FAULT DETECTION AND DIAGNOSIS TOOL FOR SCHOOLS HEATING SYSTEMS

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INTRODUCTION

Managing energy in a large number of buildings requires adapted tools. The development of Building Energy Management Systems (BEMS) makes possible to measure a great number of variables on Heating, Ventilating, and Air-Conditioning (HVAC)-systems. Today, it is known that these systems are widely used for automating HVAC-system operation, for its remote control, and for detecting operating faults with great magnitudes. But the makers of propose very few tools to aid the operator in diagnosing the defects that cause the faulty process operation. A small number of users of BEMS have developed this type of tool; however, because of the lack of time and means, they can only develop some very limited tools of this type, and this prevents them from diffusing easily these tools.

This paper presents the results of a research work performed jointly by a research centre(CSTB), the service department of a large building owner (the town of Montpellier in the south of France) and a gas utility (Gaz de France). The ultimate goal of this project is to provide the service department of French towns with tools enabling them to detect easily the most common faults occurring on hydronic space heating system used in school buildings.

This work was performed in close connection with a working group set up within the framework of International Energy Agency (AIE Annex 25 [Hyvarinen 93], [Hyvarinen 95]).

PROBLEM TO SOLVE

In France, towns own most of the primary schools and are in charge of their technical management. A typical school building has a mean surface of about 2000m^2. Its heating system consists of one to three boilers and one to five hydronic heating circuits.

The energy department of the town of Montpellier manages about 300 buildings. In order to facilitate the management of such a large number of buildings remote BEMS were installed since the mid 80's. In Montpellier more than 100 remote BEMS are connected to a central supervisor through the public switched telephone network. The BEMS are used to control the HVAC plants, to trigger alarm and to log and transfer data to the central supervisor.

As compared to large air conditioning systems, school heating systems can be considered simple (see Figure 1). The main difficulty encountered by the service teams is linked to the number of buildings to manage. The number of data which can be collected daily is huge. The main difficulty is to find a good balance between the time spent to examine these data and the improvement in energy consumption and comfort which can be achieved from this examination.

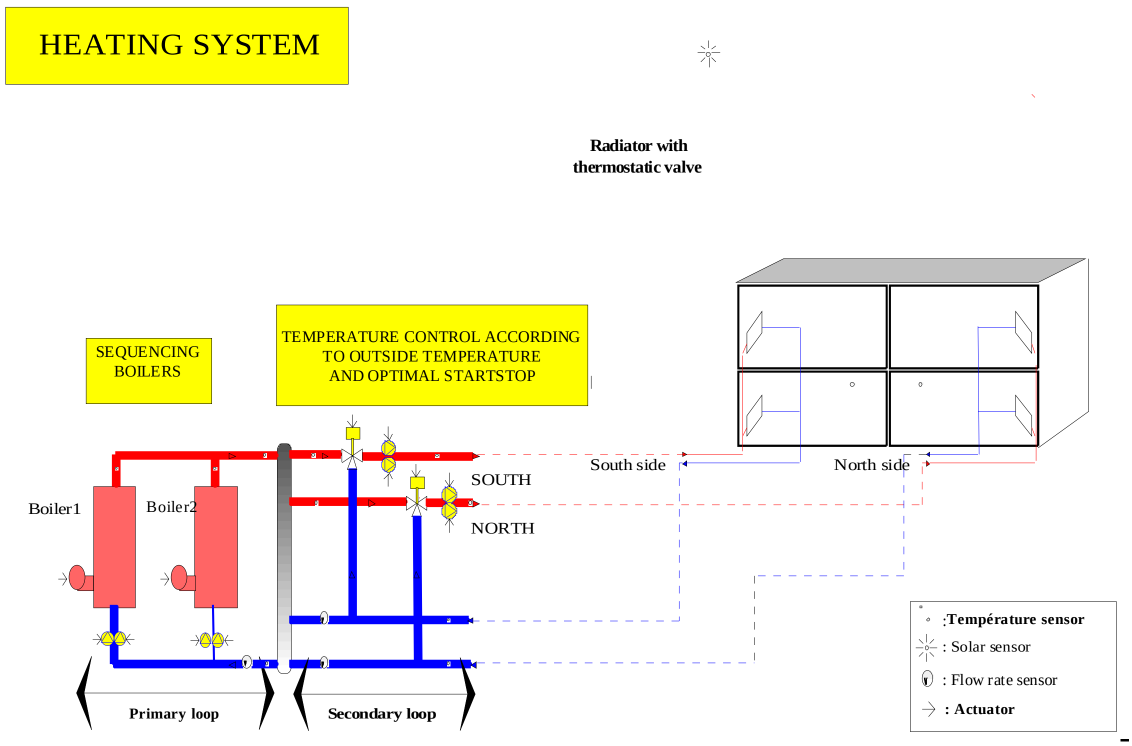

Figure 1: Typical heating system used in schools

At the beginning of the project the energy department of the town wished to take more profit of the measured information without hiring more staff for that purpose. Our challenge was to reach that goal.

ORGANISATION OF THE ENERGY DEPARTMENT

The requirements of the energy department concerning the tools are very linked to its internal organisation which is described on Figure 2.

