviation to the mean (0.20).

At present, the diagnostic rules also must be hard coded into the program. For the diagnostic tool, the dominant residuals corresponding to each fault type must be specified (see Table C22). For example:

```
if (largest residual=RFM1 & second largest residual=dTca) class(m)=1;
%condenser fouling case
```

Table C22.

Fault Type	Performance Indices						
	Tcond	Tsc5	Tsh1	Dt_eg	Dt_ca	Rfm1(subc)	Rfm2(evap)
Condenser Fouling					●		●
Evaporator Fouling		●		●			
Liquid Line Restriction			●	●		●	●
Refrigerant Undercharge		●		●		●	●
Refrigerant Overcharge	●		●				

C.29.12 Results of trials

The results of the application showed reliable fault detection for most fault types. Once a fault was detected, diagnostic results were very good and had a low occurrence of misdiagnosis. Results of fault detection using a nearest prototype classifier, in conjunction with rule-based fault diagnosis, are listed in Table C23. The performance of the nearest neighbor classifier showed similar results for most cases. It was not selected to be the detection classifier because it is more computationally intensive.

The liquid line restriction fault proved to be the most challenging to detect and diagnose. This may be partially due to the nature of the thermal expansion valve and its ability to compensate under some conditions.

Table C23.

Fault	Level	Detection % correct	Diagnosis % correct	Diagnosis % unknown	Diagnosis % incorrect	Correct detection and diagnosis (% of Total)
Normal	N/A	100				
Condenser fouling	10%	0				0.0
	20%	39.50	100			39.5
	30%	93.50	95.72	1.60	2.67	89.5
	40%	86.50	100			86.5
	50%	100	100			100
Evaporator fouling	10%	0				0
	20%	0				0
	30%	100	99.50	0.50		99.5
	40%	100	95.50	4.50		95.5
Liquid line restriction	10%	0				0
	20%	0				0
	30%	56.00	25.89	74.11		14.5
	40%	59.00	85.59	14.53		50.5
	50%	86.00	55.23	34.30	10.47	47.5
Refrigerant undercharge	45#	100	100			100
	50#	100	83.00	17.00		83.0
	55#	100	82.50	17.50		82.5
	60#	100	95.50	4.50		95.5
	65#	100	100			100
	70#	100	100			100
	75#	100	100			100
	80#	100	100			100
	85#	100	100			100
	90#	0				0
	95#	0				0
	100#	0				0
105#	0				0	
Refrigerant overcharge	110#	100	1.0			1.0
	120#	100	94.0	6.0		94.0
	125#	100	98.0	1.0	1.0	98.0
	130#	100	100			100
	135#	100	100			100

C.29.13 Satisfaction of user requirements

Not tested.

C.29.14 References

House, J. M., Lee, W.Y. and Dong, R. S. 1999. "Classification Techniques for Fault Detection and Diagnosis of and Air-Handling Unit." ASHRAE Transactions, V. 105, Pt. 1.

C.30 AN FDD TOOL BASED ON ELECTRICAL POWER MEASUREMENTS

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C.30.1 FDD tool

The FDD tool was developed to determine whether electrical-power measurements, from submeters dedicated to individual pieces of equipment or from high-speed, centrally located meters could be used to detect and diagnose faults in air-handling units (AHUs). The central meters are known as non-intrusive load monitors (NILM). Details are provided in Luo *et al.* 2001 and Norford *et al.* 2000.

C.30.2 Intended end-user

The intended end-users are building operators and service company personnel. Electrical signal processing needed for fault detection and the rules used for fault diagnosis could be embedded in an energy management and control system (EMCS) or operate as a stand-alone, personal-computer-based, component that includes the electrical-monitoring hardware and that interfaces to the EMCS. The aim of the tool, as developed and tested, was to detect and diagnose a set of typical AHU faults, affecting the mixing box, coil, and fan sections of the AHU.

C.30.3 FDD method

The FDD method is based on correlations of electrical power with such independent variables as airflow, motor-speed control signal, and cooling-coil valve position. Training data are used to establish polynomial correlations and uncertainties, based on scatter in the data and desired confidence intervals. Test data outside the uncertainty intervals indicate a fault. Chiller faults are assessed by measuring changes in cycling rate of the reciprocating chiller. Table C24 lists the correlations and associated faults that can be detected, some of which were implemented at ERS. Tests at ERS were conducted primarily with submetered electrical-power data, but limited evaluation of the central meters was also conducted.

Table C24. A non-exhaustive listing of faults associated with a given electrical-power signature.

Type of Electrical-Power Analysis	Possible Faults Causing a Deviation between Predicted and Measured Electrical Power
Polynomial correlation of supply-fan power with supply airflow	Change in airflow resistance, possibly due to stuck air-handler dampers or air-side fouling of heating or cooling coils
	Static-pressure sensor error (affects portion of fan power due to static pressure)
	Flow sensor error
	Power transducer error
	Change in fan efficiency, caused by change in blade type or pitch, or use of VFD in lieu of inlet vanes
Polynomial correlation of supply-fan power with supply-fan speed control signal	Change in motor efficiency
	Slipping fan belt
	Disconnected control loop (fan speed differs from control signal)
	Power transducer error
	Change in fan efficiency
Polynomial correlation of chilled-water pump power with cooling-coil control valve position control signal	Change in motor efficiency
	Change in water flow resistance, possibly due to constricted cooling-coil tubes or piping
	Disconnected control loop
	Power transducer error
	Change in pump efficiency
Detection of change in cycling frequency for two-stage reciprocating chiller	Change in motor efficiency
	Leaky cooling-coil valve
Detection of power oscillations	Leaky recirculation damper
	Unstable local-loop controller

C.30.4 Test building, plant and control system

The Energy Resource Station (ERS), located on the campus of the Des Moines Area Community College (DMACC), in Ankeny, Iowa, combines laboratory -testing capability with real building characteristics and is capable of simultaneously testing two full-scale commercial building systems side-by-side with identical thermal loadings. The ERS is equipped with three variable-air-volume AHUs. Two (AHU-A and AHU-B) are identical, each serving four test rooms. The ERS is sited on a north-south axis and

airs of test rooms have identical exposures (east, south, west, and internal) to external thermal loads. The unoccupied test rooms can be operated to have identical internal thermal loads, thereby allowing simultaneous, side-by-side comparison testing of many types of HVAC systems and control schemes. False loads and room lighting can be scheduled to simulate various usage patterns. The third AHU (AHU-1) serves the general areas of the facility including offices, reception space, a classroom, a computer center, a display room, service spaces, and the media center; a second classroom was added to the east side of the building during the later stages of this project. Because AHU-1 serves the occupied part of the building it is subject to variable occupant, lighting, and external and internal loads.

Heating is provided by a gas-fired boiler but was not required as part of the tests conducted in this research, other than for the preheating of the outside air during winter operation to simulate higher outside temperatures and force the HVAC systems into "economizer mode." The cooling plant consists of a two-stage, reciprocating, air-cooled chiller, a thermal energy storage (TES) unit, and chilled water supplied by the DMACC campus chilled water plant.

C.30.5 Faults to be identified

The ERS staff introduced the artificial faults listed in Table C25 and C26. After a two-week period when both the plant and the FDD method were commissioned, there were three two-week test periods. During each, a one-week controlled-test period, during which faults were known to the researchers, was followed by a one-week blind-test period. ERS staff also introduced artificial faults into AHU-1, in a test period held during Summer 1999. These faults included some that previously implemented in AHU-A and AHU-B and several new faults, as listed in Table C25.

Table C25. List of faults implemented at the Energy Resource Station.

Fault	Type	Implementation Details
Air Mixing		
Recirculation damper stuck closed	Abrupt	Physical intervention: disconnect actuator input, position manually
Leaking recirculation damper	Degradation	Physical intervention: remove damper-blade seals
Filter-Coil		
Leaking cooling-coil valve	Degradation	Physical intervention: connect by-pass between strainer air-vent and coil air vent, measure flow with existing ultrasonic meter
Reduced cooling-coil capacity (water side flow restriction)	Degradation	Physical intervention: restrict water flow to coil
Fan		
Pressure sensor offset	Degradation	Physical intervention: bleed pneumatic signal
Unstable supply fan controller	Abrupt	Software override: change controller gain until oscillation observed at low airflow rate
Slipping supply-fan belt	Degradation	Physical intervention: move fan motor to reduce tension in fan belt

Table C26. List of faults implemented in each blind-test period for AHU-A and AHU-B.

Fault	Summer 1998	Winter 1999	Spring 1999
Air Mixing			
Recirculation damper stuck closed	X	X	
Leaking recirculation damper		X	X
Filter-Coil			
Leaking cooling-coil valve		X	X
Reduced cooling-coil capacity (water side flow restriction)	X		X
Fan			
Pressure sensor offset	X	X	X
Unstable supply fan controller	X	X	X
Slipping supply-fan belt	X	X	

Table C27. Faults introduced into AHU-1 during the blind-test period and their method of implementation.

Fault	Type	Implementation
Air Mixing Section		
Stuck-closed recirculation damper	Abrupt	Application of a control voltage from an independent source to maintain the damper in the closed position for about 24 hours.
Stuck-open outside-air damper	Abrupt	Application of a control voltage from an independent source to maintain the damper in the closed position for 24 hours.
Filter-Coil Section		
Leaking heating-coil valve	Abrupt	Adjustment of output voltage to the heating-coil valve, causing it to unseat and leak for about 29 hours.
Air-side fouling	Degradation	Block the cooling coil with a curtain drawn from the bottom to cover 25%, 50%, and 75% of the 61 cm (24 in.) coil in the three fault stages.
Fan		
Drifting pressure sensor	Degradation	Introduction of a controlled leak in the pneumatic signal tube from the supply-duct static-pressure sensor to the transducer, with pressure reduced by 50, 100 and 150 Pa in the three fault stages (0.2, 0.4 and 0.6 in. H ₂ O) and each stage implemented for at least six hours.
Loss of control of supply fan	Abrupt	Supply fan VFD isolated from EMCS and operated at a constant speed for about 23 hours.

C.30.6 Sensors used

In addition to the sensors listed in Table C28, the FDD method was tested with electrical-power data obtained from two centrally located NILM meters, one installed at the building electrical-service entry and used to detect chiller operation, and one installed on the motor-control center and used to detect operation of fans and pumps.

Table C28. Required sensors.

Sensor Type	Condition
Temperature	Outside (ambient) air
Flow	Supply air
Pressure	Supply-duct static pressure
Control Signal	Cooling-coil control valve
	Supply fan
Electrical power	Chiller
	Supply fan
	Secondary chilled-water pump

C.30.7 Design data used

None required.

C.30.8 Training data required

Training data are required to establish the power correlations and to determine normal cycling rate of the centrifugal chiller. Training data are also used to determine changes in power correlations associated with individual faults, as a means of diagnosing faults from a limited number of choices. For example, both a pressure-sensor offset and a stuck-closed recirculation damper can cause supply-fan power to exceed normal values. At ERS, the power deviations for these two faults exhibited recognizably different patterns. In early stages of the work, training data were used to set fault-detection thresholds, in lieu of detecting faults from the confidence intervals associated with the power correlations.

C.30.9 User interface

A simple “command line” interface is used.

C.30.10 User selected parameters

Table C29. Thresholds and other required parameters.

Description of parameter
Fan-power correlations with airflow and speed-control signal
Maximum deviation of static pressure from set point for training data
Confidence level to establish boundary between normal and faulty data
Airflow boundary to distinguish stuck-closed recirculation damper from static-pressure offset/drift
<i>Fan power at 100% speed below which a slipping-fan-belt fault was flagged, subject to a minimum time duration¹</i>
<i>Time duration for low fan-power at 100% speed, above which a slipping-fan-belt fault was flagged</i>
Pump-power correlation with cooling-coil valve position-control signal
Valve-position control signal above which pump-power data were analyzed for a cooling-coil capacity fault ²
<i>Measured normal-operation power level of the secondary chilled-water pump</i>
<i>Minimum decrease of pump power below normal-operation value, in excess of which a coil-capacity fault was flagged</i>
Confidence level to establish boundary between normal and faulty data (used for AHU-1)
Chiller-cycling analysis
Power level above which the chiller is considered to be operating in the low-power stage
Cycling interval when the cooling-coil valve control signal is at 0%, below which a leaky-valve fault is flagged
Normalized outdoor-air temperature, below which chiller cycling is analyzed to detect a leaky recirculation damper ³
Power-oscillation analysis
Size of sliding window for averaging one-minute power data from submeters
Standard deviation of power signal above which a fault is flagged, as a percentage of average power

1. Fan-power analysis at 100% speed was used in AHU-A and B to detect the slipping fan belt. For AHU-1 this approach was replaced by the more rigorous and sensitive polynomial correlation of fan power with speed control signal.
2. Pump-power analysis relative to a measured and near-constant normal-operation value was used in AHU-A and B to detect the coil-capacity fault. For AHU-1 this approach was replaced with a polynomial correlation of pump power with valve-position control signal.
3. The normalized outdoor-air temperature is the difference between the outdoor-air temperature and the supply-air-temperature set point, normalized by the difference between the supply and room-air temperature set points.

C.30.11 Threshold selection method

Threshold parameters are currently determined heuristically. As noted above, an effort was made as the tests evolved to replace some thresholds with statistical confidence intervals.

C.30.12 Results of trials

Results with submetered power data were very satisfactory for the three blind-test periods for AHU-A and B. The pressure-sensor offset fault was detected and diagnosed successfully in all three test periods while the stuck-closed recirculation damper, the unstable fan controller and the leaky cooling-coil valve were detected and diagnosed in each of the two test periods in which they were implemented. Careful maintenance and control of the HVAC systems and a limited pallet of faults to choose from made fault diagnosis possible, whereas it would be substantially more difficult or impossible in a less-controlled setting.

The coil-capacity fault was detected and diagnosed successfully in the late-winter test period and was also found on two of the three implementation days in the spring test period. All three degradation stages of the slipping fan belt were detected and diagnosed in the summer test period but only the most severe stage was found in the winter tests. The leaky recirculation damper was the most difficult to detect. Analysis of chiller cycling frequency was limited to a narrow range of outdoor temperatures, to block the influence of outside temperature on chiller loading. Suitable conditions were present in the late-winter test and the fault was successfully detected and diagnosed. Temperatures were milder in the spring test and the fault was not found.

As noted earlier, four of the six AHU-1 faults were entirely unknown to the investigators and had not been studied on AHU-A and AHU-B. The electrical-power FDD method successfully detected three of the six faults (stuck-closed recirculation damper, pressure-sensor error, and loss of control of the supply fan), successfully diagnosed only one (pressure-sensor error), and did not find the three remaining faults. Balancing this mixed performance, it is worth noting that one of the detected faults, the loss of control of the supply fan, was not among those for which the method had been commissioned. Further, the method did not generate any false alarms.

After the AHU-1 faults were revealed to the investigators, the electrical-power FDD method was extended and applied with more care to data recorded during days when the undetected faults were implemented. The three faults still defied detection. Neither the stuck-open outside-air damper nor the air-side fouling on the cooling coil affected the supply-fan power for a given airflow. The impact of air-side fouling on cooling-coil capacity was not investigated because chiller cycling at high loads is strongly affected by unmeasured variables (internal and solar loads, for example). The leaking heating-coil valve could not be detected via a change in power consumption of the source of hot water because the boiler was not monitored. An analogous method was successful in finding the leaking cooling-coil valve, as already noted. While the leaking heating-coil

valve did introduce a heating load on the (downstream) cooling coil that affected the chiller cycling period, the change was not sufficiently conclusive to warrant flagging it as a fault.

Data from the two central NILM meters were adequate to detect all AHU-A/B faults except the reduction in cooling-coil capacity. Fault detection was typically based on a simple, heuristically determined power threshold because there was inadequate variation in flow or motor speed to establish power correlations at the time of equipment shut-down, when the NILM meters detected power changes. Diagnosis was less successful than with power submeters.

C.30.13 Satisfaction of user requirements

To date, intended end-users have not tested the method. Such tests are scheduled for the next three years.

C.30.14 References

Luo, D., L. K. Norford, S. R. Shaw, and S. B. Leeb. 2001. "Monitoring HVAC Equipment Electrical Loads from a Centralized Location – Methods and Field Test Results." Accepted for publication in *ASHRAE Transactions*.

Norford, L. K., J. A. Wright, R. Buswell, and D. Luo. 2000. "Demonstration of Fault Detection and Diagnosis Methods in a Real Building (ASHRAE 1020-RP)." ASHRAE 1020-RP Final Report.

C.31 SUMMARY OF THE DEMONSTRATION SYSTEMS

The following tables list the demonstrations according:

- Country
- Building type
- Fault type
- FDD method used
- FDD function
- HVAC system
- Sub-system type
- Intended user

Abbreviated names are used for each demonstration

Country

Country

Name

Belgium

QG Met

Canada

D1: DABO-VAV box
D2: DABO-AHU
D3: DABO-Chiller

China

Hong Kong

Finland

D1: VTT
D2: WebDia
D3: AREKA

France

D1: EMMA SCHOOL
D2: EMMA HOTEL
D3: EMMA OFFICE
D4: EMMA POOL
D5: ANN FDD

Germany

IKE

Japan

D1: Yamatake 1
D2: Yamatake 2
D3: Kyoto University

The Netherlands

D1: TNO-chiller
D2: Swimdiag

Sweden

Skanska

Switzerland

D1: QMBFD Lab
D2: QMBFD Office
D3: PAT

United Kingdom

D1: LU FDD
D2: PMAC
D3: LU-ERS

USA

D1: APAR
D2: Purdue
D3: MATCH
D4: MIT-ERS

Building Type

Building type

Name

Different types

Purdue
WebDia

Factory

IKE
DABO-Chiller

Hotel

EMMA HOTEL

Laboratory

LU-ERS
MATCH
MIT-ERS
QMBFD Lab
TNO-chiller

Office

DABO-VAV box
DABO-AHU
Hong Kong
EMMA OFFICE
QG Met
Yamatake 2
PAT
Skanska
QMBFD Office
LU FDD
PMAC
Yamatake 1

R and D centre

Kyoto University

School

ANN FDD
EMMA SCHOOL
AREKA
VTT
APAR

Swimming pool

Swimdiag
EMMA POOL

Fault type

Fault type

Name

Valve

PAT
Skanska
QMBFD Office
Yamatake 1
QG Met
LU FDD
QMBFD Lab
PMAC
Yamatake 2
ANN FDD
WebDia
VTT
LU-ERS
MIT-ERS
DABO-AHU
APAR
DABO-VAV box
IKE

Damper

QMBFD Office
QMBFD Lab
Skanska
Kyoto University
LU-ERS
Yamatake 1
IKE
ANN FDD
DABO-AHU
DABO-VAV box
Yamatake 2
APAR
PAT

Coil

LU-ERS
Yamatake 2
IKE
ANN FDD
Purdue
DABO-AHU
Yamatake 1
VTT
LU FDD
PMAC

Sensor

IKE
HK FDD
VTT
PAT
ANN FDD
DABO-VAV box
Yamatake 1
WebDia
Yamatake 2
DABO-AHU
APAR
QMBFD Office
QMBFD Lab
LU FDD
LU-ERS
MIT-ERS
QG Met

Fan

QG Met
Yamatake 2
ANN FDD
MIT-ERS
Purdue
PAT
Yamatake 1

Compressor

Purdue
TNO-chiller

Evaporator

TNO-chiller
MATCH
DABO-Chiller
Purdue

Condenser

Purdue
DABO-Chiller
MATCH

Refrigerant

TNO-chiller
MATCH
Purdue
DABO-Chiller

Control

EMMA OFFICE
QMBFD Office
APAR
EMMA HOTEL
WebDia
EMMA SCHOOL
AREKA
EMMA POOL
Yamatake 1
PAT
TNO-chiller
Kyoto University
DABO-VAV box
QG Met
Swimdiag
Yamatake 2
DABO-AHU
QMBFD Lab

Scheduling

EMMA SCHOOL
Swimdiag
EMMA HOTEL
EMMA OFFICE
EMMA POOL

Energy consumption

Swimdiag
WebDia
AREKA
PAT

Domestic hot water

WebDia
EMMA HOTEL

Space temperature too low

PAT
EMMA POOL
WebDia
EMMA SCHOOL
EMMA HOTEL
EMMA OFFICE

Space temperature too high

EMMA OFFICE
EMMA POOL
EMMA HOTEL
EMMA SCHOOL
PAT
WebDia

Simultaneous heating and cooling

EMMA OFFICE

Tariff management

EMMA HOTEL
EMMA OFFICE

<i>Humidity control</i>	EMMA POOL
<i>Pool water quality</i>	EMMA POOL
<i>Pool water temperature</i>	EMMA POOL
<i>Flow control</i>	DABO-VAV box
<i>Filter</i>	Purdue EMMA OFFICE DABO-AHU
<i>Pump</i>	MIT-ERS DABO-AHU
<i>Cooling water flow</i>	LU-ERS MIT-ERS Skanska
<i>Inlet water temperature</i>	PAT APAR
<i>Liquid line restriction</i>	Purdue MATCH
<i>Operator</i>	APAR
<i>Water consumption</i>	AREKA

FDD function

Function

Name

Fault detection

QMBFD Office
EMMA OFFICE
EMMA POOL
Kyoto University
EMMA HOTEL
EMMA SCHOOL
ANN FDD
QMBFD Lab
VTT
APAR

Fault isolation

HK FDD
QG Met

Fault detection and diagnosis

DABO-Chiller
DABO-AHU
DABO-VAV box
AREKA
Yamatake 1
Yamatake 2
PAT
TNO-chiller
Swimdiag
Skanska
LU FDD
LU-ERS
MIT-ERS
MATCH
Purdue
IKE

Fault diagnosis

PMAC
WebDia

FDD method used

<i>Method</i>	<i>Project</i>
<i>Artificial neural network</i>	ANN FDD
<i>Case based reasoning</i>	TNO-chiller
<i>Fault direction space</i>	Skanska
<i>Fault symptom tree</i>	AREKA
<i>Fuzzy expert rules</i>	PMAC
<i>Fuzzy models</i>	PMAC
<i>Knowledge based</i>	WebDia
<i>Nearest neighbour</i>	MATCH
<i>Pattern recognition</i>	DABO-Chiller
<i>Performance indices</i>	DABO-VAV box Swimdiag
<i>Physical model</i>	Swimdiag Skanska LU-ERS LU FDD
<i>Qualitative model based</i>	QMBFD Lab Skanska QMBFD Office Yamatake 1
<i>Residual analysis</i>	MATCH ANN FDD TNO-chiller VTT HK FDD Kyoto University

