DEVELOPMENT OF DIAGNOSTIC RULES
FOR A DRY BULB ECONOMIZER MIXED AIR LOOP

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ABSTRACT

Diagnostics of heating, ventilating, and air-conditioning (HVAC) systems is becoming increasingly important because of the rising cost of operation and maintenance of HVAC systems. At the same time, computer costs are tumbling allowing their use in new situations such as HVAC diagnostics.

The Army has developed standard HVAC system configurations, thus facilitating development of knowledge bases for those systems. This paper describes the development of if-then-else rules which make up part of a knowledge base for a two fan variable air volume (VAV) air handling unit. Rules for the mixed air loop with a dry bulb economizer are presented.

NOMENCLATURE

Toa = outside air temperature
Tma = mixed air temperature
Tra = return air temperature
Tsa = supply air temperature
%OA = percent outside air
%RA = percent return air

BACKGROUND

As the largest building owner in the U.S., the Army has always had a great concern over maintenance of it's HVAC systems. Typically several persons are responsible for hundreds of buildings, giving them little time for anything except "putting out fires". With increasing pressures to cut budgets, this situation is unlikely to improve anytime soon. One effort underway within the Army for some time is the development of an automated diagnostic system to more effectively utilize the time of the maintenance personnel. One part of this effort is the development of rules describing how the different HVAC systems function and malfunction. This has been facilitated by the standardization of the types of systems currently being installed. One of the more common standard systems used is the Two Fan VAV System. One of the four loops of this system, a mixed air with dry bulb economizer, is studied in the context of developing diagnostic rules.

CORPS STANDARD SYSTEMS

Because the Army has many identical buildings, the U. S. Army Corps of Engineers has developed a set of standard HVAC systems from which a designer must develop his design of the HVAC system for his specific facility (Corps of Engineers Technical Manual TM 5-815-3). This is significant in the development of knowledge bases because it means that with minimal revisions a knowledge base can be used on any system designed from the TM.

The dry bulb economizer loop of the standard variable air volume system with a return fan will be discussed to show the process by which a portion of a knowledge base was developed. First however, the diagnostic system itself will be described.

THE DIAGNOSTIC SYSTEM

The diagnostic system is a computer program intended to be interfaced to an existing data gathering system such as an Energy Monitoring and Control System (EMCS) as depicted in Figure 1. The diagnostic system consists of four functional blocks; a System Configuration Descriptor, a Data Preprocessor, a Knowledge Base, and an Inference Engine. Although this paper will focus on creating a knowledge base, the interaction of the four sections requires that all four be described.

SYSTEM CONFIGURATION DESCRIPTOR

The System Configuration Descriptor is a graphical interaction with a user which describes the equipment and control loops of an air handler unit. A session with the configurator produces three items; 1) A diagram of the air handling unit; 2) A set of text descriptions of the equipment which can be used directly by the inference engine; and 3) A set of parameters which are used by the data preprocessor to create additional text that can be used by the inference engine. These parameters can not be effectively used directly by the inference engine because they do not contain true and false facts, rather they are values for parameters which could be used by the inference engine only to ascertain if a variable is at exactly a certain value. Tables 1 and 2 contain a partial listing of items 2 and 3 above respectively for the standard VAV air handler.

Table 1 TEXT

There is a dry_bulb_economizer
All actuators are pneumatic
All controller_outputs are current
Cooling_Coil_Valve is three-way
All controllers are direct_acting
There is a ventilation_delay_mode
There is a return_fan
Fan_control is frequency
Supply_Fan_indicator_type is DP

Table 2 PARAMETERS

Economizer_offset = 10F
Economizer_deadband = 2F
Tma_setpoint = 55F
Tsa_setpoint = 55F
zone_winter_setpoint = 68F
zone_summer_setpoint = 78F
%OAmin = 15%
Near% = 15%
NearTemp = 2F
Static Pressure Setpoint = 2.5 "wc

DATA PREPROCESSOR

The data preprocessor takes data in the form of numbers such as those in Table 2 (from the configuration) and Table 3 (from data acquisition interface) to create text descriptions that the inference engine can use. For example, suppose the values in Table 3 have been recorded by the data acquisition interface. The Data Preprocessor would then create the text strings in Table 4.