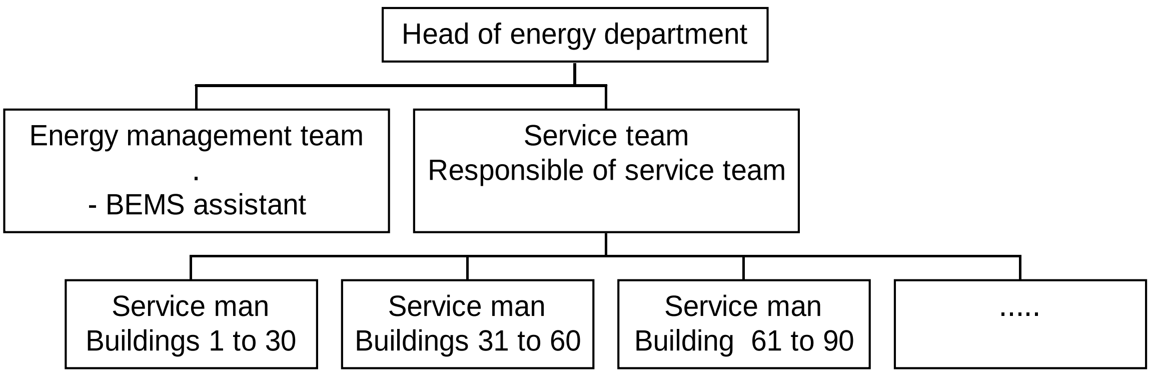

Figure 2: Energy department organisation

The role of the members of the department are the followings:

- Each service man is in charge of a group of buildings. He applies the maintenance scheduled actions. He also modify BEMS parameters in order to tune correctly the control loops and to adapt the running modes of the HVAC plant to buildings users needs. He for example modifies the schedules defining occupied and unoccupied periods when special activities occurs in schools (out of hours meetings....). Each service man has its own portable semi graphic user interface to the BEMS. This interface can be considered as the French ancestor of « network computers ». This very simple user interface enables a connection to a BEMS through the telephone network. It is well adapted to service people who have no experience of the use of a P.C.
- The BEMS assistant is in charge of analysing data measured by the BEMS and to provide advises to the service men on the way to improve the operation of the plants. He is the main user of the supervisor and makes a large part of the trouble shooting work. Its practical knowledge of the different buildings enables him to have an in depth understanding of the measured data. Its main problem is the number of data to analyse. He prepares weekly a monitoring scheme which helps him to analyse potential faults of the plants.
- The head of the energy department is responsible of the management of the department and of the long term policy concerning energy in the town's buildings. He analyses once a week the monitoring scheme prepared by the BEMS assistant and uses the result in the weekly management department meeting.

BEMS USE

The remote BEMS are used by these different users for the following purposes:

To control the installation:

This includes:

- sequence control of the boiler
- for each heating circuit
    - departure water temperature control according to outdoor temperature (heating curve) with indoor temperature compensation,
    - intermittent operation including: stop heating at the end of occupation, reduced heating to avoid indoor temperature to goes down to a low limit, boost heating with optimal start controller.

The main temperature measured for control purposes are: outdoor temperature, departure water temperature of each circuit, indoor temperature in one room representative of each circuit. These measurements are available for each building or circuit. Some other measurements such as flue gas temperature are available on some boilers.

To trigger alarms:

- alarms are triggered for faults which lead to stop the heating system such as: boiler malfunction, lack of water...

To archive data:

The data logged and transferred to the central supervisor are:

- the outdoor temperature
- the indoor temperature of one room representative of each heating network
- the departure water temperature for each circuit.

Hourly mean of the measured data are transferred every day to the central supervisor.

To provide weekly a monitoring scheme:

This scheme includes for each day of the week the following information:

- for the whole town
    - daily mean of outdoor temperature for different parts of the town
    - daily mean of solar radiation
- for each building
    - daily energy consumption for space heating
- for each heating circuit
    - daily mean indoor temperature of the representative room.

THE FORMER FAULT DETECTION APPROACH

The approach followed by the head of the service department and by the BEMS assistant for fault detection prior to the research project includes:

- in real time transfer of the alarms which can lead to the stop of the boilers,
- once a day or a week analysis of the monitoring scheme.

The main rules they applied to detect a fault using the monitoring scheme were the followings:

- verify that the energy consumption is close to 0 on Sundays,
- verify that the mean indoor temperature is not too high during week days,
- verify that the mean indoor temperature during week end is definitely lower than during week days.

This approach enabled them to detect large faults. Nevertheless it was lengthy to apply as no clear threshold can be defined on the value of the variables. Moreover the small number of variables used (2 variables per day if one include the value of outdoor temperature) does not enable to separate different faults.

Our work focuses on the improvement of this monitoring scheme.

TOOL SPECIFICATIONS

After having analyse the method used to detect faults specification of an improved tools were defined.

The main specification were:

1) As the number of building to manage is large and the human resources limited the Fault Detection and Diagnosis (FDD) tool shall provide synthetic information that can be dealt with quickly.
2) When faults are detected the results shall be presented to the service people in an easily understandable way. Graphical presentation shall be used as far as possible.
3) Each service man is responsible of the management of a group of heating systems. The FDD tool shall help them to be more responsible of their work and not to shift their responsibility towards the FDD tool.
4) As the goal is to apply the method to a large number of building without investing a lot of money in hardware the FDD tool shall work without requiring the installation of new sensors.

THE METHOD DEVELOPED

The approach followed for fault detection and diagnosis can be top down or bottom up.

In the top down approach the fault detection is performed on global index measured at the building level. Such an approach could consist for example in verifying that the energy consumption in normal or abnormal and that the building is comfortable or not.

The former approach adapted by the town of Montpellier is a typical top down approach. The monitoring scheme gives two indexes per day. The first one is directly the energy consumption. The second one is related to the comfort level.

In the bottom up approach one tries to detect the component malfunctions which are the primary causes of possible degradation of comfort or energy consumption. The main drawback of bottom up method is the need of a great number of sensors in order to enable to differentiate a large number of different faults. Its main advantage is to enable to diagnose the primary cause of a degradation of comfort or energy consumption.

Table 1 shows a list of possible faults with the symptoms associated and the impact they can have on energy consumption and comfort [LI 95].