Rule based and expert

DABO-AHU
EMMA POOL
EMMA HOTEL
AREKA
DABO-VAV box
EMMA SCHOOL
LU-ERS
MIT-ERS
PAT
Purdue
Purdue
APAR
EMMA OFFICE
LU FDD
MATCH
Swimdiag
QG Met
IKE

Sign directed graphs

Yamatake 2

Statistical analysis

Kyoto University
HK FDD
DABO-Chiller
MIT-ERS
Purdue
VTT

HVAC system

HVAC system type

Name

VAV air conditioning

Yamatake 2
DABO-VAV box
DABO-AHU
ANN FDD
QG Met
Yamatake 1
Kyoto University
LU-ERS
MIT-ERS
IKE
APAR

CAV air-conditioning

LU FDD
PAT
Skanska
QMBFD Office
VTT
QMBFD Lab
PMAC

Chiller

MATCH
TNO-chiller

District heating sub station

WebDia
AREKA

Hot water heating

EMMA SCHOOL

Direct electric heating

EMMA HOTEL

Fan coil air-conditioning

EMMA OFFICE

Roof top (package unit)

Purdue

Different types

Swimdiag
EMMA POOL

Water cooled chiller

HK FDD
DABO-Chiller

Subsystem type

<i>Subsystem type</i>	<i>Name</i>
<i>AHU</i>	Yamatake 1 DABO-AHU VTT AREKA EMMA POOL EMMA OFFICE QG Met IKE Yamatake 2 Skanska QMBFD Lab QMBFD Office APAR LU FDD ANN FDD PAT LU-ERS MIT-ERS
<i>VAV box</i>	PAT Yamatake 1 Yamatake 2 Kyoto University DABO-VAV box QG Met
<i>Boiler</i>	Swimdiag QG Met WebDia
<i>Chiller</i>	HK FDD Swimdiag MATCH TNO-chiller DABO-Chiller
<i>Heating coil</i>	QG Met
<i>Fan-coil unit</i>	EMMA OFFICE
<i>Heating floor</i>	EMMA HOTEL
<i>Domestic hot water storage</i>	EMMA HOTEL
<i>Hydronic heating circuit</i>	WebDia AREKA PAT EMMA SCHOOL EMMA POOL

<i>Electric convectors</i>	EMMA HOTEL
<i>Recovery wheel</i>	QMBFD Office PAT QMBFD Lab
<i>Chilled ceiling</i>	PAT
<i>Rooftop</i>	Purdue
<i>District heating sub station</i>	AREKA WebDia
<i>Combined heat & power</i>	Swimdiag
<i>Heat pump</i>	EMMA OFFICE Swimdiag
<i>Cooling coil</i>	PMAC

Intended user

Intended user

Name

Building operator

Skanska
EMMA OFFICE
ANN FDD
EMMA SCHOOL
IKE
QG Met
AREKA
WebDia
Kyoto University
Swimdiag
EMMA POOL
VTT
MIT-ERS
QMBFD Lab
QMBFD Office
APAR
PAT
DABO-Chiller
DABO-VAV box
PMAC
DABO-AHU

Service company personnel

QG Met
Purdue
MATCH
MIT-ERS
APAR
WebDia
Yamatake 2
Skanska
Kyoto University
QMBFD Office
TNO-chiller
VTT
Swimdiag
DABO-AHU
Yamatake 1
QMBFD Lab
DABO-Chiller
DABO-VAV box

Facility manager

EMMA SCHOOL
EMMA HOTEL
Swimdiag
PAT
LU-ERS
EMMA OFFICE
IKE
EMMA POOL

BMS supplier

QMBFD Office
QMBFD Lab
Yamatake 1
Yamatake 2
ANN FDD

Commissioning engineer

LU FDD
PMAC
TNO-chiller

Building owner

WebDia

Building manager

PAT
EMMA OFFICE
EMMA SCHOOL
EMMA HOTEL
MATCH
EMMA POOL
HK FDD

SECTION D: EVALUATION OF FDD TOOLS

J. M. House, J. E. Braun, T. M. Rossi, and G. E. Kelly

D.1 INTRODUCTION

A prototypical commercialization process is described in Section E. Figure D1 depicts this process for FDD product development and outlines the areas of the process where Annex 25 (IEA Annex 25, 1996) and Annex 34 were focused. The process usually begins with a marketing analysis to assess end-user needs and potential benefits. This information is useful in estimating allowable costs and determining a performance specification. A number of iterations may be necessary to achieve a design that realizes the performance specification and cost objectives. Early iterations are ideally tested

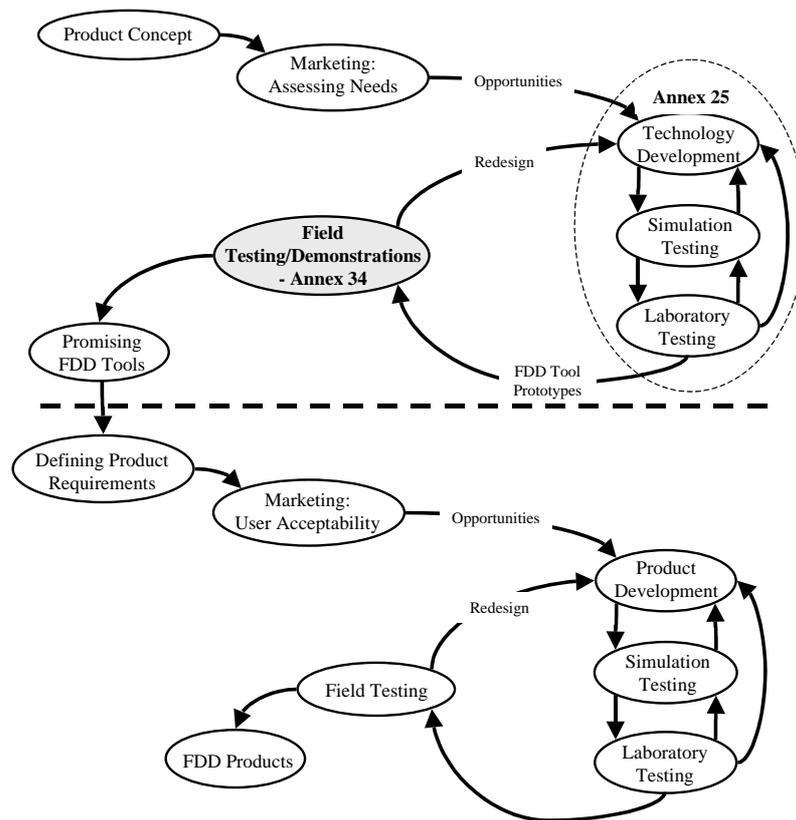


Figure D1. FDD tool development process.

using simulation tools that can predict both normal and faulty behavior. Simulations allow relatively quick testing at low cost. Next a hardware prototype may be built and tested in a laboratory environment. The laboratory testing allows faults to be introduced

in a controlled manner and considers realistic effects not present in many simulation tools. Finally, an improved prototype must be field tested before the design is finalized. Successful tools emerging from field tests (and Annex 34 efforts) are candidates for productization. This process (depicted by the portion of the diagram below the dashed line) has similar stages to those described previously with success manifesting itself in FDD products.

For any of the three types of testing (simulation, laboratory, field) performed during FDD prototype tool or FDD product development, it is necessary to have performance criteria and an evaluation approach. The evaluation criteria and approach depend on the application and performance must always be traded off versus the cost. The aerospace and nuclear power industries place a premium on detection time because equipment and sensor failures can be catastrophic. For these applications, the cost of additional sensors is accepted as necessary to ensure safe operation of the airplane or plant. Detection time is much less critical for HVAC applications because failures are far less likely to result in occupant injury or death. Hence, building owners are less willing to pay for additional sensors and building operators are less willing to tolerate false alarms.

This section describes criteria for evaluating FDD tools. This is not intended to be a recipe for evaluating FDD tools, but rather it should be viewed as a checklist of characteristics to consider when assessing the capability of a particular tool to meet specific diagnostic needs. Also presented are summaries of efforts to compare and evaluate FDD tools and general conclusions that can be drawn about the evaluation of such tools.

D.1.1 Characteristics affecting cost

The performance of an FDD tool is closely tied to a number of characteristics, some of which are identified in the introduction. The following list of characteristics is offered as a guideline of important considerations for FDD tool designers and/or purchasers. Projects described in Section C include a summary of most of these tool characteristics.

General

- What faults can be detected?
- What faults can be diagnosed?
- Under what 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?

Most of the items listed above should be self-explanatory. A possible exception is the question concerning the frequency of data sampling. This may have important implications regarding where the tool can be implemented. If sampling on the order of seconds is needed, the tool will likely need to reside in a local controller. If the sampling is less frequent, the tool could possibly run at a higher level in the distributed control system. More is said on this subject in Section B8.

It is accepted that FDD tools with greater requirements associated with the characteristics listed above will also be expected to have superior performance and higher cost. However, because FDD applied to HVAC applications is not a mature technology, it is difficult to perform a formal cost-benefit analysis of individual characteristics at this time. There are two primary reasons why this is true. First, there is limited information available regarding the frequency of occurrence of faults for particular applications, and the costs associated with those faults. Hence, assessing the benefit of FDD is difficult. Breuker and Braun (1998a) reported on the frequency and cost of faults in rooftop air conditioning units and Comstock et al. (1999) provide similar information for chillers. In general, costs reported in the cited studies came from service records and accounted for parts and labor. Information regarding energy waste or lost productivity associated with the faults, which are important motivating factors for purchasing FDD tools, was not contained in the records.

The second reason why it is difficult to perform a cost-benefit analysis stems from the fact that the technology is relatively new. Costs associated with additional sensors can

be determined easily, but the cost associated with tuning a model or method using training data is less straightforward to ascertain. This is especially true if the tuning is performed in the field. Reliable cost information for this type of characteristic will only be obtained through sufficient experience with implementing FDD tools in the field. Until reliable cost and benefit data are available, many of the characteristics listed in the preceding table will remain somewhat subjective.

Another FDD tool characteristic affecting cost is the user-interface. A detailed discussion of issues associated with user-interfaces is provided in Section B1.

D.1.2 Performance criteria

For HVAC applications, appropriate performance criteria 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, and
- 4) percent false alarms.

These performance criteria are something less than ideal because of the information they do not reveal (i.e., specific circumstances under which these results were obtained). Hence, as part of the evaluation approach, it is necessary to specify a particular test “suite” of data that is to be applied for the testing. Ideally the data documentation should include information about the severity of the fault and the external driving conditions. Simulation and laboratory data are preferred for degradation faults because it is possible to introduce the faults in a controlled manner. For abrupt faults this requirement can be relaxed and field data can be used if there is some assurance that the system or piece of equipment was otherwise operating normally. A data set consisting of seven faults encountered with air-handling units (Norford et al., 2000) and one consisting of eight faults encountered in centrifugal chillers (Comstock et al., 1999) now exist.

During the course of evaluating performance, the impact of many design changes can be ascertained, including number and type of sensors, data filtering, and approach for characterizing expected behavior. As examples, Rossi and Braun (1997) and Breuker and Braun (1998b) presented detailed results of the impact of several design parameters on the sensitivity of an FDD method in detecting and diagnosing faults in rooftop units. As described in the previous section, design changes typically have associated cost implications. In addition, methods that utilize models for expected behavior give better overall performance, but at increased costs due to training requirements. Therefore, an evaluation tool or process must consider these tradeoffs or should only be applied in

evaluating different methods that utilize similar sensor information and have similar training requirements. The FDD Test Shell was developed in Annex 34 in part to evaluate the performance of FDD tools and was used to facilitate the tool comparison described in Section D.2.1. Details of the FDD Test Shell are provided in the Appendix.

D.2 COMPARISONS OF FDD TOOLS

Several efforts to compare and evaluate FDD tools have been made in Annex 34. This subsection describes case studies involving comparisons of FDD tools developed by different individuals or teams of individuals.

D.2.1 Annex 34 joint exercise of AHU FDD tools

A. L. Dexter and J. M. House

D.2.1.1 Introduction

Annex 34 focused primarily on case studies where FDD methods were tested either in real buildings, or off-line using real building data. For the most part the case studies have been conducted independently by members of a single country and/or institution. A joint evaluation exercise of AHU FDD tools was conducted with two goals, namely, 1) to explore the effort necessary to apply various FDD tools to data sets from different buildings; and 2) to explore how the performance of FDD tools could be evaluated. By applying the methods to a common data set, a better understanding the positive attributes as well as the shortcomings of different tool could be attained. Two tools are considered here. One is a model-based tool that uses generic fuzzy models of normal and faulty operating conditions to detect and diagnose faults in the cooling coil subsystem of an AHU (Ngo and Dexter, 1999). The second tool uses simple expert rules for AHUs and performs fault detection only (House et al., 2001).

D.2.1.2 Data sets

The data sets distributed for testing included six days of normal operational data from the Japan TEPCO R&D Center and 10 days of data from the Iowa Energy Center's Energy Resource Station. The Iowa data consist of normal data and coil capacity fault data for both spring and summer conditions. The data for the two seasons come from different AHUs, although all data for a given season (normal and faulty) come from the same AHU. AHU A, which was used to generate the spring test data, is supplied with

chilled water from the main campus chiller. The chiller is sometimes turned off during the test period. This often results in chilled water supply temperatures that are above 11°C. It is arguable that this should be regarded as an operational fault. AHU B, which was used to generate the summer test data, is supplied with chilled water by a packaged chiller dedicated to the Energy Resource Station. Note that the chilled water supply temperature cycles in the range of 5°C to 9°C, but sometimes goes below 5°C.

The coil capacity fault was created by restricting the flow of water to the cooling coil and was intended to somewhat mimic the effect that would be observed by water-side fouling of the coil. The way that the “fouling” fault was introduced will reduce the authority of the valve and might cause the coil characteristic to become very non-linear. This might explain why the effect of fouling on the value of the valve control signal appears to be very small at some operating conditions. Three levels of the fault were implemented with the lowest level being a 30% reduction in the maximum flow rate through the coil, and the highest level being a 73% reduction. The faults were generally implemented in the early morning and were removed or changed the following morning. Further details of the test building and data are provided by Norford et al. (2000).

D.2.1.3 Data handling

The FDD Test Shell was used to facilitate the process of using data sets from different sources. The AHU template described in Section B4.4 defines the location of various points in the Test Shell server application table. For instance, the AHU supply air temperature is always mapped to cell number 4 of the table. Similar mappings are defined for other points. FDD tools are then interfaced to the Test Shell. The tools must be configured to request the design and measurement data they require from the server application table. This configuration is done only once because, if the AHU template is followed, data will be mapped to a consistent location in the server application table regardless of the origin of the data.

D.2.1.4 Fuzzy model-based analysis and results

Overview

The analysis and results presented in this subsection consider the Iowa data only. The data were analysed using a single-step fuzzy model-based fault diagnosis scheme based on robust generic reference models (Ngo and Dexter, 1999). It was assumed that any one of the following faults associated with the cooling coil may be present:

- Leaky valve
- Coil under capacity
- Valve stuck closed
- Valve stuck midway
- Valve stuck open

The diagnosis was based on the following measurements and control signal (with point names in parentheses corresponding to the FDD Test Shell template for AHUs as described in Section B4 and Section F):

- Heating coil discharge air temperature (HCDT)
- Cooling coil discharge air temperature (CCDT)
- Supply air flow rate (SFLOW)
- Cooling coil valve control signal (CSIG)
- Chilled water inlet temperature (CWIT)

The generic reference models are identified from normalised training data generated by simulating the behaviour of different cooling-coil subsystems designed for operation in the UK. The Iowa test data must be re-scaled to take account of differences in the design data (see Table D1). The design values of the cooling coil inlet and discharge air temperature, and the supply airflow rate are used to re-scale the data.

Table D1. The design values of the process variables.

Process Variable	UK Design Data	Iowa Design Data
CCIT	24.0°C	27.8°C
CCDT	13.0°C	12.4°C
CWIT	5.0°C to 9°C	6.7°C
CCIRH	48%	45%
CCDRH	90%	90%
SFLOW	1.0 to 5.0 kg/s	1.81 kg/s

The re-scaling ensures that the normalised variables have the same values at the design conditions and when the un-normalised variable had a value of zero. For example,

$$\Delta T' = \frac{0.714(T_{cci} - T_{ccd}) + 3.0}{30.0} \text{ where } \frac{\Delta T_{UKD}}{\Delta T_{USD}} = 0.714$$

Since the reference models are only valid for supply airflow rates greater than 40% of the design value, test data are rejected if flow rate is less than this.

The test data are not analysed if the temperature of the inlet water to the cooling coil is less than 5°C or greater than 9°C. This is the range used to specify the class of cooling coil subsystems described by the generic reference models used in the diagnosis.

The normalised test data are also checked to ensure that the values are within the range of the reference models (greater than zero and less than unity) before they are used for diagnosis.

As the data do not include a measurement of the relative humidity of the air entering the coil, a constant value of 60% is used.

Since the diagnosis is based on the steady-state behaviour of the HVAC equipment, the values of the valve control signal are pre-processed so that information about the steady-state behaviour can be extracted from the transient data obtained from the sensors. It is assumed that the dynamics of the cooling coil subsystem can be described by the following non-linear first-order system:

$$y = \frac{Kf(u)}{1 + \tau s}$$

where y is the discharge air temperature, u is the valve control signal, $f()$ represents the non-linearity, s is the Laplace transform variable, and K is the gain and τ the time constant of the system.

Let

$$u_1 = f(u), \quad u_2 = \frac{u_1}{1 + \tau s}, \quad \text{and} \quad u_3 = f^{-1}(u_2).$$

Then,

$$y = \frac{Ku_1}{1 + \tau s} = Ku_2 = Kf(u_3),$$

which has the same form as the steady-state relationship $y = Kf(u)$ between y and u . Therefore y and u_3 can be used for diagnosis based on the steady-state behaviour of the system. The size of the estimation errors will depend on how well the function $f()$ and the single time constant τ describe the non-linear and dynamic behaviour of the actual system. Simulation results have demonstrated that satisfactory results can be obtained using crude estimates of $f()$ and τ , if the time variations in u are no faster than the dynamics of the system. The time constant of the non-linear filter used to pre-process

the transient data is 180s and a square-root relationship, between the cooling coil discharge temperature and the cooling coil valve control signal, is assumed.

When the fan switches on, the temperature difference across the coil suddenly jumps to a relatively large value, whereas the associated change in the pre-processed control signal is small, because it is low-pass filtered. Hence the test data may exhibit the symptoms of a leaky valve following start-up. To avoid this problem, data are therefore rejected for 10 samples following start up of the fan.

Up to six alarm messages are generated:

- Correct operation
- Leaky valve
- Coil under capacity
- Valve stuck closed
- Valve stuck midway
- Valve stuck open

The diagnosis scheme highlights the messages according to the state of the system that is currently associated with the greatest non-zero belief in the least ambiguous result. Alarms are generated only if this state does not include the possibility of fault-free operation. There is no input interface.

Results of trials

The results of the tests are summarised in Table D2. The Iowa test data are presented in Figures D2 to D11. Note that the plotted data include the key measurements and control signals used in the fuzzy model-based diagnostic tool. In addition to the measurements and control signal listed previously (HCDT, CCDT, SFLOW, CSIG, CWIT), the outdoor air relative humidity (OAH), return air relative humidity (RAH), and mixing box damper control signal (MSIG) are presented. Note also that the summer data files begin with the file labeled iec_sum2. The file iec_sum1 was originally considered as “normal” data and later discarded because the data were collected on a day when the AHU was being configured for the fault testing. The operation on this day was not representative of normal operation.

Table D2. Diagnostic results.

Data file name	Alarms generated	Maximum final least ambiguous belief	Number of data sets used	Actual state of the system
iec_sum2	Coil capacity fault	Bel(f) = 41%	643 out of 1439	Coil capacity fault (Stage 1)
iec_sum3	Coil capacity fault	Bel(f) = 92%	670 out of 1441	Coil capacity fault (Stage 2)
iec_sum4	Coil capacity fault and valve stuck midway	Bel(fm) = 97%	499 out of 1440	Coil capacity fault (Stage 3)
iec_sum5	None	Bel(clf) = 28%	702 out of 1440	Normal operation
iec_spr1	None	Bel(clfmo) = 99%	345 out of 881	Coil capacity fault (Stage 1)
iec_spr2	None	Bel(clfmo) = 99%	398 out of 1441	Coil capacity fault (Stage 2)
iec_spr3	None	Bel(clfmo) = 99%	577 out of 1441	Coil capacity fault (Stage 3)
iec_spr4	None	Bel(clf) = 1%	227 out of 1441	Normal operation
iec_spr5	None	Bel(clfmo) = 99%	264 out of 1441	Normal operation
iec_spr6	None	Bel(clfzmou) = 100%	348 out of 1441	Normal operation

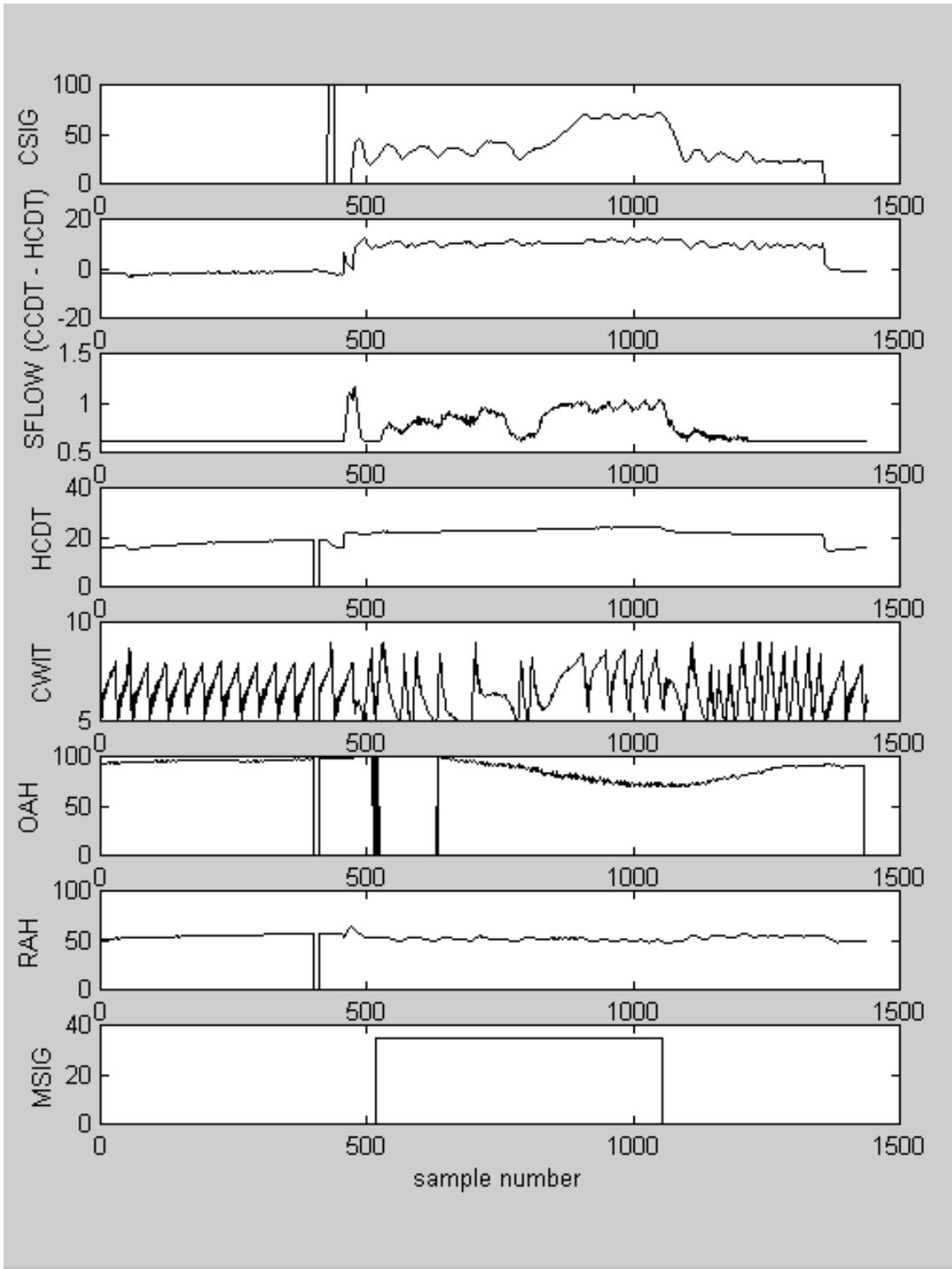


Figure D2. *Iec_sum2* test data.

