AN APPLICATION FOR CONSTRAINT SUSPENSION: FAULT DIAGNOSIS IN AN AIR CONDITIONING UNIT

ERIC JAMES MADDISON

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MASTER OF SCIENCE
DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF GLASGOW

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ABSTRACT

Building energy management systems (BEMS) not only perform real-time control functions but also provide enormous amounts of data which can be analysed for purposes of energy management and fault detection and diagnosis. Unfortunately there are few tools available to perform these tasks leaving the onus on skilled engineering staff to analyse the data manually. This has prevented the realization of the full potential of BEMS technology. This thesis examines whether the technique, known as constraint suspension, could provide an appropriate tool for fault detection and diagnosis.

The aim of this study is specifically to examine the suitability of the technique of constraint suspension within the context of the particular example of an air conditioning unit installed at a medium sized factory for the production of aerospace components.

The thesis contains 5 chapters. Chapter 1 provides a brief introduction. This is followed, in Chapter 2, by a detailed account of research to date into fault detection systems applied to BEMS. It is found that these systems require complex programming and are not readily transferred from one building to another. Chapter 3 introduces the concept of constraint suspension and argues that this could provide a general tool, based on simplified, static models, that could be readily transferred to any air conditioning plant with suitably located sensors. The chapter goes on to describe the application of constraint suspension to a particular case of an air conditioning unit installed at a medium sized factory. Chapter 4 presents some results and assesses the effectiveness of the application in diagnosing faults in the air conditioning unit, control system and control strategy. Chapter 5 concludes the study with an analysis of the air conditioning plant in a light engineering factory have been considered. The following faults have been identified and verified:

- the output of the sensor measuring the chilled water temperature out of the mixing valve,
- the BEMS driver output for the fresh air and recirculating air dampers,
- the control strategy for dehumidification.

The findings demonstrate that the system proposed, based upon constraint suspension technology, is capable of detecting and diagnosing sensor and driver faults. The rule based system of assessing the control strategy can indicate faults in the strategy. The viability of the application of constraint suspension to the detection and diagnosis of fault conditions in an air conditioning unit using simple static models has been demonstrated.

The rather arbitrary nature of locating sensors in air conditioning plant has been identified. The importance of providing a complete specification for the BEMS including exact locations and numbers of sensors to facilitate fault detection and diagnosis procedures has been highlighted.

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SYMBOLS

W	Humidifier valve position	%
X	Heater battery valve position	%
Y	Cooling coil valve position	%
Zi	Fresh air damper position	%
Zr	Return air damper position	%
Tao	Temperature outside air	°C
Tmai	Temperature of fresh air into mixing box	°C
Tmar	Temperature of return air into mixing box	°C
Tmao	Temperature of air leaving mixing box	°C
Xao	Moisture content of outside air	kg/kg
Xmai	Moisture content of fresh air into mixing box	kg/kg
Xmar	Moisture content of return air into mixing box	kg/kg
Xmao	Moisture content of air leaving mixing box	kg/kg
Tcai	Temperature of air entering cooling coil	°C
Tcao	Temperature of air leaving cooling coil	°C
Tcwi	Temperature of water entering cooling coil	°C
Tcwo	Temperature of water leaving cooling coil	°C
Tcwm	Temperature of water by-passing cooling coil	°C
Xcai	Moisture content of air entering cooling coil	kg/kg
Xcao	Moisture content of air leaving cooling coil	kg/kg
Tdp	Cooling coil apparatus dew point temperature	°C

Xdp	Cooling coil apparatus dew point moisture content	kg/kg
Uac	Cooling coil heat transfer	kw/m^2/°C
Thtai	Temperature of air entering heater battery	°C
Thtao	Temperature of air leaving heater battery	°C
Thtwi	Temperature of water entering heater battery	°C
Thtwo	Temperature of water leaving heater battery	°C
Thtwm	Temperature of water by-passing heater battery	°C
Uaht	Heater battery heat transfer coefficient	kw/m^2/°C
Xhai	Moisture content of air entering humidifier	kg/kg
Xhao	Moisture content of air leaving humidifier	kg/kg
Xas	Moisture content of supply air	kg/kg
Tas	Temperature of supply air	°C

1.0 INTRODUCTION

Building Energy Management Systems (BEMS) were first developed in the 1970s in an attempt to improve the control of the internal environment of buildings whilst reducing their energy consumption. However, while initially hailed as an advance as well as a solution to the maintenance of the building's environment, several researchers (Hartman 1989, Meredith 1989, Hittle and Johnston 1984) including Shaw (1989) started to question their effectiveness.

Shaw's (1989) observations of the demands, both in terms of time and expertise, made upon those operating BEMS allowed him to suggest that in addition there was the need to use expert systems which would assist in the management and effectiveness of BEMS. He further suggested that such difficulties prevented BEMS reaching their true potential and he thus concluded that,

"There are strong indications that the information management and interpretation problems associated with BEMS represents a major obstacle to the wider application of BEMS in Europe."

Such research findings provided a platform for further study which resulted in the BREXBAS I project (Shaw 1989). This was subsequently improved and developed as BREXBAS II (Shaw & Willis 1990). Both were based on rule based expert systems which analysed the BEMS data. The rules are derived from discussions between the programmer and a person who is considered to have an expert knowledge of the systems to be investigated.

However Haberl and Claridge (1987) proposed a different solution to the problems encountered with BEMS. Their solution used a statistically based model first proposed in 1987 and developed further in 1988 (Haberl and Claridge 1987). Faults are detected and diagnosed by comparing energy consumption of a particular set of conditions with historical energy consumption under the same conditions. The expert system in this case is also rule based, relying upon the knowledge of an expert.

While acknowledging the relative merits of both of the above systems, for instance,

- some success in fault detection and diagnosis in actual buildings,
- reduction in energy consumption,
- improved maintenance procedures,

disadvantages still remain,

- statistical modelling requires the development of complex computer programs,
- production or "if-then" rule-based systems and statistical modelling computer programs are specific to the building for which they have been developed,
- the systems are subject to the limitations of the rule base which must be specified in advance,
- rules rely on eliciting knowledge from an expert, (the project may succeed or fail in accordance with the accuracy, reliability and validity of this information),
- statistical models require a period of at least six months to allow enough data for analysis to be collected.
- faults have to produce noticeable effects such as severe energy over-consumption.

It is pertinent that neither technique has been incorporated into commercially available packages. Therefore, there is a need for a system which can be easily applied to existing BEMS technology and which can maintain its flexibility and hence be applicable to buildings in general.

An alternative approach is proposed in this study which makes use of the technique of constraint suspension (Sussman 1980) originally developed for use with digital electronic circuits (Davis 1984). The approach,

- treats each component as a simple black box with information entering and leaving it,
- uses simple steady state mathematical models (constraints) to describe the manner in which information is changed on passing through the black box.

Faults are indicated by logical inconsistencies between observed values and model predictions based on the constraints. The search for the faulty component is carried out by,

- suspending the constraint representing the behaviour of each component in turn,
- calculating values entering and leaving the component without reference to that particular component model (constraint),
- identifying whether the remaining models are logically consistent with measured and/or calculated data.

An examination into whether or not this technique could provide appropriate fault detection and diagnosis functions in a BEMS must include an investigation into the capabilities of the technique and into the cost of developing appropriate software. This thesis aims to provide evidence in support of the approach by developing a detection system in Prolog and applying this to data collected from an operating air conditioning unit. The software has been developed with genericity and commercial exploitation in mind; thus, for instance, it has been developed on the type of computer (a PC) which commonly acts as a BEMS supervisor.

The aim of Chapter 2 is to provide a detailed account of previous research into fault detection with BEMS. Chapter 3 introduces the concept of constraint suspension and argues that this could provide a general tool, based on simplified, static models, that could be readily transferred to any air conditioning plant with suitably located sensors. The chapter goes on to describe the application of constraint suspension to a particular case of an air conditioning unit installed at a medium sized factory. Chapter 4 presents the results and assesses the effectiveness of the application in diagnosing faults in the air conditioning unit, controls system and controls strategy. Chapter 5 concludes the study with an analysis of the capabilities of the proposed fault diagnosis system, its advantages and limitations and then suggests areas for future work and development.

Original contributions of this thesis are,

- specification of an appropriate constraint representation for a real air conditioning unit,
- development of an inference network generator to suspend each component in turn,
- identification of the need for a separate rule base to identify faults in control strategy implementation
- verification using real data,

2.0 FAULT DETECTION WITH BUILDING ENERGY MANAGEMENT SYSTEMS

2.1 INTRODUCTION

In the United Kingdom the market for BEMS has steadily increased since 1989 with over 2,000 installations having contract values ranging from less than £20,000 to over £350,000 (BSRIA 1991). This reflects a growing awareness of the financial viability of BEMS compared with other more conventional control systems. BEMS are now used in most commercial, industrial and public buildings as a means of controlling heating, ventilation and air conditioning as well as electrical and lighting systems. They are also used to monitor energy consumption and maintain a safe, stable and comfortable environment within the building envelope.

However there exists a body of anecdotal evidence which suggests that BEMS have not reached their full potential. The reasons for this will be considered and the potential for so called "expert systems" technology to improve the performance of BEMS in the specific area of fault detection and diagnosis will be discussed. The term expert system is used throughout to denote a computer program which solves analytical problems through facts and rules.

Statistical model based and if-then rule based strategies will be reviewed in detail and advantages and disadvantages assessed. The elements of a BEMS and their functions will be considered first in order to provide an overview of current BEMS technology.

2.2 ELEMENTS OF A BUILDING ENERGY MANAGEMENT SYSTEM

BEMS (Akbari, Warren and Harris (1987)) typically consist of a number of sensors and outstations connected to a central processor.

The SENSORS measure digital and analogue values of, for instance,

- controlled conditions such as a room temperature or humidity,
- uncontrolled conditions such as outside air temperature and humidity or daylighting levels,
- controlled device positions such as a mixing damper or control valve opening,
- on/off conditions of fans, pumps etc.,
- differential pressures across filters for replacement conditions and
- electrical power consumption.

The OUTSTATIONS perform the following functions, they

- accept digital or analogue information from the sensors,
- log the data,
- process the data and output signals to position actuators in accordance with the controls strategy to maintain the set value of the controlled condition and
- perform the functions of time clocks and optimisers.

The outstation can thus provide control of local mechanical and electrical services from a central location with a "stand alone" capability.

The CENTRAL PROCESSOR is either linked to the outstations over a Local Area Network (LAN) via modems and telephone lines or the system may be hard wired.

The central processor,

- interrogates the outstations at regular intervals and logs data,
- processes and outputs data in graphical and tabular form,
- outputs high and low level warnings and alarms,
- provides a central location for monitoring and altering controls systems and strategies at remote points and
- allows only authorised personnel to access and modify control systems strategies through a series of different levels of passwords.

A typical system is shown schematically in Figure 1.

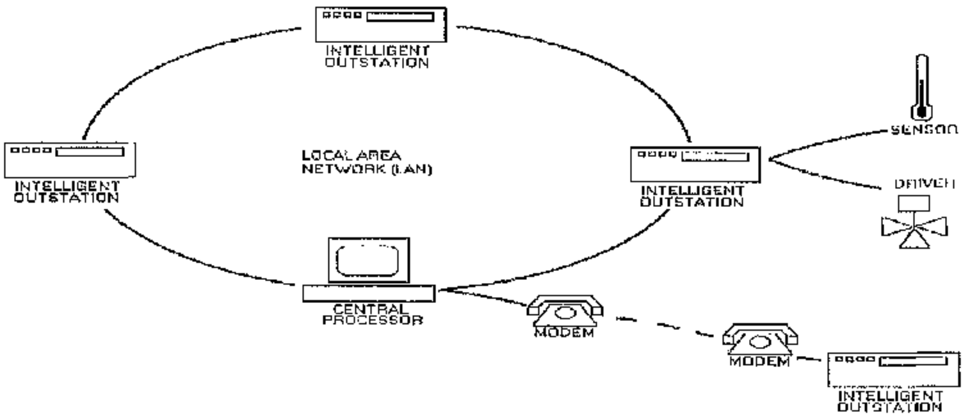


Fig. 1 Schematic Illustrating Elements of A BEMS

2.3 POTENTIAL ADVANTAGES OF BEMS

BEMS offer substantial advantages over conventional control systems by providing accurate centralised control of building services. The most significant advantage is in the reduction of energy consumption through improved, more flexible control. Other advantages include,

- the accurate and comprehensive monitoring of plant,
- a reduction in staffing levels of maintenance personnel for checking and correcting controls,
- better planned and unplanned maintenance and,
- enhanced job satisfaction of staff.

The Building Research Establishment (BRE) estimated potential energy savings of 30% in a well serviced building (Birtles, John, Smith, 1984). Savings as high as 37% averaged over a 7 year period have been noted previously (Waterman and Sperry 1985).

Other research (Spridell 1986) has demonstrated a reduction in average energy consumption from 194 w/m^2 to 140w/m^2 for a large chain of retail premises. This reduction was the result of a comprehensive series of energy conservation measures including the introduction of a BEMS during the final stage of an energy conservation programme.

2.4 **SOME PROBLEM AREAS**

Nevertheless evidence exists which suggests that many BEMS installations have failed to achieve the maximum potential.(Birtles, John and Smith (1984), Waterman and Sperry (1985) and Spridell (1986)). Not all BEMS have created the "...*win, win, win scenario*..." suggested by Meredith (1989). The reasons for this are complex and may be summarised as follows.

2.4.1 **BEMS SOLVE ALL PROBLEMS ?**

It is often perceived that installation of a BEMS system by itself will solve all problems of building operation, control and maintenance. This fails to appreciate the need for a comprehensive energy conservation strategy (Spridell 1986) to ensure that,

- all plant functions and control and management systems are performing correctly,
- personnel are suitably trained and have the ability to operate the BEMS.

2.4.2 THE USER INTERFACE

A further problem exists in the interface between the operator and the system. Hartman (1989) described the need for improvement in the "operability" and "functionality" of BEMS.

- Operability is defined as the ability of the operator to interrogate and adjust the system easily.

- Functionality means the ability of the BEMS to operate and control the HVAC equipment efficiently.

Hartman's (1989) work, together with that of Meredith (1989), have suggested improvements in the areas of operability and functionality. Many of their proposals have been adopted by manufacturers of commercial systems. The "user friendliness" and the operator/system interface of BEMS is an area of continual evolution.

2.4.3 POOR CONTROL

Yet another disadvantage of BEMS has been identified by comparing its limitations with those found in conventional control systems. Hittle and Johnson's (1984) study of the measured performance compared with performance predicted by simulation in a test building concluded the following,

- use of solar energy failed to produce any savings in energy consumption due to unreliable control elements,
- set points maintained by the controls were subject to drift from the original value until the deviation was at the extreme position,
- enthalpy control was condemned as being prone to failure due to the inaccuracy of humidity sensors, and

- enthalpy control logic required frequent re-calibration.

The control systems in this test facility were specified and installed in the same way as they would be for any conventional building. As a result, the authors (Hittle and Johnson 1984) suggested that many HVAC systems were operating out of control and consuming "massive" amounts of energy. BEMS uses the same sensors and actuators as a conventional control system. Since this is analogous to the situation described by Hittle and Johnson (1984), similar failures with BEMS may be expected. Thus this would benefit from the development of computerised monitoring and fault diagnosis routines addressed in this thesis.

2.4.4 DATA INDIGESTION

It is often not possible for the user/operator to analyse the volume of data generated by the BEMS. Ashford (1985) commented that,

"*The present generation of Building Energy Management Systems do not include comprehensive facilities for the manipulation of information obtained about operation of the plant and buildings, relying upon non structured interpretation of the data and visual displays by skilled engineers.*"

Currently there are no commercially available BEMS which have attempted to solve this particular problem and there is thus potential in developing computer based systems to improve data analysis.

2.5 SOME SOLUTIONS

2.5.1 ARTIFICIAL INTELLIGENCE ?

Ashford (1985) has suggested that information processing by knowledge based programmes could assist engineers in analysing data. In addition Ashford has emphasised that artificial intelligence was the "*key to long term development*" and that programming and data analysis were "*capable of supporting a significant advance*".

Shaw (1989) stated that heavy demands were placed on the time and expertise of persons specifying, selecting, commissioning and operating BEMS and as mentioned previously he suggested the use of expert systems.

2.5.2 EXPERT SYSTEMS APPLIED TO HEATING VENTILATION AND AIR CONDITIONING SYSTEMS

Hall and Derringer (1989) investigated the potential for expert systems in HVAC applications. They noted the following principle benefits,

- an order of magnitude improvement in the speed of accomplishing complex tasks,
- permanent retention of expertise acquired from experienced staff,
- significant improvements in the consistency of decision making,
- relatively inexperienced employees perform at near expert levels.

2.5.3 MONITORING AND DIAGNOSTIC KNOWLEDGE BASED SYSTEMS

Monitoring means the interpretation of 'captured' data by comparison of observed behaviour with models of expected behaviour.

There are two types of model, the statistical model and the simulation model. The more common type for diagnostics in building services is the statistical model; it is based on statistical data collected from a particular building; the data is analysed to eliminate spurious data which would affect the accuracy of the model in explaining the behaviour of the building in question. Simulation models use physical representations of the building and HVAC systems in order to predict behaviour.

2.6 STATISTICAL MODEL BASED APPROACHES TO BEMS EXPERT SYSTEMS

Statistical models have been applied to expert system research and development projects. Specifically in the area of building services diagnostics (Haberl and Claridge 1987). They rely on a historical data base of operating conditions which is then compared with the prevailing conditions in a search for significant differences. These may then be investigated by a rule based expert system It is important to note that this type of technique will only detect faults which lead to a significant increase in energy consumption.

2.6.1 THE WORK OF HABERL AND CLARIDGE

Haberl and Claridge (1987) developed an expert system for analysing building energy consumption. This was intended to highlight and identify possible causes of abnormal energy consumption and recommend corrective actions. Their results demonstrated that building services diagnostics using an expert system were able to reduce energy consumption in the investigated building by 15%. The expert system employed two main components,

- an energy consumption predictor and
- an expert system which analysed abnormal, observed variations from their predicted values.