Table 3 DATA ACQUISITION RESULTS

Tra = 75F
Toa = 57F
Tma = 72F
Static_Pressure = 1.8 "wc
Supply_Fan_indicator = on

Table 4 RESULTS OF DATA PREPROCESSOR

Tra is greater than Toa
Toa is less than Tra
Toa is less than economizer_turn_on
Tra is greater than Tma
Tma is less than Tra
Tma is not near setpoint
Tra is greater than economizer_turn_off
%OA is near %OAmin
%RA is greater than %OAmin
economizer is not deadband

where the percent outside air (%OA) has been calculated based upon an energy balance as in Equation 1, economizer_turn_on from Equation 2, and economizer_turn_off from Equation 3.

$$\%OA = (T_{ma} - T_{ra})/(T_{oa} - T_{ra}) \quad (1)$$

$$economizer\_turn\_on = Tra - offset - (deadband/2) \quad (2)$$

$$economizer\_turn\_off = Tra - offset + (deadband/2) \quad (3)$$

Notice the use of the word near in lines six and eight of Table 4. In many cases, there is a grey area in which it is difficult to distinguish between a true fault and a condition which is not exactly as expected but still reasonable. Here, the word near is used to provide an adjustable error band to define a reasonable range in which a fault will not be reported. This is similar to the adjustable high/low limits provided by many EMCS alarm reporting routines. In this example, %OA using Equation 1 is equal to 16.7%. Since %OAmin is 15% and near% is 20%, any value between 12% and 18% for %OA would have resulted in the text of line 8 of Table 4. Similarly the NearTemp parameter of Table 2 is used to determine whether Tma is near its setpoint. Since this is a temperature however, the deadband is given in units as opposed to a percent.

THE INFERENCE ENGINE

There are many shapes, forms, sizes, and flavors of inference engines. Essentially they perform to varying degrees, sophisticated text searching, sorting, and manipulators. One distinction that can be made between them is that of the capability of either forward or backward chaining. The one used in this work has the capability to perform both forward and backward chaining.

THE KNOWLEDGE BASE

The knowledge base consists of if then else statements which describe the conditions under which a new piece of information can be concluded to be true. In order to create these rules, the proper operation of the system to be diagnosed must be understood, therefore the mixed air loop will be described first.

ECONOMIZER/MIXED AIR LOOP DIAGNOSTIC RULES

The VAV with return fan air handler unit system has four basic loops; mixed air, supply fan, return fan, and cooling coil. Additionally there are many logic devices and switches which affect the operation and interaction of these four basic loops, the logic of which is described in the sequence of operation.

In developing diagnostic rules, some assumptions must be made. Here, the first assumption to be made is what information is correct. Here, it will be assumed that the data acquired from the system through the data acquisition interface is correct as long as it is within some reasonable range. Therefore any diagnostics to be performed on sensors and data acquisition hardware is limited to range checking, which will be performed by the data preprocessor.

Figure 2 shows the components which make up the mixed air loop; an averaging temperature sensor and transmitter, a mixed air controller, a ventilation delay contact, an economizer, an outdoor air and return air point temperature sensors and transmitters, a current to pneumatic (I/P) transducer, three damper actuators, the damper and damper linkage assemblies, pneumatic tubing, and other miscellaneous items. The mixed air loop is the most involved of the four loops because its operation is affected by many variables such as operating status (summer/winter and ventilation delay) and the relative temperatures of the return and outside air temperatures. Its function in summer mode is to attempt to maintain the temperature of the mixed air stream at its setpoint through modulation of the return, relief, and outside air dampers. In winter mode, the economizer sets the dampers to minimum outside air, a condition which is set by the designer to meet ventilation requirements. Ventilation delay mode simply closes the outdoor and relief air dampers and opens the return air dampers, thus attempting to provide 100% return air for the purpose of pre-heating a building prior to occupancy without bringing in cooler outside air. This also occurs at other unoccupied times.