Top Down

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Bottom up

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Global result	Symptom	Possible faults
Building not comfortable	- indoor temperature too low during occupied period	
		- bad tuning of heating curve
		- malfunction of indoor temperature compensator
		- blocked control valve
		- defect of outdoor temperature sensor
		-...
	- indoor temperature too low at the beginning of the occupied periods:	
		- boost heating too late
		- maximum value of the departure water temperature set too low
		- blocked valve
		- ...
Energy consumption too high	- indoor temperature during occupation too high	- bad tuning of heating curve
		- malfunction of indoor temperature compensator
		- blocked control valve
		-....
	- indoor temperature close to the occupation set point before occupation period	
		- boost heating too early
		- leaky control valve
		-...
	- heating during unoccupied period	
		- leaky control valve
		- bad scheduling of optimal start controller
		- intermittent heating not in operation
		- bad setting of controller clock
		- ....
	- flue gas temperature too high or low	- bad combustion
		- dirty or scales boiler heat exchanger
		-....

Table 1: Symptoms, possible associated faults and global effect (partial list)

FIRST APPROACH

Our first attempt in developing an FDD method was to use a fully top down approach. The first idea was to refine the monitoring scheme already used in Montpellier.

The choice of a top down approach seemed obvious due to the requirements defined above:

- research of a synthetic method applicable to a large number of buildings
- use of existing sensors.

The approach chosen to determine whether the energy consumption was normal or not was based on the energy signature of the building. Our approach was to apply a daily energy signature. Figure 3 shows the example of the energy consumption in one school building. The different week days are split.

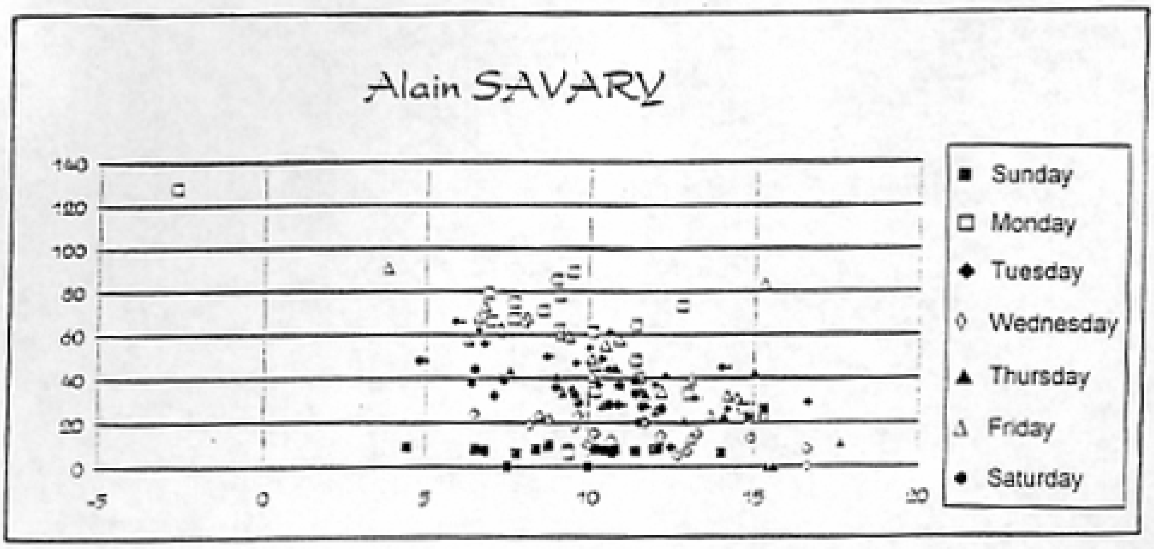


Figure 3: Energy consumption for different week days

Figure 3: Energy consumption for different week days

This figure shows clearly that the energy signature of a building (considered as the relation between energy consumption and outdoor temperature) differs from one weekday to the other. Our trials to different signatures for the different days were not successful. The width of the energy signature was for many faults larger than the energy consumption difference between a faulty system and a non faulty system. This can be seen on

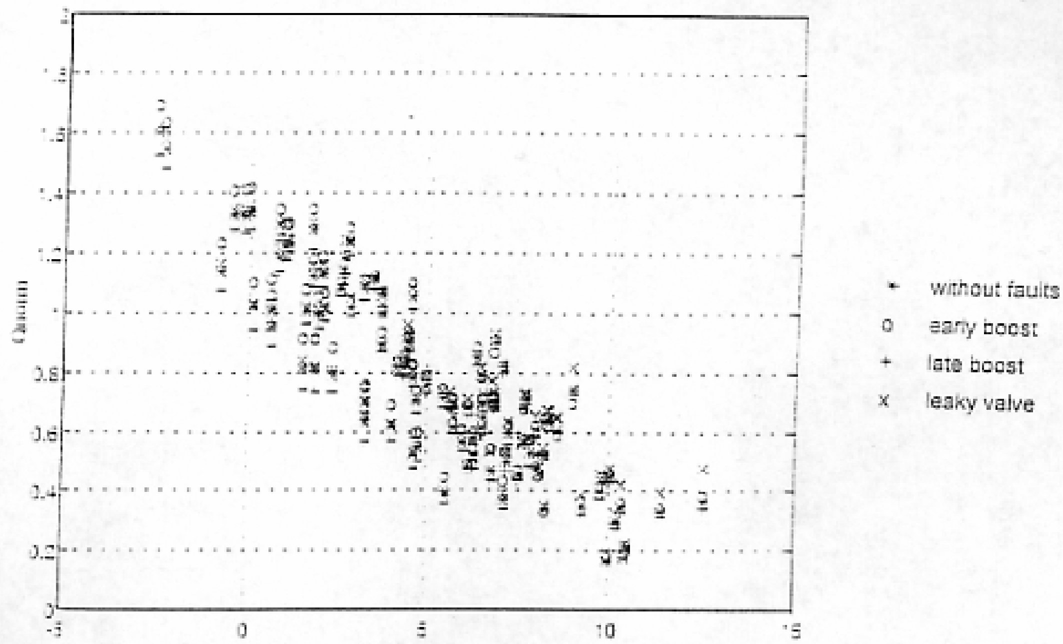


Figure 4: Simple energy signatures for faulty and non faulty system

Figure 4: Simple energy signatures for faulty and non faulty system

So the faults were not detectable with a simple energy signature.

