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A SYSTEM CONCEPT FOR REAL TIME SIMULATION OF HVAC-SYSTEMS FOR BUILDING OPTIMISATION, FAULT DETECTION AND DIAGNOSIS.

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ABSTRACT

The reliability, availability and the efficient use of the HVAC- and control systems will be emphasized in the use and maintenance of the buildings in the future. These characteristics can be affected by integrated planning and product development. A parallel way is to develop methods for the real time analysis of the behaviour of processes and for the fault diagnosis i.e., process diagnosis.

This paper presents the collaboration started in 1991 within IEA, Energy conservation in buildings and community systems programme in its Annex 25: Real time simulation of HVAC-systems for building optimisation, fault detection and diagnosis (BOFD). The main goal of the Annex is to develop methodological procedures - within a defined concept - for real time and automatic performance optimisation, diagnosis and fault detection of HVAC-processes. The ultimate goal of the project will be building optimisation and fault detection method prototypes that are implementable in building energy management systems (BEMS). The building optimisation and fault detection methods to be developed utilize normal BEMS instrumentation and operate in real time.

The paper concentrates on the BOFD-system concept defined during the first year of the annex. The concept consists of definition and description for building optimisation, discussion on how reference performances for building optimisation should be determined, interrelationships between optimal control and building optimisation and fault detection system, general system structure, ideas for user interface and system realisation.

INTRODUCTION

Together with the development of technical systems also the processes and systems in a building get more difficult for a normal operator to understand. The buildings get more intelligent but the users not. Reasoning the relationship between cause and effect is more difficult than in the past because of the complex relationships in building's processes. The building processes are normally supervised with building automation system and a suitable supervision or management software. The operator's task is mainly to initiate separate sequences and actions. When the process goes in a failure state the available supervision programs do not aid sufficiently in finding the underlying cause (defect) to the fault and the reasoning the defect is thus left to the operator. In buildings failures may mean inefficient usage of energy and uncomfortable working environment. To avoid this, the operator should continuously monitor the process and find the defective subprocess. Especially when operating a complex building it would be good if the operator was provided with tools which would support him in decision making for building optimisation as well as recovery from a faulty state. The tools should focus on underlying defects and give instructions on corrective actions to be taken in a simple and understandable way.

To resolve a failure in a process various methods can be used. The development of defects can be monitored with special condition monitoring instrumentation to obtain information with regard to need for maintenance. These systems are usually separate from building automation systems and need the instrumentation of their own, for instance vibration analysis systems which are used in industrial processes can be used for condition monitoring. Also different maintenance programs can be used to prevent serious defects and to schedule the maintenance in the most suitable way. In maintenance programs the process ~~is inspected and~~ maintained after constant time intervals independent of the true condition of the process. The main disadvantage of the present condition monitoring systems is that they are expensive because of special instrumentation or that they can not be operated in real time applications.

The main purpose of a real time fault diagnosis system is to monitor the operation of various process components and subprocess and to detect, locate and, - if possible - even predict the defects causing faulty operation. In an ideal case the system should resolve the primary defect and give instructions for undertaking the corrective actions. In practice this is hardly possible but the fault diagnosis system should be considered more as a tool for gaining process information and as an aid for an operator in reasoning the defects that cause the faulty process operation.

The process instrumentation in BEM systems is nowadays quite extensive and there is no need to build a separate fault diagnostics system instrumentation. The fault diagnostics system should utilise the normal process instrumentation as extensively as possible and some extra instrumentation can be applied only if needed for some special reason. In this way the fault diagnosis methods can be applied in a reasonable price to a large enough set of process components and subprocess and they give the best possible benefit.

General objectives

In the near future, energy savings will be obtained mainly through optimal control of HVAC-systems. Lowest energy consumptions, one of the basic factors to reduce managing costs, will be reached together with well-organized maintenance, fast detection and correction of defects and best use of equipment performances. Those aims are to be met partly at the conception of the new systems but also by an adequate choice of control strategies as well as by predicting plant and building behaviour and comparing those predictions (target performances) with actual performances.

Annex 25 objectives

The main goal of the Annex is to develop methodological procedures - within a defined concept - for real time and automatic performance optimisation, diagnosis and fault detection of HVAC-processes. The ultimate goal of the project will be BOFD prototypes that are implementable in BEM-systems.

Part objectives are:

- to evaluate the best (most suitable) modelling approaches for the real time simulation of HVAC-systems
- to develop concepts for the suitable methods for fault analysis (qualitative availability analysis of HVAC-systems)
- to collect a data base of the most important troubles and faults in HVAC-systems
- to demonstrate the implementation of the concepts in conjunction with a real BEM-system. This will help and promote the technology transfer to industry.
- to apply optimal control for building optimisation purposes

IEA

International Energy Agency

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IEA ANNEX 25

A SYSTEM CONCEPT FOR REAL TIME SIMULATION OF HVAC-SYSTEMS FOR BUILDING OPTIMISATION, FAULT DETECTION AND DIAGNOSIS

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The Annex concentrates on the energy performance diagnosis of a building and HVAC-systems and the fault detection of HVAC-components and subprocess.