In the Corps of Engineers guide specifications, the summer/winter mode for the economizer is determined by comparing the return air temperature with the zone setpoint, 68F in the winter and 78F in the summer. If the return air temperature is less than 73F then the economizer should go into its winter mode, otherwise it should be in its summer mode. The knowledge base rule for this would be:

> Rule #1
>
> If Tra is greater than Zone_average_setpoint then economizer mode should be summer else economizer mode should be winter

Here the word "should" was used instead of "is" because the conclusion was inferred as opposed to a positive confirmation such as a contact closure.

When the economizer is in winter mode, the dampers go to minimum %OA position. However, in the summer mode, the economizer also decides whether to go to minimum %OA position (economizer off) or modulation (economizer on) depending on the relative temperatures of the return and outside air and the values of the offset and deadband selected by the designer. Figure 3 shows the conditions under which the economizer would be on or off for a 10F offset and a deadband of 2F. Additionally, there are conditions under which the economizer state depends on pas history of the two temperatures, as indicated by the area labeled deadband. This deadband of temperatures around Tra - offset prevents cycling of damper positions. When the economizer is on, it does not turn off until Toa is greater than Tra - offset + (deadband/2). When the economizer is off, it does not turn on until Toa is greater than Tra - offset - (deadband/2). Offset is a value calculated based upon psychometrics and typical weather conditions and deadband is a rule of thumb value to prevent cycling of the dampers.

As previously stated, in summer mode the dry bulb economizer function is to keep the mixed air temperature at setpoint. However, since this can only be accomplished if one of the airstreams is equal to or less than the setpoint. The majority of the time, the actual temperature of the mixed airstream is generally greater than the setpoint. For instance, if the return air temperature is 75F and the outside air temperature is 67F, then it is not possible to obtain a mixed air temperature of 55F. The best that can be accomplished is 67F, and the practical expectation is somewhat warmer due to damper leakage from the return airstream.

If the economizer is in its summer mode and everything in the mixed air loop is operating correctly, either one of four things should be true for a steady state condition:

1) The mixed air is near its setpoint, OR
2) The economizer is in the deadband zone, OR
3) Toa is less than Tra - offset - (deadband/2) and The outside air damper is near maximum position, OR
4) Toa is greater than Tra - offset + (deadband/2) and Toa is less than Tra.

Determining whether or not the loop is at steady state is fairly easy for a human, given a time plot of the variable in question. Quantifying this into a knowledge base, however, is difficult. Our approach has been to fit a curve to the variable over time and from that determine whether it is in steady-state. If the curve is well approximated by a straight line and the absolute value of the magnitude is small, a steady-state condition likely exists. At present, the diagnostic system does not do this automatically, it must be determined by the operator from a time plot. It is expected that in the near future, this determination well be completed automatically.

Diagnostics of the ventilation delay mode is fairly simple:

Rule # 2

If mixed air loop is steady_state and
economizer mode is ventilation delay and
%OA is greater than %OAmin then
mixed air loop fault

where whether the economizer mode is in ventilation delay would be determined by the lack of a contact closure and passed to the diagnostic system through data acquisition.

Suppose that the economizer should be in summer mode and that the mixed air loop is at steady state. If none of the four cases described is true, i.e. the mixed air temperature is not near setpoint, that the %OA is not near a minimum or maximum, and the economizer is not in the deadband zone, then it can be concluded that there is a fault because one of them must be true if operation is normal. Several rules can be postulated.

Rule #3

If mixed_air_loop is steady state and
economizer mode should be summer and
economizer is not in deadband and
Tma is not near setpoint and
%OA is not near min%OA and
%OA is not near max%OA then
There is a mixed air loop fault.