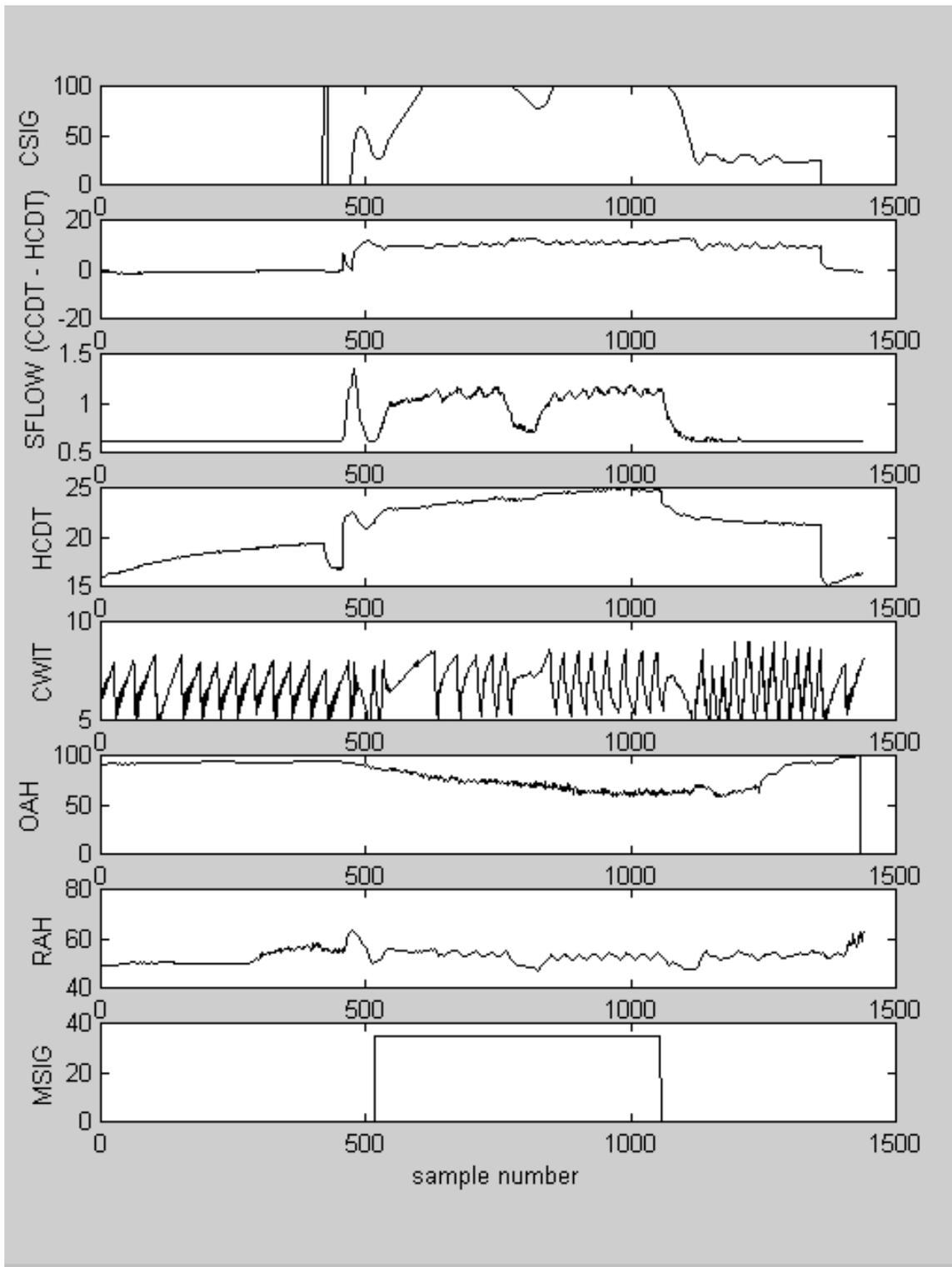


Figure D3. Iec_sum3 test data.

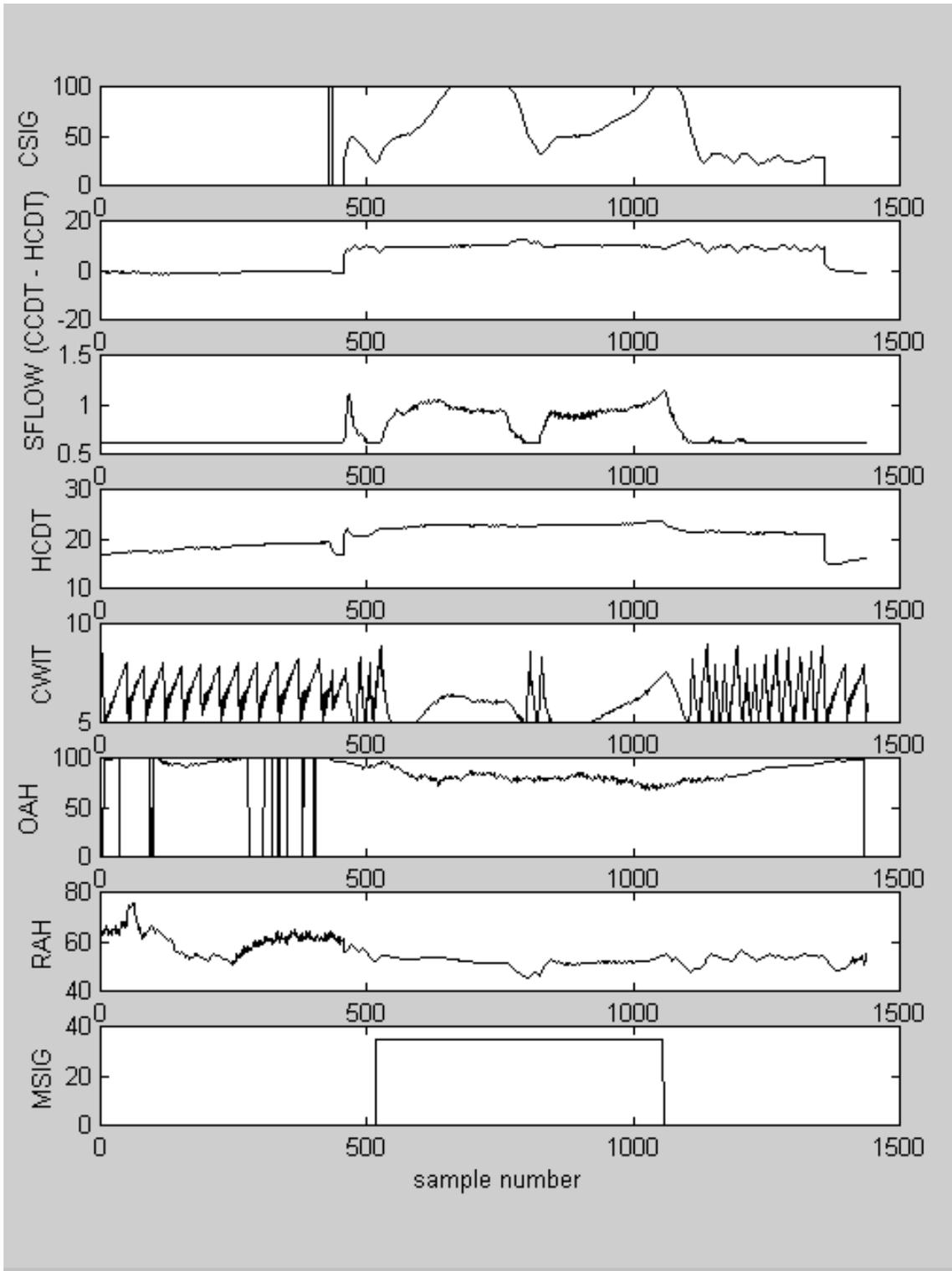


Figure D4. *Iec_sum4* test data.

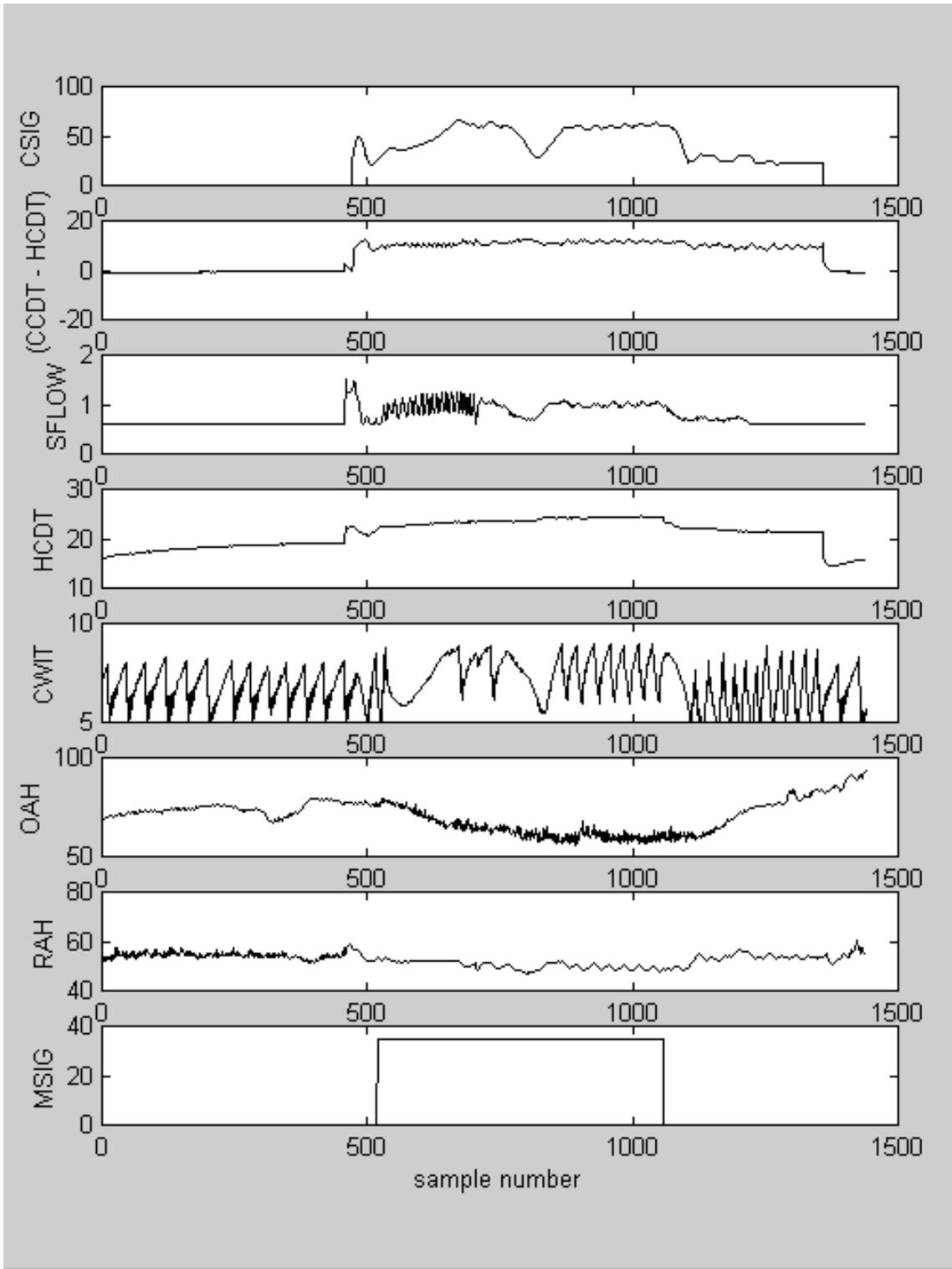


Figure D5. *Iec_sum5* test data.

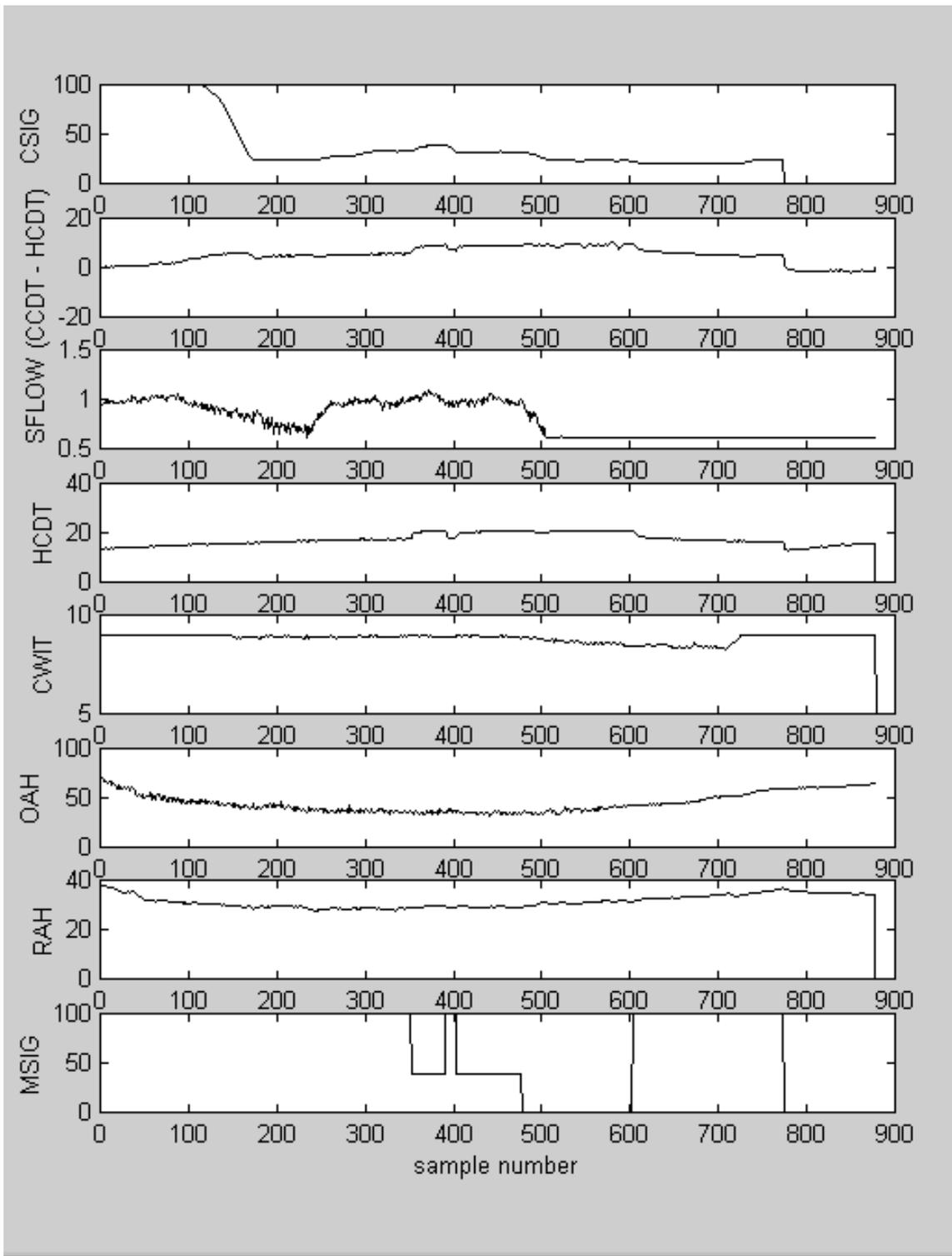


Figure D6. Iec_spr1 test data.

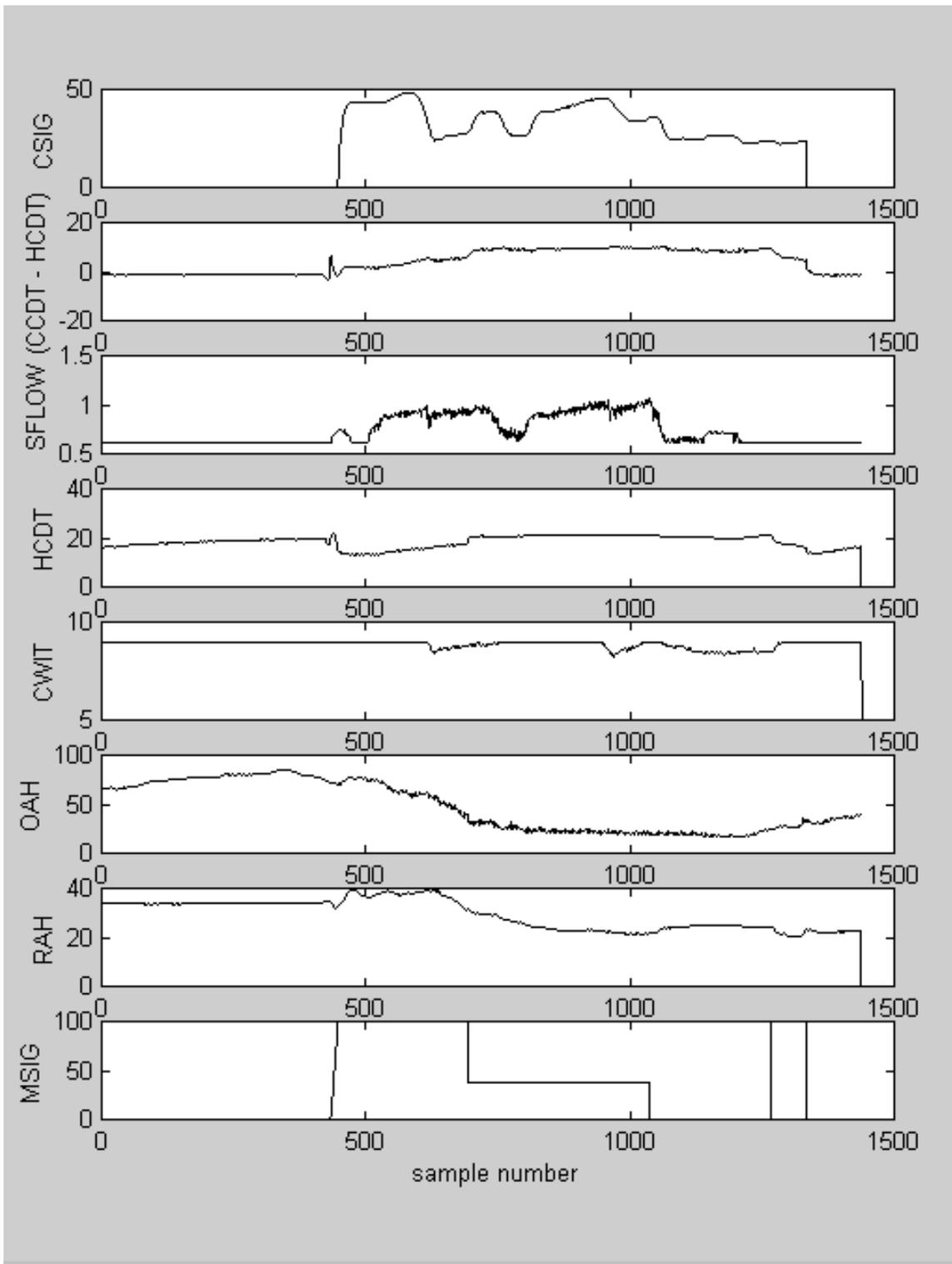


Figure D7. *Iec_spr2* test data.