The energy consumption predictors - PCONs (**P**redictors of **CON**sumption) comprise the statistical part of the programme. These are algebraic equations which predict normal energy consumption, based on historical data, for each energy meter. This data is obtained using regression techniques (CEES 1986). The PCONs are linked together in a network which describes the inter-relationships of the different fuel types and energy follows,

- environmental parameters - wind speed, temperature and humidity, sunlight etc.,
- operational parameters - occupancy, operating hours, and
- system parameters- damper settings, thermostat set points etc.

The correlations between these parameters were investigated using comparisons of linear correlation coefficients . Significant variations in energy consumption were then analysed by an expert system based on a backward chaining inference engine using 'IF-THEN' rules to investigate causes of high or low energy consumption.

The pilot study (Haberl and Claridge 1987) resulted in a 15% saving in energy consumption during the first six months of operation.

Similar savings were also possible with conventional BEMS; however, the setting up of the expert system and the initial energy audit revealed energy wastage which would not have been detected otherwise (Haberl and Claridge 1987). Haberl and Claridge (1987) concluded that "*the application of their methodology had yielded mixed results.*" Some abnormalities were detected but others remained unnoticed, unfortunately these were not identified in the paper. Nevertheless the pilot study did produce a significant reduction in energy consumption although data collection was limited since it was based on weekly diagnostic reports from the expert system.

2.6.2 THE WORK OF NORFORD

Norford et al (1987) examined energy consumption patterns of two buildings which had monitoring instrumentation installed as part of a previous study (Norford et al 1985). They recognised that full use of BEMS data logging and analytical abilities was limited by the omission of a number of 'add on components'. The study concentrated on monitoring energy consumption and instrumented electric power, water and air flows and temperatures. These were monitored in this case to assess individual chiller, heat pump, and fan energy performance. The sensors required for this monitoring were considered to be "extras" since they would not normally form part of a conventional BEMS controlling HVAC systems (Norford et al 1987). They assumed that the information obtained would be of the kind that a BEMS could utilise and log. The study served to highlight areas where inappropriate installation of BEMS provides inadequate monitoring for energy consumption analysis.

2.6.3 SUBSEQUENT DEVELOPMENTS

The pilot study of Haberl and Claridge (1987) has been refined and developed into a building energy consumption analysis package using expert systems technology for diagnosing causes of variations in energy consumption. The software named BEACON (**B**uilding

Energy **A**nalysis **CON**sultant) was used by in house maintenance personnel (Haberl et al 1988). The system provided a warning beacon to administrators and maintenance staff to indicate abnormal energy consumption with a built in diagnostics capability. A minimum of six months of daily readings were required for accurate operation of the system.

Their work (Haberl et al 1988) in 1988 expanded the buildings covered by the system and also refined the operator/computer interface by developing macros which could be operated by a single key stroke. Menu driven functions, which can be easily used by maintenance staff with a minimum of training were introduced. The rule based and data based processing were separated by the introduction of a hybrid expert system. Archiving of information was automated to reduce the disk storage space required and automatic error checking procedures were developed.

The authors (Haberl et al 1988) stressed that BEACON's success was dependant upon the identification and implementation of energy conservation measures during the course of etablishing the knowledge base. BEACON would enable the building to run at optimum efficiency - "*it allows for consistent interpretation of the comparative consumption graphs and can provide for institutional memory*" (Haberl et al 1988).

2.6.4 SUMMARY

Buildings and HVAC plant are unique. No two buildings are exactly alike and no two systems operate identically. A knowledge base for each building takes time to develop and cannot be readily applied to another building.

The major drawbacks of statistically based diagnostics are,

- their relative inaccuracy and slowness,
- they are building specific,
- they need a period of time for the building to be in operation before sufficient and accurate statistical data is available for use.
- they require meters at all points of energy consumption (for example, electric motors, heater batteries). These meters are not usually part of a BEMS.

2.7 PRODUCTION BASED APPROACHES TO FAULT DIAGNOSIS

Alternative applications of expert systems technology which avoid some of the difficulties associated with simulation and statistically driven systems have been suggested (Marney and Foord 1984, Shaw 1989, Culp 1989, Shaw and Willis 1991). These may be termed production or "if-then" rule-based systems. Such alternative approaches to the problem of fault diagnosis provide a simpler formulation not requiring complex models. They are based on pre set conditions such as maximum room temperature being violated to initiate the fault diagnosis routine. The system then follows a set of if-then rules to diagnose the fault condition from input BEMS data.

Marney and Foord (1984) proposed that the "broad brush" nature of general purpose software packages did not suit fault diagnosis. They developed an alternative strategy based on a hierarchical structure of block diagrams describing equipment from the most basic to the most detailed levels. This was called Functional System Documentation (FSD). A decision tree was incorporated with a single key user system. Data could be entered into the program by the operator answering simple "yes/no" questions. The system would then interpret the data and produce a diagnosis based upon the input information and the functional rules (fault library).

Culp (1989) proposed a similar technique to that of Marney and Foord (1989). His expert system questioned the maintenance mechanic who then entered the data from his observations. The expert system provided information on equipment status from the data base of planned maintenance. It eliminated recently repaired or maintained components as possible faults. A series of if-then backward chaining rules with a fault library used the data input by the mechanic to determine the most likely cause of the problem or failure. The expert system required the mechanic to check the cause and carry out remedial action. The mechanic then entered the diagnosis as being correct together with the remedial measures. The expert system recorded the remedial actions into the data base. A system operating on these lines has been validated and has been in use since 1986.

Further development of this type of expert system for diagnostics allows the expert system to interrogate BEMS directly instead of through the mechanic (Anderson et al 1989). This interrogation is triggered by the expert system detecting a controlled parameter which is outside set limits. Having carried out the interrogation and diagnostics, the expert system would provide corrective maintenance instructions. The expert system could, additionally, produce preventive maintenance schedules and integrate these with emergency maintenance procedures. A practical system along these lines has been developed and successfully demonstrated (Anderson et al. 1989).

The BREXBAS system developed by the Building Research Establishment (Shaw 1989),(Shaw, Willis, 1991) is a further example of such a system and is considered in more detail.

2.7.1 THE BREXBAS SYSTEM

The BREXBAS system was developed from an original 1986 building emulator into a prototype system in use on a 'real' building. The building emulator was a computer simulation of an LTHW heating system (Shaw 1989) which generated sensor values every 15 minutes. The simulation produced data based on simulated plant failures which BREXBAS assessed. From this it produced continuous plant status reports. Such reports identified breakdowns and gave recommendations based upon the findings of the expert system.

The success of the initial BREXBAS emulator lead to the development of the prototypical system in use at an office in Epsom, Surrey (Shaw, Willis, 1991). This system has a BEMS linked to an expert system; it has the ability to interpret its own data and produce recommendations for the building manager. The system, called BREXBAS II is used to monitor the low pressure hot water (LPHW) heating system only. It is dedicated to the space temperatures in half the building and does not maintain a data base or carry out trend analyses. The system operates in much the same manner as the statistically based packages once a fault condition has been detected in that it uses a series of if-then rules to determine the cause of the fault.

BREXBAS II performs the following sequence.

1. Ascertain current condition (e.g. space, supply and temperature values).

2. Evaluate the current condition (i.e. it compares this with the design criteria).

3. Investigate possible faults and advise on how to re-establish and maintain an acceptable condition.

After one year of operation the system had performed satisfactorily. However, several areas for improvement were identified.

- BREXBAS II does not store previous conclusions from earlier analyses; this results in unnecessary, and often repetitive information for the user.
- Fault diagnosis and performance assessment based on space temperature monitoring is limited and,
- central plant performance and trend analysis is recommended for future systems.

The proposal to carry out trend analysis moves the system in the direction of the statistically based systems considered previously.

The researchers (Shaw and Willis, 1991) concluded that "*tailoring of information to specific buildings and plant items should be a relatively simple task*". They also stated that the use of expert systems for predictive maintenance and trend analysis had potential and that BREXBAS II had demonstrated the viability of the expert system in interpreting BEMS data. However knowledge elicitation was the linch-pin on which the project could succeed or fail: "*The elicitation of knowledge from an expert is a highly skilled task, and most projects will succeed or fail on this part of the work*".

Although it was hoped that the BREXBAS system would be applied to commercially available BEMS systems within 5 years of the initial trials this has not occurred.

2.7.2 **SUMMARY**

Both Marney and Foord (1984) and Culp (1989) have illustrated that practical fault diagnosis expert systems need not rely on BEMS monitored data. Anderson et al (1989) and Shaw and Willis (1991) have provided a system whereby the BEMS data is automatically entered into the expert system. However although these alternatives initially appear to offer a simple and effective solution several disadvantages are inherent within the methodology. These are,

- a rule base must be generated for each individual item of equipment such as compressors, fans and so forth;
- diagnostics routines must be obtained by knowledge elicitation from the building maintenance staff;
- creation of knowledge bases are time consuming;
- knowledge bases may be specific to the particular building;
- fault libraries are limited by a priori knowledge;
- rule based systems are limited by the abilities of the maintenance staff to provide accurate information.

2.9 TO CONCLUDE

This literature review has examined the development of expert systems that are based on statistical and simulation models as well as alternative approaches. Advantages and disadvantages of each method have been considered. Although each approach has been developed into a practical operating system, none has been applied to HVAC systems in general. The reasons for this may lie in the inherent inflexibility of the fault diagnosis routines employed. In each case, the fault diagnosis is carried out on a rule based system with a library of possible faults. These require an a priori list of possible faults and a complete knowledge of,

- how each system and sub-system may fail,
- the interactions between systems and sub-systems,
- the "symptoms" arising as a result of every possible failure,
- the possible causes of every possible failure.

To build such a knowledge base is time consuming. It is highly dependant upon the skill of the programmer in eliciting the knowledge from maintenance personnel and engineers. It is also highly dependant upon the technical ability of maintenance personnel and engineers in knowing where failures can occur and how such failures are manifest. This information may not be transferrable from one building to another.

Therefore there is a need to develop an expert system which is simple and universally applicable.

3.0 CONSTRAINT SUSPENSION AND BEMS

3.1 INTRODUCTION

Whilst the fault diagnostic techniques of Haberl and Claridge (1987), Norford et al (1985, 1987), Shaw (1987) and Shaw and Willis (1991) appear at first sight to be appropriate in their ability to analyse BEMS data, various disadvantages, as discussed previously, have come to light. Some of these disadvantages centre on complexity and this leads to the following question: is it possible to develop a system of fault diagnosis capable of receiving and analysing BEMS data based on simple models using steady state equations? The use of steady state models is worthy of our consideration because, most of the time, HVAC plants operate in a steady state mode. This would ameliorate problems of genericity, making the system more commercially acceptable. A further disadvantage centres on the need for apriori information about possible faults.

Constraint suspension (Davis (1984), DeKleer and Williams (1987)) may be able to overcome these difficulties. Davis (1984) has suggested that constraint suspension *"may apply to any system that might be modelled in terms of information transmission, ranging from hardware to software, to organisations."* Constraint suspension in this application would afford the following benefits,

- it is usually based on a steady state model,
- it does not depend upon apriori knowledge about faults,
- advantages include simplicity and universal application,
- it defines the limitations of the knowledge base,
- it is capable of diagnosing symptoms resulting from previously unknown problems.

Constraint suspension allows systematic isolation of all possible faults and eliminates the need for fault dictionaries and decision trees.

This chapter develops a method for detection and diagnosis of faults in sensor readings, actuator positions and controls strategy based on constraint suspension.

3.2 THE CONSTRAINT SUSPENSION TECHNIQUE

3.2.1 CENTRAL THEMES OF THE CONSTRAINT SUSPENSION TECHNIQUE

Davis (1984) first applied constraint suspension to digital electronic circuits whilst Leary and Gawthrop (1987) applied it to process plant. Davis's (1984) goal was to develop a theory of reasoning which would use previous knowledge of the structure of the system and its behaviour as "*a powerful tool for troubleshooting*".

The central themes of this technique are,
- the structure is the inter-relationship of the modules (components) and constraints with one another,
- the behaviour of a system is represented by the constraints,
- constraints are the mathematical representations of the behaviour under investigation,
- a constraint determines the input-output behaviour of the component,
- candidate generation is the term used for the identification of components of the system which may be responsible for observed unexpected behaviours,
- paths of causal interaction are defined as the manner in which components affect each other.

Davis's (1984) intention was to combine physical and functional organisational aspects into a unified structure. The elements of this unified structure are terminals ports, and components (modules) (Figure 2).

Fig. 2 Constraint Suspension
Ports-Components-Terminals

- Terminals are the points of observation of the system.
- Ports are entries and exits for information going to and coming from the components.
- Components are envisaged as black boxes. The way in which information entering the black box (component) is changed is defined by the mathematical model of that component, that is the constraint.
- Components are inter-connected by the superimposition of their terminals.

The pathways of causal interaction describe the ways in which the various components are inter-connected. In Davis's (1984) digital circuit example pathways of causal interaction may be by wires, thermal bridges, electromagnetic connections short circuits and other links which may affect the overall behaviour of the model. Davis proposes that some inter-connections may result in faults. For instance a short circuit is an inter-connection which is a fault. It is important that the structure is accurately and explicitly modelled with all inter-connections considered so as to prevent the omission of possible faults arising. This leads to the concept of a hierarchy of interconnecting models where the system tries the most likely model first.

3.2.2 HOW THE TECHNIQUE OF CONSTRAINT SUSPENSION WORKS

Constraint suspension is the means by which faults can be diagnosed by removing each constraint in turn from the network and investigating whether this leaves the remaining network in a consistent state. If simulation and measured values are now in agreement the removed constraint, as the mathematical representation of the component, will therefore identify the faulty component.

The constraint suspension approach to fault detection is explained by reference to its application to the simple electronic circuit shown in Figure 3a.

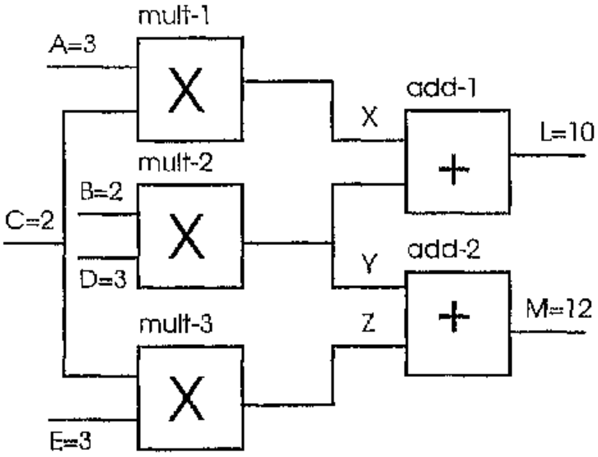


Fig. 3a Schematic Illustrating Constraint Suspension in a Digital Electronic Circuit.

A *constraint* is a set of equations defining the input/output behaviour of a component. Thus, for instance, add-1 in Figure 1 could be represented by the 3 equations,

$$L = X + Y \qquad ..(3.1)$$

$$X = L - Y \qquad ..(3.2)$$

$$Y = L - X. \qquad ..(3.3)$$

These 3 equations enable any input or output to be calculated if all other inputs and outputs are known. The intended behaviour of the device can then be modelled as a network of interconnected constraints and its output predicted by solving the resulting calculational path or inference network. If there is a fault in the device, there will be an inconsistency between the predicted outputs and the measured outputs. Constraint suspension would then attempt to find a constraint whose retraction would leave the network in a consistent state. Each constraint is removed in turn to see whether the remaining network is consistent. In each case, the calculational path would be different resulting in a set of *inference* networks.

If, for the electronic circuit shown, the first output is 10 instead of 12 with the inputs remaining unchanged (Figure 3a). The technique would perform the following:

suspend add-1: results in the inference network shown in Figure 3b which is consistent and hence would explain the discrepancy;

suspend add-2: does not affect the output of add-1 and hence is unlikely to be the cause;

suspend mult-1: results in the inference network shown in Figure 3c which would explain the discrepancy;

suspend mult-2: add-1 is now OK ⇒ mult-2 is outputing 4 and is hence faulty. But this would mean that the second output would also read 10 unless add-2 was also faulty and this is less likely;

suspend mult-3: does not affect the output of add-1.

Clearly either add-1 or mult-1 are faulty and the choice between them could only be made by measuring Y. Multiple faults and more subtle faults (e.g. bridging) could also be possible but these would only be investigated once the elementary fault hypotheses had been ruled-out.

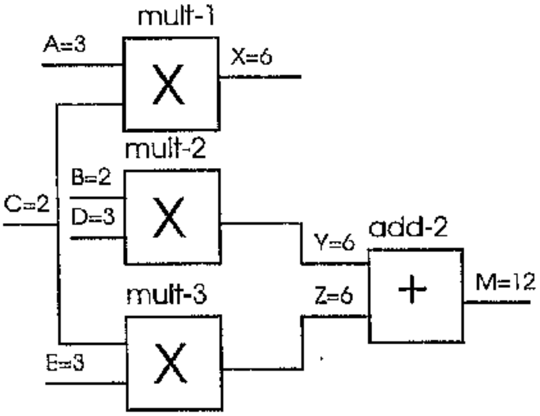


Fig. 3b   Computational Path when - Add-1 Suspended

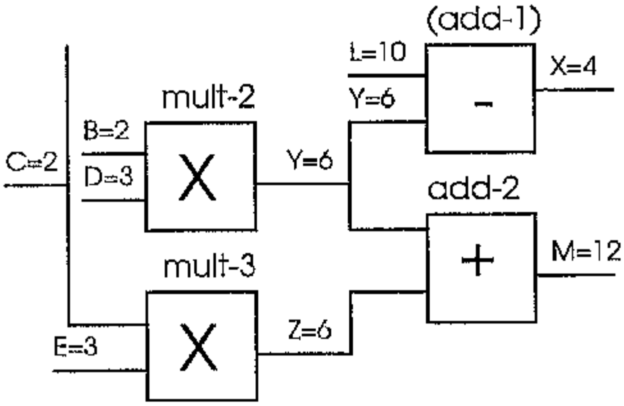


Fig. 3c   Computational Path When - Mult-1 Suspended

In performing the various suspensions, measured values have been propogated backwards and forwards through the circuit. For instance, suspend mult-1 resulted in the following argument: X CANNOT be calculated from A*C=6 but from B*D=Y=6 & X+Y=10 & C*E=Z=6 ⇒ X=10-6=4 (≠6) & Y+Z=12=output and hence mult-1 could be generating 4 in error. The numerical estimates resulting from the evaluation could be verified if a suitable measurement point was available.