Essentially this says that if the economizer is in its summer mode and the mixed air temperature is not at its setpoint then the dampers should allow the greatest possible airflow of whichever airstream is the coolest. For instance, if Toa is less than Tra - setpoint - (deadband/2), then %OA should be near max%OA or Tma should be near Tma_setpoint. However, this is not extremely useful. It says only that there is a fault somewhere in or in-between one or more of 20 or so components. A more detailed explanation of what is wrong is needed. Perhaps the comparator is malfunctioning. Depending on the implementation, a comparator malfunction could be either hardware or software. How would a technician test it? He might measure the signals from the mixed air controller and the economizer. If the economizer is on and operating correctly, the signals (Iip and Ima of Figure 2) should be equal. Hence, rule #4:

Rule #4

If economizer should be on and
mixed_air_control_signal is not equal to
comparator_control_signal
then comparator fault

It now becomes obvious that the state of the economizer required by the sequence of operation be determined through another rule:

Rule #5

If Toa is less than economizer_turn_on and
economizer_mode should be summer and
economizer is not deadband then
economizer should be on

It is instructive at this point to describe the role of the inference engine. The information gathered by the data preprocessor and configuration descriptor is sufficient to conclude from rule #1 that the economizer should be in summer mode. The inference engine can then conclude from rule #5 that the economizer should be on. Finally, all premises of rule #4 are found true, hence the comparator is concluded to be at fault. It is this ability to use known facts to conclude new facts that makes an inference engine so powerful.

Now lets assume that everything up to and including the comparator is functioning correctly. The fault could be either the I/P transducer, the pneumatic line, the damper actuators, the damper linkages, or the dampers themselves. If more information were available such as the pressure out of or into the I/P the fault could be further pinpointed. The degree to which a fault can be pinpointed is always a function of the information available.

The signal leaving the I/P however is usually available only in a gauge reading and not it an electronic form. In this case, there are two options. The diagnosis could stop here and simply tell the operator to go look for a problem at the I/P transducer, pneumatic tubing in between it and the damper actuators, the damper actuators, the damper linkage, or the dampers themselves. Analysis can go further if the operator has access to the mixed air controller setpoint. Increasing the mixed air setpoint should increase the mixed air temperature, and conversely decreasing the setpoint should decrease it if the I/P transducer and components controlled by it are working correctly (this assumes that the mixed air controller and comparator are working properly). Assuming that the additional information is available, rules six and seven explain how it could be used.

Rule #6

If mixed_air_controller is not a fault and
comparator is not a fault and
economizer should be on and
Tma_setpoint change does not change I/P output and
compressed air supply is ok then
I/P transducer is fault.

Conversely, if the I/P output does change with all other conditions the same, the I/P transducer is functioning correctly.

Rule #7

If mixed air controller is not a fault and
comparator is not a fault and
economizer should be on and
Tma_setpoint change does change I/P output and
compressed air supply is ok then
I/P transducer is not fault.

There is a problem with this rule. The diagnostic system has no way of knowing if changing the mixed air setpoint will change the I/P output. Although past data could be analyzed, this may be little help since the fault may be recent. One other possibility is to change the setpoint and observe the I/P output. To do this our diagnostic system has two inference engines. One is a forward chaining and the second is a backward chaining. The backward chaining is needed so that if the forward chaining can not determine a fault and needs additional information which can not be inferred from existing rules, it can ask the user for additional input. For instance, it can ask the user, "when you change the mixed air setpoint does the I/P transducer change its output?" With this additional information, the forward chaining inference engine takes over again and the cycle starts over again until either a fault is detected or no conclusions are found. This is illustrated in Figure 4. With this ability, rule #6, #7, or #8 can be determined to be either true or false from the operators response.

Rule #8

If there is a mixed air loop fault and
comparator is not fault and
I/P transducer is not fault Then
Fault exists between I/P transducer and Damper

There are several possible causes of this fault. A broken or kinked pneumatic line for instance could result in the dampers going to their default position. Or, damper linkages could be broken. Even an object in the duct physically preventing damper motion could be the problem.