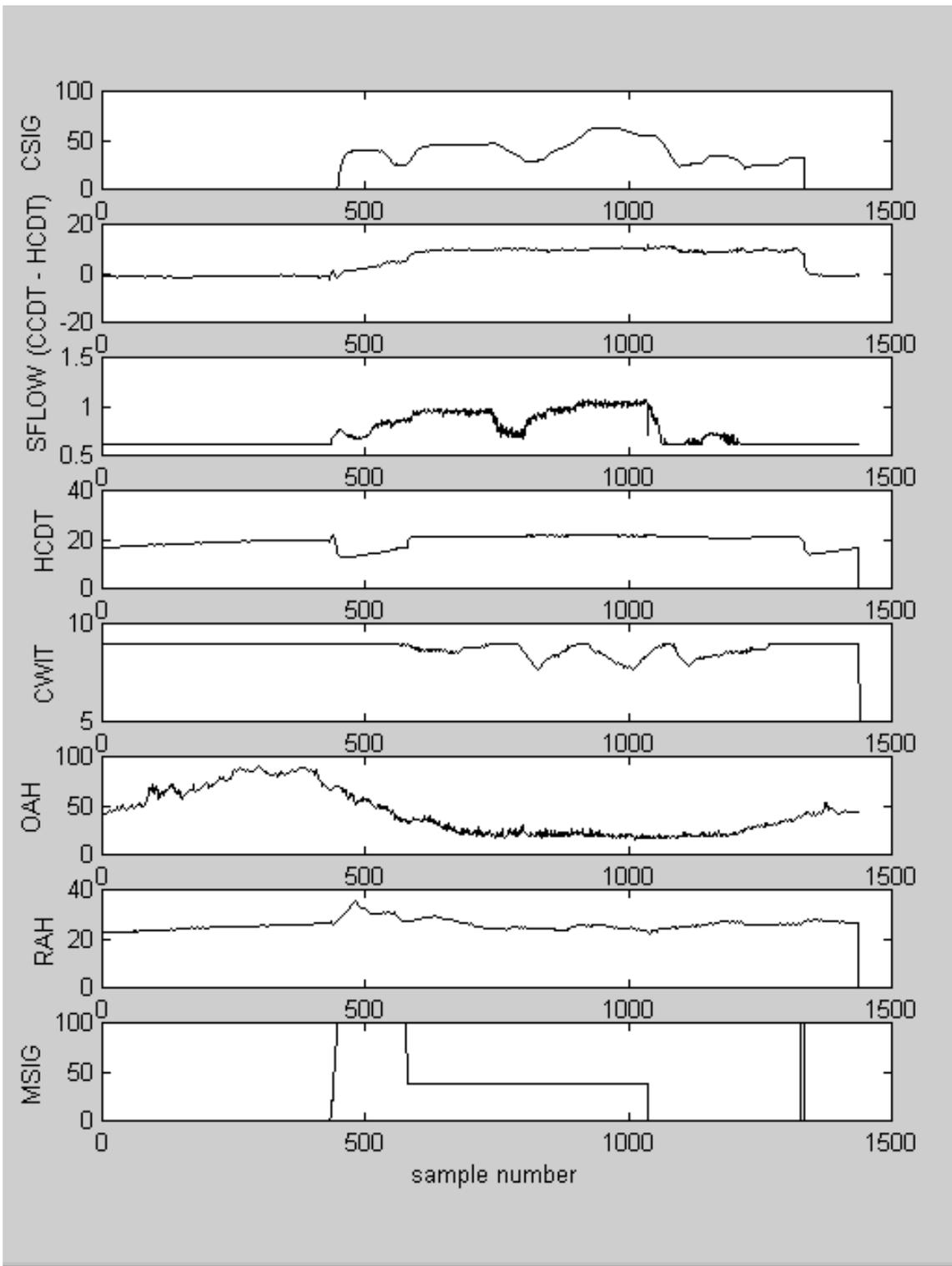


Figure D8. Iec_spr3 test data.

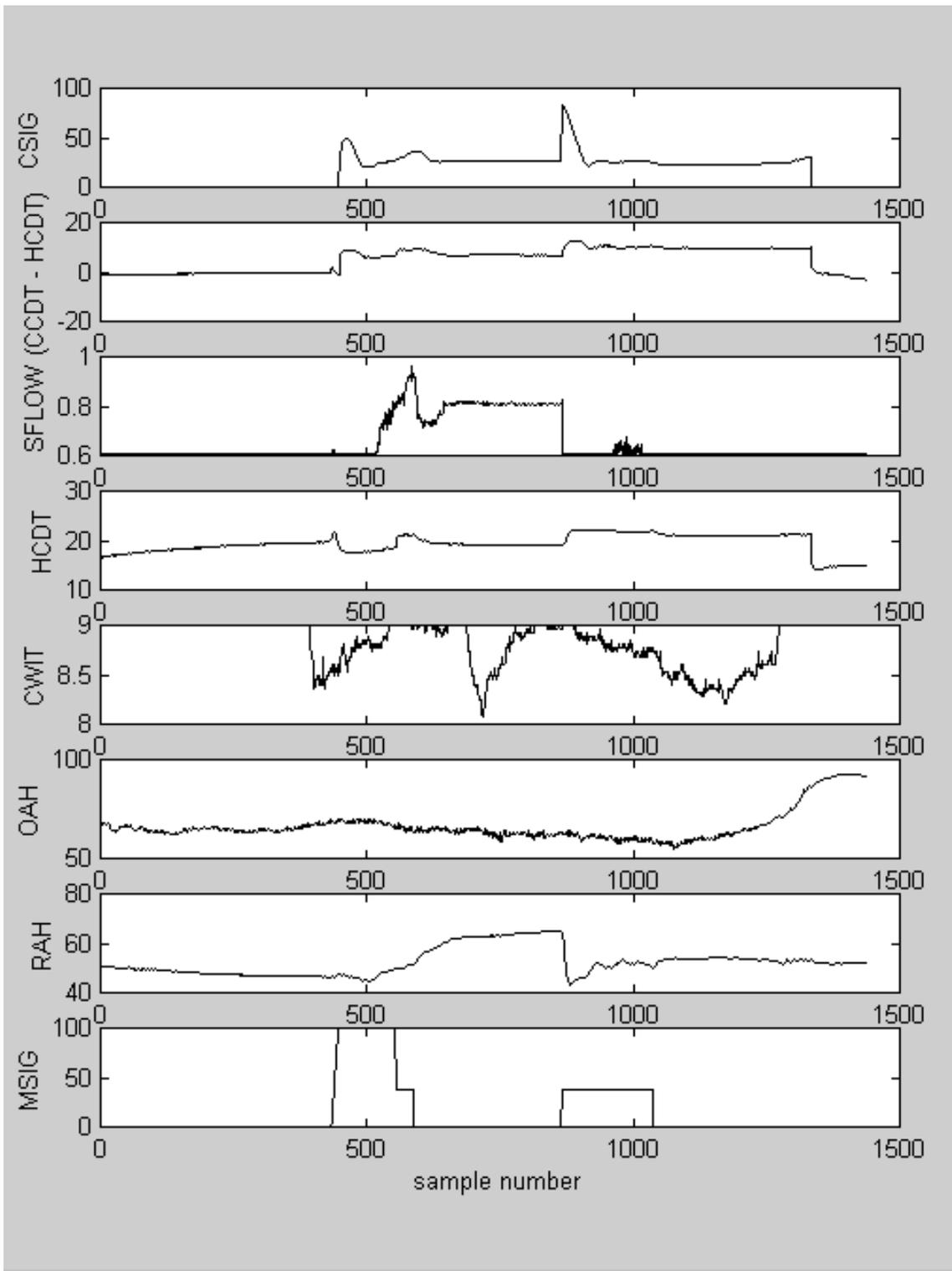


Figure D9. Iec_spr4 test data.

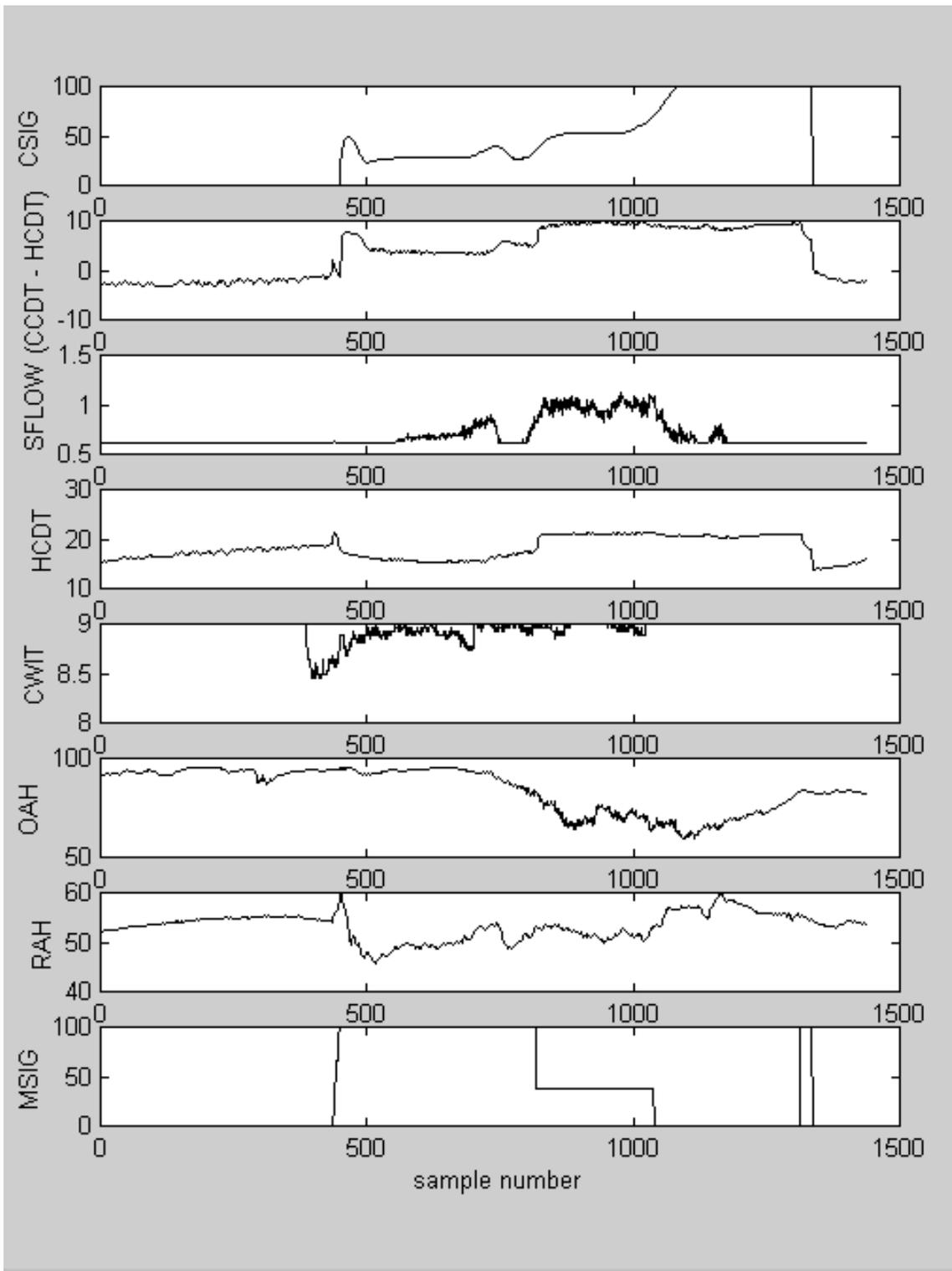


Figure D10. *Iec_spr5* test data.

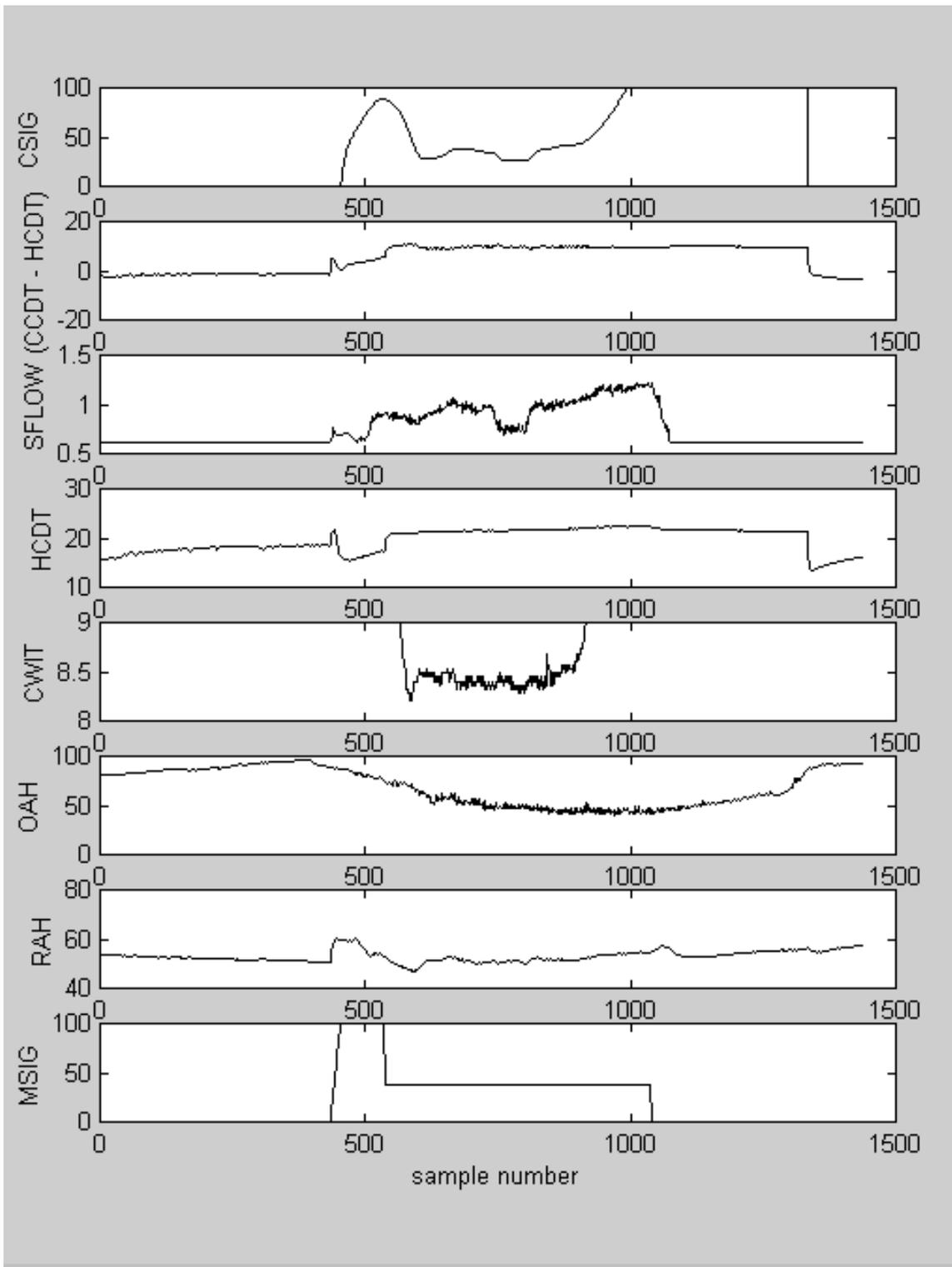


Figure D11. Iec_spr6 test data.

Iec_sum2 [Label: Coil capacity fault (Stage 1)]

The test data are rejected at the start of the run because the supply air flow rate is less than 40% of the design value, and the chilled water supply temperature is less than 5°C for some of the time. Only 643 of the 1439 samples are used for diagnosis. The result of the diagnosis is over 41% belief in the coil being under-capacity. An alarm is generated correctly at sample number 904.

Iec_sum3 [Label: Coil capacity fault (Stage 2)]

The test data are rejected at the start and end of the run because the supply airflow rate is less than 40% of the design value. Only 670 of the 1441 samples are used for diagnosis. The result of the diagnosis is over 91% belief in the coil being under-capacity. An alarm is generated correctly at sample number 568. It is interesting to note that there is no unambiguous evidence that the coil is under capacity. The belief in the coil being under capacity is generated by combining evidence, which is collected at different operating points, that

- (a) “the coil is under capacity or the valve is stuck closed or midway”
- (b) “the coil is either fault-free or under capacity, or the valve is leaking or stuck closed”
- (c) “the coil is either fault-free or under capacity, or the valve is leaking or stuck midway or open”.

Iec_sum4 [Label: Coil capacity fault (Stage 3)]

The test data are rejected at the start and end of the run because the supply airflow rate is less than 40% of the design value. Only 499 of the 1440 samples are used for diagnosis. The result of the diagnosis is over 97% belief in either the coil being under-capacity or the valve being stuck mid-way. An alarm is generated at sample number 612. The diagnosis scheme cannot differentiate between the coil being under capacity and the valve being stuck mid-way because all of the test data, which are collected when the valve is less than 50% open, are rejected.

Iec_sum5 [Label: Normal operation]

The test data are rejected at the start and end of the run because the supply airflow rate is less than 40% of the design value. Only 702 of the 1440 samples are used for diagnosis. The result of the diagnosis is inconclusive and no alarms are generated. There is over 28% belief in either fault-free operation or the coil being under-capacity or the valve being leaky. An alarm is generated at sample number 612.

Iec_spr1 [Label: Coil capacity fault (Stage 1)]

The test data are rejected at the end of the run because the supply airflow rate is less than 40% of the design value. The chilled water supply temperature is greater than 9°C

for some periods of time. Only 345 of the 881 samples are used for diagnosis. The result of the diagnosis is highly ambiguous (there is, however, no belief that the valve is stuck closed!) and no alarms are generated.

Iec_spr2 [Label: Coil capacity fault (Stage 2)]

Only 398 of the 1441 samples are used for diagnosis. The results are very similar to those obtained for run iec_spr1. The diagnosis is highly ambiguous and no alarms are generated.

Iec_spr3 [Label: Coil capacity fault (Stage 3)]

Only 557 of the 1441 samples are used for diagnosis. The results are very similar to those obtained for run iec_spr2. The diagnosis is again highly ambiguous and no alarms are generated.

Iec_spr4 [Label: Normal operation]

Only 227 of the 1441 samples are used for diagnosis. The diagnosis is again inconclusive though it is slightly less ambiguous (There is more than 1% belief that either the subsystem is fault-free or the coil is under capacity or the valve is leaking). However, no alarms are generated. It should be noted that this is thought to be a change over day. If so, the data are therefore not guaranteed to be representative of normal operation.

Iec_spr5 [Label: Normal operation]

Only 264 of the 1441 samples are used for the diagnosis, which is again highly ambiguous, and no alarms are generated. Although the valve saturates because the (Campus) chiller turns off in the afternoon, the data are rejected, as the supply water temperature is outside of the range 5°C to 9°C. False alarms are therefore avoided.

Iec_spr6 [Label: Normal operation]

The diagnosis, which is based on only 348 of the 1441 available samples, is yet again highly ambiguous and no alarms are generated. As in run iec_spr5, the supply water temperature rises above 10°C in the late afternoon causing the valve to saturate. As before, false alarms are avoided because the data are rejected because the supply water temperature is greater than 9°C.

Summary

The fuzzy model-based method of analysis did not generate false alarms at any time. A coil capacity fault was diagnosed correctly on all three summer days when the fault was present, although the belief in the fault was much smaller on the day when the fault was implemented at its lowest level of severity. However, the coil capacity fault was not

identified during the spring test period, even on the day when the fault was implemented at the highest level of severity.

D.2.1.5 Fault detection results based on expert rules

Overview

This subsection presents results obtained using the rule-based FDD method for AHUs referred to as APAR (AHU Performance Assessment Rules) described by House et al. (2001). APAR is capable of detecting faults and offering possible explanations for the fault based on the rules indicating the presence of a fault. The Iowa data include data for normal operation and data representing a loss of capacity in the cooling coil. The TEPCO data represent normal operation.

The following sensors are used for the Iowa data:

- Supply air temperature (SAT)
- Return air temperature (RAT)
- Mixed air temperature (MAT)
- Outdoor air temperature (OAT)

The method also uses the control signals to the cooling coil valve (CSIG), the heating coil valve (HSIG), and the mixing box dampers (MSIG).

The TEPCO building data *do not include a mixed air temperature or a control signal to the mixing box dampers*. Thus, rules using the mixed air temperature were eliminated from consideration and the control signal to the mixing box dampers was artificially set to zero to indicate the use of minimum outdoor air for ventilation.

In addition to the measurement data and control signals listed previously, implementation of APAR requires knowledge of certain design and operational data, namely:

- Setpoint value of the supply air temperature (SATSP),
- Minimum and maximum values of control signals for the heating coil control valve, cooling coil control valve and mixing box dampers,
- Percentage outdoor air necessary to satisfy ventilation requirements,
- Changeover temperature from mechanical cooling with 100% outdoor air to mechanical cooling with minimum outdoor air,
- Occupancy status (OCC), and
- Description of sequencing/economizer cycle strategy.

This information was known for the Iowa data. The percentage outdoor air necessary to satisfy ventilation requirements was not needed for the TEPCO building because the rules utilizing this design information also use the mixed air temperature. With the mixed air temperature unknown, these rules were eliminated from consideration. The changeover temperature from mechanical cooling with 100% outdoor air to mechanical cooling with minimum outdoor air was also unknown and was taken to be 70°F. The occupancy status was not available, hence, the building was considered occupied whenever the cooling coil valve was open. Finally, only limited information was known about the sequencing strategy of the AHU. Based on information obtained from the TEPCO staff, it was determined that the AHU has two typical modes of operation during occupied periods, namely, mechanical cooling with minimum outdoor air, and heating with minimum outdoor air.

No training data are needed to implement APAR; however, a number of user selected parameter values must be established. User selected parameters and the associated values are:

- Rule thresholds, $\varepsilon_t = 3^\circ\text{F}$, $\varepsilon_f = 0.3$, $\varepsilon_c = 0.05$,
- Temperature rise across the supply fan, $\Delta T_{sf} = 2^\circ\text{F}$,
- Temperature rise across the return fan, $\Delta T_{rf} = 2^\circ\text{F}$,
- Minimum temperature difference for assessing ventilation rates, $\Delta T_{\min} = 10^\circ\text{F}$,
- Percentage outdoor air necessary to satisfy ventilation requirements, $(Q_{Oa}/Q_{Sa})_{\min} = 0.35$, and
- Maximum number of times that the mode can change without considering the operation unstable, $MT_{\max} = 6$.

The value of the smoothing parameter used to compute the exponentially-weighted moving averages is 0.03. Values of the thresholds and other parameters were determined heuristically.

Results of trials

Table D3 summarizes the results obtained for the Iowa data and includes the operational status reported by the Iowa Energy Center staff. Note that rules are implemented in APAR such that if they are true (or satisfied), a fault is detected. Satisfaction of Rule 14 implies that the cooling coil valve control signal is saturated at a full open position while the system operates in Mode 3 (mechanical cooling with 100% outdoor air). Rule 20 is identical; however it corresponds to operation in Mode 4 (mechanical cooling with minimum outdoor air). Satisfaction of either Rule 14 or Rule 20 results in a warning indicating the system is out of control. A fault is indicated if, in addition to the saturated control signal, the supply air temperature exceeds its setpoint value by more than 3°F, thereby causing comfort to be sacrificed (or potentially sacrificed). This comfort

threshold was not exceeded by the Iowa data. Rule 10 indicates that a significant difference exists between the mixed air temperature and outdoor air temperature when the AHU operates in Mode 3 (with 100% outdoor air, the temperatures should be the same).

Table D3. APAR results for the Iowa data.

Data file name	Rule satisfied	Time when satisfied	Actual state of operation ¹
iec_sum2	None		Coil capacity fault (Stage 1)
iec_sum3	20	Hours 12-13 and 15-18	Coil capacity fault (Stage 2)
iec_sum4	20	Hours 12-13	Coil capacity fault (Stage 3)
iec_sum5	None		Normal operation
iec_spr1	14	Hour 2	Coil capacity fault (Stage 1)
iec_spr2	10	Hour 9	Coil capacity fault (Stage 2)
iec_spr3	None		Coil capacity fault (Stage 3)
iec_spr4	10	Hour 9	Normal operation
iec_spr5	20	Hours 19-21	Normal operation
iec_spr6	20	Hours 18-22	Normal operation ²

- 1 Stage 1 corresponds 30% reduction in the maximum flow rate, Stage 2 to a 58% reduction, and Stage 3 to a 73% reduction.
- 2 The Iowa Energy Center staff changed the gains for the static pressure control loop in an effort to cause unstable control of the supply pressure. The changes did not cause the oscillations that were expected, so the data were treated as normal.