BUILDING OPTIMISATION AND FAULT DETECTION SYSTEM CONCEPT

Definition for building optimisation /1/

Building optimization is defined as to maintain a building in an optimal state from the viewpoints of energy consumption and indoor environment through controls, adjustments and/or remodelling of the building services engineering systems and, sometimes, the thermal/optical performance of the building structure (figure 1).

Building optimization may be defined separately for design phase and operation phase. In a strict sense, these two phases cannot be separated, because the optimal design, which could be established after execution of load simulations and system simulations in a dynamic as well as static mode, should be followed by the optimal controls based on the same performance function, constraints and characteristic performance or equipments as used in simulations. However, the total optimization in this sense is so hard to realize, that a practical execution of buildings optimization may be separately performed at each phase of design and operation of a building. Annex-25 objectives are in the operation phase of the HVAC-system, thus the building optimization is limited only to the operation phase, which will actually results in a partial building optimization.

The performance function and constraints for an optimization are the energy consumption which should be minimized and the environmental qualities which should be kept within an allowable level, respectively. The reference data for energy consumption may be the designed value, energy budget regulated by law or any other standards and/or the database of energy consumption for other buildings which includes sufficiently useful information on building and HVAC-system for statistical analysis to enable a reasonable comparison.

Off-line simulation is a useful tool not only at the design phase but also at the operation phase for building optimization. Various parameters describing building thermal characteristics as well as control gains may be identified beforehand in the optimal control algorithms with the use of real-time simulation and learning methods. Then the off-line simulation will have sufficient precision to predict the air-conditioning load, energy consumption and the quality of indoor environment, thus allowing to find out any non-optimal state of performance by comparing with the actual data.

Other kinds of prediction models with the parameter estimation through real-time learning are available. It may have the structure of the multi-inputs to describe important factors affecting the characteristic value as a single output. Parameters, which may be called the weighting factors of each input value, may be estimated by the filter model, auto-regressive model or any other data handling methods.

Expert systems for reasoning of non-optimal state are practical method of diagnosis for the sake of building optimization. Quite often, the expert system gives a good answer for remodelling, redesign and retrofitting of some sub-systems of HVAC. In that case, the database should include the actual results of energy consumption and any other sufficiently useful information of the building and the system fitting for statistical analysis. Knowledge database should also be accumulated to reach a satisfactory solution in a short way. Questionnaires and hearing from designers and engineers as well as maintenance personnel are indispensable.