SUMMARY AND CONCLUSIONS

The mixed air with dry bulb economizer loop of a VAV air handling unit with a return fan has been discussed. Several rules for this particular system have been presented. This is not a complete or comprehensive set of rules, but a set of rules from which a robust set of rules could be developed. Because the Army has prescribed a set of standard systems, these rules should apply to any systems built to the Army's that specification for the mixed air loop.

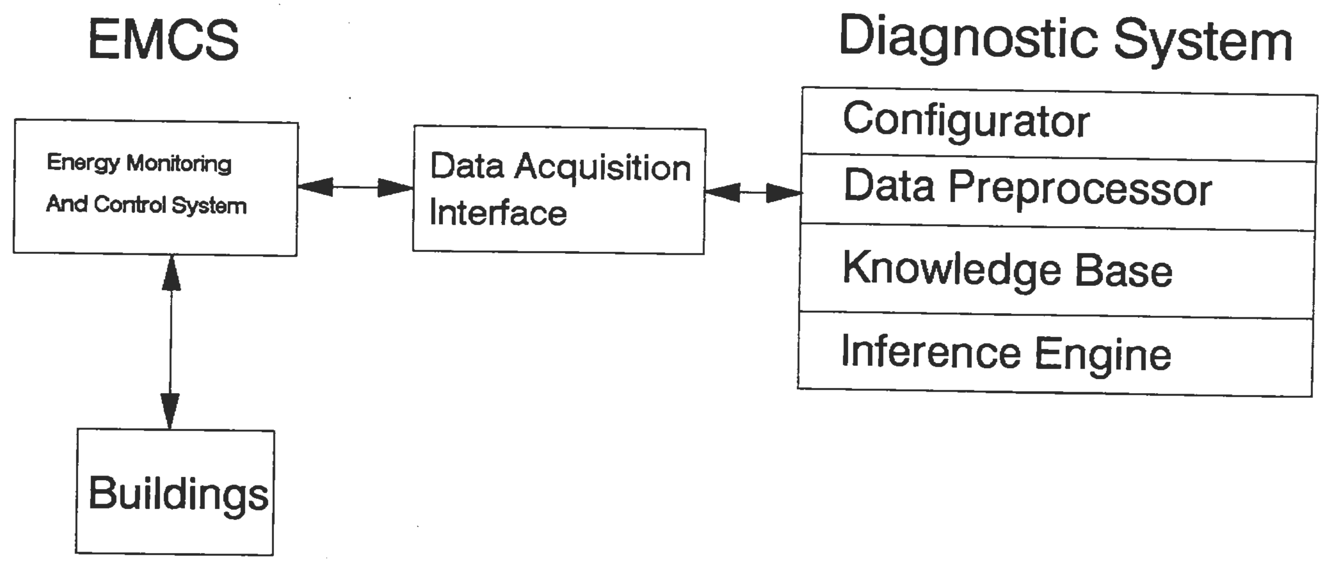