In the HVAC case considering the example of a heater battery, for instance, such an analysis may correspond to a BEMS driver value for the control valve position differing from the position inferred from the constraints. This does not necessarily indicate that a fault exists in the control valve, it rather points to fault exists in the control valve, it rather points to an inconsistency between measured and inferred values. The fault may very well be located elsewhere.

3.2.3 THE APPLICATION TO AN AIR CONDITIONING UNIT

Constraint suspension applied to HVAC plants is complicated since the constraints do not represent simple digital components such as adders, subtractors and gates but heat exchangers and control elements which require more complex mathematical models. Thus while the structure of the ACU is simple the behaviour is complex. In addition the sparseness of measurement points and the number of variables involved in the diagnosis encourages the development of efficient programming techniques.

The ACU may be considered as a self-contained unit since it is assumed that,

- thermal inter-connections due to heat transfer between adjacent components and thermal transfer to/from the surroundings is insignificant,
- air leakage to/from the surroundings is considered negligible,
- there are no other apparent inter-connections.

The constraint suspension procedure must be adapted to deal with the particular difficulties encountered with HVAC systems. HVAC systems are unlike digital electronic circuits since,

- any measured sensor value may be incorrect (Hittle and Johnson 1984),
- they have complex constraints,
- probes cannot be inserted to determine intermediate values.

Sensors can be represented by the constraint,

$$input = output \qquad ..(3.4)$$

Potential faults in sensors are easily identified since it is only necessary to compare the inferred sensor value (calculated from the constraint network) with the measured sensor value.

Where the inferred sensor value is not equal to the measured sensor value there is a potential fault. Candidate generation is now a simple matter of comparing calculated (inferred) values with measured values for each sensor.

The physical organisation of a typical air conditioning unit consists of (Figure 4),

- the mixing box section,
- the cooling coil section,
- the heater battery section,
- the humidifier section,
- sensors, and
- BEMS drivers.

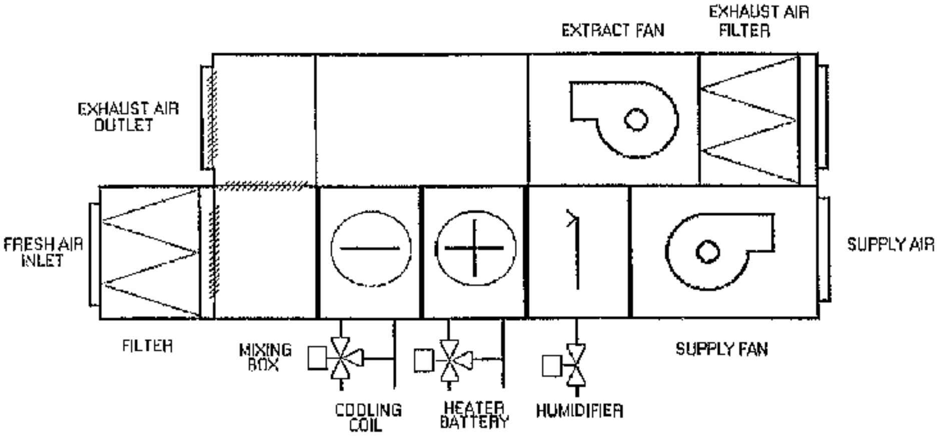


Fig. 4 Physical Arrangement of a Typical Air Conditioning Unit

The fan section is not considered since it does not change the state of air passing through it and so cannot be considered as a component in terms of constraint suspension. Furthermore fan failure faults can be easily detected and diagnosed.

Figure 5a shows the inference network obtained when the constraint, describing the BEMS driver for the humidifier valve (the component) is suspended. In this instance,

- the valve opening is calculated from the moisture contents of the air antering and leaving;
- the moisture content of the air entering the humidifier must be inferred from the cooling coil constraint (the mathematical representation of the cooling coil);
- the temperature and moisture content of the air entering the cooling coil must be inferred from the mixing box constraint (the mathematical representation of the mixing box);
- the temperature of the air leaving the cooling coil must be inferred from the heater battery constraint (the mathematical representation of the heater battery);

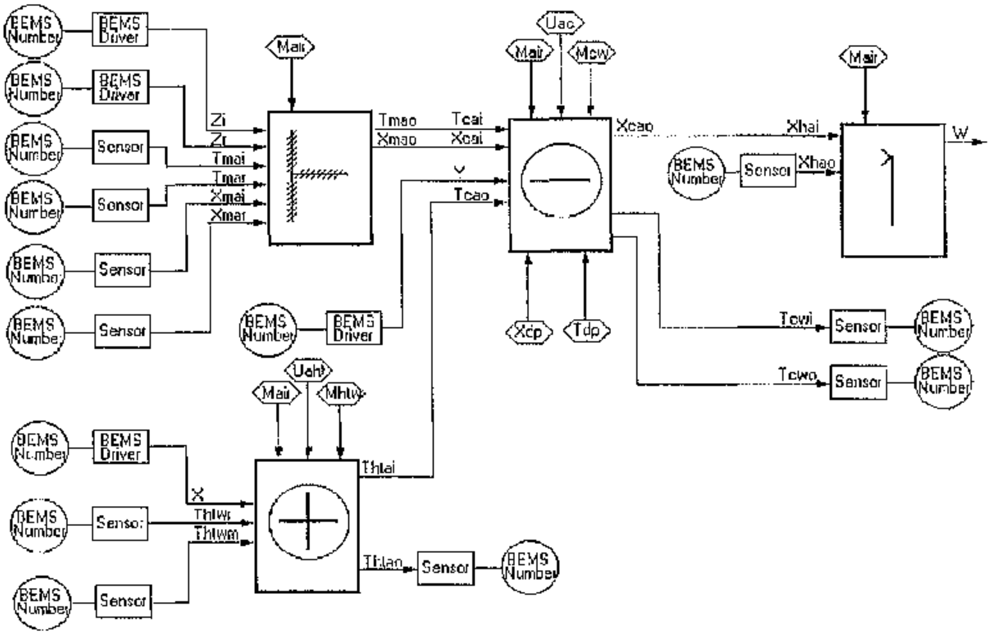


Fig. 5a Inference Network to Infer Humidifier Valve Position

The inference network changes according to which sensor or driver values are being inferred. The example of the inference network to infer the values of cooling coil valve position illustrates this (Figure 5b).

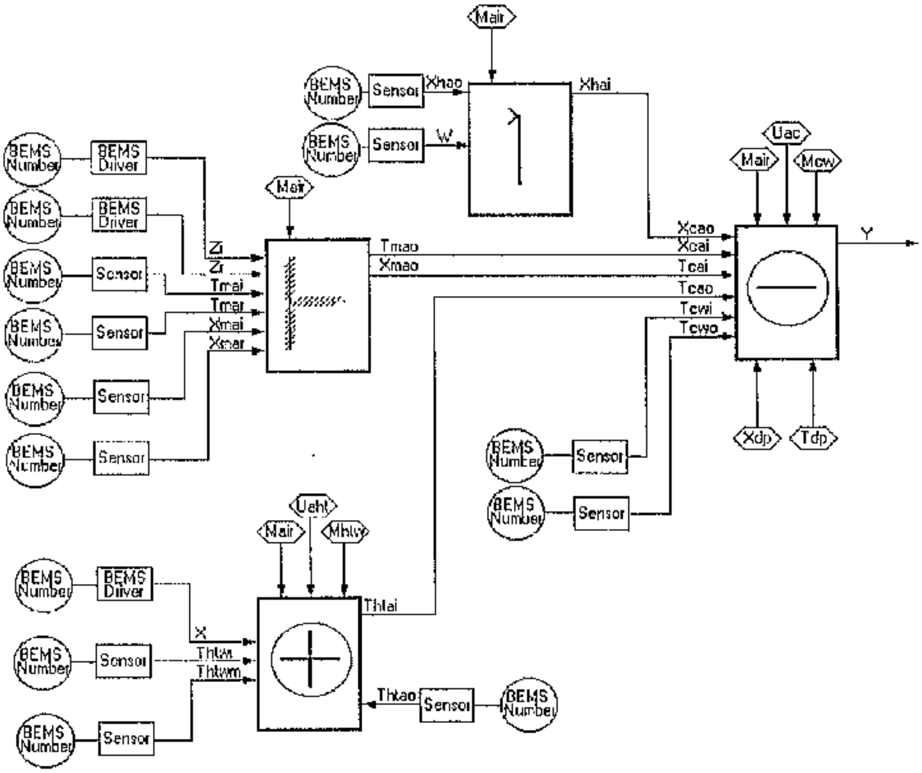


Fig. 5b Inference Network to Infer Cooling Coil Valve Position

In the HVAC case constraints can be derived from heat balance equations and heat exchanger models such as the number of transfer unit (NTU) method of modelling heat exchanger behaviours (Holman 1985). Steady state models are considered appropriate for this application for the reasons discussed in Appendix 1.

It is possible for many candidates to appear as potential faults and it is necessary to set up the computer programme so that the most likely will be considered first. A series of rules to increase the sensitivity and specificity of the computer programme are therefore applied.

1. In order to account for the coarse nature of the static model, only those variations, between inferred and measured data, which are at least 10% of the measured value will be considered as suspect.

2. Some faults are more common than others.

3. Some values must be less than one and greater than unity, for instance valve and damper positions.

4. Other values have limits imposed upon them due to for instance the chiller, boiler plant performance or climate.

These rules reduce the number of potential candidates to a more manageable level and hence increases the speed of diagnosis.

3.2.4 THE NEED FOR A DIFFERENT APPROACH TO CONTROL STRATEGIES

The technique of constraint suspension is not suited to the detection of faults in the implementation of controller strategies. This is because it is difficult to model the input output relationship of a Proportional-Integral-Derivative (PID) controller due to the effect of the integrator term. The integrator will always attempt to compensate for faults. A simple rule-based system is applied to the results obtained from the constraint suspension technique. This is considered appropriate since it is usual to specify the control strategy by a series of "if-then" rules.

3.3 MODELLING AND COMPUTER REPRESENTATION

3.3.1. THE MIXING BOX

The constraint is based on simple mass and energy balances:-

$$Tmao = Tmar + Z(Tmai - Tmar) \qquad ..(3.5)$$

$$Xmao = Xmar + Z(Xmai - Xmar) \qquad ..(3.6)$$

where:-

Tmao = mixing box air temperature out,

Tmar = mixing box return air temperature,

Tmai = mixing box fresh air temperature,
Xmao = mixing box air moisture content out,
Xmar = mixing box return air moisture content,
Xmai = mixing box fresh air moisture content,
Z = mixing box control damper position
(percentage fresh air).

A more rigorous treatment of the energy balances would consider enthalpies rather than temperatures. However, for the degree of accuracy required for the analysis of the mixing box performance and the range of temperatures encountered in air conditioning processes the simple balance used above is sufficiently accurate (Jones 1967).

The normal approach would be to recognise the directional flow of the air through the mixing box, by defining inputs as,

- air mass flow rate,
- position of control damper,
- outside air temperature,
- recirculation air temperature,
- outside air moisture content,
- recirculation air moisture content,

and outputs would then be as,

- mixed air moisture content,
- mixed air temperature,

This situation is illustrated schematically in Figure 6a. Here a rectangular box is used to denote a "component" and a hexagon is used to denote a constant. The constraint would be represented by the above equations.

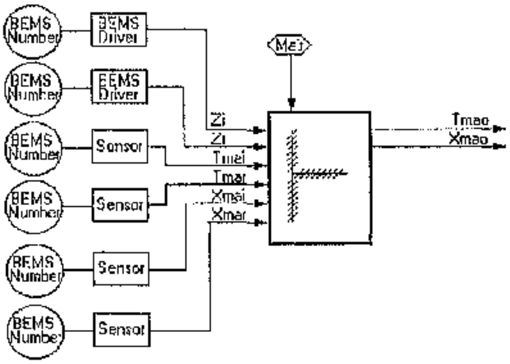


Fig 6a Mixing box Schematic to Infer Values for Tmao/Xmao

However, in certain instances it may be desirable to infer damper position or other values which would normally be considered as inputs. In these cases the mixed air moisture content and temperature would be treated as inputs and the damper position would become an output. This could be represented, schematically, as Figure 6b and as part of the constraint by rearranging the above equations to solve for Z.

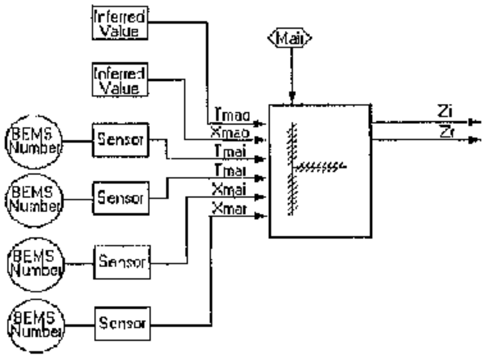


Fig 6b Mixing box Schematic to Infer Values for Z

3.3.2. THE COOLING COIL

The constraint in the case of the cooling coil is derived from simple mass and energy balance equations as well as the more complicated expressions arising from the application of the number of transfer units (NTU) method of modelling heat exchanger behaviour. The control valve is modelled with the cooling coil. This is because it is not easy to derive a cooling coil model which is independent of the control valve model. This is due to the absence of essential sensor information.

Two sets of equations are needed to describe heat exchanger behaviour because of the dependancy upon the ratio of the heat capacities of the fluids flowing through heat exchanger. Either water or air can be the minimum fluid, that is the fluid with the minimum heat capacity. The constraints are:-

$$MC_{cool} = YM_{w}C_{w} \qquad ..(3.7)$$

$$MC_{hot} = M_{air}C_{air} \qquad ..(3.8)$$

$$C = \frac{MC_{cool}}{MC_{hot}} \qquad ..(3.9)$$

$$C < 1 \qquad ..(3.10)$$

$$N = \frac{Uac}{MC_{cool}} \qquad ..(3.11)$$

$$E = \frac{1}{C}\{1 - e^{[-C(1-e^{-N})]}\} \qquad ..(3.12)$$

$$Tcao = Tcai - CE(Tcai - Tcwi) \qquad ..(3.13)$$

$$Xcao = Xcai - \frac{(Xcai - Xdp)(Tcai - Tcao)}{(Tcai - Tdp)} \qquad ..(3.14)$$

$$C = \frac{MC_{hot}}{MC_{cool}} \qquad ..(3.15)$$

$$C < 1 \qquad ..(3.16)$$

$$N = \frac{Uac}{MC_{hot}} \qquad ..(3.17)$$

$$E = 1 - e^{\{(-1/C)(1-e^{-NC})\}} \qquad ..(3.18)$$

$$Tcao = Tcai - CE(Tcai - Tcwi) \qquad ..(3.19)$$

$$Xcao = Xcai - \frac{(Xcai - Xdp)(Tcai - Tcao)}{(Tcai - Tdp)} \qquad ..(3.20)$$

where:-

Y = cooling coil control valve position

Mw = mass flow rate of water

Mair = mass flow rate of air

C = capacity ratio

N = number of transfer units

Uac = cooling coil heat transfer coefficient

E = cooling coil heat exchanger effectiveness

Tcai = cooling coil air temperature in

Tcao = cooling coil air temperature out

Tdp = cooling coil apparatus dew point temperature

Tcwi = cooling coil water temperature in

Xcai = cooling coil air moisture content in

Xcao = cooling coil air moisture content out

Xdp = cooling coil apparatus dew point moisture content

The usual approach is to accommodate the directional flow of the air through the cooling coil by defining inputs as,

- air mass flow rate,
- entering air temperature,
- entering air moisture content,
- position of control valve,
- cooling water temperature in,
- cooling water temperature out,
- water mass flow rate,
- cooling coil heat transfer coefficient,
- cooling coil apparatus dew point temperature,
- cooling coil dew point moisture content,

and outputs as,

- leaving air (off-coil) temperature,
- leaving air (off coil) moisture content,

This situation is illustrated schematically in Figure 7a. Note that Uac is deemed to be a "component" that can be suspended. This is discussed in Section 4.2.

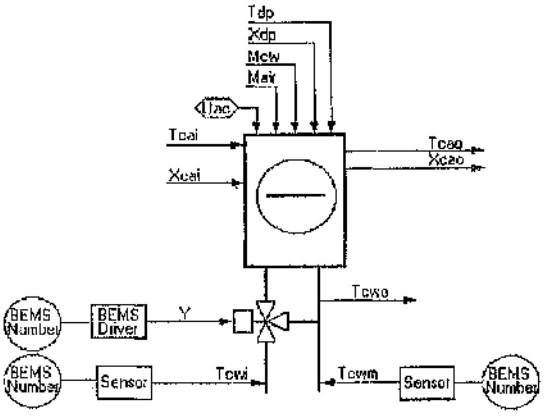


Fig. 7a Cooling Coil Schematic to Infer Values for Tcao/Xcao

As with the mixing box it may be necessary to infer values which would usually appear as inputs. In these cases inputs and outputs are interchangeable. The equations linking them are manipulated to remain consistent.

For example for the valve position (Y) to be an output, the inputs and outputs could be represented, schematically, as Figure 7b and the set of equations derived by rearranging to solve for Y.