There could have been a chance to solve that problem using more complex energy signature including dynamic effects but we have finally chosen an other approach.

SECOND APPROACH

As a fully bottom up approach was not appropriate due to the number of sensors required we decided to use an intermediate approach. This approach consists in trying to detect the main symptoms of faults which can lead to an increase of energy consumption or to a comfort degradation. We decided to focus on the symptoms of faults which can be seen on the indoor temperature and the water departure temperature. The idea was no more to diagnose the primary cause of a fault but to detect symptoms and to let service men find the primary cause by themselves.

The symptoms we tried to detect are the one described in column 2 of Table 1. As the flue gas temperature measurement was not available in most cases, boiler faults will not be detected.

The method developed includes:

- a pre-processor which concentrate the information contained in the hourly measurement of indoor temperature, departure water temperature and outdoor temperature in the following 6 indexes

- a classifier which diagnoses the possible faults from these indexes.

The principle of the method is described on Figure 5.

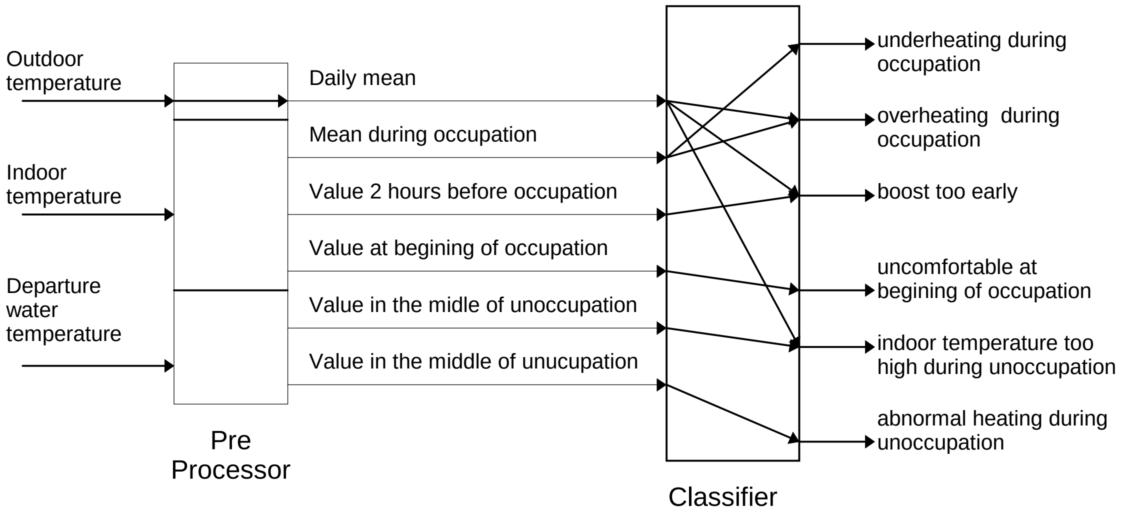


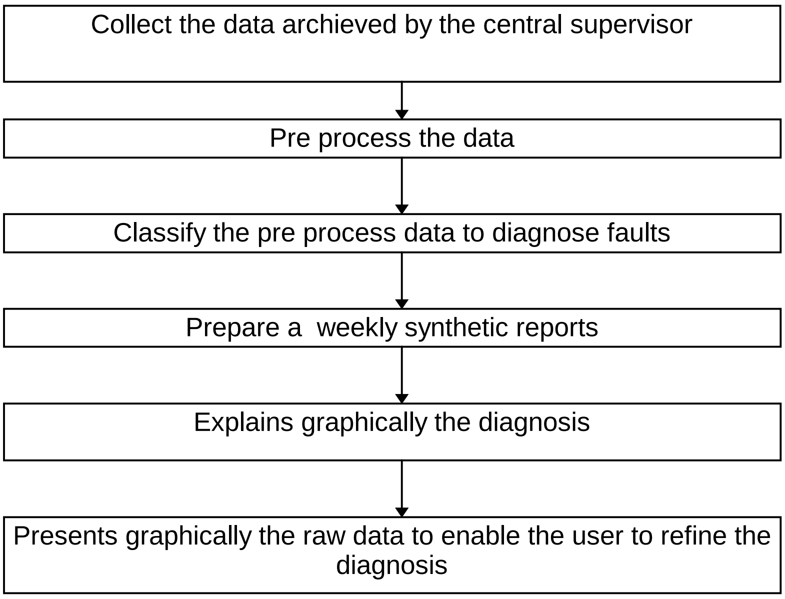
Figure 5: Structure of the fault detection and diagnosis method

The pre-processor calculates 5 daily values from the hourly measurement. Its role is to concentrate the information from 72 (24*3) measurements to only 6 indexes which are then transferred to the classifier. The pre processor functions can be easily performed by any data base management system using simple query. The only requirement is to know the occupation schedules. The choice of the pre processor outputs was done in a former research work ([LI 96], [LI 97]).

The classifier includes a set of 7 « if then » rules. Most of the rules take into account only one of the output of the pre-processor, some of them take into account two outputs.

THE PROTOTYPE SOFTWARE DEVELOPED

In order to validate the method with its end users a software called EMMA (as Energy Management at the MunicipAl level) was developed. Its functionnalities are the followings:



COLLECTING DATA FROM CENTRAL SUPERVISOR

At this stage of the software development the data transfer from the supervisor to EMMA is performed by a specific routine which reads the files archived on the supervisor.

This approach was very easy to implement but it does not enable us to take profit of the data base structure used by the central supervisor. So we have to redefine from scratch a data structure including the following data:

- building name

- heating circuit name

- address of the measurements (outdoor temperature, indoor temperature, water departure temperature) in the data base of the central supervisor

- occupation schedule of each circuit.