Based on this description of the rules, the satisfaction of Rules 14 and/or 20 appears to indicate the presence of the coil capacity fault. House et al. (2001) list “undersized cooling coil” as one possible explanation for satisfaction of Rules 14 and 20. Of course there are other possible explanations and additional sensor information or commissioning tests would be needed to further isolate the source of the problem.

Iec_sum2 [Label: Coil capacity fault (Stage 1)]

No rules were satisfied by this data set. APAR can only distinguish this type of fault when the load is sufficient to force the cooling coil valve completely open. As shown in Figure D2, despite the rather large degradation in the maximum possible flow rate of water through the coil, the cooling coil valve (CSIG) does not saturate at the full open position. For all the summer data sets analyzed, the AHU operates in Mode 4 (mechanical cooling with minimum outdoor air) for 14 hours and operates in the unoccupied mode otherwise. A typical data set consists of approximately 24 hours of data.

Iec_sum3 [Label: Coil capacity fault (Stage 2)]

Rule 20 is satisfied for 6 hours on this day, resulting in a warning indication from APAR. Figure D3 shows the control signal to the cooling coil valve saturated at full open for several hours. Not shown in Figure D3 is the fact that the supply air temperature is unable to reach the setpoint value during the time period when the control signal is saturated, although it does not exceed the comfort threshold described previously.

Iec_sum4 [Label: Coil capacity fault (Stage 3)]

The results are very similar to those for iec_sum3. Rule 20 is satisfied for 2 hours on this day, resulting in a warning indication from APAR.

Iec_sum5 [Label: Normal operation]

No rules were satisfied by this data set.

Iec_spr1 [Label: Coil capacity fault (Stage 1)]

Rule 14 is satisfied for 1 hour on this day, resulting in a warning indication from APAR. Figure D6 shows the control signal to the cooling coil valve saturated at full open for several hours at the beginning of the day.

Iec_spr2 [Label: Coil capacity fault (Stage 2)]

Rule 10 is satisfied for 1 hour on this day, indicating that the outdoor and mixed air temperatures are significantly different when they should be approximately the same (outdoor air dampers are 100% open). In this case the average outdoor air temperature is slightly more than 3°F lower than the average mixed air temperature. Given the known problems associated with measuring mixed air temperatures (Carling and Isakson, 1999, Carling and Zou, 2001), and given that dampers are known to leak, the threshold associated with this rule should probably be increased in order to avoid false or nuisance alarms. In this particular case, however, the alarm stems from the fact that moving averages of the temperatures and control signals are used to evaluate the rules. The hour when the rule is satisfied corresponds to the first hour of occupancy of the day. When a new data file is considered, all moving averages are reinitialized. It appears that the exponentially weighted moving averages used at the end of the first hour of occupancy are based on an insufficient amount of data to be representative of the variables they estimate. The transient behavior associated with the startup operation on the first day of a data file compounds this problem.

Iec_spr3 [Label: Coil capacity fault (Stage 3)]

No rules were satisfied by this data set.

Iec_spr4 [Label: Normal operation]

The output of APAR is the same as that for iec_spr2. Once again, the fault is indicated in the first full hour of occupancy and is related to transient behavior during this time period.

Iec_spr5 [Label: Normal operation]

Rule 20 is satisfied for 3 hours on this day, resulting in a warning indication from APAR and pointing to the possibility of a coil capacity fault. Figure D10 shows the control signal to the cooling coil valve saturated at full open for several hours at the end of the day. Figure D10 also shows that the chilled water inlet temperature is quite high at the end of the day, exceeding 48°F (9°C) whereas the design value is 44°F (6.7°C). As noted in Section 2.1.2, during the spring tests, the chiller serving AHU A was often shut down in the evening and restarted the following morning. This created the situation where the setpoint value of the supply air temperature could no longer be maintained. This could be considered an operational fault, but should not be considered a fault of the AHU since it was responding appropriately to the circumstances. It should be pointed out, however, that one of the possible explanations offered by APAR when Rule 20 is satisfied is that the inlet temperature to the cooling coil may be too high. Hence, it could be argued that this is not a false alarm, even though the staff considers the operation of the chiller to be normal.

This is a situation for which a hierarchical FDD scheme would be appropriate. Rather than including a rule for each AHU that checks the status of the chilled water, a single rule checking the chilled water supply temperature to all AHUs could be implemented in a higher level FDD scheme.

Iec_spr6 [Label: Normal operation]

The results are very similar to those for iec_spr5. Rule 20 is satisfied for 5 hours on this day, resulting in a warning indication from APAR. The explanation for the results obtained by APAR is the same as that for iec_spr5.

Table D4 summarizes the results obtained for the TEPCO data. Note that the TEPCO data used in this exercise is considered to represent normal operation. Note also that because it was summer, the AHU stayed in Mode 4 (mechanical cooling with minimum outdoor air) during all occupied hours of operation. The lack of a mixed air temperature measurement made it necessary to eliminate several rules from consideration. The results in Table D4 indicate that the same rule was satisfied at the same time each day. Rule 25 is satisfied if the supply air temperature is not equal to the supply air temperature setpoint and the AHU control signals are not all saturated simultaneously (i.e., the system is not out of control).

Table D4. APAR results for the TEPCO data.

Data file name	Rule satisfied	Time when satisfied	Actual state of operation
Jpn_n714	25	Hour 9	Normal Operation
Jpn_n715	25	Hour 9	Normal Operation
Jpn_n811	25	Hour 9	Normal Operation
Jpn_n812	25	Hour 9	Normal Operation
Jpn_n818	25	Hour 9	Normal Operation
Jpn_n819	25	Hour 9	Normal Operation

All faults indicated in Table D4 are false alarms and stem from the transient behavior during the first hour of occupancy each day and the fact that the moving averages are based on insufficient data at this point in time. As described previously, the moving averages are reinitialized when a new data file is processed. Interestingly, if two files are combined (i.e., Jpn_n714.txt and Jpn_n715.txt are merged), the first day of operation again produces this false alarm, but the second day does not. In fact, the moving averages of the supply air temperature and its setpoint value are nearly the same during the first hour of occupancy the second day. Hence, if APAR is used with longer data sets or in an online sense, the problems stemming from the use of exponentially weighted moving averages should be alleviated.

Summary

APAR was somewhat successful in detecting the coil capacity fault. The fault was detected on two summer days for which the fault was implemented at the middle and highest levels of severity. The first summer day with the fault (lowest level of severity) was deemed to be normal by APAR. APAR was less successful detecting the fault for the spring conditions. The three days during which the fault was implemented resulted in only one hour of operation with the fault was detected.

Some false alarms occurred for both the Iowa data and the Japan data. The cause of the false alarms was transient startup behavior coupled with moving averages of temperatures that were based on insufficient amounts of data. This problem with data filtering can be alleviated by disabling the evaluation of rules during the first hour of occupancy of each day.

D.2.2 Swedish comparison of AHU fault detection tools

P. Isakson and P. Carling

D.2.2.1 Introduction

Two fault detection tools for air handling units (AHUs) are compared in this section: a ruled based method, APAR, described by House et al. (2001), and a qualitative model-based fault detection method, QMBFD, described by Gruber (2000a, 2000b).

The data sets used in this comparison were produced at the Iowa Energy Center (IEC), Energy Resource Station (ERS), for ASHRAE 1020-RP *Demonstration of fault Detection and Diagnosis Methods in a Real Building* (Norford et al., 2000). Data sets for eleven days (August 4–9, 1998, May 20–22, 1999, May 24–26, 1999) were provided with the NIST Test Shell installation program (See Section F). In addition, other measured data sets from the summer, winter and spring tests, together with a classification by the IEC staff of the operational status of the AHU, were distributed on CD-ROM. Altogether, 55 data sets (days of tests) were considered. The data sets are summarized in Table D5. In Table D5, L1, L2 and L3 represent increasing levels of severity associated with degradation faults. Additional information pertaining to labeling of the data sets is contained in the footnote following Table D5.

Table D5: Types of operational status of the AHU used by the IEC staff to classify the sets of experimental data.

Fault	Operational status	Level [§]		
		L1	L2	L3
F1	Recirculation damper stuck closed			
F2	Leaking recirculation damper	x	x	x
F3	Leaking cooling coil valve	0.6 GPM	0.9 GPM	1.8 GPM
F4	Cooling coil capacity reduction	40%	50%	70%
F5	Pressure sensor drift and offset			
F6	Unstable supply fan pressure controller			
F7	Slipping fan belt	x	x	x

[§] The designation F0 is used to mean “Normal operation”, L4 to mean “No level given”, L5 to mean “Both level 1 and 2 applied during the day”, and L6 to mean “All three levels applied during the day”.

Because of the objectives of the ASHRAE project, the available information on the operational status of the plant is somewhat limited. After preliminary inspection of the data it was decided that the fault detection tools should be applied only between the hours 08:00 in the morning and 17:00 in the afternoon. The AHUs are typically operated until 22:00, however it was felt that a different mode of operation occurred after 17:00 that did not satisfy the minimum outdoor air requirement.

Table D6 lists the recorded quantities that were used with the two fault detection tools. Twelve additional measured quantities were imported for use when visually inspecting the data. The outdoor sensor *oa_temp* (or *od_temp*) was used for the outdoor air temperature, *Toa*. However, for practical reasons, the sensor in the duct upstream of the AHU (*oa_duct*) was used with the Winter Test Data and, by mistake, with the NIST Test Shell data. As the setpoint value for the supply air temperature (*sup_stp*) was not available in the Winter Test Data, it was assumed that $T_{sas} = 12.8^{\circ}\text{C}$.

Table D6. Recorded data used with the two fault detection tools.

		Sensor	APAR	QMBFD
<i>Tsa</i>	Supply air temperature	<i>da_temp</i>	x	x
<i>Tra</i>	Return air temperature	<i>ra_temp</i>	x	x
<i>Tma</i>	Mixed air temperature	<i>ma_temp</i>	x	
<i>Toa</i>	Outdoor air temperature	<i>oa_temp</i> <i>oa_duct</i>	x	x
<i>Uc</i>	Control signal to cooling coil valve	<i>clg_vlv</i>	x	x
<i>Uh</i>	Control signal to heating coil valve	<i>1 - htg_vlv</i>	x	x
<i>Uoa</i>	Control signal to mixing box dampers	<i>oa_dmpr</i>	x	x
<i>Tsas</i>	Setpoint value of the supply air temperature	<i>sup_stp</i> 12.8°C	x	
<i>Uoamin</i>	Minimum value of the control signal to the outdoor air damper	<i>min_oda</i>	x	

D.2.2.2 Fault detection tools

APAR

APAR is a rule-based method for AHUs. It comprises a specific set of rules for each mode of operation of the AHU. The rules, which perform consistency checks based on commonly measured temperatures and control signals, are based on the steady-state function of the AHU. Firstly, control signals and occupancy status are used to identify the particular mode of operation, i.e. heating, free cooling, mechanical cooling in combination with free cooling, or mechanical cooling. Secondly, the relevant set of

rules based on the mode of operation is applied to moving averages of the measured signals. To further suppress the influence of transient conditions, the rules are applied only to the last averaged value in each hour, during which the AHU operated in a single mode only.

The implementation of APAR is based on the description given in a draft working paper. However, the rules and other algorithms activated in this study comply with House et al. (2001). Table D7 lists the parameters that require consideration during commissioning of APAR. In addition it lists the parameter values used in this study.

Table D7. User selected parameters for APAR. The parameters need to be checked at commissioning time or, in the case of the last three, retrieved from design data.

Description	Name	Unit [§]	Value
Rule threshold, temperatures	ϵ_t	°C	1.7
Rule threshold, air flow rates	ϵ_f		0.30
Rule threshold, control signals	ϵ_c		0.05
Temperature rise across return fan	ΔT_{rf}	°C	1.1
Temperature rise across supply fan	ΔT_{sf}	°C	1.1
Minimum temperature difference for accessing ventilation rates	ΔT_{min}	°C	5.6
Percentage outdoor air necessary to satisfy ventilation requirements	$(Q_{oa}/Q_{sa})_{min}$	-	0.35
Maximum number of mode switches in one hour. (Not used in this study.)	MTmax	-	6
Minimum value of control signal for heating coil valve	Uhmin	-	0
Maximum value of control signal for heating coil valve	Uhmax	-	1
Minimum value of control signal for cooling coil valve	Ucmin	°C	0
Maximum value of control signal for cooling coil valve	Ucmax		1
Minimum value of control signal for mixing box damper	Uoamin	min_oda	
Maximum value of control signal for mixing box damper	Uoamax	-	1
Occupancy status	08:00 – 17:00		
Set point value of the supply air temperature, Tsas	sup_spt / 12.8°C		
Changeover temperature from mechanical cooling with maximum to minimum outdoor air	Tco [#]		18.3
Exponential smoothing constant	λ		0.03

[§] The values are converted from IP to SI and the results rounded.

[#] The value Tco = 18.3°C is chosen, since that is the value of econ_stp given in all of the data files.

QMBFD

QMBFD focuses on the function of an AHU, as manifested by the temperature difference between the return and supply air, $T_{RA}-T_{SA}$, and between the outdoor and supply air, $T_{OA}-T_{SA}$, respectively. This aspect of the function is visualized by a point in a zone-diagram, which is comprised of fifteen separate zones as depicted in Figure D12. The state of the controller is defined by qualitative values of the mixing box damper control signal, the heating coil valve control signal, and the cooling coil valve control signal. For each particular zone there are controller states that are valid and there are values that are invalid. At each timestep QMBFD first determines the zone of the current temperature point, and then it determines whether the current controller state is valid for that particular zone. This scheme works when the AHU is in steady state. QMBFD uses a simple steady-state detector and disregards all indications of faults when the AHU is deemed not to be in steady state. Table D8 lists the parameters that require consideration during commissioning of QMBFD. In addition it lists the parameter values used in this study.

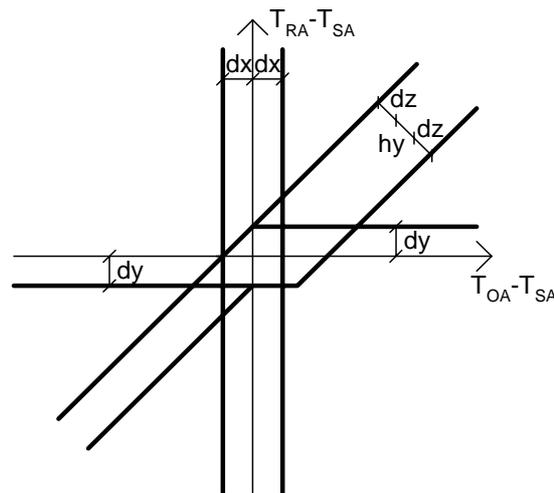


Figure D12. The zone diagram with its fifteen zones is a key concept in the QMBFD method. The zones left of the y-axis correspond to cooling modes and right of the y-axis to heating modes. Ideally, the temperatures T_{OA} , T_{RA} and T_{SA} are measured at the inlets of the mixing box and the outlet of the cooling coil, respectively. To allow for inaccuracies in the measurements, the model and the steady state detector there are, between the major zones, additional zones that permit the controller to be in either of the states associated with the adjacent zones.

Table D8. “User” selected parameters for QMBFD, none of which should be modified by the end user. The values of the first eight parameters need to be checked at commissioning, and the values of the last three need to be retrieved from design data.

Description	Name	Unit	Value
Tolerance in the zone diagram	dx	°C	0.8
Tolerance in the zone diagram	dy	°C	0.6
Tolerance in the zone diagram	dz	°C	0.7
Tolerance in the zone diagram	hy	°C	0.5
Threshold for temperatures in the steady-state detector	dTss	°C	0.5
Threshold for control signals in the steady-state detector	dCss	%	4
Time constant of the steady-state detector	I	sec	900
Tolerance for control signal used to convert to qualitative values	eC	%	1
Maximum fraction of recirculated air (for comfort reasons)	Xramax	-	0.62
Temperature rise across return fan	dTrf	°C	1.11
Temperature rise across supply fan	dTsf	°C	1.11

QMBFD cannot be fully tailored to the sequencing control strategy applied at the ERS. Inherent to this method is that a changeover occurs from cooling with maximum outdoor air to cooling with maximum return air, when the return air temperature is equal to the outdoor air temperature, $T_{ra} = T_{oa}$, (or possibly $(T_{ra} - T_{sa}) / (T_{oa} - T_{sa}) = \text{constant}$). At the ERS, the change over takes place when the outdoor temperature $T_{oa} = 18.3^{\circ}\text{C}$. The condition $T_{ra} = T_{oa}$ has therefore been used.

The choice of outdoor sensor to use with QMBFD was not clear-cut. Two sensors are available, `oa_duct` in the duct upstream the AHU, and `od_temp` placed on the north wall of the building. The BEMS uses the latter and thus QMBFD should also use it, since extra sensors should always be avoided for economic reasons.

D.2.2.3 Implementation of the fault detection tools

The two fault detection tools are implemented as Matlab functions as follows:

$$R = FddMethod(X, P, C)$$

where R , X , P , and C are Matlab structures. X holds experimental data, P parameter values, and C comments. Intermediate results are stored in R . Furthermore, enough information is stored in R to trace the result to the version of the function, experimental data, and parameter values that were used. The functions are intended for off-line use and execution speed is a concern.

The Matlab functions have been tested for correctness in two ways. Complete agreement was demonstrated between APAR results produced with the above Matlab function and those obtained by NIST (also reported in this chapter). However, some adjustments were required to ensure that identical input data had been used. The QMBFD implementation was tested with artificial data that represented all of the different operating zones. Secondly, the same implementations have been extensively used in another study (Carling, 2002) in which the results were scrutinized thoroughly.

D.2.2.4 Results of the comparison

Figure D13 summarizes the result of the comparison of QMBFD and APAR. Each “line” of the diagram represents one set of data. From left to right each line includes a timestamp, the letter A or B to denote AHU A or AHU B, operational status (see Table D5), a stacked bar for QMBFD, a stacked bar for APAR, and finally the operational status repeated. The total length of the stacked bar shows the fraction of time the method was active (i.e. the steady-state requirements were fulfilled). The filled part of the bar shows the fraction of time the method indicated a fault. The operation status, “F0, L0” indicates Normal Operation.

A graphical user interface tool was used to browse each data set together with the fault indications. In most cases it is easy to see why faults are indicated (or why not), e.g. because the value of one temperature is larger than that of another. However, in many cases it is difficult to see the causality between the faults that had been introduced and the response of the fault detection tool.

Numerous batch-jobs were run with, what was originally thought to be, minor variations in the values of the “user selected parameters”. More often than not, the effect on the results was much larger than had been anticipated. For example, when comparing these APAR results with those obtained at NIST, it was learned that it matters how a “whole hour” is defined. Dividing the data file in 60-minute intervals starting at line one, and using even hours based on the timestamps (i.e. 08:00 – 09:00) etc., may yield different results. QMBFD appears to produce numerous false alarms. This was a surprise since QMBFD produced very few alarms (false or correct) using data from the Swedish case study. The two main reasons for the “false” alarms reported here are QMBFD’s failure to account for the change over temperature, $T_{co} = 18.3^{\circ}\text{C}$, and the fairly large differences that occur between the outdoor air temperature sensor and that close to the inlet duct of the AHU.

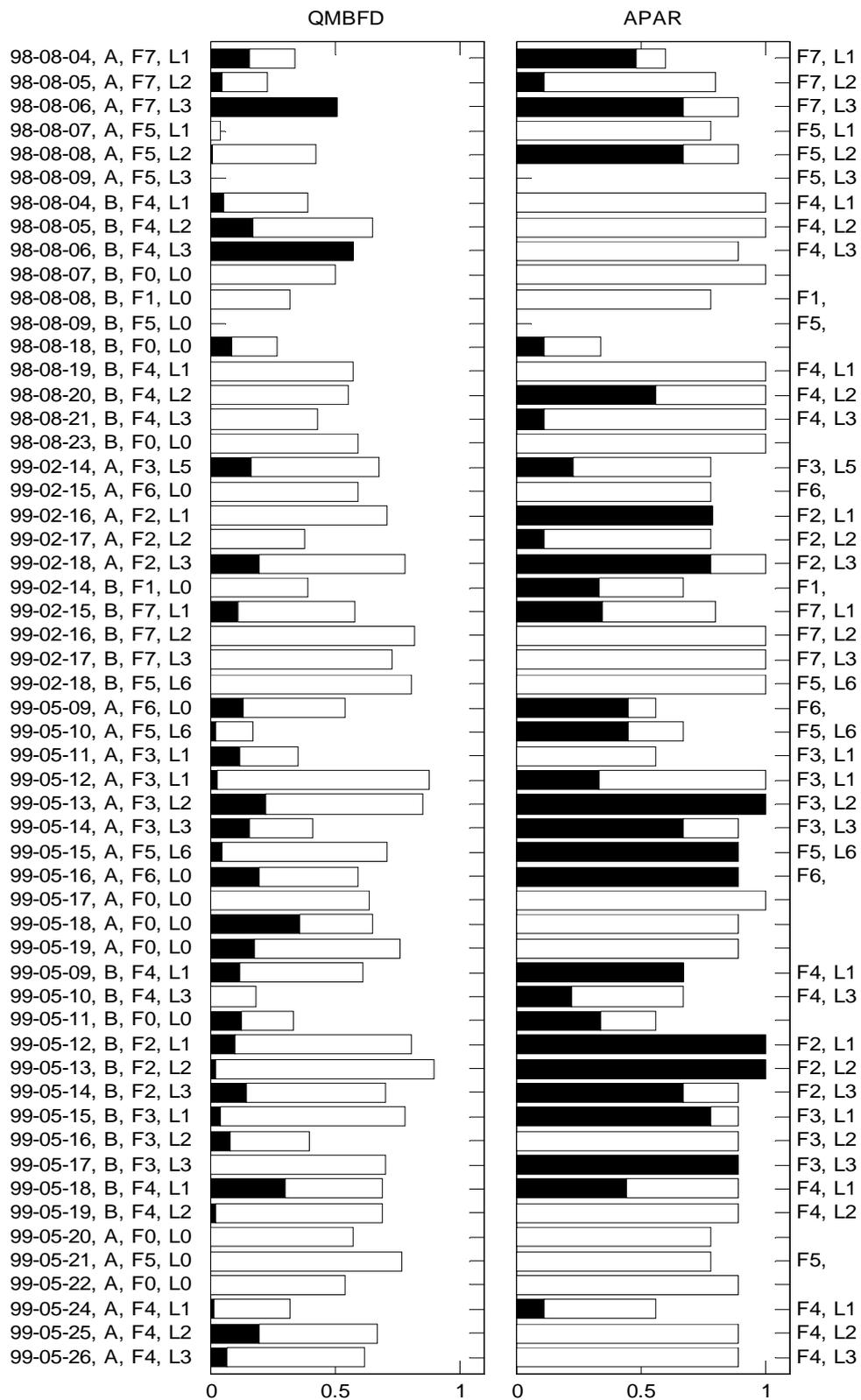


Figure D13. Result of confronting QMBFD and APAR with 55 data sets from AHU A and AHU B of ERS at Iowa Energy Center.