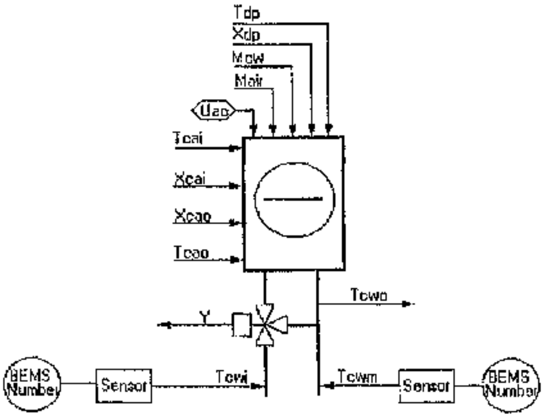


Fig. 7b Cooling Coil Schematic to Infer Values for Y

3.3.3. THE HEATER BATTERY

The constraint in this case is based on the same approach as for the cooling coil. For instance the control valve is modelled with the cooling coil. For this particular application the heating water will always be the fluid with the minimum heat capacity. The products of the flow rates and specific heats, are such, that even with the maximum water flow rate the heating water will still be the minimum fluid. Therefore only one set of equations is needed to model the behaviour of the heater battery; these are:-

$$MC_{cool} = M_{air}C_{air} \qquad ..(3.21)$$

$$MC_{hot} = XM_{w}C_{w} \qquad ..(3.22)$$

$$C_{ht} = \frac{MC_{hot}}{MC_{cool}} \qquad ..(3.23)$$

$$C_{ht} < 1 \qquad ..(3.24)$$

$$Nht = \frac{Uaht}{MC_{hot}} \qquad ..(3.25)$$

$$Eht = 1 - e^{\{((\frac{-1}{C_{ht}})(1-e^{-NhtCht}\}} \qquad ..(3.26)$$

$$Thtao = Thtai - C_{ht}E_{ht}(Thai - Thtwi) \qquad ..(3.27)$$

where:-

X = heater battery control valve position
mw = mass flow rate of water
mair = mass flow rate of air
Cht = capacity ratio
Nht = number of transfer units
Uaht = heater battery heat transfer coefficient
Eht = heater battery heat exchanger effectiveness
Thtai = heater battery air temperature in
Thtao = heater battery air temperature out
Thtwi = heater battery water temperature in

By defining inputs in terms of the directional flow of the air, heater battery inputs may be considered as,

- entering air temperature,
- entering water temperature,
- leaving water temperature,
- control valve position,
- water mass flow rate,
- air mass flow rate,
- overall heat transfer coefficient,

and outputs as,

- leaving air temperature.

These are shown schematically in Figure 8a.

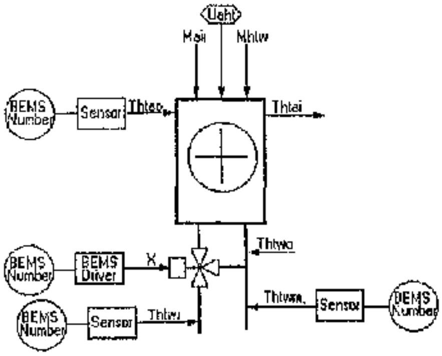


Figure 8a Heater Battery Schematic to Infer Values for Thtai

Again, for the heater battery, other values such as control valve position may need to be modelled. Although these may usually be considered as inputs, the set of equations can be obtained by rearranging the above to solve for X. The schematic arrangement is shown in Figure 8b.

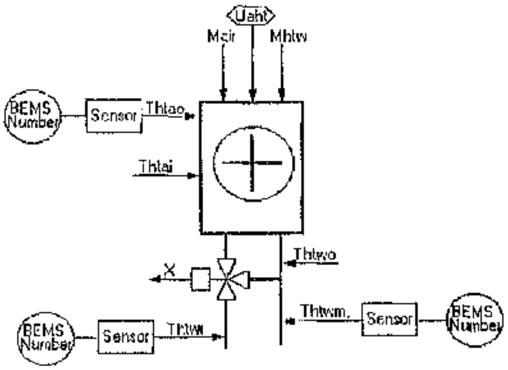


Figure 8b Heater Battery Schematic to Infer Values for X

3.3.4. THE HUMIDIFIER

The humidifier in this example, is of the direct steam injection type. The direct steam injection method of humidification has a negligible effect on sensible heat gain to the air. Therefore changes to the air temperature leaving the humidifier can be ignored.

The equation for the humidifier is therefore:-

$$Xhao = Xhai + WM_{steam} \quad ..(3.28)$$

where:-

W = humidifier control valve position

Msteam = maximum flow rate of steam

Xhao = humidifier air moisture content out

Xhai = humidifier air moisture content in

Considering the directional flow of the air through the humidifier section defines the inputs as,

- air mass flow rate,
- entering air temperature,
- entering air moisture content,
- position of control valve,
- maximum steam mass flow input,

and the outputs as,

- leaving air temperature,
- leaving air moisture content,

These are shown schematically in Figure 9a.

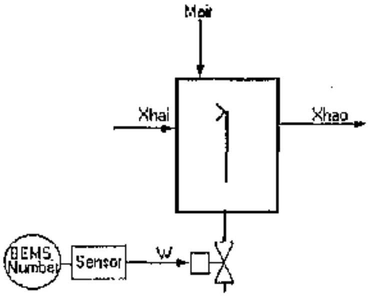


Fig. 9a Humidifier Schematic to Infer Values for Xhao

The equation can be rearranged to infer, for instance, the valve position as an output if required.

This is shown schematically in Figure 9b.

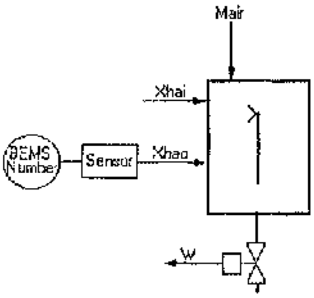


Fig. 9b Humidifier Schematic to Infer Values for W

3.4 THE REASONING PROCESS

3.4.1 INTRODUCTION

This application of constraint suspension is implemented in turbo-prolog (Borland International 1986). PROLOG is a commercially available language suitable for use with personal computers. The language is declarative. This means that PROLOG can reason from a set of facts and goals to solve problems. This facility of PROLOG allows for flexible and adaptable approaches with respect to problem solving.

PROLOG is able to perform the logical reasoning required. In addition PROLOG can perform mathematical calculations.

The reasoning procedure is shown schematically (Figure 10) and is described in the following sections

3.4.2 THE APPROACH

1. INPUTING MEASURED BEMS SENSOR DATA

The sensor data (Figure 10) is collected by the BEMS and displayed on the BEMS central processor visual display unit in schematic form. This BEMS data is manually entered into the PROLOG data base and displayed in a table.

2. SUSPENDING CONSTRAINTS FOR COMPONENT (SENSOR)

In accordance with the constraint suspension technique (Section 3.2) each constraint is suspended in turn and inferred values calculated. All other BEMS measured values (if treated as inputs) are assumed to be correct.

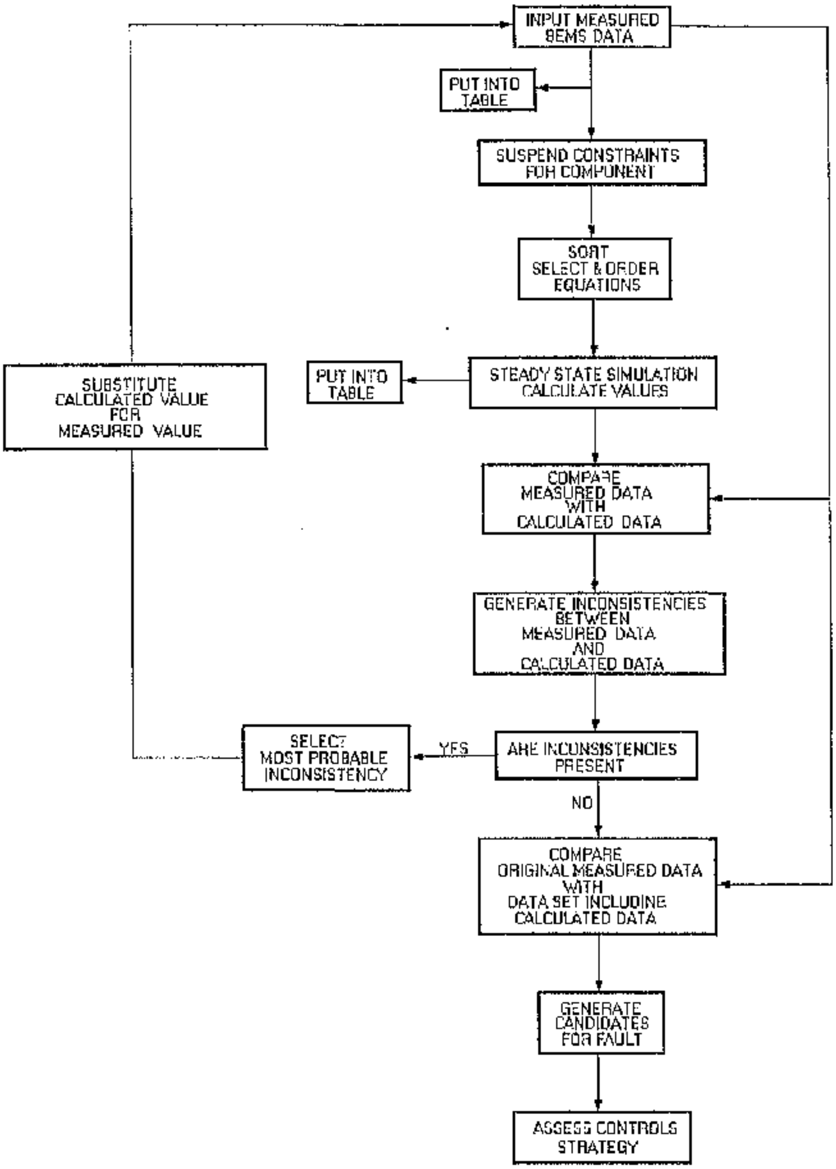


Fig 10 Flow Chart Showing Reasoning Process of Program

The computational arrangement of the components may or may not resemble the physical arrangement. Figure 5a illustrates the arrangement of components for inferring a value for the humidifier valve BEMS driver, (W). It is necessary to consider a different inference network for each constraint suspended (for example Figure 5b), in order that an inferred value may be derived. The procedure must therefore be able to select and order constraints to calculate each value.

3. SORTING, SELECTING AND ORDERING EQUATIONS

The procedure for selecting the equations is described with reference to the functional organisation (Figure 5a) for the humidifier valve position, (W) ,

1. Select the equation required to calculate the humidifier valve position, (W).
2. Select the data required to calculate humidifier valve position, (W).
3. Identify the data held in the data base, that is the,
   mass flow of air, (Mair),
   humidifier air moisture content out, (Xhao).
4. Identify the data to be inferred, that is the,
   humidifier air moisture content in, (Xhai).
5. Select the equation(s) required to calculate humidifier air moisture, (Xhai).
6. Select the data required to calculate humidifier air moisture content in, (Xhai).
7. Identify the data held in the data base, that is the,
   mass flow of air, (Mair),
   mass flow of cooling water, (Mcw),
   cooling coil heat transfer coefficient, (Uac),
   cooling coil apparatus dew point temperature, (Tdp),
   cooling coil apparatus dew point moisture content (Xdp),
   cooling coil valve position, (Y).
8. Identify the data to be inferred, that is the,
   cooling coil air moisture content in, (Xcai),
   cooling coil air temperature in, (Tcai),
   cooling coil air temperature out, (Tcao).
9. Select the equation(s) required to calculate,
   cooling coil air moisture content in, (Xcai),
   cooling coil air temperature in, (Tcai),
10. Select the data required to calculate,
   cooling coil air moisture content in, (Xcai),
   cooling coil air temperature in, (Tcai).

11. Identify the data held in the data base, that is the,
   mass flow of air, (Mair),
   mixing box fresh air temperature, (Tmai),
   mixing box fresh air moisture content, (Xmai),
   mixing box return air temperature, (Tmar),
   mixing box return air moisture content, (Xmar),
   mixing box fresh air damper, (Zi),
   mixing box return air damper position, (Zr).
12. Identify the data to be inferred,
   no data to be inferred.
13. Select the equation(s) required to calculate,
   cooling coil air temperature out, (Tcao).
14. Select the data required to calculate,
   cooling coil air temperature out, (Tcao),
15. Identify the data held in the data base, that is the,
   mass flow of air, (Mair),
   heater battery heat transfer coefficient, (Uaht),
   heating water mass flow rate, (Mhtw),
   heating water flow temperature, (Thtwi),
   heating water return temperature, (Thtwm),
   heater battery valve position, (X).
16. Identify the data to be inferred, that is ,
   no data to be inferred.

When there is no more data to be inferred then a set of equations has been assembled and ordered to infer the humidifer control valve position (W) and the calculation can now be performed.

The above procedure (steps 1-16) is continously repeated for each sensor and component. The calculated values are output and presented in tables alongside the original measured data base.

4. COMPARING MEASURED SENSOR DATA WITH CALCULATED SENSOR DATA

After all the various constraints have been suspended and the inferred values calculated, measured and inferred values are finally compared. This comparison produces a set of percentage differences between measured and inferred values.

5. GENERATING INCONSISTENCIES BETWEEN MEASURED SENSOR DATA WITH CALCULATED SENSOR DATA

The set of percentage differences is analysed to generate a set of inconsistencies. This will be used to identify potential faults (candidate generation). The number of potential faults is limited by applying the rules listed in Section 3.2.3.

6. SELECTING THE MOST PROBABLE CANDIDATE

By applying the rules listed (Section 3.3.7) to the set of potential faults, the most probable fault can be selected.

7. SUBSTITUTING CALCULATED VALUE INTO DATA BASE

The calculated inferred value for the candidate (sensor) selected is substituted into the data base containing the measured BEMS values.

8. REITERATING THE PROCESS

The procedure is repeated until the set of inferred calculated values is consistent with the set of measured values, (that is, each inferred value agrees with each measured BEMS value). The final set of measured values includes those inferred values which have been substituted into the data base.

9. GENERATED CANDIDATES FOR FAULTS

Inferred values substituted for measured values in the data base are detected by comparing the original data base of measured values with the final data base which now includes both measured and substituted inferred values. Faults are identified by those components associated with the substituted inferred values.

3.5 IMPLEMENTATION

3.5.1 CONSTRAINT REPRESENTATION

The mathematical model equations for the mixing dampers, heater, cooler and humidifier can be re-arranged so that different variables can be calculated. Thus a number of sets of equations can be produced for each component. These sets are input into Prolog as computational procedures of the form

```
component(name,set_number,{input_variables},{variables_calculated}):-
                                  {variables_calculated} = some function of the {input_variables}.
```

For the different components these might include procedures with left-hand sides,

```
component(mixer,1,{Zi,Zr,Tmai,Tmar,Xmai,Xmar,Mair},{Tmao,Xmao})
component(mixer,2,{Tmai,Tmar,Tmao},{Zi,Zr})
component(cooler,1,{Tcai,Xcai,Y,Tcwi,Tcwm,Mcw,Uac,Mair,Tdp,Xdp},{Tcao,Xcao,Tcwo})
component(cooler,2,{Tcao,Xcao,Tcai,Xcai,Tcwi,Tcwm,Mcw,Uac,Mair,Tdp,Xdp},{Y,Tcwo})
component(heater,1,{X,Uaht,Mair,Thtwi,Thtwm},{Thtai,Thtao}
component(heater,2,{X,Uaht,Mair,Thtai,Thtao,Thtwm},{Thtwi}
component(humidifier,1,{W,Mair,Xhai},{Xhao}
component(humidifier,2,{Mair,Xhai,Xhao},{W}
```

Sensors, parameters and BEMS output devices need not be represented by components at all since they are all instances of the same 'through' device i.e. output=input. These components are therefore merely represented as the set *inputs*:

$\{w,x,y,zi,zr,tmai,tmar,xmai,xmar,thtwi,thtwm,thtao,xhao,tcwi,tcwo,uac,uaht\} \subseteq \mathit{inputs}$

A database is then constructed of all the left-hand sides together with the set *inputs*. Note that here we use {} and [] to discriminate between sets and lists where order matters.

3.5.2 INFERENCE NETWORK GENERATION

Although prolog is quite capable of automatically selecting those procedures that are needed to form a particular inference network and of subsequently performing an evaluation, it was felt that this might be computationally inefficient. Instead the two tasks are performed separately with a file transfer linking the two together.

Figure 5a shows the inference network needed to infer the humidifier valve opening W. The computational order can be represented by 2 ordered lists, *constraints* and *set_numbers*, where

components = [mixer,heater,cooler,humidifier]
set_numbers = [1,2,3,1] say,
and *set_numbers* defines the sets of equations needed to solve the particular component models. These lists can be generated, automatically, by retracting w from *inputs* in the database and then performing the following recursive search of the database starting with *outputs* = {w} and *components* = {mixer,heater,cooler,humidifier}.

1. Identify a component(name,set_number,{input_variables},{variables_calculated}):

   ({variables_calculated} $\cap$ *outputs*) $\neq$ {} & name $\subseteq$ *components* ;

2. remove name from *components*, remove ({variables_calculated} $\cap$ *outputs*) from *outputs* and remove ({input_variables} $\cap$ *inputs*) from *inputs* ;

3. let *outputs* = *inputs* $\cup$ *outputs* ;

4. If *outputs* = {} then success and stop,
   if *components* ≠ {} then go to 1. else backtrack until all possibilities have been exhausted.

3.5.3 EVALUATION

Each inference network is then evaluated by calling the sequence of procedures identified by *constraints* and *set_numbers*.

3.6 CONTROL STRATEGIES

The control strategy is assessed by using a series of 'if-then' rules in conjunction with the values contained in the data base which now incorporates both measured and substituted inferred values. The use of 'if-then' type rules circumvents the need to quantify the integral terms in the Proportional + Integral (P+I) controllers.

The control strategy thus performs the following actions;

1. Room thermostat adjusts the supply air temperature controller to maintain room air temperature.

2. Room humidistat adjusts the supply air humidity controller to maintain room air humidity.

3. Supply air temperature controller adjusts heater battery control valve, fresh,return and exhaust air (mixing) dampers and cooling coil control valve in sequence to maintain supply air temperature

4. The cooling coil dehumidifies the air when the humidity set point in the room is exceeded. Dehumidification has priority over air temperature control requirements if more cooling is required to satisfy dehumidification demand.