This data base structure is implemented under a standard database management software.

5 of the 6 items in the first menu presented on Figure 6 are related to this data transfer.

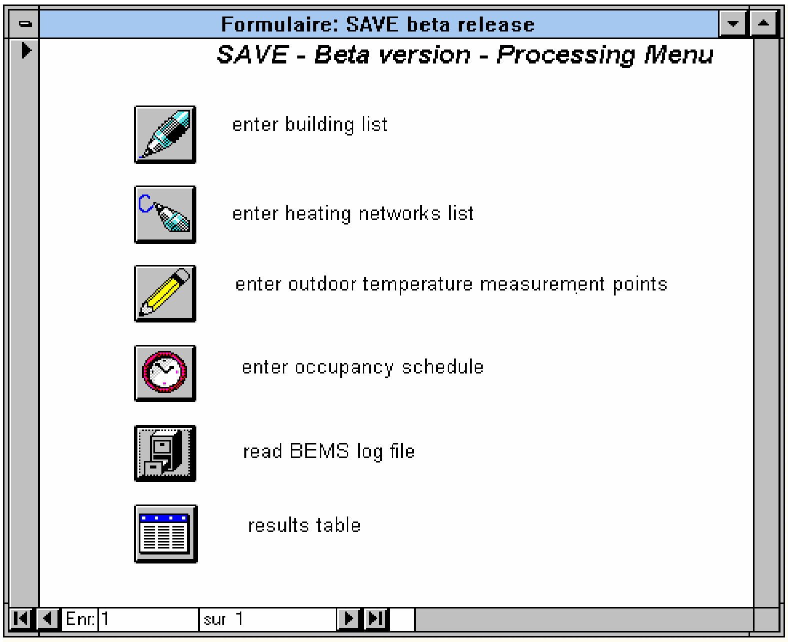


Figure 6 User interface of the software: first menu

This approach enabled us to work quickly and without needing an in depth with the central supervisor manufacturer. The objective for the next stage of the development will be to define with BEMS manufacturers a more integrated approach.

PRE PROCESSING DATA

The pre-processing is at this stage performed with the database management software. As pre-processing consists only in calculating mean values on specific period of time it was performed using standard functions.

Once again this approach was easy to implement. Its main drawback is to force to transfer daily the 72 raw data (3 temperature every hour) for each heating circuit.

In the future one can imagine to implement the pre processing function in the out station of each BEMS. This will enable to decentralise this task and will reduce the number of data to transfer to the supervisor by a factor 10. As the pre processing functions are very simple that could probably be achieved in today outstation.

CLASSIFYING DATA TO DIAGNOSE FAULTS

The classifiers consists in a set of if then else rules which are easily implemented with standard query functions from the DBMS.

PRESENTING A WEEKLY SUMMARY

The weekly summary gives 3 tables:

Table 1 presents daily energy consumption for each building. It is not used for fault detection but was required by service people

Table 2 presents a weekly synthesis. It gives:

- the list of heating circuits,

- for each of them the number of days during which a fault is detected.

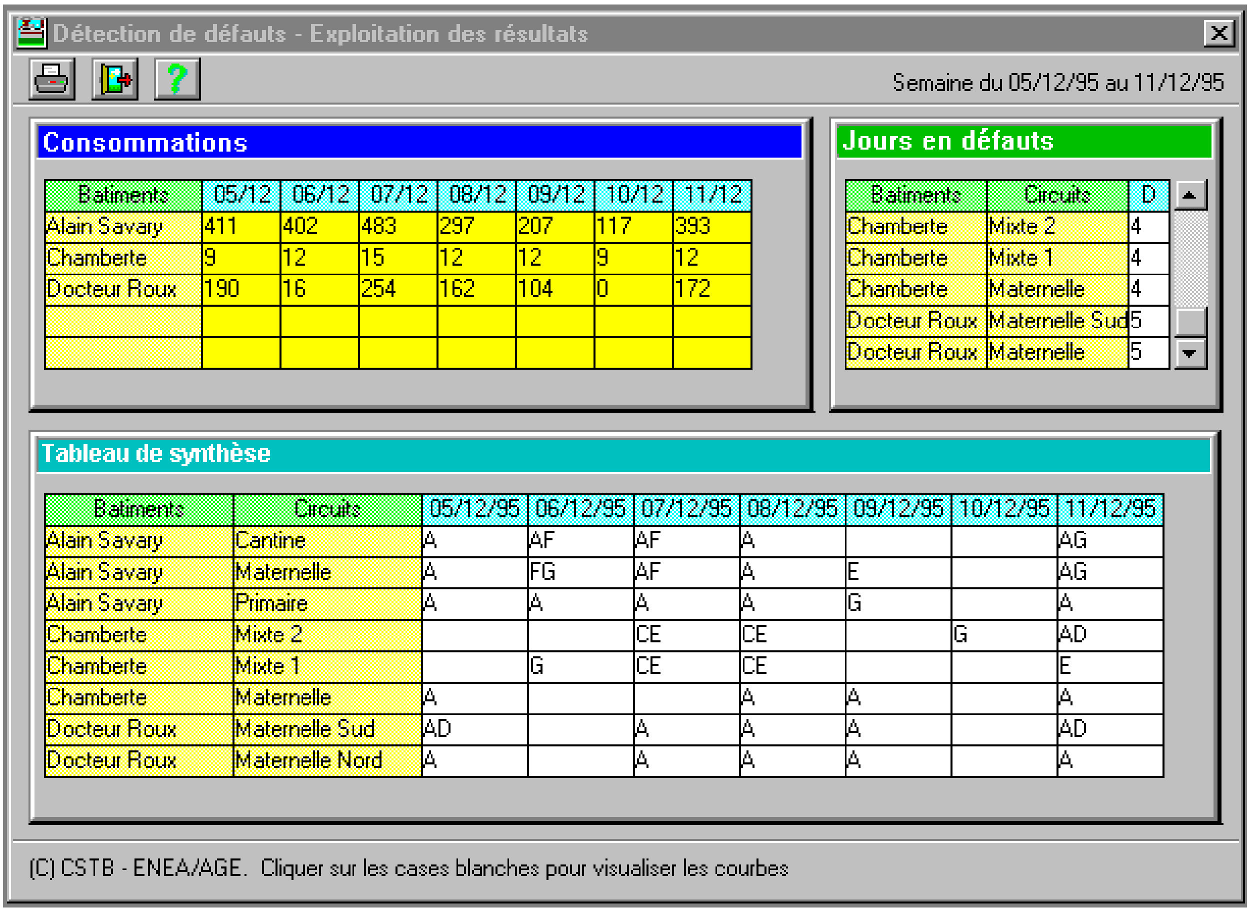
This report enables service people to focus quickly on faulty circuits.