D.2.3 ASHRAE 1020-RP

Perhaps the best way to evaluate FDD tools is to perform side-by-side comparisons. Norford et al. (2000) reported on a study aimed at comparing two AHU FDD methods. The comparison included data for seven different faults collected during multiple seasons of the year. Both abrupt and degradation faults were considered. The data were collected at the Iowa Energy Center Energy Resource Station, a real building that serves as a test facility for energy-efficient technologies. The test procedure consisted of the following three steps:

- 1) preliminary commissioning tests,
- 2) one-week of control tests in which faults were implemented and the researchers were told what faults were implemented (including severity), at what time they were implemented, and for how long they were implemented, and
- 3) one-week blind tests in which the researchers knew only that the faults considered during the control tests would be implemented at some time during that week.

Step 1 was performed once, while steps 2 and 3 were performed once during summer conditions, again during winter conditions, and a final time during spring conditions. Both FDD methods proved capable of consistently detecting the faults, with a small number of exceptions. Fault diagnosis procedures were improved over the course of the tests and at the conclusion were also generally effective. However, diagnosis was made considerably easier than in what are likely to be typical conditions, due to the limited number of known faults, the known magnitude of the faults, and the excellent maintenance of building equipment and sensors.

The test procedure was then altered in order to evaluate the performance of the methods without the benefit of the control test data. The new test procedure was carried out on a different AHU and the researchers were not told what faults were implemented. The performance of the methods suffered with the removal of step 2. In particular, the ability to diagnose the implemented faults was poor.

This research project pointed out just how difficult it is to detect and diagnose faults in real buildings. Furthermore it pointed out how difficult it is to evaluate the tools. A follow-up study is being considered that would entail blind testing of FDD tools by an independent party. This would take the expert knowledge of the tool developer out of the loop and help establish how well the tool can be used by someone other than its developer.

D.3 DISCUSSION OF RESULTS

Three separate efforts to compare and/or evaluate FDD tools (in some cases the tools only perform fault detection) are described in the previous section. Each effort used data described by Norford et al. (2000). Two of the efforts (Sections 2.1 and 2.3) involved researchers applying their own fault detection or FDD tool to the data. The third effort (Section 2.2) was perhaps the most unbiased evaluation. In that case researchers other than the developers of the fault detection tools performed the evaluation. The only shortcoming of this effort was that the implementation of the tools in software was performed by the independent party. Considerable testing was performed by the independent party to ensure that their implementations produced results consistent with the implementations of the tool developers.

These evaluation efforts helped the researchers involved gain a better understanding of how FDD tools should be compared and/or evaluated, as well as the difficulty with performing such a task. Importantly, the efforts benefited from the existence of a well-documented data set that included embedded (and labeled) fault conditions. Without such data sets, meaningful evaluations cannot be performed. However, despite the considerable effort devoted to documenting the data sets, it was sometimes difficult to fully understand operating strategies and to correlate data with data labels. And this was under extremely favorable conditions that included well-instrumented and tightly monitored systems. Again, evaluations under less stringent conditions could easily become meaningless.

The evaluations forced tool developers to apply their methods to data sets that were unfamiliar. This served as an important reminder of inherent implementation issues that must be addressed, such as the time required to find information necessary to configure FDD tools. The evaluations also forced tool developers to specify values of thresholds that would be used when processing the data. In the case of the fuzzy model-based approach, there are no thresholds to set so this is not an issue. For the other tools, however, it is an important issue because the thresholds must be specified by someone, perhaps the end user. If they can be changed, the performance of the tool can be changed. In order to perform meaningful evaluations, thresholds must be determined on a training data set and then remain fixed during the processing of a separate testing data set.

Work performed in Annex 34 has proven that evaluating the performance of FDD tools is a difficult task, particularly in real buildings. Performance degradation faults can take months or years to manifest themselves. Hence, it is not practical to perform short-term FDD tool evaluations (on the order of weeks or months) in real buildings of degradation faults unless the faults are somehow simulated. The simulated characteristics may not be representative of those of naturally occurring faults (see Section B2). Meaningful

performance evaluations in real buildings can only be obtained if tools for detecting degradation faults are deployed in a significant number of systems over a period of several years and faults are allowed to occur naturally.

Evaluating the performance of tools for detecting abrupt failures in real buildings is significantly easier. First, by their nature, abrupt failures typically produce changes in operating characteristics within minutes or hours of their occurrences. Second, abrupt failures are typically straightforward to simulate. Hence, if the building owner or operator allow faults to be simulated (or artificially implemented), testing can be performed efficiently in real buildings. If this is not an option, the evaluation process is more difficult and will require careful coordination with the building maintenance staff to verify that faults detected by an FDD tool actually occurred, and vice versa.

D.4 CONCLUSIONS

The evaluation of FDD tools can be viewed from the standpoint of cost versus performance. Currently it is difficult to determine certain costs, such as those for model development and method training, because the technology is relatively new. The feasibility of tools having such requirements will be determined over time as the added benefit is weighed against improved performance. Performance can be equally or more challenging to measure than cost. Although quantitative performance criteria can be and have been defined, it is sometimes difficult to apply them, 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. Finally, evaluations of tool(s) by an independent party who was not involved in their development can provide valuable information regarding of the strengths and weaknesses of the tool(s).

D.5 REFERENCES

Breuker, M.S. and J.E. Braun. 1998a. Common Faults and Their Impacts for Rooftop Air Conditioners, *IJHVAC&R Research* Vol. 4(3), pp. 303–317.

Breuker, M.S. and J.E. Braun. 1998b. Evaluating the Performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment, *IJHVAC&R Research* Vol. 4(4), pp. 401–425.

Carling, P. and Isakson, P. 1999. Temperature Measurement Accuracy in an Air-handling Unit Mixing Box. The 3rd International Symposium on HVAC, ISHVAC '99. Shenzhen, China.

Carling, P. 2002. Comparison of Three Fault Detection Methods Based on Field Data of an Air-handling Unit. Accepted for Trans. ASHRAE.

Carling, P. and Zou, Y. 2001. A Comparison of CFD-simulations and Measurements of the Temperature Stratification in a Mixing Box of an Air-handling Unit. Accepted for publication in the International Journal of Energy Research.

Comstock, M. C., Chen, B. and Braun, J.E. 1999. *Literature Review for Applications of Fault Detection and Diagnostic Methods to Vapor Compression Cooling Equipment*. Ray W. Herrick Laboratories. Purdue University. HL 99-19: Report #4036-2.

Gruber, P. 2000a. Erfahrungen mit einem qualitativen modellbasierten Fehlerdetektor für zentrale Luftaufbereitungsanlagen, 11. Schweizerisches Status-Seminar Energie- und Umweltforschung im Bauwesen, Pp. 331–337. (reference available at <http://www.empa.ch> by searching for "Gruber")

Gruber, P. 2000b. Fehlerdetektor für die Lüftung, Gebäudetechnik 5/00/Okttober, Pp. 30–32.

House, J. M., Vaezi-Nejad, H., and Whitcomb, J. M., 2001, An Expert Rule Set for Fault Detection in Air-handling Units, Accepted for Trans. ASHRAE Vol. 107(1).

IEA Annex 25, 1996, *Building Optimization and Fault Diagnosis Source Book*, Eds. J. Hyvärinen and S. Kärki, Technical Research Centre of Finland.

Ngo, D. and Dexter, A. L. 1999. A Robust Model-based Approach to Diagnosing Faults in Air-handling Units, Trans. ASHRAE Vol. 105(1), pp. 1078–1086.

Norford, L. K., Wright, J. A., Buswell, R. A., and Luo, D. 2000. *Demonstration of Fault Detection and Diagnosis Methods in a Real Building*. Final Report of ASHRAE 1020-RP. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.: Atlanta.

SECTION E: POTENTIAL FOR COMMERCIAL EXPLOITATION

E.1 GENERAL COMMENTS

Kristin Heinemeier

E.1.1 Introduction

The intent of Annex 34 work is to demonstrate Fault Detection and Diagnostics (FDD) methods in real buildings, in order to learn more about real world challenges, barriers and benefits of FDD technology. FDD will only have an impact on global energy consumption if it is implemented in a large number of buildings, and this will not happen unless commercial entities embrace the technology, and make it available and attractive to a large number of customers. Thus, the potential for commercial exploitation of FDD is a key success criterion of the Annex.

Many products and services are commercially successful because customers have used the product or service for quite some time, and they perceive a strong benefit to having that product or service. FDD, however, is an example of a technology that is responding to a need that is perceived by researchers, policymakers, and industry insiders, more so than a strong demand from customers. The introduction of a new technology such as this can be thought of as a “chicken and egg” proposition: customers will not demand the technology until it has demonstrated benefits, and benefits cannot be demonstrated in a persuasive way until a large number of customers have purchased the technology. Field demonstrations such as those undertaken by Annex 34 therefore play a vital role in kickstarting the commercialization cycle. However, it will take more than a handful of field studies to ensure commercialization. Many other issues are involved, and the sooner researchers take up these issues, the easier it will be for commercializers to move the technology beyond the research stage.

E.1.2. Commercialisation

In order to better understand the road to commercialization for FDD and how Annex activities will lead up to commercialization, it is helpful to understand the commercialization process that a typical technology would ideally go through.

Identification of market need

Ideally, any technology and product development process would begin by identification of market need. If there is no market need, there is no potential for commercialization, regardless of the technical quality of the tool. Identification of needs can be done by commercial entities, or by researchers, and should include an understanding of the issues that face the targeted customer set, identification of the key problems that plague these customers, analysis of the implications of those problems on operations and costs,

and needs that emerge from those problems. Market requirements can be defined broadly, or narrowly. For FDD, this was done during Annex 25 activities – through assessment of the most important faults in commercial buildings, although more detailed analysis should be conducted by commercializers. This work was documented in the Annex 25 documentation.

Identification of technical approach

Identification of a proposed technical approach, and development of the technology should follow market need assessment, although in practice, it is often done in parallel. In this stage, many different technologies may be investigated, and only those that are likely to successfully address market needs should be further developed. The development of several different FDD methods was also documented in Annex 25 literature. Many of these methods showed a great deal of technical promise, although it was recognized that a demonstration phase was needed to further develop the technology and move it towards commercialization.

Demonstration of prototype technology

An important stage in product development, and the stage that was the focus of Annex 34, is demonstration of prototypes. Before any products can be developed, and even before any meaningful market feedback can be obtained, it is helpful to demonstrate the technology in real-world situations. Many things are discovered in field demonstrations that could not have been anticipated during the technical development or market assessment stages. Examples of findings that were made during Annex 34 activities are problems with accuracy of mixed air sensors and customer need for adjustable sensitivity thresholds for fault detection.

Identification of product requirements

Product requirement specification is a more detailed assessment of how a tool will be used to address the needs identified in the market assessment. Some of the issues that should be addressed in a product requirements definition stage are shown in Box 1. This is typically done by an entity that intends to productize the FDD tool, although it can be done in close collaboration with technology developers. In some cases, this level of specification was done in Annex 34 activities.

Market research for market and user acceptability

It is desirable to conduct yet another test before true product development is initiated. Prototypes that illustrate exactly how the FDD tool would be used to address customer problems can be taken to potential customers, to get their feedback as to functionality and usability. Box 2 describes the findings from a set of focus groups that were conducted as a part of Annex 34.

Product development

With a clear product requirements specification, validated by real users, based upon a technology that was well documented during technology development, product development should be a fairly smooth process. Ideally, product development will follow clearly defined processes that ensure quality outcomes. This stage can include software development (design, additional prototyping, implementation, and component and integration testing), as well as additional pilots, and adequate laboratory testing. Product development can be done by technology developers, although it is a very

different process than technology development, and is typically done by a separate team. Ideally, many of the technologies developed and demonstrated in Annex 34 will be picked up by product development teams, and developed into products that will be successful in the marketplace.

Product rollout

Product rollout can be informal, or can follow a formal productization process. Some of the steps in this stage include field alpha- and beta-tests, and development of user documentation and training materials, marketing and sales collateral information, as well as any tools that must accompany implementation of the tool in the field (such as auditing and installation tools, engineering notes, and process documentation).

Support and maintenance

In all the rush to get a product developed and out the door, it is common that energy and budgets are depleted by this point. One should plan, however, for significant time and development dollars to be reserved for support of customers and maintenance of the software. This can include answering questions about installation or operation of the tool, as well as fixing bugs in the software. Especially for new products, this is crucial to the success of the product.

Evaluation and improvement

Finally, one should not overlook the stage of evaluating the success of the tool in the market, and tracking its performance for individual customers. This type of feedback is crucial in preparing for the next revision of the software, which should be even more appropriate for users.

E.1.3 Commercialisation

There are a number of important issues that will affect the potential for commercialization of FDD. However, there are five principal issues that come up again and again, and should be addressed by all developers.

How much it will save

This is the most often asked question concerning commercialization potential. Almost all building performance technologies will have to be justified on a cost-benefit basis, and therefore the benefits must be established or at least estimated or implied. Savings come primarily in the form of reduced operating costs: energy costs, in-house or outsourced maintenance costs (labor and materials), wear and tear on equipment. Savings can also be claimed for reduced down-time of equipment (keeping the facility up and running and producing), or productivity of building occupants who are more comfortable due to correctly operating equipment. Any technology developer will have to be explicit about what equipment problems the system is designed to identify. Only then can one assess what value this will have to a customer: Is this an important problem to potential customers? How much is it costing customers now to continue existing operations without identifying and solving this problem?

Customers will want to be satisfied that the system will save them money in *their* facilities. This assurance will come from demonstrations of the technology in other real-world buildings, documented case-studies that are published in reliable sources, pilot demonstrations in some of the customer's facilities, detailed engineering audits and engineering calculations of savings for that customer, or guarantees of savings.

Identification of the Customer

This is one of the key issues any entity commercializing FDD will want to clarify. A tool designed to help troubleshoot problems with a chiller in a large office building will be very different from a tool used to identify energy wasting buildings from among a portfolio of buildings. Two separate issues must be addressed: Who will *use* the tool? and Who will *buy* the tool? Obviously, the user must be identified to make sure that the usability of the tool is appropriate, and information is presented in the appropriate way. However, the purchaser is of great interest to commercializers...often the tool must appeal to a different category of individual than the user, and that must be taken into account in assessing costs and benefits. Some of the potential users are: people who fix problems in buildings (often building engineers or technicians), people who assign work to those who actually fix problems (often a chief building engineer or facility manager), people who are responsible for making sure facilities are working properly (facility manager or energy manager), or an employee of a centralized service center (either corporate operations or an outsourced service firm). Any one of these individuals might be an appropriate user or purchaser of FDD, but not all tools will be appropriate for all users.

The source of input data

Another key issue in commercialization that is often raised is the source of input data. It is generally recognized that sensors of sufficient accuracy for most FDD methods and data collection equipment are available – either for commercial or industrial applications. However, financial considerations typically require that less expensive sensors are used, or that sensors that are already installed for an in-place building management system (BMS) be used for this purpose. In this case, consideration will have to be made of how appropriate existing sensors are for the FDD method (type, accuracy, installation, location, calibration...). Also, can the existing BMS itself be used as a data collection device? This will minimize costs, although potential customers will be concerned that the FDD method might interfere with existing operations of the BMS.

System cost

Related to the source of input data is the overall cost of the system – real or perceived. This is clearly important in any cost-benefit analysis. Costs should include costs of all equipment that must be added, as well as all software that is used. Costs that are sometimes overlooked include initial assessment and auditing costs, training, installation, configuration, ongoing maintenance, and support. Ongoing operation is an issue that customers will be quite concerned about: How much of their personnel's time will be required to use the tool, or will it be a net time saver?

Another issue related to costs is how the costs are assigned and distributed. Costs can be incurred on an upfront basis, or some sort of a monthly basis. The perception of risk can be reduced if costs are shared by the customer and the FDD provider, as well as savings.

System reliability

Finally, a key issue is the reliability of the system. Potential customers will want to know how often the system will generate false alarms. In some cases, too many false alarms will render a very good FDD method completely 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.

E.1.4. Recommendations for improving potential for commercial exploitation

Annex 34 has taken FDD from the realm of basic research to a point where it is ready to be commercialized. Technologies that were developed successfully in Annex 25 have been demonstrated successfully in the field. It is now up to technology developers to begin working with commercial interests to ensure that effective products can be developed that will compete successfully in the market, and have a real impact on the energy performance of buildings globally.

Many industrial partners have participated in the Annex, through sponsorship of technology developers, as well as through direct participation in market analysis activities. Researchers have worked effectively with these industrial partners to develop appropriate technologies, and industrial partners have shown a great deal of interest in moving forward with commercialization of FDD tools.

Some of the next steps that will ensure commercialization of these technologies include:

- Researchers continue working with their industrial partners to conduct effective demonstrations of FDD methods in the field, and address any marketization issues the partners have.
- Industrial partners begin marketization activities, including clearly defining market and product requirements, conducting market research to identify the best ways to bring the technologies to customers, and beginning product development.
- Government policy and R&D organizations must maintain a role in productization, since the societal incentives for improved building performance through FDD are in some cases stronger than individual commercializer or customer incentives for technology adoption.
- All three entities must have continued dialog and open discussion about technology development.

E.1.5 References

Heinemeier, K. H., Richardson, R. M., and Kulathumani, K. "User and Market Factors that Influence Diagnostic Tool Development" Workshop on Diagnostics for Commercial Buildings – from Research to Practice, Pacific Energy Center, San Francisco, June 16–17, 1999. <http://poet.lbl.gov/diagworkshop/>

Box 1 – Marketability Issues

As an Annex 34 activity, a more detailed analysis of marketability issues was documented in Heinemeier et al. 1999. These issues are summarized here.

- **Intent of system**
 - *Fault detection vs. diagnosis*: Does the tool detect problems or go on to identify underlying causes?
 - *Commissioning vs. ongoing operations*: Is the tool intended to be used in a commissioning capacity, to search out problems early in a system's performance, or is it to be used to detect emerging problems?
- **Value of system**
 - *Single or multiple faults*: Is it a single-purpose tool aimed at a particular fault, or a general fault detection mechanism?
 - *System encountering problem*: What system or equipment in a building is affected by the type of problems detected? Is this system common in the facilities of the intended users?
 - *Probability of problem*: How often does the detected problem occur (in what percentage of buildings, how often throughout the year in a given building?)?
 - *Consequences of problem*: Are the problems significant for customers, or merely annoyances?
 - *Easier detection alternatives*: Can the problems be detected in a simpler or less expensive manner?
- **Action to be Taken**
 - *Manual diagnosis*: Would a user be required to take additional action to detect the root cause of the problem, or to verify the diagnosis?
 - *Triage for technician dispatch*: Can the tool help a user to identify what service provider to call or what tools to bring to the site?
 - *Fixing identified problems*: What can the user do when the fault is identified? If there is no feasible remedy, there is little value to the user in detecting the fault.
 - *Design feedback*: Does the tool provide feedback to designers, so that this type of problem can be prevented in the future?
- **Required System Reliability**
 - *Probability of false alarm*: What is the likelihood that the tool will indicate a fault when there really is no fault? (This had better be low).
 - *Probability of detecting failure*: What is the likelihood that the tool will indicate a fault when it exists? (This had better be high – equally important).
- **Notification**
 - *Alarms*: What mechanism is used to alert the user to the presence of the fault?
 - *Wording of alarm message*: What is the appropriate level of detail to give to a user in annunciating a fault?

- *Identify cost impact of problem:* Can the tool assist the user in prioritizing responses by identifying the cost impact of ignoring the problem?
- *Acknowledging alarms:* What must a user do to acknowledge an alarm? This should not be overly burdensome, yet it must reflect the severity of the problem.
- *Adjustable thresholds:* Can the sensitivity of the fault detection be altered by the user, so that a manageable number of faults are reported?
- *Commissioning or ongoing:* Is the mechanism for reporting the alarm appropriate to the way the tool is used: either as an interruption to other activities or a tool used actively to detect problems?
- *Corollary information:* Is information beyond the existence of the fault available, to allow the user to learn more about the situation?

- **User**
- *Building operator:* Is the building operator the intended user? This will require a tool with short learning curve and very carefully crafted user interface.
- *On-site FDD expert:* Is an FDD expert the intended user? This may allow for a steeper learning curve.
- *Remote FDD expert:* Is a remote FDD expert the intended user? This may allow for a steeper learning curve, but may require access to information about the system being diagnosed.

- **System Cost**
- *Hardware:* What existing sensors can be used, and what additional sensors will have to be added? Will computers or wiring have to be added?
- *Software:* Is there a significant cost for the FDD software itself, or any related software?
- *Services:* Are services required to use or install the tool?
- *In-house effort:* How much in-house effort will be required for using or installing? This is often overlooked.
- *Installation and configuration:* Is installation and configuration a time-consuming activity? Who can carry it out?
- *Data sources:* What other data sources are needed (e.g. weather, utility information)?
- *Training and documentation:* How much training and documentation is needed to ensure effective use?

- **Market**
- *Market sectors:* Is this tool applicable to all commercial buildings, or only to a subset of building types.
- *Building size:* Can this be used effectively in small, medium, and large buildings?
- *Existing vs. made market:* Does this tool replace something that is already well accepted, or will the need for it have to be communicated to potential customers?
- *How will FDD be provided:* Is the tool provided as an algorithm embedded in a piece of equipment or Building Automation System? Is it a standalone application (if so, how does it get its data)? Is it provided as a service?

Box 2 – Customer and User Focus Groups on Marketability of FDD

An example of market research in support of commercialization of FDD methods can be found in Heinemeier et al, 1999. This type of study is an important step in productization, because it will help to ensure market acceptance. This study is summarized here.

Conducted by: Honeywell, Inc., on September 15 and 16, 1998, in Minneapolis, MN, USA.

Objectives: Conduct customer focus groups to identify customer interest in FDD in general, and the Whole Building Diagnostician product, in particular. It was recognized that findings would be somewhat anecdotal, and difficult to generalize, but focus groups are an effective way of identifying key customer concerns.