5. The humidistat will modulate the humidifier valve when the room humidity falls below the room set point.

6. The mixing damper controller will modulate to achieve the supply air temperature if the desired supply air temperature is between the outside air temperature and the return air temperature.

7. The mixing damper will close to a minimum of 10% if the return air temperature lies between the outside air temperature and the desired supply air temperature.

8. The mixing damper will open to 100% if the outside air temperature lies between the return air temperature and the desired supply air temperature.

These strategies can be shown on scheduling diagrams (Figs 11-13).

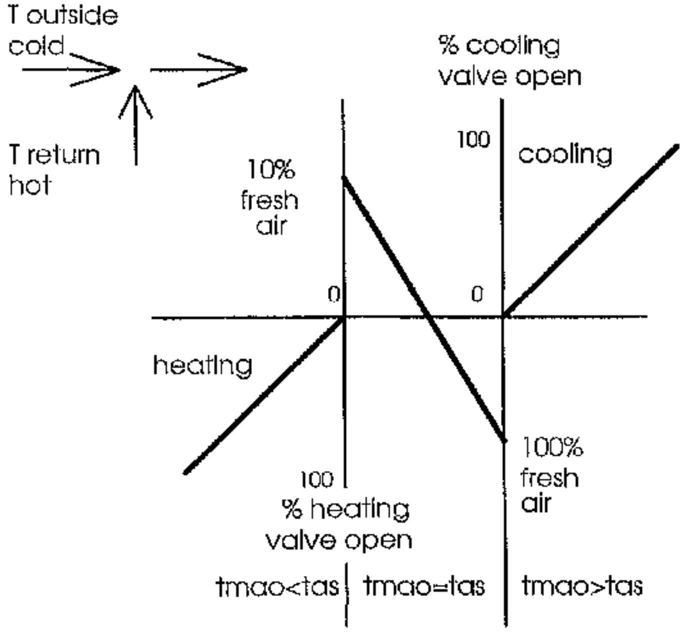


Fig 11 Scheduling Diagram for Supply Temperature Air less than Room Air Temperature

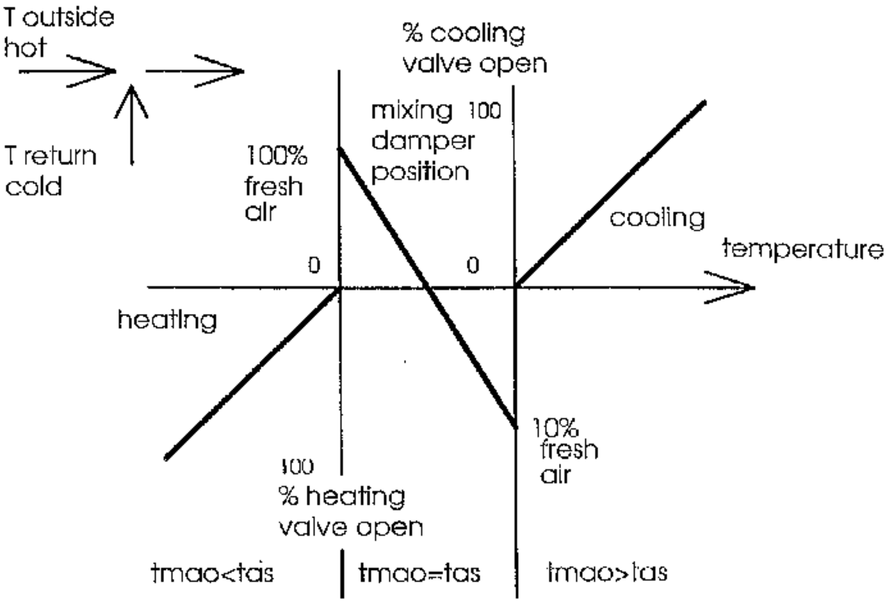


Fig 12 Scheduling Diagram for Room Air Temperature less than Supply Air Temperature

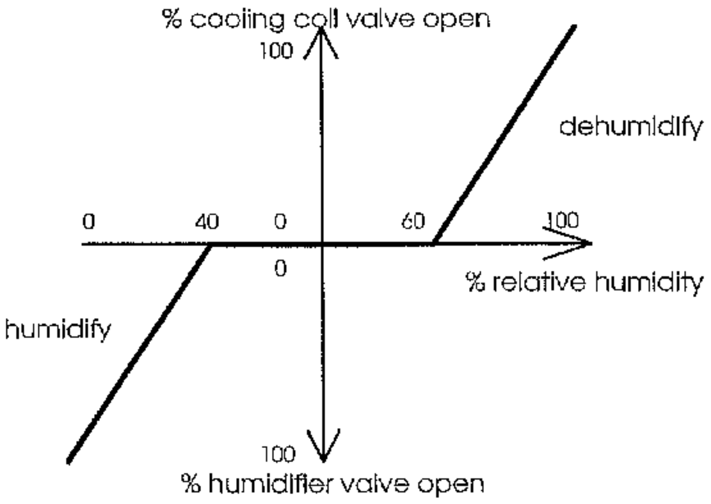


Fig. 13 Scheduling Diagram for Humidification/Dehumidification

It is usual in the U.K. to assume that if the outside temperature is hot then it is also humid and to switch to 10% fresh air regardless of the need for reheat.

It is necessary to translate the above diagrams into usable sets of 'if-then' rules. These rules are simplified by considering the processes involved in air conditioning, with the associated valve and damper positions summarised in Table 1.

TABLE 1 CONTROL STRATEGY SUMMARY

PROCESS	Humidifier Valve	Heater Battery Valve	Cooling Coil Valve	Mixing Damper	
	(W)	(X)	(Y)	(Z)	
				Thtao<Tmar	Tmar<Thtao
Heating only	0	0 - 1	0	Tmai<Tmar 0.1-1.0 Tmai>Tmar 1.0	Tmai<Tmar 0.1 Tmar<Tmai 1.0
Cooling only	0	0	0 - 1	Tmai<Tmar 1.0 Tmai>Tmar 0.1	0.1-1.0
Heat + Humidify	0 - 1	0 - 1	0	Tmai<Tmar 0.1-1.0 Tmai>Tmar 1.0	Tmai<Tmar 0.1 Tmar<Tmai 1.0
Cool + Dehumidify	0	0	0 - 1	Tmai<Tmar 1.0 Tmai>Tmar 0.1	0.1-1.0
Cool Dehumidify Reheat	0-1	0 - 1	0 - 1	Tmai<Tmar 1.0 Tmai>Tmar 0.1	0.1-1.0
Mix	0	0	0	0.1 -1	0.1 -1

In addition the strategy for humidification or dehumidification must be superimposed. This is a simple if-then rule based on humidification being called for if the room relative humidity falls below 40%. Dehumidification is called for if the room relative humidity rises above 60%.

- **If** Xhar < 0.4 **then** humidify
- **If** Xhar > 0.6 **then** dehumidify

The following 'if-then' rules are derived from Table 1,

- **If** 0 < X < 1 **and** Y = 0 **then** heating only:-
  If Thtao < Tmar and Tmai < Tmar then Z = 0.1 - 1.0,
  If Thtao < Tmar and Tmai > Tmar then Z = 1.0,
  If Thtao > Tmar and Tmai < Tmar then Z = 0.1,
  If Thtao > Tmar and Tmai > Tmar then Z = 1.0,

- **If** X = 0 **and** 0 <Y < 1 **then** cooling only or cooling and dehumidification:-
  If Thtao < Tmar and Tmai < Tmar then Z = 1.0,
  If Thtao < Tmar and Tmai > Tmar then Z = 0.1,
  If Thtao > Tmar then 0.1 < Z < 1.

- **If** 0 < W < 1 **and** 0 < X < 1 **and** Y = 0 **then** heating and humidification:-
  If Thtao < Tmar and Tmai < Tmar then Z = 0.1 - 1.0,
  If Thtao < Tmar and Tmai > Tmar then Z = 1.0,
  If Thtao > Tmar and Tmai < Tmar then Z = 0.1,
  If Thtao > Tmar and Tmai > Tmar then Z = 1.0,

- **If** 0 < X < 1 **and** 0 < Y < 1 **then** cooling dehumidification and reheat:-
  If Thtao < Tmar and Tmai < Tmar then Z = 1.0,
  If Thtao < Tmar and Tmai > Tmar then Z = 0.1,
  If Thtao > Tmar then 0.1 < Z < 1.

- If X = 0 **and** Y = 0 **then** mixing:-
  0.1 < Z < 1.

4.0 RESULTS

4.1 INTRODUCTION

This chapter attempts to verify the method of chapter 3 by applying it to collected BEMS data from an operating air conditioning unit (ACU). The results are presented from three sets of data obtained from the schematic output from the BEMS and three 'runs' of the fault detection and diagnosis programme. The measured and calculated data will be presented in tables and will be described and analysed.

The constraint suspension technique is first applied to the air conditioning unit at sensor level it is then applied to component level. Finally the control strategy is assessed using the rule base.

Before the results analysis a brief description of the air conditioning unit is given

4.2 SYSTEM DESCRIPTION OF THE AIR CONDITIONING UNIT

The ACU is one of two Woods type Airpac Air Handling Units 489006/09F serving a 4000 square metre factory space for light engineering production of aerospace components. The building is of steel frame construction with metal/mineral wool/metal sandwich cladding and roof. There are no windows or roof lights.

The ACU comprises a mixing box, cooling coil, heater battery, humidifier and fan sections. The extract section is mounted above the supply section. Control dampers are opposed blade type operated by Belimo actuators and are assumed to have a linear characteristic. Control valves are Honeywell equal percentage type with electric motor drives and are assumed to have a relatively high authority. Temperature and humidity sensors are Honeywell.

Cooling coil and heater battery coils are copper tube/aluminium fin type and the humidifier is a steam injection type.

Manufacturer's data for the air conditioning unit is as follows:-

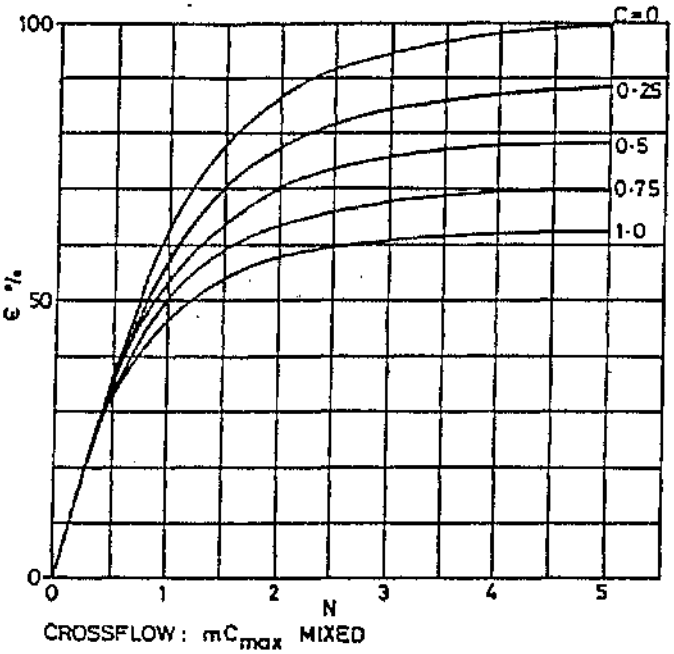
Air Volume Flow Rate	13.0 m /s
Heater Battery on coil temperature	16.5 deg C
Heater Battery off coil temperature	23.0 deg C
MTHW flow temperature	120.0 deg C
MTHW return temperature	90.0 deg C
MTHW flow rate	0.81 Lt/sec
Cooling Coil on coil temperature	22.2 deg C db
	15.9 deg C wb
Cooling Coil off coil temperature	12.0 deg C db
	11.0 deg C wb
Cooling water flow temperature	5.5 deg C
Cooling water return temperature	11.0 deg C
Cooling water flow rate	8.7 Lt/sec
Cooling Coil apparatus dew point	10.0 deg C

The air conditioning unit manufacturer was unable to provide the heat transfer coefficients for the cooling coil and the heater battery. They must therefore be estimated from the data. The selection of the heat transfer coefficient and the effect this has on the method is discussed in the next section.

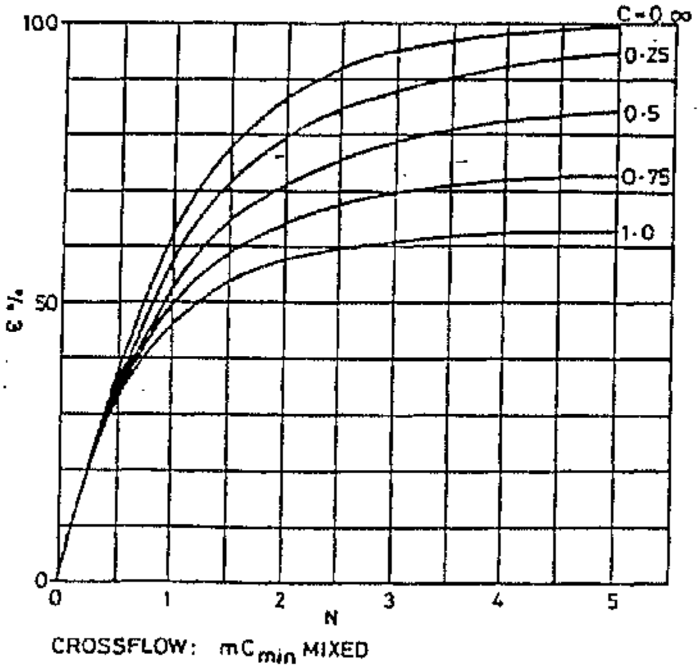
4.2 SELECTION OF HEAT TRANSFER COEFFICIENTS

In the absence of manufacturer's data for the values for heat transfer coefficients values were calculated from the BEMS data using the NTU method described previously. This is rather crude and it is important to establish whether the analysis will, as a consequence be sensitive to errors in the estimation. This is because the sensor data may not be correct and computational error may give variations in heat transfer coefficient values. In addition errors may the relationships between heat exchanger effectiveness (ε) and number of transfer units (N). Since number of transfer units is proportional to heat transfer coëfficient, variation in heat transfer coefficient will produce a variation in heat exchanger effectiveness. This will, in turn, result in variations in those variables which depend on a calculated value for the heat exchanger effectiveness. For example the variation of valve position with heat transfer coefficient to obtain one particular off-coil condition is summarised in Tables 2-3 and the results shown on Graphs 3-4. These indicate that a small variation in the heat transfer coefficient will produce a variation in the valve position.

The foregoing analysis shows that small variations in heat transfer coefficient can significantly affect the calculated value of valve position. Hence, where there are logical inconsistencies in the overall model the value of heat transfer coefficient should be investigated first. Further development of the model to use more complex methods of modelling valve position may be beneficial in this case; however, it must be remembered that this will be at additional development cost.



Graph 1 Cross Flow Heat Exchanger Effectiveness MC$_{max}$ Mixed



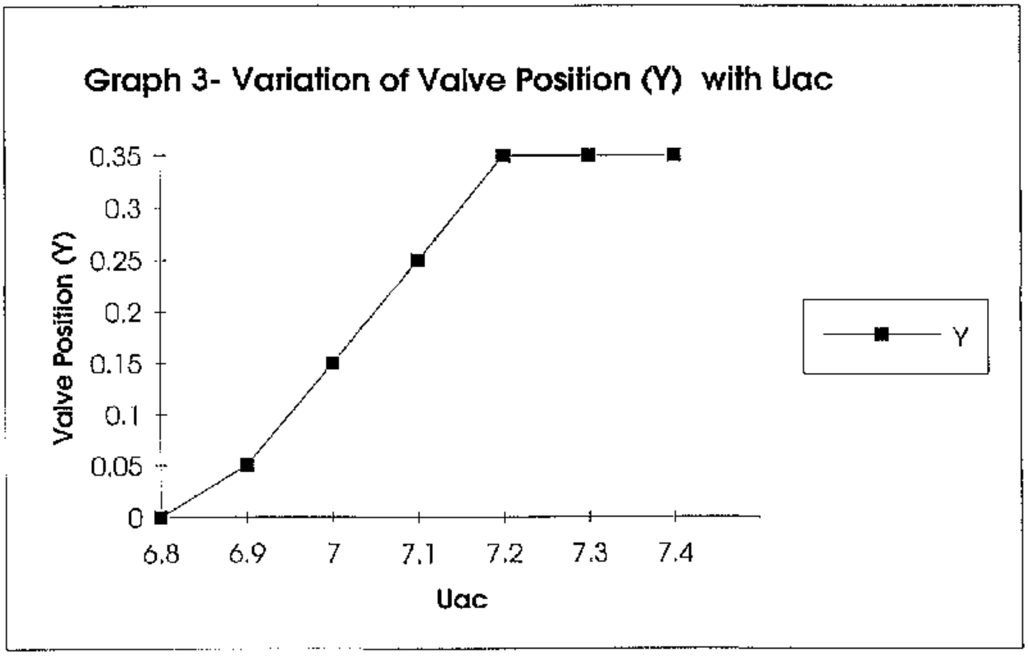
Graph 2 Cross Flow Heat Exchanger Effectiveness MC$_{min}$ Mixed

Uaht	1	1.05	1.1	1.2	1.25	1.3	1.35
X		0.15	0.35	0.45	0.55		

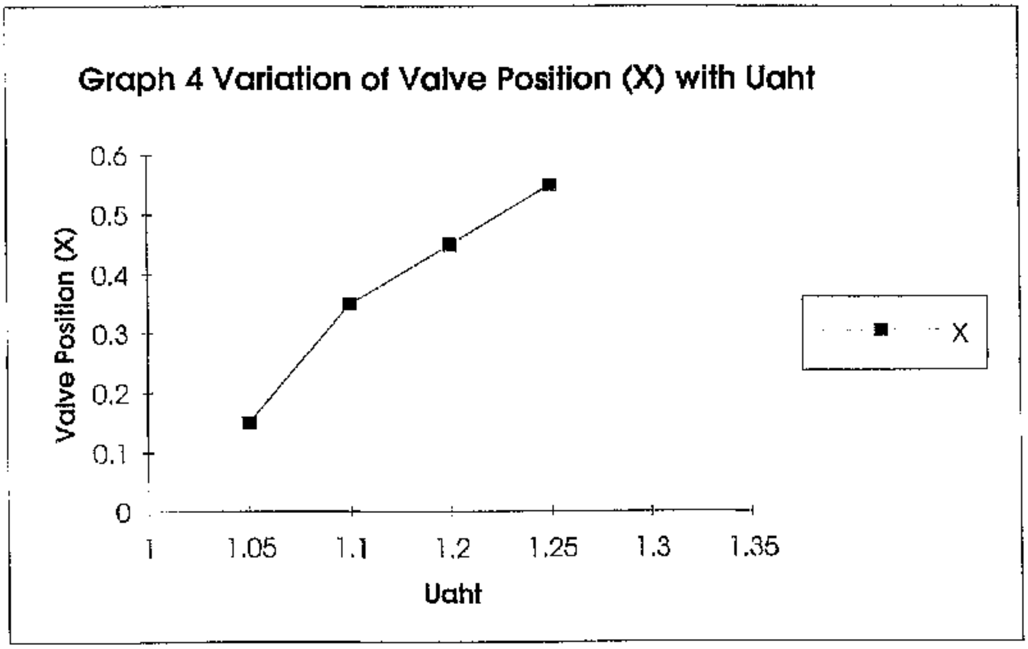
Table2 Variation of Heater Battery Valve Position with Heat Transfer Coefficient

Uac	6.8	6.9	7	7.1	7.2	7.3	7.4
Y	0	0.05	0.15	0.25	0.35	0.35	0.35

Table 3 Variation of Cooling Coil Position with Heat Transfer Coefficient



Graph 3- Variation of Valve Position (Y) with Uac



Graph 4 Variation of Valve Position (X) with Uaht

4.3 ANALYSIS OF RESULTS

4.3.1 DATA SET 1 CONSTRAINT SUSPENSION FOR SENSORS

The calculated values and data set obtained by suspending sensor and parameter constraints are compared in Table 4. Those obtained by suspending other components are given in Table 5. There is a numerical correlation between the calculated values and the data set except for the values for cooling coil water temperature mixed (Tcwm). This variable (Tcwm) represents the temperature of the cooling water return downstream of the mixing valve.