Table 3: presents daily details. It gives:

- the list of heating circuits

- for each of them and for each day of the week the list of faults detected.

Figure 7 is an example of the summary.



Consommations

Batiments	05/12	06/12	07/12	08/12	09/12	10/12	11/12
Alain Savary	411	402	483	297	207	117	393
Chamberte	9	12	15	12	12	9	12
Docteur Roux	190	16	254	162	104	0	172

Jours en défauts

Batiments	Circuits	D
Chamberte	Mixte 2	4
Chamberte	Mixte 1	4
Chamberte	Maternelle	4
Docteur Roux	Maternelle Sud	5
Docteur Roux	Maternelle	5

Tableau de synthèse

Batiments	Circuits	05/12/95	06/12/95	07/12/95	08/12/95	09/12/95	10/12/95	11/12/95
Alain Savary	Cantine	A	AF	AF	A			AG
Alain Savary	Maternelle	A	FG	AF	A	E		AG
Alain Savary	Primaire	A	A	A	A	G		A
Chamberte	Mixte 2			CE	CE		G	AD
Chamberte	Mixte 1		G	CE	CE			E
Chamberte	Maternelle	A			A	A		A
Docteur Roux	Maternelle Sud	AD		A	A	A		AD
Docteur Roux	Maternelle Nord	A		A	A	A		A

Figure 7: Example of summary

EXPLAINING THE DIAGNOSIS

A key point for service people was to have a clear explanation of the reasons of the diagnosis. These reasons shall be understood by people who have a good practical knowledge of heating systems but no theoretical knowledge of modelling or fault detection.

The choice made is to present graphically the diagnosis reasons. As each diagnosis is based on one or two « if then rules » a 2 D plot is sufficient to explain it. The pre processed data are represented on a graph with on the x axis the mean outdoor temperature and on the y axis the pre processed data which is used for the diagnosis. Each graph covers one week with one data per day. The if then rules are presented on the graph using coloured zones. White zone correspond to non faulty data, grey zones correspond to faulty data.

Figure 8 and Figure 9 present two examples of graphs which are used to explain the diagnosis of normal or abnormal temperature during occupied period.

The user has access to these graphs by double clicking on the summary on the number of faults of the week.

Figure 8 is related to a building named « Chamberte ». One can notice that the mean indoor temperature during the occupied period is for one day fully in the abnormal zone (grey part) of the graph and for two other days on the boundaries between normal and abnormal zones of the graph. On Figure 9 (building « Docteur Roux ») all the points are in the normal zone (white zone).