Participants: A large pool of potential participants was identified from area business directories, and invited by telephone to participate. An effort was made to get a mix of individuals working with large and small buildings, single and multiple building facilities, different businesses, public and private sector, and those with and without BMSs and service contracts. Three groups were selected: eight service technicians, seven potential users (typically building engineers), and seven potential purchasers (typically facilities managers).

Process: A neutral facilitator presented the concept of FDD, and asked for feedback on the concept. The WBD product was then presented by one of the developers, who then left the room. Participants were then asked for feedback on this product in general. Specific information was solicited on how FDD-type tasks are typically done today, what value the participant found in FDD and WBD, how likely they would be to purchase it, how much they would pay, and how they would expect it to be provided.

Major Findings:

- Potential customers are *very* skeptical about the ability of a tool to identify and reduce energy waste and outdoor air problems in their buildings, in a way that will save them money and effort.
- FDD tools must be demonstrated in buildings that potential customers can relate to, in order to overcome this skepticism.
- It is important to clearly communicate to customers that their existing BMSs *are not* already providing the functionality that is found in these tools. Alternatively, these functions could be added to their existing BMSs.
- Potential customers will want to know what the cost of the system and the expected savings *in their buildings*, in the form of a payback time. Alternatively, they will want to reduce their risk in implementing the technology by acquiring it on a shared-savings basis.
- One of the first questions potential customers will have is *Where are the data coming from?*
- Focus groups should be done earlier in the product development process, to help identify the most necessary areas for diagnostics, the required functionality, and the best user. Several rounds of focus groups may be necessary, to ensure that valuable information is obtained from the target population.

E.2 FEEDBACK FROM INDUSTRIAL PARTNERS IN NATIONAL PROJECTS INCLUDING ISSUES AFFECTING COMMERCIALISATION

Peter Gruber

E.2.1. Feedback from industrial partners

There are ca 50 partners involved in this project. They are listed in section E4. The partners are active in different sectors. The number of partners in each of the following sectors are:

- Building automation: 17
- HVAC equipment: 5
- Energy supplier: 5
- Consulting: 4
- Construction: 4
- Building maintenance: 3
- Building owner: 2

The results presented here are collected from various sources. First they are the output of the Breakout sessions on Commercial Exploitation at different meetings. Secondly different contributions have been taken into account which the authors have been received during the Annex working period. These contributions are:

- J. Pakanen as co-organiser of the Annex 34 project, carried out a inquiry among the industrial partners of Annex 34, where he asked the following questions to all the partners:
 - What are the benefits from the collaboration with research institutes?
 - What are the essential properties of a good FDD method?
 - What issues should be discussed in the final report?
- J. Pakanen presented a working paper in Boras, Sweden., covering also aspects of a good FDD method
- H. Izumiyama from Kajime Corporation and H. Onojima from Obayashi Corporation from Japan expressed their view in a document sent directly to the authors.

In the following the contributions are integrated in the answers to the three questions posed by J. Pakanen.

1) What are the benefits from the collaboration with research institutes?

The main points mentioned to this question were:

- Contacts and personal relations to FDD specialists. The annex creates a lively environment, in which ideas can be exchanged between industries and research

institutes. The contacts are insofar also important because the industry can formulate their need with respect to a successful implementation of a FDD method.

- Access to most recent information about FDD and adoption of FDD knowledge. The annex is a forum where the active partners report about the latest progress in the development of their methods. Thus a state of the art of the applied FDD methods can be obtained.
- Shorter development time of FDD systems and an improvement of their quality. As the results are available to all participants, the development and the implementation of a method to a specific application can be shortened. Results in this respect are: simulation software, simulation models for correct and faulty behaviour, documented data sets, comparisons between methods, experience from field tests, useful FDD methods
- Publicity and marketing aspects. Collaboration with research institutes can be used strategically as a commitment of the industry to be open to the new developments.

2) *What are the essential properties of a good FDD method?*

To this questions the following comments were made:

- Simplicity. The method must be simple and/or easy in various way:
 - 1) easy to understand and to explain. The user must be able to follow the main idea that lies behind the method. Otherwise he will not easily accept the method (see Section B1, B3).
 - 2) easy to commission. The configuration of the method to a specific plant or system must be simple and straightforward. The parametrisation of the method should require only a short training period and few training data for identification. The setting up is best done by a trained specialist (see Section B3)
 - 3) easy to use. The user must feel comfortable with the operation of the method. The user interface must therefore be such that it allows the user to interfere actively or passively. Support facilities must exist. The FFD tools must be tailored to each application and to the specific user of the tool: contractors, commissioning engineers, operators (see Section B1).
 - 4) easy to integrate. The FFD method is easy to hook up, to embed and to integrate in a building automation system. Standard software and communication possibilities are mandatory (see Section B1).
 - 5) easy to change. Detection of new fault conditions are integrable in a modular way. The tool is also as independent on system as possible (see Section B1).
- No or very few false alarms. The false alarm rate decides to a high degree, whether a method will be accepted by the operator. It might be advisable to let the user decide about the threshold level (see Section B1, B3 and B6).
- No disturbance of normal operation. The method must be such that normal operation is not interrupted or disturbed.
- Detection and Diagnosis can be separate. Qualitative monitoring capabilities are expected.
- Robustness. In order to facilitate the operation of a method, the generic and robust features of the method are crucial. It allows to make the commissioning and the adaptation to changing operating conditions easy (see Section B3).
- Cost effective. This means beside the simplicity requirements as mentioned above also few additional hardware and no additional human assistance during operation (see Section B1).

- Impact on savings of energy and comfort. The savings apply to a specific fault situation. The impact must be shown with real plants and systems. The method must be proven not only at one demonstration site but at least at several different sites (Section B1).
- A technology, that if taken away from the user, would mean a real loss to the user. The method must be such that the user can rely on it and that he will even become dependent on it (see Section B1).

3) *What issues should be discussed in the final report?*

The industrial partners expect to find the following topics covered in the final report:

- Advantages of FDD Tools. A strong pleading including the benefits will be useful for the industry when it comes to promoting or defending certain methods in a company. It will help convince the management (see Section A1).
- Practical experience from the project, feedback from practitioners. For the industrial partners it is important to know how the method has been accepted and judged by practitioners (see Section C).
- Comparison of FDD systems. What interests most are the limits, the strengths and weaknesses of each method. When can a method be applied? Are there any test results? How were the methods evaluated (see Section D)?
- Application information. What are the chances of success? Which applications should be tried first (see Section E5)?
- Overview of technologies. Each FDD system should be described such that the main ideas can be understood (see Section A8).
- Additional sensors versus reliability. Additional sensors always mean additional costs. So additional benefits in term of reliability, redundancy, accuracy, etc. should be discussed (see Section A9).
- User's needs. Each method is also characterised by the user's needs that the method is intended to respond to. From the experience in the field it is interesting to know, how well each method accomplished the given target (see Section B1).

E.2.2 Issues affecting commercialisation

Each developer of a method should answer the following questions in order to estimate the chance for a commercial realisation of the method. The questions also force the developer to focus on crucial issues.

- 1) Who are the intended users of the FDD tool?
- 2) How thoroughly has it been tested?
 - How many HVAC systems has it been tested on?
 - Has it been used by building operators?
- 3) How easy would it be to use it on other systems?
 - How long is the set-up time?
 - How many thresholds have to be set-up?
 - How much design information is needed?

- 4) What are the additional costs?
 - What computing power does it require?
 - How many additional sensors does it require?
 - What would it take to develop a product based on the given FDD algorithm
 - Are there any licensing fee or patent issues to be solved?
- 5) How does it perform in practice?
 - What is the false alarm rate?
 - How sensitive to faults is it?
 - How sensitive is it to measurement errors and inaccurate design information?

E.2.3. Example: FDD for rooftop air conditions

J. Braun, Purdue University, W. Lafayette, IN, USA

- 1) Who are the intended users of the FDD tool?

It is intended that the diagnostic tool be integrated within the controller of packaged air conditioners and sold with either the original equipment or as a field installed retrofit. Ultimately, the intended end-users are building operators and service company personnel.

The aim of the tool is to detect faults that can lead to occupant discomfort, equipment wear, environmental hazard, and excessive energy consumption.

The following faults have been considered:

- Refrigerant leakage
- Refrigerant overcharge
- Fouled condenser coil or malfunctioning condenser fan
- Fouled evaporator filter or malfunctioning evaporator fan
- Compressor wear
- Non-condensables in the refrigerant
- Liquid refrigerant line restriction

- 2) How thoroughly has it been tested?
 - How many HVAC systems has it been tested on?
 - Has it been used by building operators?

Three different rooftop units have or are being evaluated: 1) a 5-ton unit system with a fixed orifice expansion device, 2) a 5-ton system with a thermal expansion valve (TxV), and 3) a 7.5-ton unit with a TxV. Experiments have been conducted in a laboratory setting under both transient and steady-state conditions where faults could be introduced at known levels and under reproducible conditions. The methods have not been used by building operators.

- 3) How easy would it be to use on other systems?
 - How long is the set-up time?
 - How many thresholds have to be set-up?
 - How much design information is needed?

Three different methods have been developed and evaluated, each with different performance and setup requirements: 1) statistical, rule-based method, 2) sensitivity ratio method, and 3) simple rule-based method. The first two methods do not require design information but do require a model that necessitates extensive testing of each size unit within a family under normal operating conditions. The third method does not require testing, but does require performance at design conditions. Through analysis of laboratory test data, reasonable default values for threshold parameters have been established.

- 4) What are the additional costs?
 - What computing power does it require?
 - How many additional sensors does it require?
 - What would it take to develop a product based on the given FDD algorithm?
 - Are there any licensing fee or patent issues to be solved?

All three methods could be implemented within a microprocessor controller. However, the simple rule-based method is the simplest to implement. All three methods give good performance. The statistical rule-based method performs best but requires nine temperature measurements and one humidity measurement. The sensitivity ratio method requires six temperature measurements and one relative humidity sensor. The simple rule-based method only requires six temperature measurements. Since the simple rule-based method does not use a model (normally developed on a specified unit), it is more general and could significantly reduce the cost of engineering FDD systems for specific units.

- 5) How does it perform in practice?
 - What is the false alarm rate?
 - How sensitive to faults is it?
 - How sensitive is it to measurement errors and inaccurate design information?

The methods have been tested extensively in the laboratory. Table E1 gives results from the evaluations of Breuker and Braun (1998) for a 5-ton unit with a fixed orifice device. The table gives FDD sensitivity quantified by fault level and its corresponding effect on system performance for five faults. The performance effects of the different faults at the point of detection are quantified in terms of changes in cooling capacity (affects comfort), efficiency (affects energy consumption), and compressor superheat and discharge temperature (affects compressor life). Tests were run over a wide range of operating conditions with the unit cycling on and off in response to different loads. The columns labeled “1st” and “All” give FDD sensitivities associated with correctly diagnosing the fault for a single point within the data set and all steady-state points within the data set. In general, the technique was able to correctly detect and diagnose faults before there was a loss of about 5% in cooling capacity and efficiency. This is undoubtedly before the unit would need any service.

Chen and Braun (2000) evaluated the performance of the sensitivity ratio and simple rule-based methods for a 5-ton unit with a TxV. Figures E1 and E2 present the sensitivities of the sensitivity ratio and simple rule-based methods determined from tests in the laboratory with the unit cycling on and off to maintain the zone temperature setpoint under different load conditions. The results are presented in terms of the fault level where an alarm was set for each fault type. The methods were able to correctly diagnose faults at all three load levels with reasonable sensitivity. The presence of non-condensables was only tested at the full load conditions.

Table E1. Performance of statistical, rule-based FDD prototype.

Performance index	Refrigerant leakage		Liquid line restriction		Compressor valve leak		Condenser fouling		Evaporator fouling	
	(% leakage)		(% Δp)		(% $\Delta \eta_v$)		(% lost area)		(% lost flow)	
	1st	All	1st	All	1st	All	1st	All	1st	All
Fault level (%)	5.4	Max	2.1	4.1	3.6	7.0	11.2	17.4	9.7	20.3
% Loss capacity	3.4	> 8	1.8	3.4	3.7	7.3	2.5	3.5	5.4	11.5
% Loss COP	2.8	> 4.6	1.3	2.5	3.9	7.9	3.4	5.1	4.9	10.3
ΔT_{sh}	5.4	> 11	2.3	4.8	-1.8	-3.6	-0.6	-1.6	-1.7	-2.7
ΔT_{hg}	4.8	> 10	2.4	4.8	0.0	0.0	1.8	2.3	-1.2	-2.7

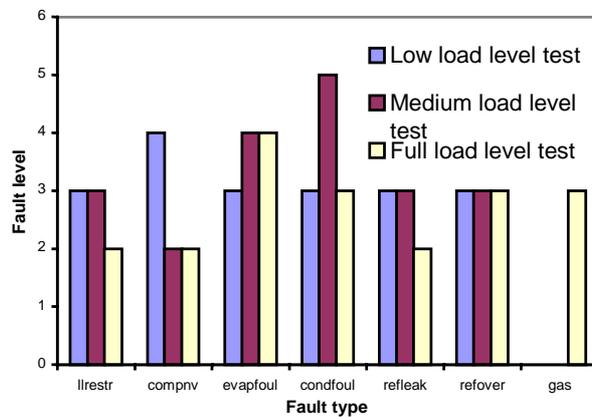


Figure E1. Sensitivity ratio method sensitivity.

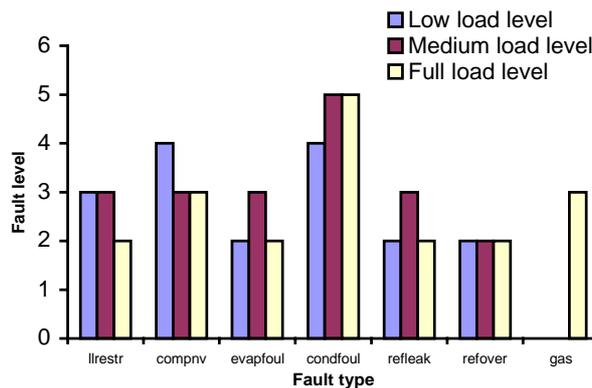


Figure E2. Simple rule-based method sensitivity.

References

Breuker, M.S. and Braun, J.E. 1998. Evaluating the performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment, *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research*, Vol. 4, No. 4, pp. 401–426.

Rossi, T.M and Braun, J.E. 1997. A Statistical, Rule-Based Fault Detection and Diagnostic Method for Vapor Compression Air Conditioners, *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research*, Vol. 3, No. 1, pp. 19–37.

Chen, B. and Braun, J.E. 2000. Simple Fault Detection And Diagnosis Methods for Packaged Air Conditioners, *Proceedings of the 2000 International Refrigeration Conference*, Purdue University, W. Lafayette, IN.

E.2.4 Example: EMMA tools

H. Vaezi-Nejad

Intended end-users

Municipal service team who used remote control BEMS to survey school or nursery school buildings.

The building heating system consists of hydronic heating systems.

How thoroughly has it been tested?

The testing and validation procedure has followed 6 main steps.

- 1st step: the method has been evaluated with simulated data.
- 2nd step: a first software has been tested off-line with the data of Montpellier municipality

- 3rd step: the software has been validated on-line in Montpellier
- 4th step: the software has been improved with Limoges service team (increasing the robustness and the easiness of dissemination)
- 5th step: the municipality of Limoges constantly uses the software since 1997
- 6th step: Dissemination to other towns is going on in cooperation with EMCS manufacturers and the association of engineers of French towns.

Each municipality uses EMMA to survey around 100 buildings.

How easily would it be use on other systems?

3 installation days are estimated:

- 1 day for analyzing the BEMS and equipment of the municipality.
- 1 day for installing the tools and teaching to end-users how to use it.
- 1 day for maintenance and hot line service.

3 main thresholds have to be set-up but the end-user can do this task (simple physical values can be used to set-up the thresholds).

No design information is needed.

What are the additional costs?

Computing power:

- PC Pentium 75 Mhz.
- Screen resolution 800*600 pixels.
- 16 Mbyte of RAM.
- 4 Mbyte free space on the hard disk.
- Windows 95 or Windows NT 4.0 or higher.

No additional sensor is required.

The development of FDD algorithms is a short-term process as the algorithms are simple “if/then” rules.

No license.

How does it perform in practice?

The rate of false alarm and the sensitivity of detection can be fixed by the end-user with a qualitative approach: the end-user decides (by selecting in the menu of EMMA software) if he needs **Low, Normal or High** detection sensitivity.

The FDD method is low sensitive to measurement errors as we filter data, eliminate ambiguous values and use mean values.

E.3 A PERSONAL VIEW OF COMMERCIAL EXPLOITATION

John Seem

The development of practical fault detection and diagnostic systems for HVAC equipment is a difficult problem because of a number of reasons. First, HVAC control systems use very few sensors to keep the system costs low. The lack of sensors makes it difficult to continuously perform mass and energy balances in order to detect faults. Second, a practical fault detection and diagnostic system must require no or little time to set up. Third, the fault detection method must be numerically efficient in order to operate in low cost computer control systems. Fourth, HVAC systems exhibit non-linear behaviour. For example, actuators in many HVAC systems have a large amount of hysteresis. This makes it difficult to obtain linear models for HVAC systems. Fifth, a number of systems in operation today are not operating in a stable manner. The control loops may be unstable due to controller tuning problems or design problems. This makes it difficult to use fault detection systems that rely on steady-state behaviour. Sixth, there are many types of HVAC systems and a number of systems are custom built in the building. This makes it difficult to develop a single system model for use in a HVAC fault detection system.

In spite of all the difficulties of developing a practical fault detection system, Annex 34 has performed research to develop and test fault detection and diagnostic systems in actual buildings. There is a great deal to be learned from all the methods studied in this Annex. I think that the work of this Annex is a great contribution to the body of literature in the HVAC area.

E.3.1 Technology transfer from annex to industrial researchers

The body of knowledge learned during this annex should be transferred to industrial researchers in the HVAC industry. There are several ways that this knowledge can be transferred. First, the participants of the annex should publish detailed papers that contain enough information for industrial researchers to duplicate the work of the annex. Second, the participants of the annex should give presentations at technical meetings to describe their work. Third, the participants of the annex should continue working on fault detection systems and if possible join into co-operative research agreements with industry. Fourth, the final report of this Annex should be for sale at technical meetings of organisations like CIBSE and ASHRAE. Fifth, the final report for this Annex should be available from companies like www.amazon.com.

E.3.2 Technology transfer from researchers to product engineers

Prior to transferring technology from research to product, the research engineer should be extremely confident that the technology is robust and free from faults. It is very costly to transfer technology that does not work.

To successfully transfer technology from research to product engineers, the research engineer and product engineer(s) should work together in a team environment for several months. The research engineer needs to understand the constraints of the product engineer, and the product engineer needs to understand the technology. Also, the product engineer must be confident with the technology. (Note: giving a product engineer a detailed technical document will not result in the successful transfer of technology.)

E.4 LIST OF INDUSTRIAL PARTNERS

The following companies and organisations took part in the collaboration projects with research institutes. They provided the projects with financial and/or technical aid. Many companies also regularly sent their representatives to take part in the Annex working meetings.

1. Regulvar inc., Canada, (Building automation)
2. Public Works and Gouvernemental Services Canada, Canada, (Building maintenance)
3. Akitec inc., Canada, (Building automation)
4. Building Management Services Department, Wayfoong Property Limited Johnson Control, China
5. Helsinki construction bureau, Finland, (Building maintenance)
6. Computec Oy, Finland, (Building automation)
7. Oy LPM-Group Ltd, Finland, (HVAC equipment)
8. OY KOLMEKS AB, Finland, (HVAC equipment)
9. Ouman Oy, Finland, (Building automation)
10. Tac-Com Oy, Finland, (Building automation)
11. S. Stenfors Oy, Finland, (Building automation)
12. Honeywell Oy, Finland, (Building automation)
13. Oulun Energia, Finland, (Energy supplier)
14. Tampereen Sähkölaitos, Finland, (Energy supplier)
15. Siemens Building Technology Oy, Finland, (Building automation)
16. Jämätek Oy, Finland (HVAC equipment)
17. Fortum Oil and Gas Oy, Finland (Energy supplier)
18. Li-Plast Oy, Finland, (HVAC equipment)
19. Oilon Oy, Finland, (HVAC equipment)
20. Akvaterm Oy, Finland, (HVAC equipment)
21. Loval Oy, Finland, (HVAC equipment)

22. Planungsgruppe IFB Dr. Braschel AG, Germany, (Consulting)
23. Hewlett Packard GmbH, Building Services Group, Germany, (Building owner)
24. EDF Research and Development Division, France, (Energy supplier)
25. SATCHWELL SA, France, (Building automation)
26. TRILOGIE, France, (Building automation)
27. NAPAC, France, (Building automation)
28. SIEMENS Landis & Staefa FRANCE, France, (Building automation)
29. ECOTRAL, France, (Building maintenance)
30. OBAYASHI CORPORATION, Japan, (Constructing)
31. KAJIMA CORPORATION, Japan, (Constructing)
32. FUJITA CORPORATION, Japan, (Constructing)
33. Yamatake Building Systems Co.,Ltd, Japan, (Building automation)
34. Yamatake Corporation, Japan, (Building automation)
35. TOKYO ELECTRIC POWER COMPANY, Japan, (Energy supplier)
36. OSAKA GAS CO., LTD, Japan, (Energy supplier)
37. DBU - Industrial technology b.v., The Netherlands
38. PRIVA Computer Systems, The Netherlands
39. The Nedalo group, TXU Company, The Netherlands
40. SKANSKA, Sweden, (Constructing)
41. IV Svenska AB, Sweden, (HVAC equipment)
42. TAC AB, Sweden, (Building automation)
43. Ångpanneföreningen (ÅF), ÅF-VVS Projekt, Sweden, (Consulting)
44. Siemens Landis & Staefa, Switzerland, (Building Automation)
45. Building Research Establishment Ltd (BRE), United Kingdom, (Consulting)
46. Caradon Trend Ltd, United Kingdom, (Building automation)
47. Eastern Group Plc, United Kingdom, (Building owner)

48. Ove Arup & Partners, United Kingdom, (Consulting)
49. Prudential Portfolio Managers Ltd, United Kingdom, (Building owner)
50. Field Diagnostic Services, Inc, USA, (Consulting)
51. Johnson Controls, Inc., USA, (Building automation)
52. McQuay International, USA
53. Honeywell, Inc., USA, (Building automation)

E.5 DISSEMINATION AND OUTLINE OF EXPLOITATION PLANS

Canada

A workshop is planned for control manufacturers, consultants and end-users.