Therefore it may be suggested that there is a fault in the temperature sensor.

TABLE 4. RESULTS FROM ORIGINAL: DATA SET 1

(original data set) **Suspended Constraint**

Constraint	Data	W	X	Y	Zi/Zr	Xmai Tmai	Xmar Tmar	Thtwi	Thtwm	Uaht	Tcwi	Tcwm	Uac	Thtao	Xhao
W	0.000	0.029													
X	0.273		0.25												
Y	0.448			0.45											
Zi	0.30				0.293										
Zr	0.69				0.707										
Xmai	9.4					10.04									
Tmai	0.003					0.004									
Xmar	0.006						0.006								
Tmar	22.2						22.48								
Thtwi	98.3							110.5							
Thtwm	76.0								75.96						
Uaht	1.189									1.196					
Tcwi	7.17										7.73				
Tcwm	20.0											9.181			
Uac	5.47												5.104		
Thtao	22.76		21.91	20.29	20.29	20.29	20.29					20.29	20.29	20.28	20.29
Xhao	0.006		0.006						0.006						0.006
Tmao		18.25	18.25	18.25	18.45	18.45	18.45	18.25	18.25	18.25	18.25	18.25	18.25		18.25
Xmao		0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006		0.006
Thtwo															
Thtai					15.52	15.52	15.52					15.52	15.52	15.52	15.52
Xcao		0.006			0.006	0.006	0.006	0.006	0.006	0.006	0.005		0.006		0.006
Tcai		15.52	17.14	15.52	18.45	18.45	18.45				15.62				18.25
Xhai												0.006			0.006
Tcao		20.29	15.37	16.49				15.37	15.37	15.37	20.29				
Tcwo															
Xhal															

4.3.2 DATA SET 1 CONSTRAINT SUSPENSION FOR COMPONENTS

The calculated values are shown in Table 5. These results indicate consistency with the mathematical models and the sensor values.

TABLE 5. RESULTS FROM ORIGINAL: DATA SET 1 COMPONENT CONSTRAINTS SUSPENDED

(original data set) **Suspended Constraint**

Constraint	Data	Mixing Box	Heater	Humidifier
W	0.000			
X	0,273	0,273		0,273
Y	0.448	0.448		0.45
Zi	0.30			
Zr	0,69			
Xmai	0.003	0.004		
Tmai	9.4	9.39		
Xmar	0,006			
Tmar	22,2			
Thtwi	98.3		109.83	
Thtwm	76.0			
Uaht	1.189			
Tcwi	7.17	7.17		7.17
Tcwm	9.19	8.38		8.39
Uac	5.47			
Thtao	22.76	20.29		20.29
Xhao	0.006			
Tmao			18.32	18.32
Xmao			0.005	0.005
Thtwo		67.6		67.62
Thtai		15.5		15.52
Xcao		0.006		0.0058
Xcai		0.0053		
Tcai		18.32		18.32
Xhai		0.005	0.006	
Tcao		15.52	15.52	
Tcwo		9.38		9.38
Xhai				

4.3.3 CONTROL STRATEGY FOR DATA SET 1

The output from data set 1 is shown schematically in Figure 14. The input data taken from a BEMS printout is shown schematically in Figure 15.

By applying the rules listed in Section 3.6 it can be observed that the outside temperature is less than the supply temperature which is in turn less than the return air temperature. The humidifier valve is closed and the Heater battery and cooling coil valves are both modulating. This indicates that cooling, dehumidification and reheating is taking place. Since the outside air temperature is less than the return air temperature the mixing damper should be modulating to supply between 10% - 100% fresh air. However consideration of the control strategy indicates that the plant should be humidifying since the relative humidity is at 38.19%. The control strategy for humidification/dehumidification would therefore appear to be incorrect in this case.

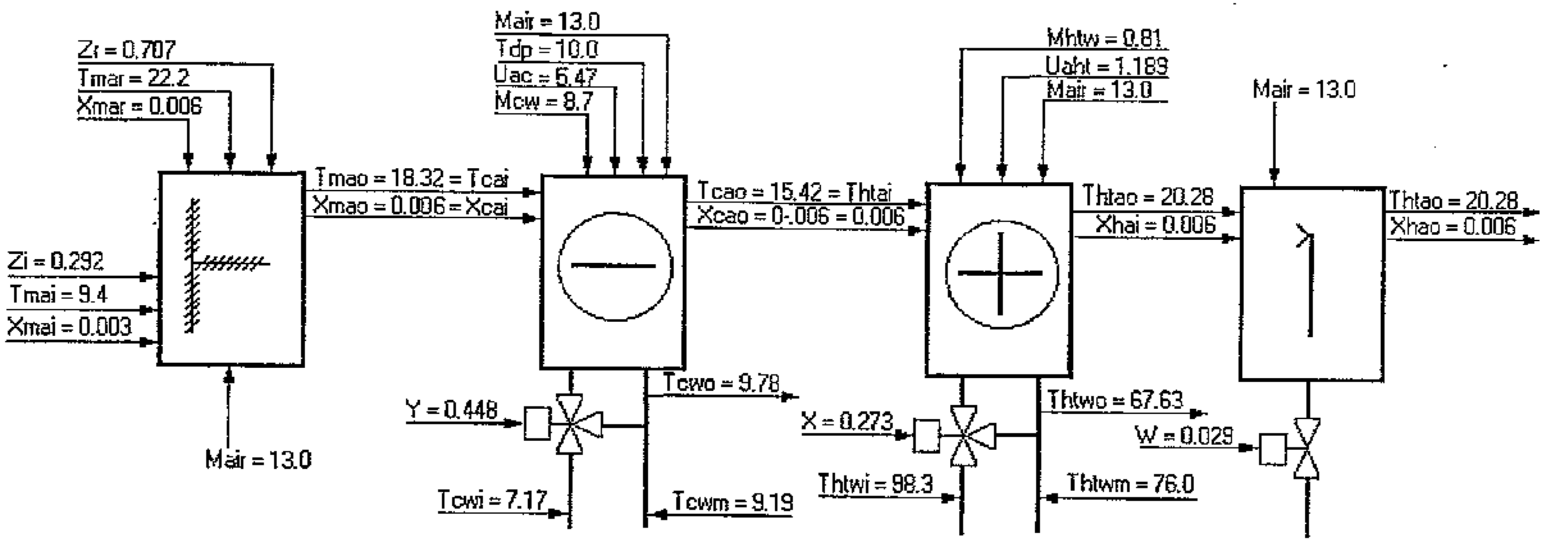
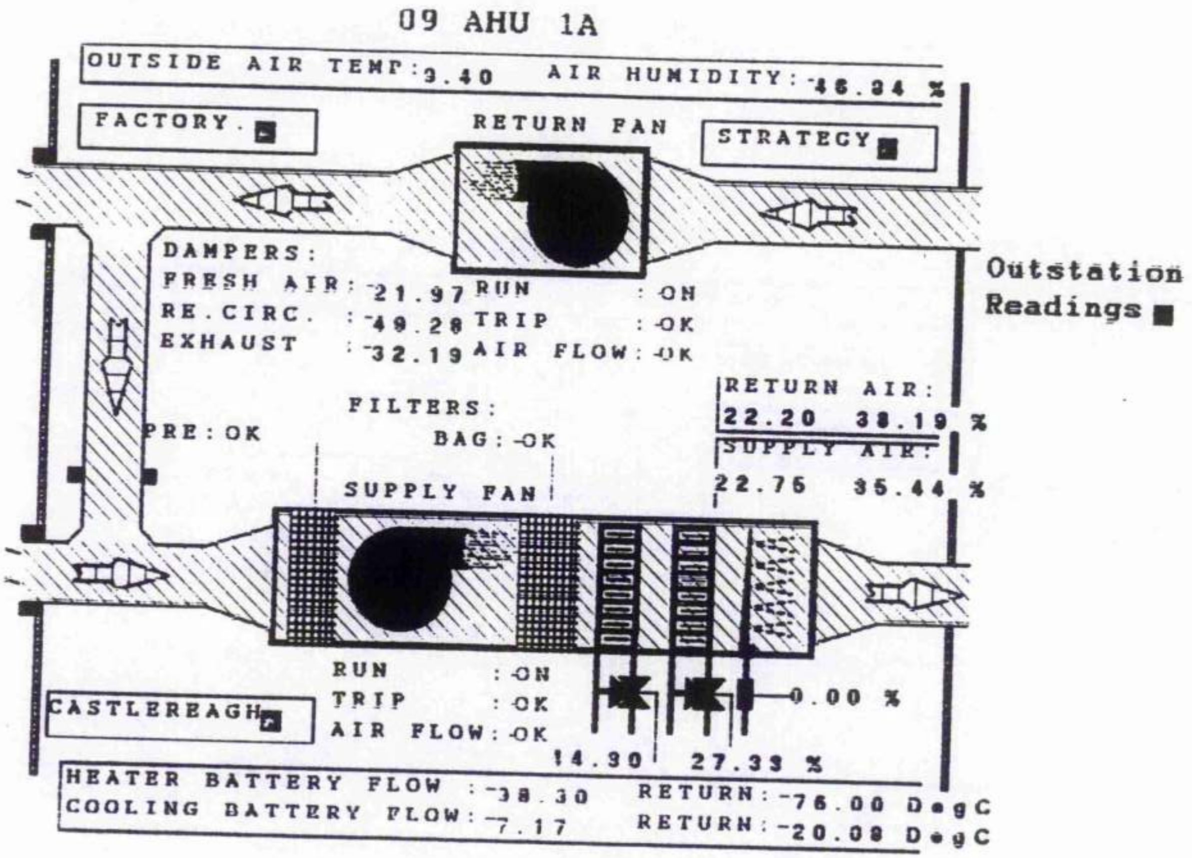


Fig. 14 Schematic of Air Conditioning Unit Showing Results from Data Set 1



09 AHU 1A

OUTSIDE AIR TEMP: 3.40 AIR HUMIDITY: -46.34 %

DAMPERS:
FRESH AIR: -21.97
RE.CIRC. : -49.28
EXHAUST : -32.19

RETURN FAN
RUN : ON
TRIP : OK
AIR FLOW : OK

FILTERS:
PRE: OK
BAG: OK

SUPPLY FAN
RUN : ON
TRIP : OK
AIR FLOW : OK

RETURN AIR:
22.20 38.19 %
SUPPLY AIR:
22.75 35.44 %

14.30 27.33 % 0.00 %

HEATER BATTERY FLOW : -38.30 RETURN: -76.00 DegC
COOLING BATTERY FLOW: -7.17 RETURN: -20.08 DegC

Fig. 15 Schematic of Air Conditioning Unit Showing BEMS Data Input for Data Set 1

4.3.4 DATA SET 2 CONSTRAINT SUSPENSION OF SENSORS

The calculated values obtained by suspending sensor and parameter constraints are shown in Tables 6-8 and those obtained by suspending other components are given in Table 9. These have little numerical correlation with the measured values. The following values show the least correlation:-

- **Humidifier Valve Position (W)**
  The value of W from the model is 1.140. Since this value must always be less than 1 and greater than or equal to zero there is an inconsistency between the model and the measured values.

- **Heater Battery Valve Position (X)**
  The meaured value of X at 0.1458 is inconsistent with the model value of 0.45.

- **Cooling Coil Valve Position (Y)**
  The model could not produce a value for Y from the measured data set.

- **Fresh Air Damper (Zi)**
  The fresh air damper cannot assume a negative value, therefore there is an inconsistency between the model and the data.

- **Recirculation Air Damper (Zr)**
  The recirculating air damper position must always be less than 1 and greater than or equal to zero there is an inconsistency between the model and the measured values.

- **Fresh Air Temperature (Tmai)**
  The fresh air temperature for the location and time of year is most unlikely at 31.88 deg C and therefore an inconsistency exists.

- **Cooling Coil Water Temperature in (Tcwi)**

The model value of temperature for the cooling water into the cooling coil is inconsistent with the data values. A temperature of 52.41 deg C will not be achieved by the chiller plant. Furthermore the model values from other constraint suspensions at 8.22 deg C are not consistent.

- **Cooling Coil Water Temperature Mixed (Tcwm)**
  The model value of temperature for the cooling water from the cooling coil valve at 9.35 deg C is inconsistent with the data values. Furthermore the model values from other constraint suspensions at 10.69 deg C and 48.10 deg C are also not consistent.

- **Cooling Coil Heat Transfer Coefficient (Uac)**
  Although the cooling coil heat transfer coefficient is not measured. It can be compared with manufacturers data or a value calculated from design data. It cannot have a negative value and therefore the data is not consistent with the model.

- **Cooling Coil Air Temperature Out (Tcao)**
  Heater Battery Air Temperature In (Thtai)
  Although these values are not measured they may be compared since they are calculated from different sets of constraints and should be equal. The values of 12.84, 17.87, and 24.32 deg C indicate an inconsistency in the model.

- **Cooling Coil Water Temperature Out (Tcwo)**
  This value is not measured, however like the two previous variables it is calculated from different sets of constraints and these values may be compared. Values of 76.34, 10.27, and 44.6 deg C indicate an inconsistency.

The large number of inconsistencies identified, would suggest an equally large number of potential faults. It is possible to substitute all calculated values in turn into the data set and continue the process in an attempt to establish the most likely inconsistencies for fault diagnosis. This process may be time consuming and there is some basis for deciding which values should be substituted first. Since some components are more likely to fail than others prior knowledge can reduced the search routine and pattern.

In this example, the experience of running the program and calculating values manually, indicates that this model is extremely sensitive to small variations in the value of the heater battery heat transfer coefficient. The value for this factor, calculated from the model is therefore substituted for the value originally included in the data set. The calculation process is repeated and a second set of values produced.

TABLE 6 RESULTS FROM ORIGINAL DATA SET 2

(original data set) **Suspended Constraint**

Constraint	Data	W	X	Y	Zi/Zr	Xmai Tmai	Xmar Tmar	Thtwi	Thtwm	Uaht	Tcwi	Tcwm	Uac	Thtao	Xhao
W	0.00	1.140													
X	0.146		0.45												
Y	0.448														
Zi	0.777				-0.825										
Zr	0.188				1.825										
Xmai	0.006					0.009									
Tmai	12.61					31.88									
Xmar	0.008						0.021								
Tmar	22.13						101.8								
Thtwi	101.4							124.9							
Thtwm	80.00								76.81						
Uaht	1.166									1.071					
Tcwi	8.22	52.41									52.4				52.4
Tcwm	18.35	48.11			10.69	10.69	10.69					9.35			48.1
Uac	5.47												-11.25		
Thtao	22.45		22.73	28.90	28.90	28.90	28.90				28.90	28.90	28.90	28.90	28.9
Xhao	0.008														0.004
Tmao		14.46	14.46	14.46	29.90	29.98	29.99	14.46	14.46	14.46	14.46	14.46	14.46		14.46
Xmac		0.000	0.003	0.006		0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008		0.004
Thtwo		76.35		76.35	76.35	76.35	76.35		72.61		76.35	76.35	76.35	76.35	76.35
Thtai		24.33	18.15	24.32	24.32	24.32	24.33		17.87	17.,87	17.87	24.32	24.32	24.32	24.32
Xcao		0.004				0.008	0.008								
Tcai		14.46			21.10	21.10	21.10								
Xhal															
Tcao			12.84		24.32	24.32	24.33	12.84	12.84	12.84					
Tcwo		44.61			12.69	12.69	12.69								44.61
Xhai			0.008		0.008	0.008	0.008	0.008							

The calculated values substituting the value for Uaht calculated from the model are shown in Table 7. These have better numerical correlation with the measured values but a number of values are still indicating inconsistencies. In particular the following values show the least correlation:-

- **Humidifier Valve Position (W)**
  The value of W from the model is 0.736. This is not consistent with the measured valueof 0.0.