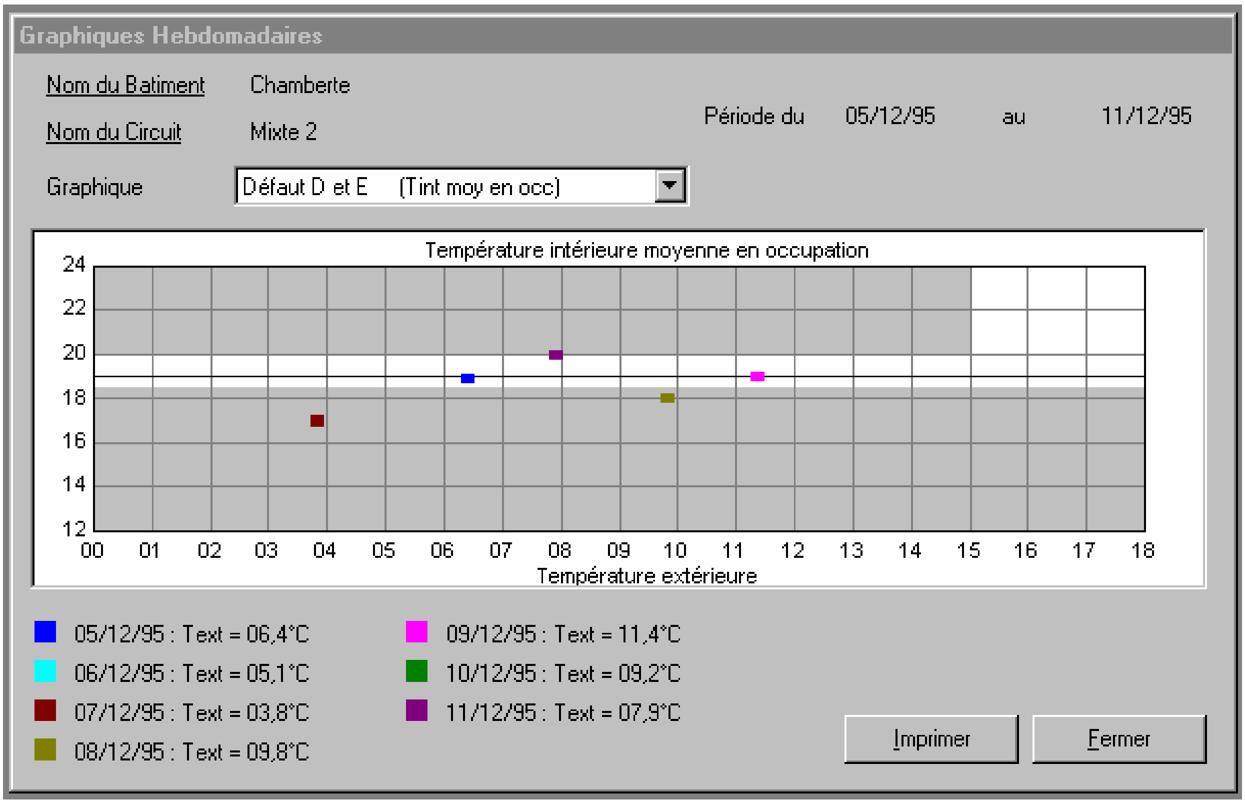


Figure 8: Diagnosis of abnormal indoor temperature during occupied period

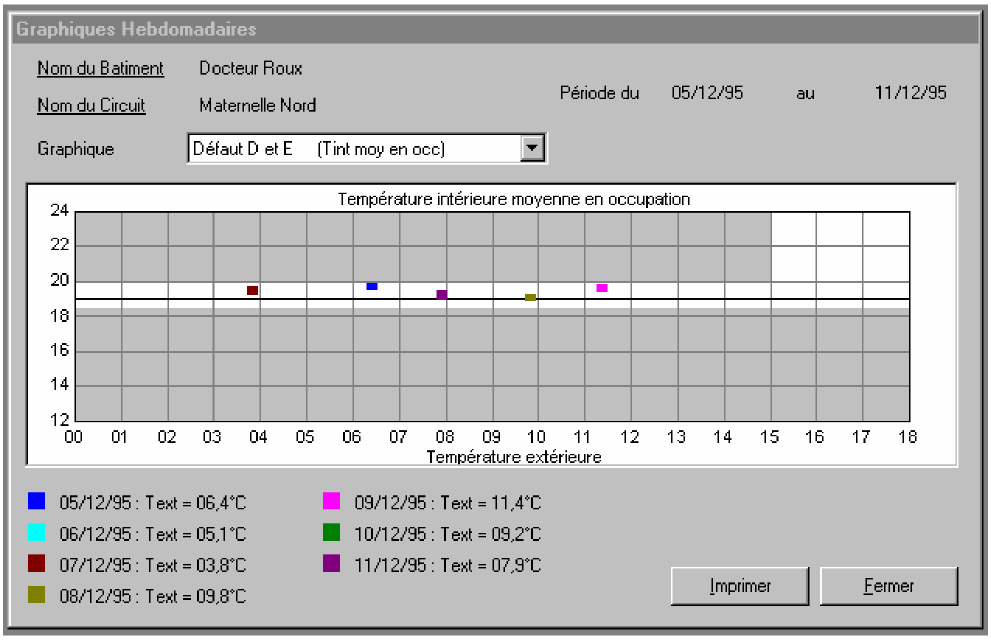


Figure 9: Diagnosis of normal indoor temperature during occupied period

The diagnosis obtained does not enable to know directly which component is faulty. So service people have to get to the root of the fault. In order to facilitate that work the software enables also to plot the daily evolution of indoor temperature, outdoor temperature and water temperature. Daily plot are obtained by double clicking on the list of fault of a circuit for a given day.

Figure 10 presents the evolution of these three temperatures for one day corresponding to Figure 9 . There is no fault detected on that day. One can notice that it is much easier to see that no fault is present on Figure 9 than on Figure 9 which is a typical figure available on today's BEMS.

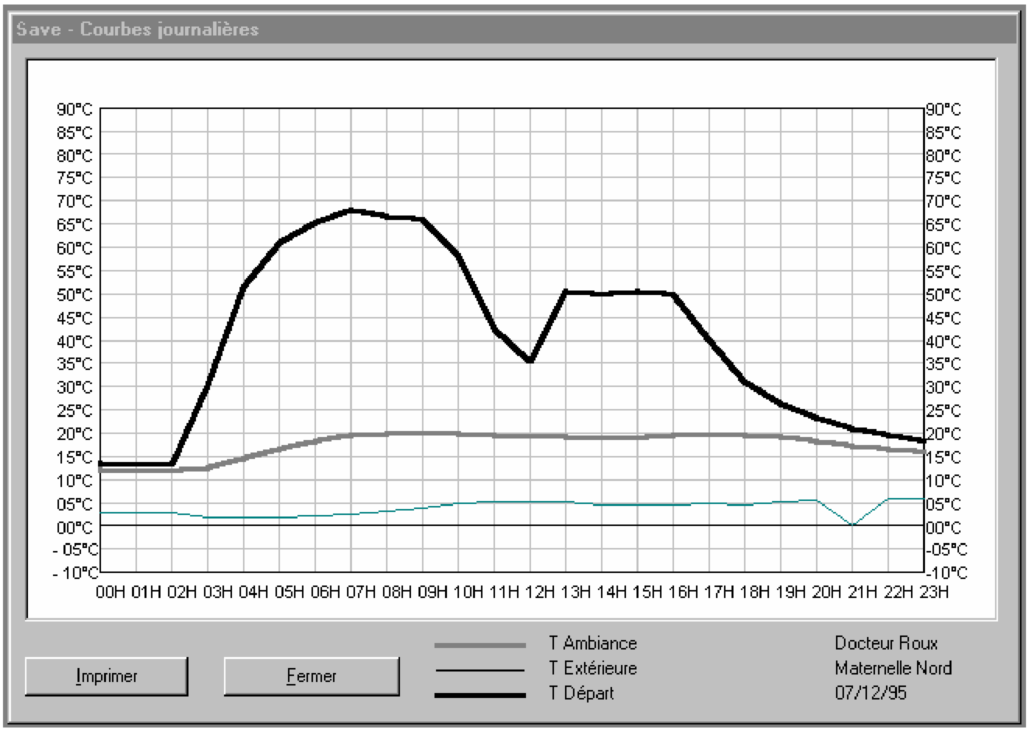


Figure 10: Measured values for a non faulty period

Figure 11 presents the evolution of these three temperatures for one day corresponding to Figure 8. It appears that the boost is to late to enable the indoor temperature to reach its set point at the beginning of the occupation period.