Presentation is to be made at the "AQME" (Association Quebeoise de la Matrise de l'Energie) annual conference for building owners, building maintenance personnel, consultants and energy providers.

Three further demonstration projects are planned: one in a federal Building, one in a provincial building, and one in a private sector office building.

A guide is to be produced that will help consultants to specify FDD tools.

Sweden

In May 2000 a demonstration meeting for the industry was arranged. The fault detection prototype tool as well as the visualisation prototype tool (DataBrowser), developed in the Swedish project, were demonstrated. Control manufacturers, HVAC consultants, representatives from The Swedish Society of HVAC Engineers, etc attended the meeting. In total around 40 people were present.

Switzerland

The qualitative model based fault detector (QMBFD) has been implemented in the Visonik sub-station PRV manufactured by Siemens

A heat recovery efficiency supervision block has been implemented in the Aerogyr controller manufactured by Siemens

An article entitled "Fehlerdetektor für die Lüftung" was published in the application oriented magazine Gebäudtechnik, 5, 2000.

UK

A one day seminar on "Fault Detection and Diagnosis in Buildings" was held at the Building Research Establishment in February 1999 to present the results of the UK Annex 34 national project to practitioners. The speakers were:

- Richard Fargus: An Introduction to Fault Detection and Diagnosis
- Arthur Dexter: Performance Monitoring and Automated Commissioning
- Jon Wright: Condition Monitoring
- Chris Chapman: Dissemination and Exploitation Routes

An article entitled "Practical Application of Automatic Fault Detection and Diagnosis Techniques" was published in the CIBSE Trade Journal 1999.

USA

A presentation on "Non-intrusive Electrical Load Monitoring: A Review of its Development and Application for Energy Monitoring and Fault Detection" was made by Les Norford at the Honeywell Technology Center in December 1996.

A two-day workshop on "Diagnostics for Commercial Buildings – from Research to Practice" was held at the Pacific Energy Center in San Francisco in June 1999 (see <http://poet.lbl.gov/diagworkshop/>). The Annex 34 speakers were:

- Les Norford: Electric Power Measurements: Disaggregation and Interpretation
- Jim Braun: Automated Fault Detection and Diagnostics for Vapor Compression Cooling Equipment
- Kristin Heinemeier: User and Market Factors that Influence Diagnostic Tool Development
- John House: An Overview of Building Diagnostics
- Todd Rossi: Deployment of Diagnostics for Commercial Buildings: New Business Opportunities.

A symposium on "Recent Results from Fault Detection and Diagnostic Research" is to be held at the ASHRAE Winter Annual Meeting in January 2001. The Annex 34 speakers will be:

- Jim Braun: Simple Rule-Based Methods for Fault Detection and Diagnostics Applied to Packaged Air Conditioners
- Arthur Dexter: Fault Diagnosis in Air-conditioning Systems: a Multi-step Fuzzy Model-based Approach
- John House: An Expert Rule Set for Fault Detection in Air-handling Units.

APPENDIX 1: THE FDD TEST SHELL

J. M. House and T. M. Rossi

1 OVERVIEW

The FDD Test Shell is a platform based on Microsoft Windows dynamic data exchange (DDE) that facilitates the interaction of FDD modules (data, reference models, and FDD methods) developed in any application development environment that supports DDE. Data are provided to a DDE server application that can then be accessed by any number of client FDD applications. The data source can be a data file, an experimental test rig, a simulation model, or a BEMS. By standardizing the location of specific measurements and control signals in the server application, FDD client applications can be configured once to interface to the server application and thereby use the data, regardless of its origin. The Windows DDE platform was chosen because it is commonly available and it allows shared FDD resources to be developed in a variety of application development environments. This includes Microsoft Visual C++, Borland OWL C++, MATLAB, Visual Basic, Excel, etc. This appendix provides a description of the FDD Test Shell, including instructions for obtaining and using the software.

2 ARCHITECTURE

2.1 The coordinator program

Figure 1 illustrates the architecture of the FDD Test Shell. The modular architecture provides a structured way to share data, models and methods. At the heart of the Test Shell is a DDE server program called the Coordinator. The Coordinator consists of data tables and graphical templates for displaying data of specific types of equipment. The Coordinator tables and the information they contain are described below:

1. Experiment Table – time series operational data
2. Model Table – output of reference models whose inputs come from the Experiment Table
3. Model Residual Table – difference of values in the Experiment and Model Tables
4. Design Table – values of design data
5. Design Residual Table – difference of values in the Experiment and Design Tables.

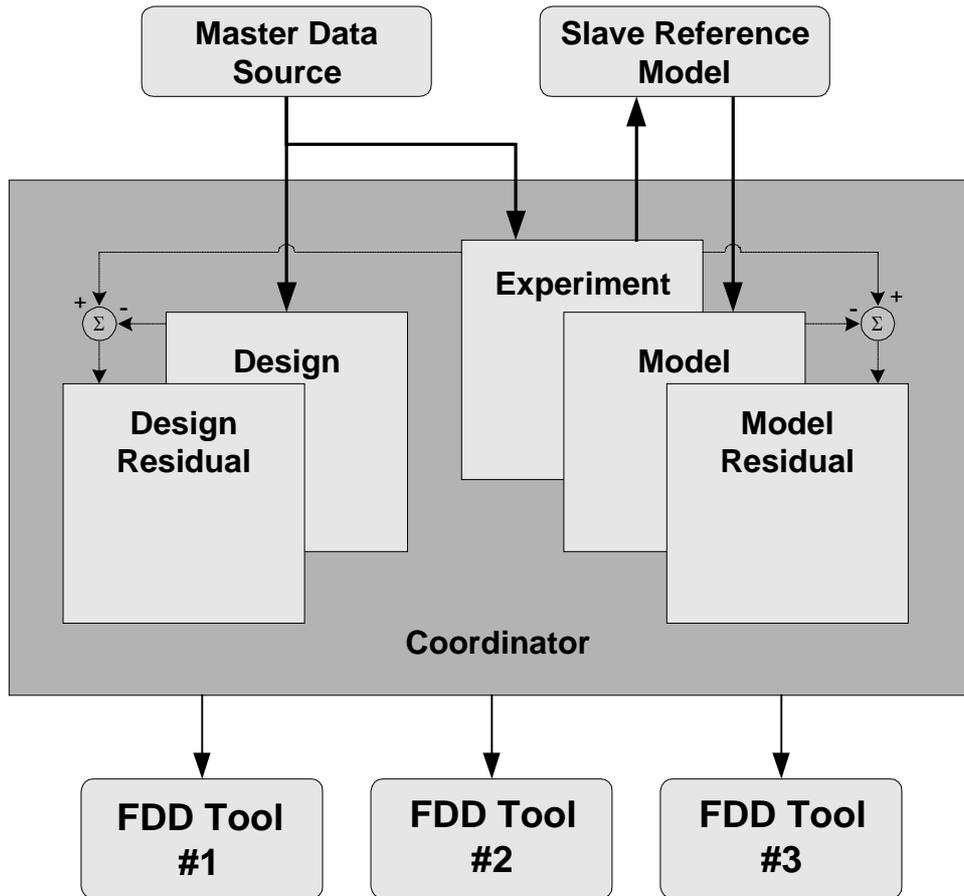


Figure 1. FDD Test Shell Architecture (needs updated).

The Master Data Source program pokes data into the Experiment table within the Coordinator. As noted previously, the Master Data Source program can be an experimental rig (e.g., HPVee or LabView), a simulation model, or a file containing columns of data. A separate program referred to as the File Data Source Program, has been written to poke data from a file into the Coordinator. In the case of data files, the Annex 34 data standard (see Section B.4) specifies that the first row of data consists of design values of the measured data. In addition to poking time series data into the Experiment Table of the Coordinator, the File Data Source program also pokes the design data into the Design Table to enable access to this data by FDD methods.

The Coordinator advises the Slave Reference Model program when the Master inserts new data. The Reference Model (assuming one exists) then requests input data from the Experiment table, calculates reference output values (usually representing normal performance), and pokes the results into the Model table. The Coordinator automatically calculates the difference between the Experiment and Model tables and puts the results in the Residual table. In addition, as new data stream through the Experiment table, the Design Residual table is automatically updated to reflect the difference between the Experiment and Design tables.

The FDD programs can request data from any of the Coordinator's tables or be advised when new data are available. They operate on the data and present results on independent user interfaces. The Coordinator's Experiment table may be used independently of the Slave Reference Model. For instance, if the implementation of an FDD method has embedded models or does not utilize models of reference operation, raw data can be requested directly from the Experiment table. Also, design data can be requested directly from the Design table.

The Coordinator currently includes graphical templates for air-handling units (AHUs) and vapor compression cycles. As time series data stream through the Coordinator, the appropriate graphic is updated to reflect the current values of the available data. The standard data contained in the templates are described in Section B.4.

The DDE Service Name for the Coordinator is "Coordinator". The tables in the Coordinator correspond to the DDE Topics: "Experiment", "Model", "Design", "Residual", and "DesignResidual". Each table contains DDE Items "1" through "60" corresponding to the number of cells contained in each table.

The Coordinator responds to DDE Advisory loops. When an advise loop is requested for a particular Topic/Item, the Coordinator will advise the client program when the cell's value changes. This has been used to trigger an FDD calculation in Matlab.

2.2 The file data source program

The File Data Source program was developed to insert data saved in an ASCII file into the Coordinator. The file contains columns of data beginning with a time stamp. The time stamp can be represented in a variety of formats. A mapping feature defines which columns are inserted into specified Coordinator cells. The program allows for a variety of transformations of data from the column input to the representation needed by the FDD method. For instance, a number of common unit conversions are implemented to alleviate the need for this in the FDD method. Details of the standard developed to simplify access to data sets using the File Data Source program are provided in Section B.4.3. Further details of the File Data Source program are provided in Section F.5.

2.3 Using reference models with the coordinator

Reference models (assuming they exist) react to advisories from the Coordinator that new data are available in the Experiment Table. They request input values from the Experiment table, calculate reference or baseline output values, and poke them both into the Model table. The Coordinator calculates the difference between the Experiment and Model tables and inserts the results in the Residual table.

This feature facilitates the comparison of different FDD methods using the same reference model. This provides a means of separating the effect of reference models and FDD methods when assessing overall performance. To do this, the FDD methods can only use data from the residual table. An FDD method that either includes its own reference model or does not require one can still use the Experiment table for its data.

3 REQUIREMENTS FOR INTERFACING TO THE COORDINATOR

The only requirement for interfacing to the Coordinator is that all application programs need to be written for Microsoft Windows and be DDE compatible. Applications can be older 16 bit Windows 3.1 programs or newer 32 bit programs. Most data acquisition systems, including LabView and HPVee, include DDE interfaces. DDE is a standard feature of MATLAB for Windows since version 5.0. It is also possible to develop C++ programs using Microsoft Visual C++ or Borland OWL in 16 or 32 bit formats. Visual Basic also provides a DDE interface.

Master Data Source programs control new data flow into the Coordinator. The DDE Poke command is used to insert data into any cell in the Experiment Table. Slave Reference Model programs (assuming they exist) set up an Advise loop with the Coordinator to be notified when the time, stored in cell #1, changes. When this occurs, the Slave program requests input data from cells in the Experiment Table, and then calculates its reference outputs. The Slave program then pokes the input and output data into the Model Table after which the Coordinator automatically fills the Residual table and advises the FDD methods that new data are available. The FDD methods then request needed information from any table in the Coordinator and analyze that data.

4 DOWNLOADING THE FDD TEST SHELL

An overview of the FDD Test Shell and links to Test Shell software and documentation created during the course of Annex 34 can be found at the following URL:

<http://www.acrx.com/Home/nist.htm>

The current version of the FDD Test Shell can be obtained by clicking on the link “FDD Test Shell Installation Program (updated February 4, 2000)” or by entering the following URL:

<http://mercury.fielddiagnostics.com/test/fddtestshell/TS1.4/TestShell2.4.00.html>

This site provides downloading instructions and contains a link that accesses an executable file for installing the FDD Test Shell. During installation it is recommended

that the Installation Wizard be allowed to place the files in the default locations to ensure consistency with documentation provided.

5 AN FDD TEST SHELL CONFIGURATION EXAMPLE

When downloaded, the FDD Test Shell includes data files from the Iowa Energy Center and the Japan TEPCO building. These data files are described in the discussion of the joint exercise of AHU FDD tools in Section D.2.1. The instructions below describe how to use these data files with the Test Shell.

1. Launch the Coordinator program by using the Windows Start menu and selecting the following submenu items: Start/Programs/FDDTestShell/Coor. Select Air Handling Unit under the Templets menu.
2. Launch the File Data Source program by using the Windows Start menu and selecting the following submenu items: Start/Programs/FDDTestShell/Datafile.
 - a) In the File Data Source window, select Open under the File menu.
 - To use the Spring data from the Iowa Energy Center, select the subfolder `c:\ progra~1\ fds\ fddtes~1\ fileda~1\ iowa` and click on `iec_spr.dfs`. Click on OK to close the window.
 - To use the Summer data from the Iowa Energy Center, select the subfolder `c:\ progra~1\ fds\ fddtes~1\ fileda~1\ iowa` and click on `iec_sumb.dfs`. Click on OK to close the window.
 - To use the Japan data, select the subfolder `c:\ progra~1\ fds\ fddtes~1\ fileda~1\ jap` and click on `japan.dfs`. Click on OK to close the window.
 - b) In the File Data Source window, the data file currently accessed is listed below the “File”, “Project”, “Options”, etc. menu headings. To choose an alternative data file for processing, select Configuration under the File menu.
 - In the Configuration window, click on the Select button and choose the appropriate file. Iowa Spring data files are named:
 - `iec_spr1.txt`
 - `iec_spr2.txt`
 - ...
 - `iec_spr6.txt`

Iowa Summer data files are named:

- iec_sum1.txt
- iec_sum2.txt
- iec_sum3.txt
- iec_sum4.txt

Japan data files are named:

- jpn_n714.txt
- jpn_n715.txt
- jpn_n811.txt
- jpn_n812.txt
- jpn_n818.txt
- iec_n819.txt

Click on OK to close the data file selection window.

- The speed at which data streams through the Coordinator can be increased or decreased by changing the “Time Multiplying Factor” in the Configuration meeting. A multiplying factor of unity implies that Coordinator is updated with new data in accordance with the time stamp of the data. A multiplying factor greater than unity causes the data to stream through the Coordinator faster than real time.
 - Click on OK to close the Configuration window.
- c) To start the flow of data, select Run under the Project menu of the File Data Source window. Design data will be presented in the “Data from design” table of the Coordinator. Operational data will be presented in the “Data from experiment” table of the Coordinator and in the Air Handling Unit graphic. To stop the flow of data, select Stop from the Project menu of the File Data Source window.

To examine the mapping from the data files to the AHU template, refer to the files “Iowa AHU Template” and “Japan AHU Template” in the directory C:\ Program Files\ FDS\ FDDTestShell\ FileDataSourceacE of these files contain a table that explains what data are contained in each cell of the Coordinator “Data from experiment” table, a name for each data point that corresponds to the name used in the AHU graphic, and the column number in the data file that contains each point. In addition, points with design values are indicated by providing the design value in the final column of the table.

APPENDIX 2: STANDARDIZED POINT NAMING CONVENTION

Edward Morofsky, Public Works and Government Services Canada, Canada

The standardized point naming convention described below is used by PWGSC and is presented based on discussions at the last meeting in Montreal. Such a convention has many obvious advantages. Sharing information and data among countries may benefit from the use of such a convention. The English – French duality of the following convention may also be applicable in sharing data within IEA with non-English speaking countries.

The point identifier is composed of three (3) fields as indicated below:

<area>.<system>.<point>

The "point" field references as unique sensor or collection of data values and point type specific attributes within a specific vendor controller. The "system" name references a group of points which interact with specific mechanical, electrical or building service function (fire, security, lighting, etc.) and for operator display and interactive purposes are grouped. The "area" field refers to the building in which the systems and points are located. The full point name <area>.<system>.<point> references a unique point. At system initialization, each OWS will map "areas" and "systems" to specific nodes. The "area", "system" and "point" name fields are each composed of ten (10) alphanumeric characters.

- Air Handling Unit No.#1, Supply Air Temperature point label = AH1 SAT
- Secondary Water Circulating Pump No. #2 Status point label = SW CP2 S.

Table 1 attached contains Point Identifiers and Expansions, Table 2 contains System Identifiers and Expansions and Table 3 contains Area Identifiers and Expansions.

The Naming Convention is described in the "Energy Management and Control Systems Design Manual" published by PWGSC and is available for download in WordPerfect 5.2 for Windows at [www.tech-env.com/download/cab_ protocol](http://www.tech-env.com/download/cab_protocol) in English and French.

TABLE 1 POINT Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
A F H P S T SP	Alarm Flow rate Humidity Pressure Status Temperature Static pressure
OADMIN OADMAX OAT OAH OAF	Outside air dampers (min.) { control} Outside air dampers (max.) { control} Outside air temperature Outside air humidity Outside air flow rate
RAD RAT RAH RASP	Return air damper { control} Return air temperature Return air humidity Return air static pressure
MAD ** MAT MAPSP	Mixed air dampers ** Mixed air temperature Mixed air plenum static pressure
** "MAD" for applications where outside air and return air dampers are controlled from one (1) only output signal.	
EAD EAT EAF	Exhaust air damper { control} Exhaust air temperature Exhaust air flow rate
PFPD0 PFA FFPD FFA	Pre-filter pressure drop Pre-filter pressure drop alarm Final filter pressure drop Final filter pressure drop alarm
HCV HCDT HCEWT HCLWT BPDC BPD FZSTAT	Heating coil valve Heating coil discharge temperature Heating coil entering water temperature Heating coil leaving water temperature Face & bypass damper (control) Face & bypass damper position Freeze detector or stat
CC CCV CCS CCDT CCEWT CCLWT	Cooling coil { control} Cooling coil valve { control} Cooling coil valve status Cooling coil discharge temperature Cooling coil entering water temperature Cooling coil leaving water temperature

TABLE 1 POINT Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
HUM HUMCV HUMVS SAH	Humidifier { control} Humidifier valve { control} Humidifier valve status Supply air humidity
SPP SPS SPF SPDP	Spray pump { control} Spray pump status Spray pump flow Spray pump discharge pressure
SF[1] SF[1]S SFH SFHS SFL SFLS SFV	Supply fan [#1] { control} Supply fan [#1] status Supply fan high speed { control} Supply fan high speed status Supply fan low speed { control} Supply fan low speed status Supply fan VAV volume
SAF SAT SAH SASP	Supply air flow Supply air temperature Supply air humidity Supply air static pressure
RF[2] RF[2]S RFH RFHS RFL RFLS RFV	Return fan [2] { control} Return fan [2] status Return fan high speed { control} Return fan high speed status Return fan low speed { control} Return fan low speed status Return fan Volume
RAF RAT RAH	Return air flow Return air temperature Return air humidity
EF[3] EF[3]S EFV	Exhaust fan [3] { control} Exhaust fan [3] status Exhaust fan Volume
EAT EAF	Exhaust air temperature Exhaust air flow rate
CHWF CHWST CHWSP CHWRT CHWRP CDNEWT CDNEWP CDNLWT CDNLWP	Chilled water flow Chiller Supply ** water temperature Chiller Supply ** water pressure Chiller Return ** water temperature Chiller Return ** water pressure Condenser entering ++ water temperature Condenser entering ++ water pressure Condenser leaving ++ water temperature Condenser leaving ++ water pressure

TABLE 1 POINT Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
** "Supply" means flow away from chiller to distribution system. "Return" means flow of chiller from distribution system. ++ "Entering" means flow from distribution system to the chiller condenser system. "Leaving" means flow away from chiller condenser system to heat sink.	
CT[1] CTWET CTWEP CTWLT OAT OAH CT[1]S	Colling tower [#1] Cooling tower entering ** water temperature Cooling tower entering ** water pressure Cooling tower leaving water ++ temperature Outside air temp Outside air relative humidity Cooling tower [#1] status
** "Entering" means flow from distribution piping system to distribution spray headers or distribution basin. ++ "Leaving" means flow from cooling tower collection basin and in direction of distribution piping system..	
CHWP[4] CHWF CHWPP CHWPS CHWRT CHWST	Chilled water pump [#4] { control } Chilled water flow rate Chilled water pump discharge pressure Chilled water pump status Chilled water return temperature Chilled water supply temperature
CP[3] CPF CPDP CP[3]S	Circulating water pump [#3] { control } Circulaitng pump flow rate Circulating pump discharge pressure Circulating pump [#3] status
CDN[2] CDNF CDNDP CDNPS	Condenser water pump [#2] { control } Condenser water pump flow rate Condenser water pump discharge pressure Condenser water pump status
HTA LTA HTC LTC HLA LLA HLC LLC	High temperature alarm Low temperature alarm High temperature cut-out Low temperature cut-out High level alarm Low level alarm High level cut-out Low level cut-out
HWF HWST HWRT	Heating water flow rate Heating water supply temperature Heating water return temperature

TABLE 1 POINT Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
STP STF	Steam pressure Steam flow rate
SPT SPH SPSP	Space temperature Space humidity Space static pressure (add reference point)
GA SA TA Z[5]A	General alarm Smoke alarm Trouble alarm Zone [#5] alarm
<p>NOTES : The word "{control}" is shown in the expansion to indicate the purpose of the point. It shall NOT be used on any EMCS project expansion list.</p>	

TABLE 2 SYSTEM Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
CHW CNDW DTW GLYCOL HTHW HWH RADN SECWTR SOLAR	Chilled water system Condenser water system Dual temperature system Glycol system High temperature hot water system Hot water heating system Radiation system Secondary water system Solar system
CDSRET HPSTEAM LPSTEAM	Condensate return system Steam – High pressure system Steam – Low pressure system
DCW DHW DHWC SAN STM	Domestic cold water system Domestic hot water system Domestic hot water circulation system Sanitary sewage – pumped system Storm water – pumped system
SPKD SPKW FHC	Sprinkler – dry pipe system Sprinkler – wet pipe system Fire standpipe & hose system
CH[1]	Chiller [#1]
BLR[2]	Boiler [#2]
HUM	Humidification system
** Use only when humidification system consists of central steam boiler and distribution piping system. Do not use when humidifiers are part of HVAC unit.:	
FA SC LGT	Fire alarm system Smoke control system Lighting control system

TABLE 3 AREA (BUILDING) Identifiers and Expansions	
English Identifier (10 characters max.)	English Expansion (40 characters max.)
TUPPER	Sir Charles Tupper
BRKCLAX	Brooke Claxton
JEANMANCE	Jeanne Mance
JCARL	Sir John Carling
GOCBLNDN	Govt of Canada Bldg., London, Ont.

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