- **Heater Battery Valve Position (X)**
  The meaured value of X at 0.1458 is now consistent with the model value of 0.15.

- **Cooling Coil Valve Position (Y)**
  The model could not produce a value for Y from the measured data set.

- **Fresh Air Damper (Zi)**
  The value of Zi from the model is 0.107 this is not consistent with the measured value of 0.777

- **Recirculation Air Damper (Zr)**
  The value of Zr from the model is 0.893 This is not consistent with the measured value of 0.188.

- **Fresh Air Temperature (Tmai)**
  The fresh air temperature for the location and time of year could possibly be at 20.86 deg C and therefore an inconsistency may exist.

- **Cooling Coil Water Temperature In (Tcwi)**
  The model value of temperature for the cooling water into the cooling coil at 27.13 deg C is inconsistent with the data value at 8.22 deg C.

- **Cooling Coil Water Temperature Mixed (Tcwm)**
  The model value of temperature for the cooling water from the cooling coil valve at 9.35 deg C is

inconsistent with the data values. Furthermore the model values from other constraint suspensions at 25.70 deg C are also not consistent.

- **Cooling Coil Heat Transfer Coefficient (Uac)**
  Although the cooling coil heat transfer coefficient is not measured. It can be compared with manufacturers data or a value calculated from design data. It cannot have a negative value and therefore the data is not consistent with the model.

- **Cooling Coil Air Temperature Out (Tcao)**
  Heater Battery Air Temperature In (Thtai)
  Although these values are not measured they may be compared since they are calculated from different sets of constraints and should be equal. The values of 12.84, and 17.57 deg C indicate an inconsistency in the model.

- **Cooling Coil Water Temperature Out (Tcwo)**
  This value is not measured, however like the two previous variables it is calculated from different sets of constraints and these values may be compared. Values of 10.27, and 24.53 deg C indicate an inconsistency.

The number of inconsistencies indicated has been reduced. However there is still a large number of potential faults. Again a knowledge of the process and the most probable potential faults will help to reduce the search pattern.

In this case the values of damper positions are the most likely candidates for faults. The new calculated values for the damper positions are therefore substituted for the values originally included in the data set.

TABLE 7. RESULTS FROM DATA SET 2 WITH CALCULATED VALUE OF UAHT SUBSTITUTED

(Uaht value substituted) **Suspended Constraint**

Constraint	Data	W	X	Y	Zi/Zr	Xmai Tmai	Xmar Tmar	Thtwl	Thtwm	Uaht	Tcwi	Tcwm	Uac	Thtao	Xhao
W	0.00	0.736													
X	0.146		0.15												
Y	0.448			-											
Zi	0.777				0.107										
Zr	0.188				0.893										
Xmai	0.006					0.000									
Tmai	12.61					20.86									
Xmar	0.008						0.021								
Tmar	22.13						56.24								
Thtwl	101.4							124.9							
Thtwm	80.00								78.74						
Uaht	1.071									1.071					
Tcwi	8.22	27.13									27.13				27.13
Tcwm	18.35	25.69			9.68	9.68	9.68					9.35			25.70
Uac	5.47												-5.81		
Thtao	22.46		23.04	22.33	22.33	22.33	22.33				22.33	22.33	22.33	22.33	22.33
Xhao	0.008														0.005
Tmac		14.46	14.46	14.46				14.46	14.46	14.46	14.46	14.46	14.46		14.46
Xmao		0.006	0.006	0.006				0.006	0.006	0.006	0.006	0.006	0.006		0.006
Thtwo		76.35		76.35	76.35	76.35	76.35		74.87	76.35	76.35	76.35	76.35	76.35	76.35
Thtai		17.76	18.47	17.57	17.57	17.57	17.57		12.84	17.87	17.76	17.76	17.76	17.76	17.76
Xcao		0.005													0.005
Tcai		14.46			21.10	21.10	21.10								14.46
Xhai															
Tcao			12.84		17.57	17.57	17.57	12.84	12.84	12.84					
Tcwo		24.53			10.86	10.86	10.86					10.27			24.53
Xhai					0.009	0.009	0.009								

The calculated values substituting the value for Uaht, Zi and Zr calculated from the model are shown in Table 8. These give a very close approximation between the data and the model with the exception of the value for the temperature of cooling coil water out of the mixing valve. This has a model value of 10.559 deg C against a data value of 18.35 deg C.

From this information it may be inferred that there are inconsistencies in the values of:-

- **Fresh air damper position (Zi)**
- **Recirculating air damper position (Zr)**
- **Chilled water temperature out of mixing valve (Towm)**

This in turn, indicates potential faults in the dampers and in the sensor measuring the water temperature out of the mixing valve.

The calculated values of the damper positions are consistent with the conventional control strategy for the outside conditions whereby a minimum of 10% fresh air is introduced when fresh air temperature is below supply air temperature.

The values for the sensor measuring the water temperature out of the mixing valve may indicate a faulty sensor.

Since the BEMS is calling for damper positions which are inconsistent with those positions which may be expected it is reasonable to assume that there is also a fault in the controls.

TABLE 8 RESULTS FROM DATA SET 2 WITH CALCULATED VALUES OF ZI & ZR SUBSTITUTED

(Zi/Zr substituted) **Suspended Constraint**

Constraint	Data	W	X	Y	Zi/Zr	Xmai Tmai	Xmar Tmar	Thtwi	Thtwm	Uaht	Tcwi	Tcwm	Uac	Thtao	Xhao
W	0.00	0.096													
X	0.146		0.15												
Y	0.446			0.55											
Zi	0.107				0.107										
Zr	0.892				0.892										
Xmai	0.006					0.010									
Tmai	12.61					12.57									
Xmar	0.008						0.009								
Tmar	22.13						22.12								
Thtwi	101.4							101.9							
Thtwm	80.00								80.0						
Uaht	1.071									1.072					
Tcwi	8.22	8.21									8.21				8.21
Tcwm	18.35	25.69			9.68	9.68	9.68					10.56			9.670
Uac	18.35												5.47		
Thtao	22.45	22.33	23.04	22.33	22.33	22.33	22.33				22.33	22.39	22.33	22.33	
Xhao	0.008														0.008
Tmao		21.11	21.11	21.11	21.11			21.11	21.11	21.11	21.11	21.11	21.11		21.11
Xmao		0.008	0.008	0.008				0.008	0.008	0.008	0.008	0.008	0.008		0.008
Thtwo		76.35		76.35	76.35	76.35	76.35		76.35	76.35	76.35	76.35	76.35	76.35	76.35
Thtai		17.76	16.80	17.57	17.57	17.57	17.57		17.87	17..87	17.76	17.76	17.76	17.76	17.76
Xcao		0.008		0.008											0.008
Tcai		21.11			21.11	21.11	21.11								21.11
Xhai		0.008													
Tcao		17.76		17.80	17.76	17.76	17.75	17.76	17.76	17.76					
Tcwo				11.11	10.86	10.86	10.86					12.46			10.86
Xhai					0.009	0.009	0.009								

4.3.5 <u>DATA SET 2 CONSTRAINT SUSPENSION OF COMPONENTS</u>

The calculated values are shown in Table 9. These results indicate consistency with the mathematical models and the sensor values.

TABLE 9. <u>RESULTS FROM ORIGINAL: DATA SET 2 COMPONENT CONSTRAINTS SUSPENDED</u>

(original data set) **Suspended Constraint**

Constraint	Data	Mixing Box	Heater	Humidifier
W	0.000			
X	0.146	0.146		0.146
Y	0.446	0.448		
Zl	0.107			
Zr	0.892			
Xmal	0.006			
Tmal	12.61			
Xmar	0.008			
Tmar	22.13			
Thtwi	101.4		101.90	
Thtwm	80.0			
Ualt	1.1071			
Tcwl	8.22	8.22		8.44
Tcwm	9.68	9.69		9.88
Uac	5.47			
Thtao	22.45	22.39		22.39
Xhao	0.008			
Tmao			18.32	18.32
Xmao			0.0077	0.0078
Thtwo		76.34		76.34
Thtai		17.81		17.81
Xcao		0.008		0.0076
Xcai		0.0080		
Tcai		21.19		21.11
Xhai		0.008		
Tcao		17.81	17.81	
Tcwo		10.68		11.04
Xhai			0.008	

4.3.6 CONTROL STRATEGY FOR DATA SET 2

The output from data set 2 is shown schematically in Figure 16. The input data taken from a BEMS printout is shown schematically in Figure 17.

The rules listed in 3.6 are applied to these results. It can be observed that the outside temperature is less than the supply temperature which is in turn only slightly less than the return air temperature. The humidifier valve is closed and the heater battery and cooling coil valves are both modulating This indicates that dehumidification and reheating are taking place. Since the outside air temperature is less than the return air temperature the mixing damper should be modulating to supply air between 10% and 20% fresh air. This would appear to be the case. However, with a return air relative humidity of 47.94% the plant should not be dehumidifying. The control strategy for humidification/dehumidification would therefore appear to be incorrect.

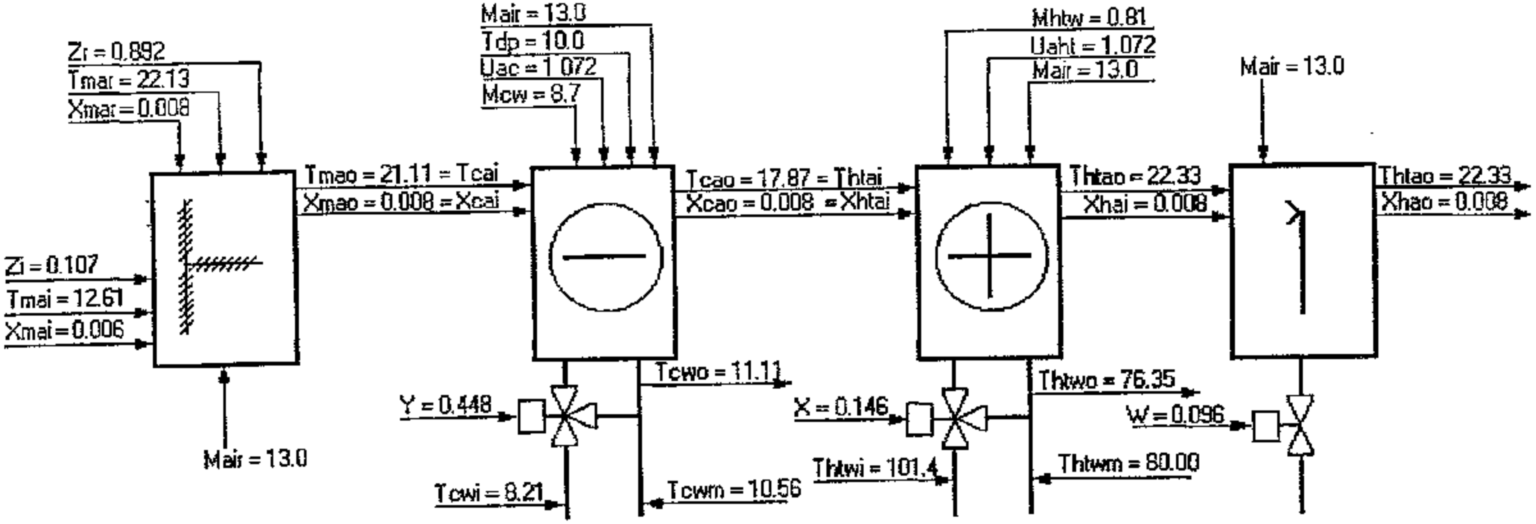
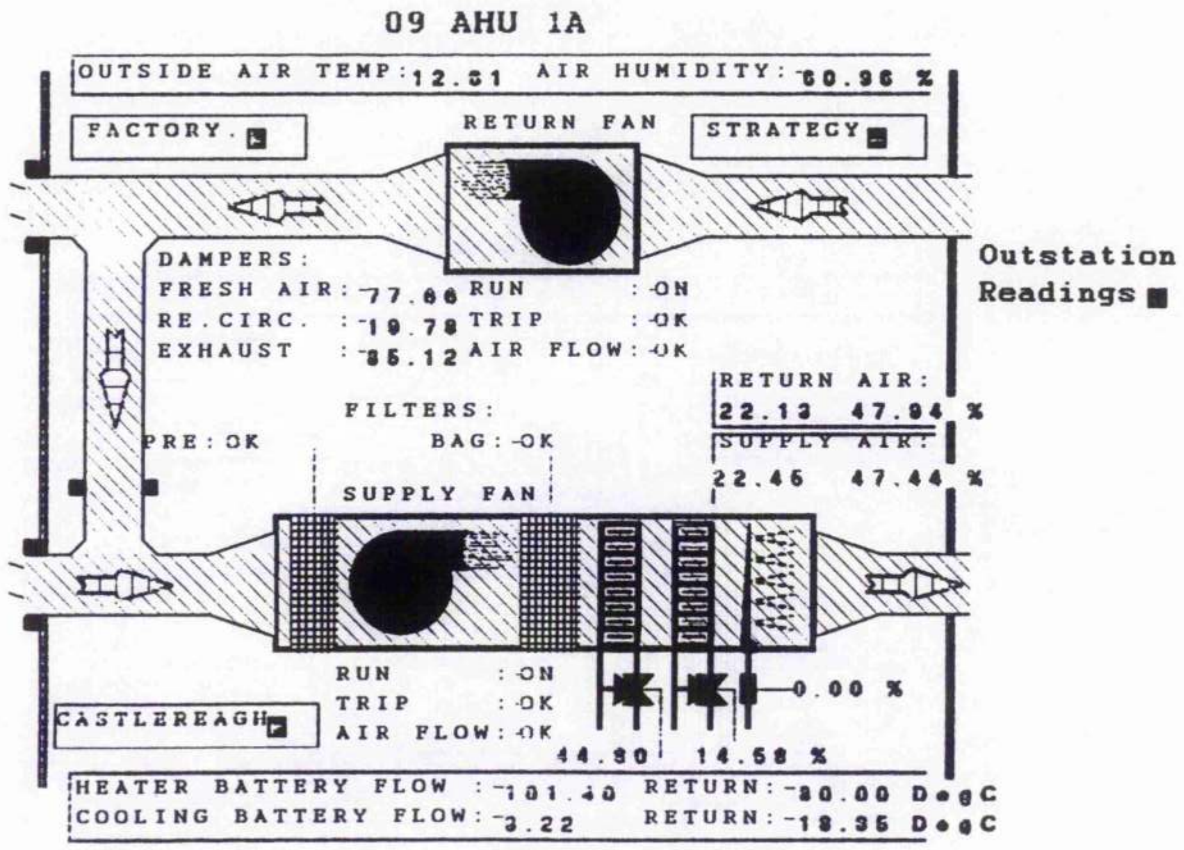


Fig. 16 Schematic of Air Conditioning Unit Showing Results from Data Set 2



09 AHU 1A

OUTSIDE AIR TEMP: 12.31 AIR HUMIDITY: -60.96 %

DAMPERS:
FRESH AIR: -77.66
RE.CIRC. : -19.78
EXHAUST : -35.12

RETURN FAN
RUN : -ON
TRIP : -OK
AIR FLOW: -OK

RETURN AIR:
22.13 47.94 %
SUPPLY AIR:
22.46 47.44 %

FILTERS:
PRE: OK
BAG: -OK

SUPPLY FAN
RUN : -ON
TRIP : -OK
AIR FLOW: -OK

-0.00 %
44.30 14.58 %

HEATER BATTERY FLOW : -101.40 RETURN: -30.00 DegC
COOLING BATTERY FLOW: -3.22 RETURN: -18.35 DegC

Fig. 17 Schematic of Air Conditioning Unit Showing BEMS Data Input for Data Set 2

4.3.7 DATA SET 3 CONSTRAINT SUSPENSION OF SENSORS

The calculated values obtained by suspending sensor and parameter constraints are shown in Tables 10-11. Those obtained by suspending other components are given in Table 12.

The discrepancies between calculated values and Data Set 3 are as follows:-

- **Cooling Coil Valve Position (Y)**
  The model could not produce a value for Y from the measured data set.

- **Fresh Air Damper (Zi)**
  The fresh air damper position must have a value less than one.

- **Recirculation Air Damper (Zr)**
  The recirculation damper cannot have a negative value.

- **Recirculation Air Temperature (Tmar)**
  The recirculation air temperature will not have a value of -21.95 deg C.

- **Cooling water Temperature In (Tcwi)**
  The temperature of the cooling water into the cooling coil is measured at 7.92 and calculated at 5.39.

- **Cooling Water Temperature Mixed (Tcwm)**
  The measured temperature from the cooling coil valve is 20.37 deg C. This is not consistent with the values of 7.000, 10.02, and 9.137 deg C. which in themselves show significant variation.

- **Cooling Coil Heat Transfer Coefficient (Uac)**
  The cooling coil heat transfer coefficient has a calculated value of 7.2 this shows a significant variation from the initial trial value of 5.47.

- **Non Measured Values**
  There are slight variations in the calculated values for Heater battery air temperature in (Thtai), Cooling coil air temperature in (Tcai) and Cooling coil water temperature out (Tcwo).

The number of inconsistencies can be reduced by substituting the new value for cooling coil heat transfer coefficient as before.