Figure 1 Diagnostic System Block Diagram

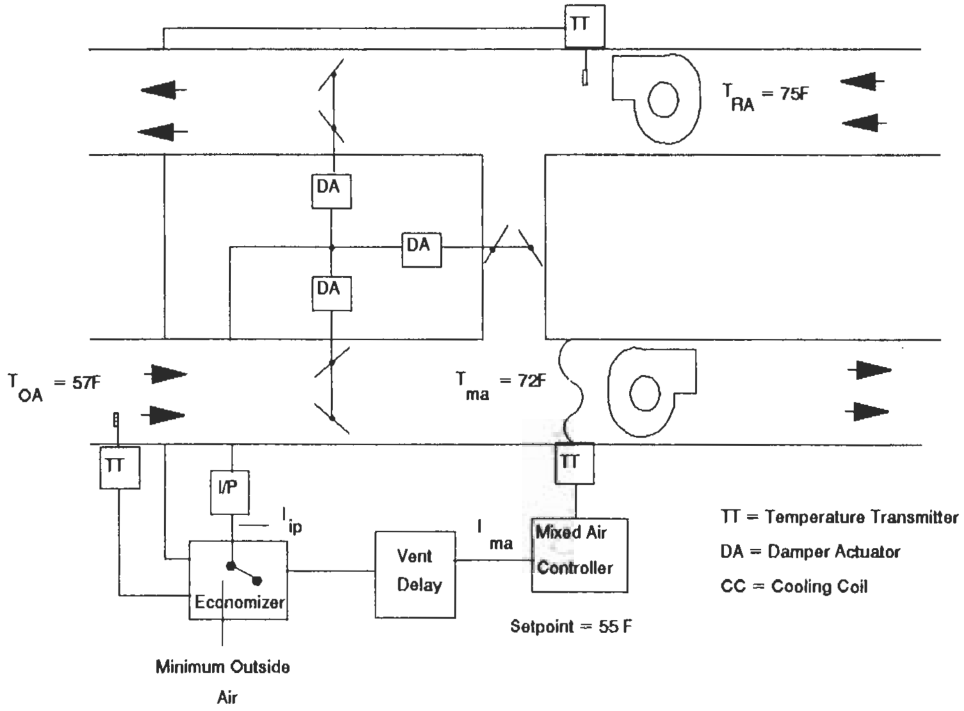

Figure 2 Mixed Air Loop

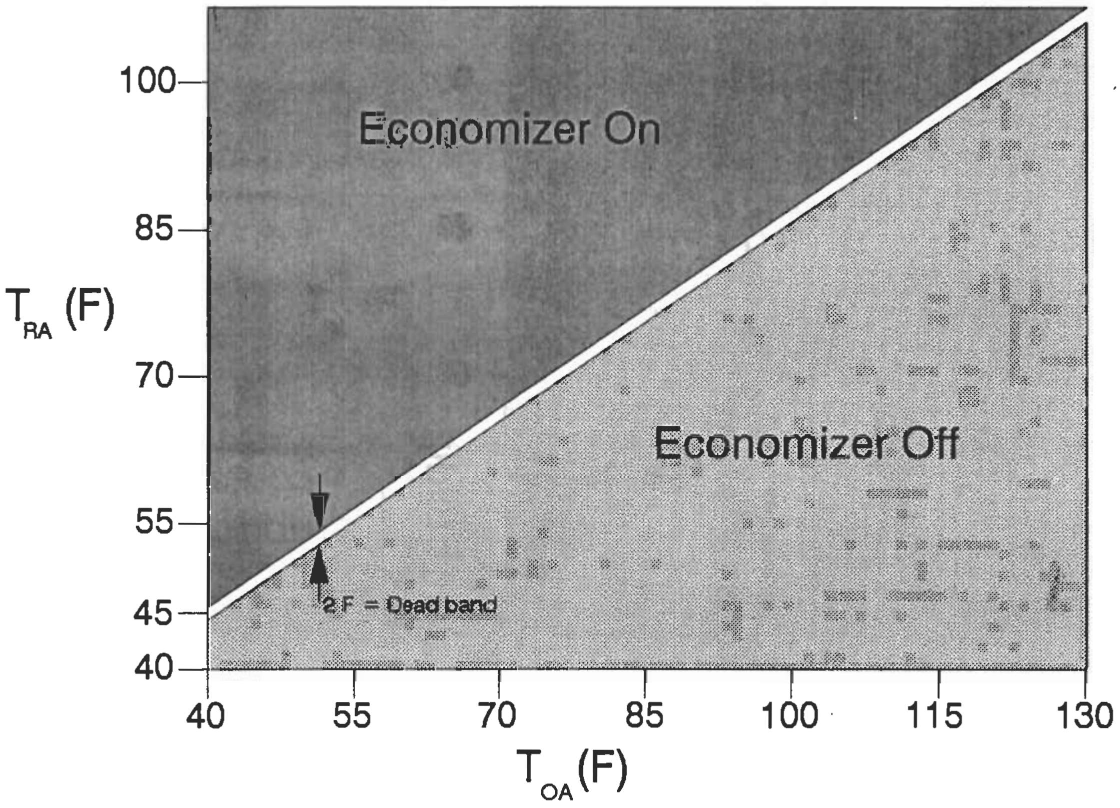

Figure 3 Dry Bulb Economizer (5F) offset and (2F) Deadband

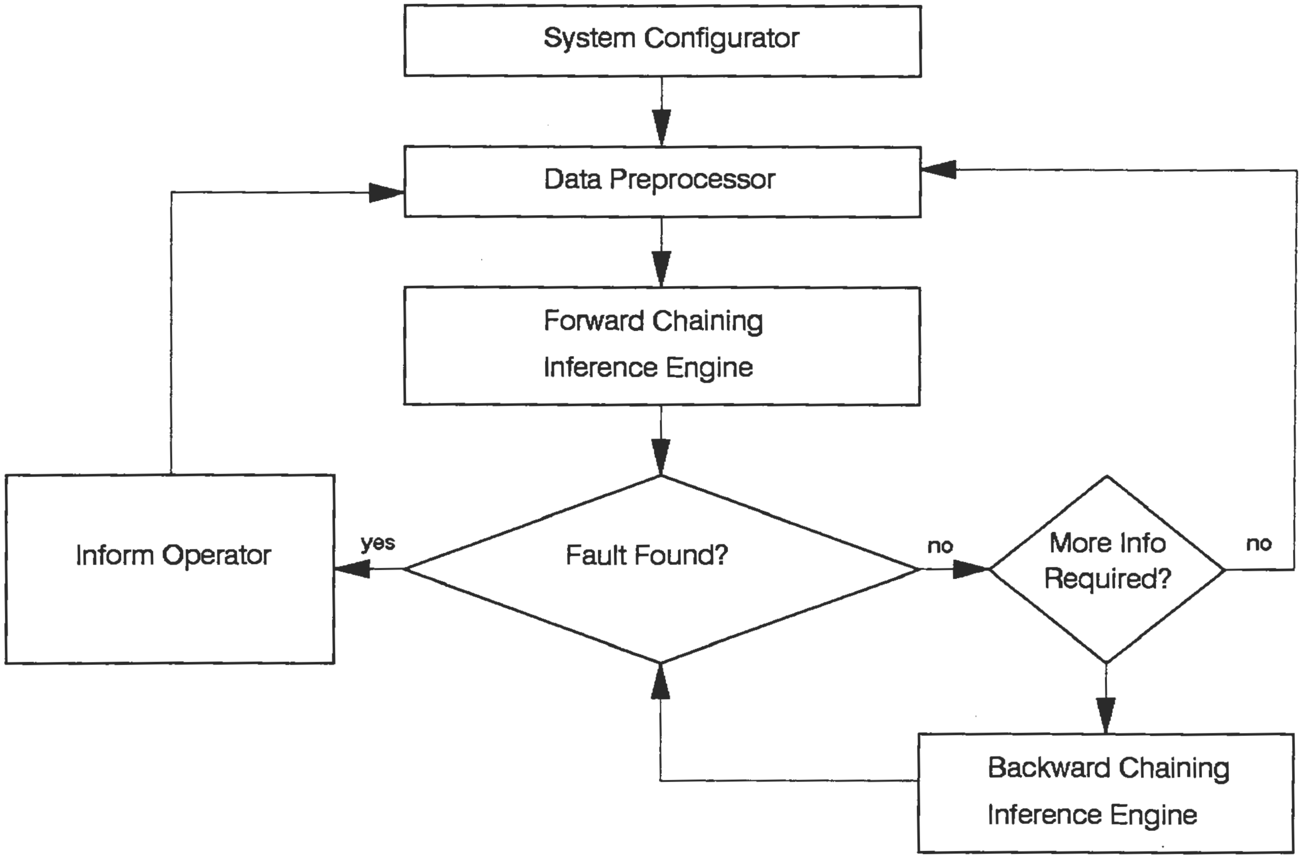

Figure 4 HVAC DIAGNOSTIC SYSTEM FLOW CHART