The software is able to perform this global diagnosis but not to explain the primary cause of the fault. Looking to Figure 11 the BEMS assistant was able to diagnose that the set point of the thermostat limiting the departure water temperature during the boost was probably to low. So the water departure temperature never passed above 70°C which prevents having an efficient boost.

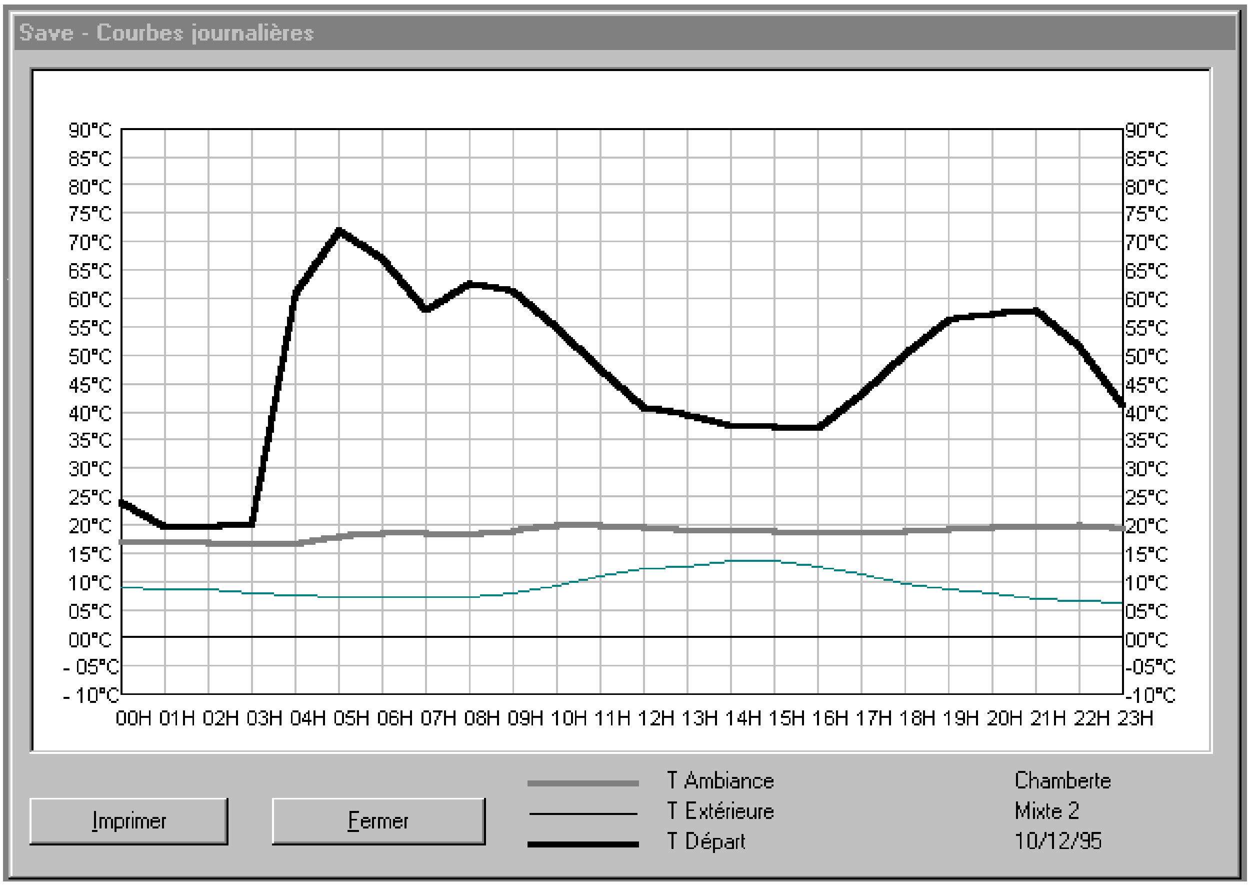


Figure 5: Measured values for a faulty period

SOFTWARE VALIDATION AND DISSEMINATION

The first software test was performed during the 1995-1996 heating season by the energy department of the town of Montpellier. This first validation leads to a lot of comments dealing mainly with the user interface. The user interface described above takes profit of all these comments. The main comment was that it was necessary to have access to the summary, to the explanation of the diagnosis and to the plots of the temperature in the same software and from the same user interface.

The second validation is going on during the 1996-1997 heating season and is performed by the town of Montpellier. The first goal of this validation is to verify that the software is effectively used by end users and help them in their daily work.

The third validation will go on during the end of the 1996 1997 heating season. It will consist in installing the software in the service department of two French towns which were not involved in its development in order to verify that it really fulfil their requirements. At this stage we are organising a co-operation with two BEMS manufacturers in order to determine with them:

- how to transfer the data from different BEMS to the EMMA software,

- the possibilities to integrate the functionalities of EMMA in BEMS standard softwares.

This third validation is also organised in co-operation with the Association of Engineers of French Towns (AIVF) which includes a large number of potential users of such software. The dissemination of the software will be organised after this third validation in co-operation with this association and BEMS manufacturers.

PROSPECT

A new IEA working group (Annex 34) is being set up to study the application of fault detection and diagnosis techniques in real buildings. No doubt that this annex will enable to test many faults detection and diagnosis software in different types of buildings.

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