TABLE 10. RESULTS FROM ORIGINAL DATA SET 3

(original data set) **Suspended Constraint**

Constraint	Data	W	X	Y	Zl/Zr	Xmal Tmai	Xmar Tmar	Thtwi	Thtwm	Uaht	Tcwi	Tcwm	Uac	Thtao	Xhao
W	0.00	0.049													
X	0.188		0.20												
Y	0.448														
Zl	0.976				1.3										
Zr	0.200				-0.3										
Xmai	0.007					0.008									
Tmai	19.48					18.58									
Xmar	0.008						0.022								
Tmar	22.20						-21.95								
Thtwi	101.3							98.24							
Thtwm	79.60								79.77						
Uaht	1.072									1.072					
Tcwi	7.92	5.39			7.92	7.92	7.92				5.39				5.39
Tcwm	18.35	7.000			9.137	9.137	9.137					10.02			7.000
Uac	5.47												7.2		
Thtao	20.60		20.26	20.49	20.49	20.49				20.49	20.49			20.49	20.49
Xhao	0.007														0.008
Tmao		19.53		19.53				19.53	19.53	19.53	19.53	19.53	19.53		19.53
Xmao		0.007	0.007	0.007				0.007	0.007	0.007	0.007	0.007	0.007		0.007
Thtwo		74.59		74.59	74.59	74.59	74.59		74.80	74.59	74.59	74.59	74.59	74.59	74.59
Thtai		15.86	15.62	15.65	15.86	15.86		16.51	15.86	15.86	15.86	15.86	15.86	15.86	15.86
Xcao		0.007			0.007	0.007	0.007								0.007
Tcai		19.53			18.65	18.65	18.65								19.53
Xhai				0.007			0.007			0.007	0.007	0.007			
Tcao				15.86	15.86	15.86	16.52	16.52	16.52						
Tcwo		8.30			10.12	10.12	10.12					11.74			8.3
Xhai					0.008	0.008	0.008								

The calculated values after substituting the new value for Uac are shown in Table 11. These results give a very close numerical correlation between the data set and the calculated values. The only exception to this is the value for the chilled water temperature out of the cooling coil mixing valve. This inconsistency indicates a potential fault in the sensor measuring this value.

TABLE 11. RESULTS FROM DATA SET 3 WITH CALCULATED VALUE OF UAC SUBSTITUTED

(Uac substituted) **Suspended Constraint**

Constraint	Data	W	X	Y	Zl/Zr	Xmal Tmal	Xmar Tmar	Thtwl	Thtwm	Uaht	Tcwl	Tcwm	Uac	Thtao	Xhao
W	0.00	0.049													
X	0.188		0.20												
Y	0.448			0.45											
Zi	0.076				0.96										
Zr	0.200				0.02										
Xmal	0.007					0.007									
Tmal	19.48					19.47									
Xmar	0.008						0.023								
Tmar	22.20						22.19								
Thtwl	101.3							101.3							
Thtwm	79.60								79.60						
Uaht	1.072									1.072					
Tcwi	7.92	7.92			7.92	7.92	7.92	7.92			7.92				7.92
Tcwm	20.50	9.52			9.50	9.52	9.52	9.52				10.49			9.52
Uac	7.2												7,200		
Thtao	20.50	20.49	20.26	20.49	20.49	20.49	20.49			20.49	20.49	20.49	20.49	20.49	20.49
Xhao	0.007														0.008
Tmao		19.53		19.53				19.53	19.53	19.53	19.53	19.53	19.53		19.53
Xmao		0.007	0.007	0.007				0.007	0.007	0.007	0.007	0.007	0.007		0.007
Thtwo		74.59		74.59	74.59	74.59	74.59		74.80	74.59	74.59	74.59	74.59	74.59	74.59
Thtai		15.86	15.62	15.86	15.86	15.86		15.86	15.86	15.88	15.86	15.88	15.86	15.86	15.88
Xcao		0.007		0.007	0.007	0.007	0.007								0.007
Tcai		19.53			19.53	19.53	19.53								19.53
Xhal				0.007			0.007			0.007	0.007	0.007			
Tcao				15.91	15.86	15.86	15.86		15.86	15.86					
Tcwo		10.83		11.03	10.83	10.83	10.83					12.57			10.83
Xhal					0.008	0.008	0.008								

4.3.8 DATA SET 3 CONSTRAINT SUSPENSION OF COMPONENTS

The calculated values are shown in Table 12. These results indicate consistency with the mathematical models and the sensor values.

TABLE 12. RESULTS FROM ORIGINAL: DATA SET 3 COMPONENT CONSTRAINTS SUSPENDED

(original data set) **Suspended Constraint**

Constraint	Data	Mixing Box	Heater	Humidifier
W	0.000			
X	0.1875	0.1875		0.1875
Y	0.448	0.448		
Zl	0.976			
Zr	0.02			
Xmai	0.0072			
Tmai	19.48			
Xmar	0.0079			
Tmar	22.20			
Thtwi	101.30		101.30	
Thtwm	79.6			
Uaht	1.072			
Tcwi	7.92	7.92		7.78
Tcwm	9.52	9.61		9.40
Uac	7.20			
Thtao	20.50	20.45		20.45
Xhao	0.0074			
Tmao		19.41	19.53	19.53
Xmao		0.0075	0.0072	0.0072
Thtwo		74.59		74.59
Thtai		15.81		15.81
Xcao		0.0074		0.0072
Xcai		0.0076		
Tcai		19.46		19.53
Xhai				
Tcao		15.81	15.85	
Tcwo		10.81		10.72
Xhai		0.0074	0.0074	

4.3.9 CONTROL STRATEGY FOR DATA SET 3

The output from Data Set 3 is shown schematically in Figure 18. The input data taken from a BEMS printout is shown schematically in Figure 19.

Applying the rules listed in 3.6 to the conditions shown. The outside temperature is less than the supply temperature which is in turn less than the return air temperature. These differences are small. The humidifier valve is closed and the cooling coil valve and heater battery valves are both modulating. This indicates that cooling, dehumidification and reheating are taking place. The outside air temperature is less than the room air temperature. The control damper should therefore be fully open to supply 100% fresh air. This is the case However, with a return air relative humidity of 46.5% the plant should not be dehumidifying. The control strategy for humidification /dehumidification would therefore appear to be incorrect.

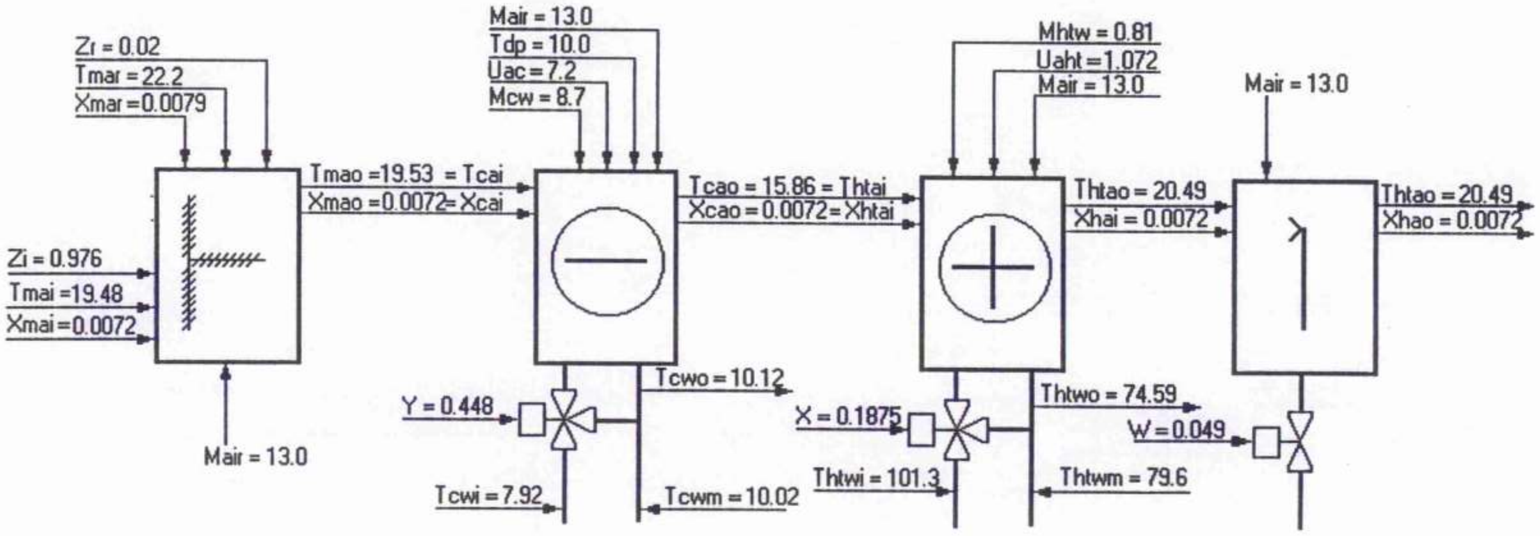
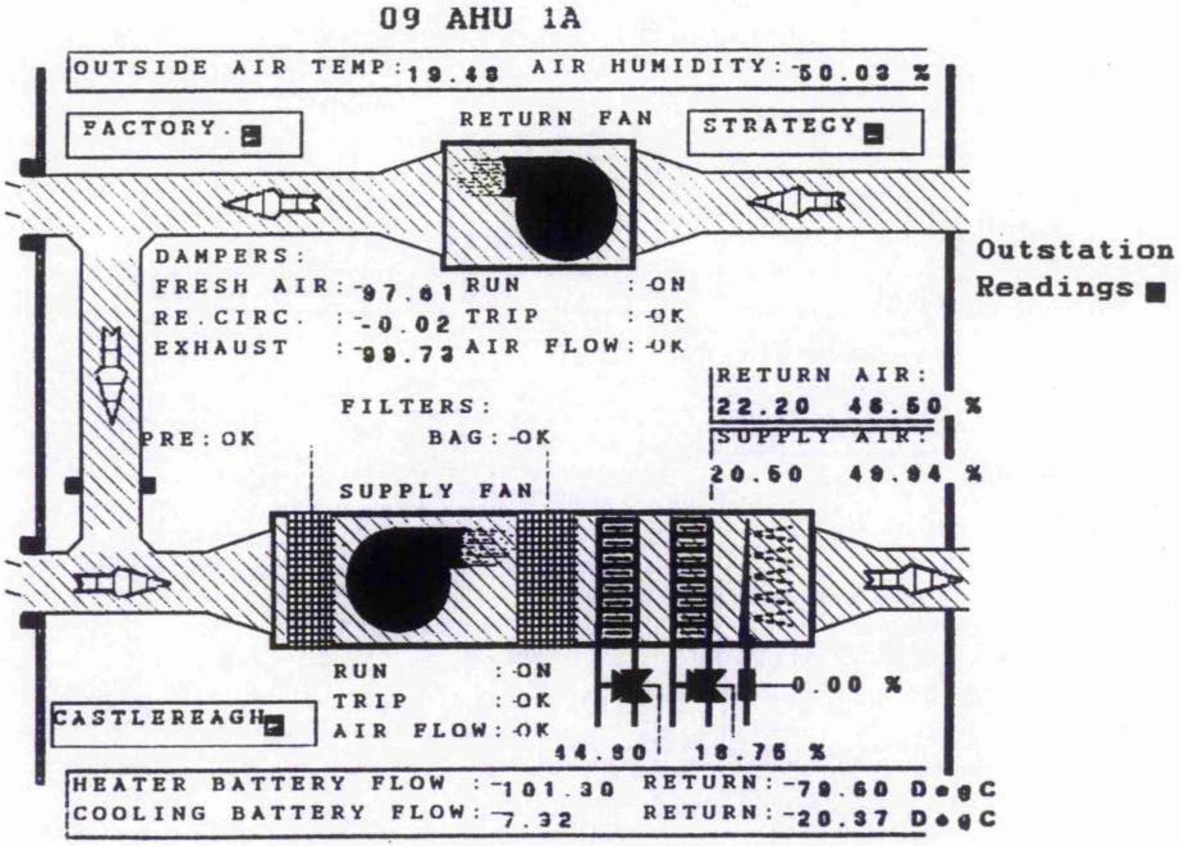


Fig. 18 Schematic of Air Conditioning Unit Showing Results from Data Set 3



OUTSIDE AIR TEMP: 19.48 AIR HUMIDITY: 50.03 %

DAMPERS:
FRESH AIR: 97.61
RE.CIRC. : -0.02
EXHAUST : 99.73

RUN : ON
TRIP : OK
AIR FLOW: OK

FILTERS:
PRE: OK
BAG: OK

RETURN AIR:
22.20 46.50 %
SUPPLY AIR:
20.50 49.94 %

RUN : ON
TRIP : OK
AIR FLOW: OK

44.80 18.75 %
0.00 %

HEATER BATTERY FLOW : 101.30 RETURN: 79.60 DegC
COOLING BATTERY FLOW: 7.32 RETURN: 20.37 DegC

Fig. 19 Schematic of Air Conditioning Unit Showing BEMS Data Input for Data Set 3

5.0 CONCLUSIONS

The fault detection capabilities of BEMS systems have been assessed and areas for improvement have been considered. The particular difficulties of information management and interpretation have been identified as a major obstacle to the effective operation of a BEMS. The application of expert systems technology is proposed as a means of solving these problems and the systems which have been developed to date have been reviewed. Whilst offering solutions to the problems of data analysis and interpretation, statistical model based and if-then (production) based expert systems both have some disadvantages,

- statistical modelling requires the development of complex computer programs,
- production or "if-then" rule based systems and statistical modelling computer programs are specific to the building for which they have been developed,
- the systems are subject to the limitations of the rule base,
- rules rely on eliciting knowledge from an expert, (the project may succeed or fail in accordance with the accuracy, reliability and validity of this information),
- statistical models require a period of at least six months to allow enough data for analysis to be collected,
- faults have to produce noticeable effects such as severe energy over consumption.

The application of the technique of constraint suspension to fault detection and diagnosis in HVAC plant using BEMS generated data offers a number of advantages over previous methods,

- it is based on a steady state model,
- it does not depend upon apriori knowledge about faults,
- it is simple and universally applicable,
- it defines the limitations of the knowledge base, or "*programmes competence*" (Davis 1984),
- such model based systems are capable of diagnosing symptoms resulting from previously unknown problems.

By examining the application of this technique to a particular HVAC system this thesis has made the following original contributions,

- the specification of an appropriate constraint representation for a real air conditioning unit and
- the development of an inference network generator to suspend each component in turn and
- the identification of the need for a seperate rule base identify faults in control strategy implementation.
- the verification of the method using real data from an operational BEMS.

Three different sets of data from a BEMS used to control an air conditioning plant in a light engineering factory have been considered. The following faults have been identified and verified:

- the sensor measuring the chilled water temperature out of the mixing valve was faulty in all data sets,
- the BEMS driver output for fresh air and recirculating air dampers for data set 2 was faulty,
- the control strategy for dehumidification in all data sets was incorrect.

The findings demonstrate that the system proposed, based upon constraint suspension technology, is capable of detecting and diagnosing sensor and driver faults. The rule based system of assessing the control strategy can indicate faults in the strategy. The viability of the application of constraint suspension to the detection and diagnosis of fault conditions in an air conditioning unit has been demonstrated for a particular plant operating during a single season of the year. Hence further work should include, the analysis of data collected during other times of the year. The interpretation of the results has been fairly subjective and it is recommended that guidelines should be prepared to advise on how to interpret the output from constraint suspension.

This technique uses simple static models which are easily understood and easily applied to air conditioning plant in general. The case for static modelling is discussed in Appendix 1, however, there will always be concern about the accuracy of the models. This can only be addressed by performing a large number of case studies to explore the effects of incorrect parameters, totally incorrect modelling assumptions etc. Extensive work of this nature may not be necessary in order to provide the BEMS operator with an aid to interpretation of data.

The rather arbitrary nature of locating sensors in air conditioning plants has been identified. For example the cooling coil and heater battery control valves could have been modelled separately and the heat exchanger models simplified if the temperature sensors in the flow and return pipework were positioned between the valve and the heat exchanger and not before the control valve. Some installations do not monitor these conditions. If it is desirable to incorporate fault detection and diagnosis procedures such as those suggested here, it is important to ensure there are sufficient sensors and that these are located sensibly.

This, in turn, raises the question as to whether or not constraint suspension could be applied at the design stage to advise on these matters.

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APPENDIX 1

1.0 THE CASE FOR USING STEADY STATE MODELS

1.1 INTRODUCTION

Steady state models have been used throughout this study for the following reasons,

- the constraint supension technique originally applied to digital electronic circuits (Davis 1984) uses steady state models,
- the logic programming language used (PROLOG) does not readily handle complicated mathematical techniques,
- this programme conducts fault detection and diagnosis routines. Models which use complex simulations can devote more time to simulating than to diagnosis of faults.
- because steady state models are easy to use and understand, it is of value to explore their validity in this application.
- simple models are more likely to find a universal application and appeal.

The objective of this chapter is,

- to demonstrate the appropriateness of applying low accuracy, steady state assumptions.

1.2 COMPARISON BETWEEN STEADY STATE AND DYNAMIC MODELS

In determining the suitability of steady state models for the application to ACUs various types simulation models have been assessed. The types of mathematical model (Clarke 1986) are,

- simple steady state,
- simple dynamic,
- response function,
- numerical (finite difference)

Static simulation models use the simplifying assumption that all conditions are in a steady state, that is, they do not change with time. This greatly reduces the amount of computer processing at the expense of accuracy.

Dynamic models, in comparison with steady state models are generally more accurate. However, as complexity increases, it becomes increasingly difficult to differentiate between,
"*detailed models which are performing accurately and detailed models which are not performing accurately*". (Lomas, 1991).

Dynamic simulation models have the advantage of allowing for changes of parameters with time. Some degree of dynamic simulation is necessary if the building fabric response is to be modelled. However dynamic simulation also requires the control elements and sensor responses to be included and considered since they are time dependant. Inclusion of these elements leads to concerns with regard to validation.

1.3 THE ISSUE OF ACCURACY

The issue of accuracy of the model is always of importance. This becomes more so if accuracy of the model is difficult to validate, then acceptance of the technique is unlikely. The accuracy and validation of dynamic models has been questioned (BRE 1984), (Bowman and Lomas 1985), (Lomas 1991).

1.4 ASSUMPTIONS FOR THE USE OF STEADY STATE MODELS

The following assumptions also allow the use of simple static models without introducing uncertainties,

- the building's internal environmental conditions are acceptable. This is reasonable since if this were not so then the building occupants would complain.

- the plant supply conditions are correct. If this were not so then the internal environmental conditions would not be acceptable.

It is therefore appropriate to apply steady state modelling since,

- it is capable of determining significant numerical variations arising from faults resulting in poor energy efficiency,
- it also has the advantage of simplicity and ease of calculation.