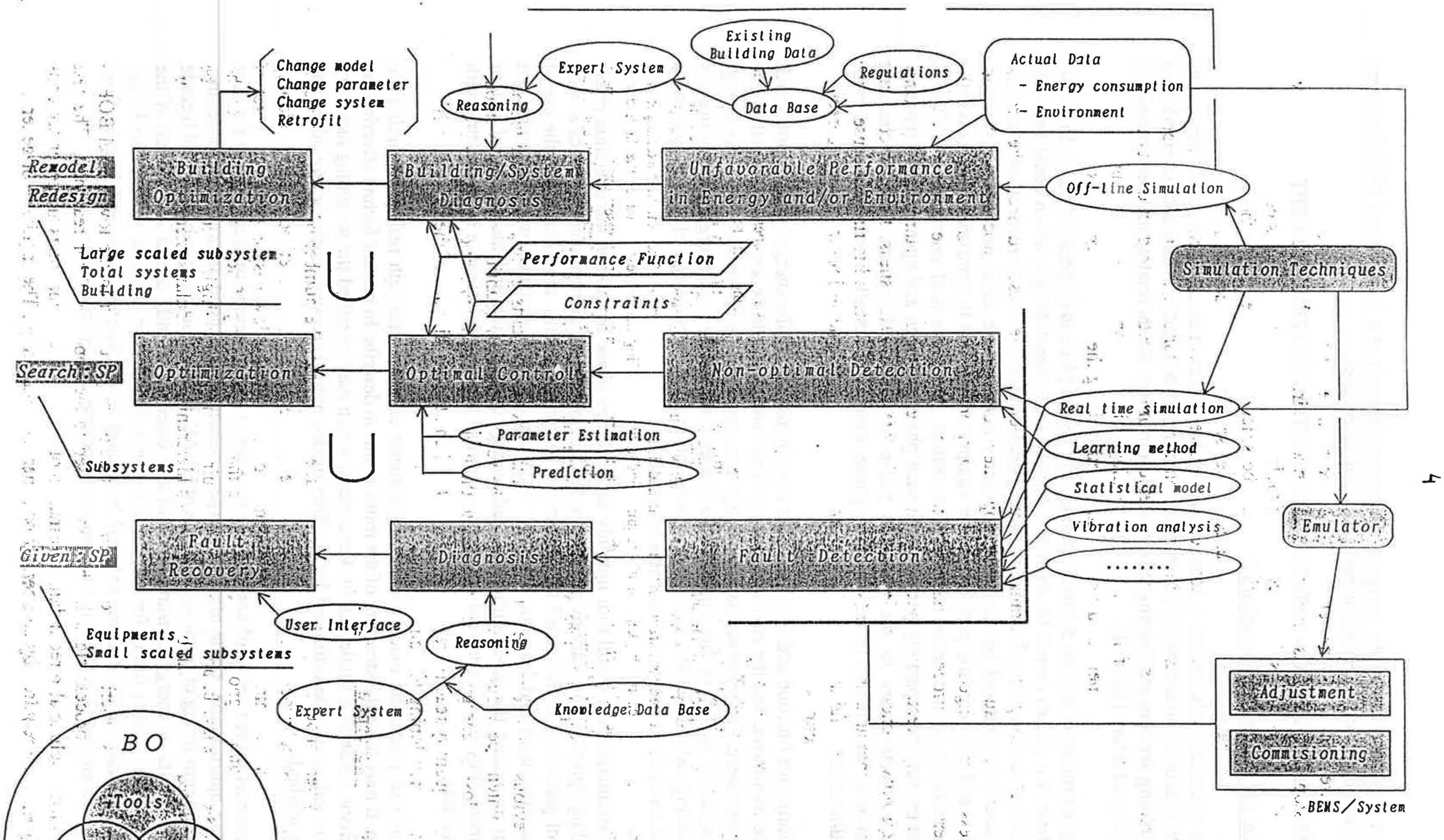

Fig. 1

CONCEPT AND METHODOLOGY OF BUILDING OPTIMIZATION

RELATION AMOUNG BUILDING OPTIMIZATION, OPTIMAL CONTROL AND FAULT DETECTION/DIAGNOSIS

Fault detection /2/

Process failure is usually considered to be an event where the required operation of the process suddenly stops. Process is assumed to operate in a required way when the "product" quality is within predetermined limits. In the context of fault diagnosis this definition is not sufficient. The requirements for the process operation should be stricter and for example the operating point deflection from that of the designed (target value) should be considered as a defect causing a process fault. The defect thus does not necessarily have to effect the "product" quality in any way because small deflections can be corrected automatically by controllers. The broader definition of a defect is needed to be able to detect a defect before it effects the product quality and thus to be able to predict the failures. In failure diagnosis the emphasis should thus be put on monitoring the development of a defect and on minimising the damages or losses caused by a defect.

A defect causes a process's faulty operation which can be observed from the process measurements. The faulty operation can propagate to other parts of the process or to the other subprocess due to changed operating points or the influence of the fault can be removed by using controllers. From the process signals some test quantities are generated the variation of which is a symptom of defect. The generation of test quantities can be done in numerous ways. Once the test quantity reaches some predetermined level related to the seriousness of the defect the test quantity is set into an alarm state (symptom) and the reasoning is started to find the cause of the 'alarm - symptom - failure' chain. The alarm state is set once the seriousness of the defect requires corrective actions.

> A defect may be a slowly increasing dirtiness in a heat exchanger. This causes a faulty operation (drift of the operating point or deviation of temperatures) of the heat exchanger. The defect and the fault are small in the beginning but they increase while the heat exchanger gets more dirty. The failure may result in changes in the inlet and outlet temperatures. The purpose of the heat exchanger is to transfer heat between primary and secondary circuit. The loss in heat transfer from the primary to the secondary circuit can be compensated by increasing the flow or primary circuit inlet temperature which both mean additional energy consumption. Once the heat exchanger is so dirty that the heat cannot be kept in it's required value by controlling the process variables the fault comes 'observable' to the utiliser of the heat and the fault starts to propagate. In real life this observability might mean that an occupant in the building feels that it is too cold. Thus by observing the development of dirtiness instead of waiting for complains from the occupants the loss of energy can be noticed earlier.

In the previous example the defect occurs when the exchanger starts getting dirty and the need for the maintenance should be assessed from the value of the test quantity i.e. from the amount of harm or loss of energy the defect causes to the user. If the development of the defect is rapid also the test quantity reaches rapidly the alarm level and the 'prediction' of the defect is difficult. With slowly developing test quantities the prediction is easier.

BOFD-system concept and structure

A BOFD-system should be designed so that it does not restrict the number of different process units (buildings, subprocess, components) or the number of different methods. For developing new methods in a running system the system structure should allow easy expanding the set of fault detection and diagnosis methods and also that the connecting of new process units to the BOFD-system is easy. In addition the costs required to monitor a single component can not be high. These requirements can be fulfilled with a hierarchial and modular system structure (figure 2).

The test quantities describing defects in process units are generated in the lower level BOFD-modules from the process signals. They are passed to the upper level for reasoning. The test quantities may include also redundant information of faults. The test quantities are generated continuously or when required by an operator or upper level reasoning. The inquiries for generating

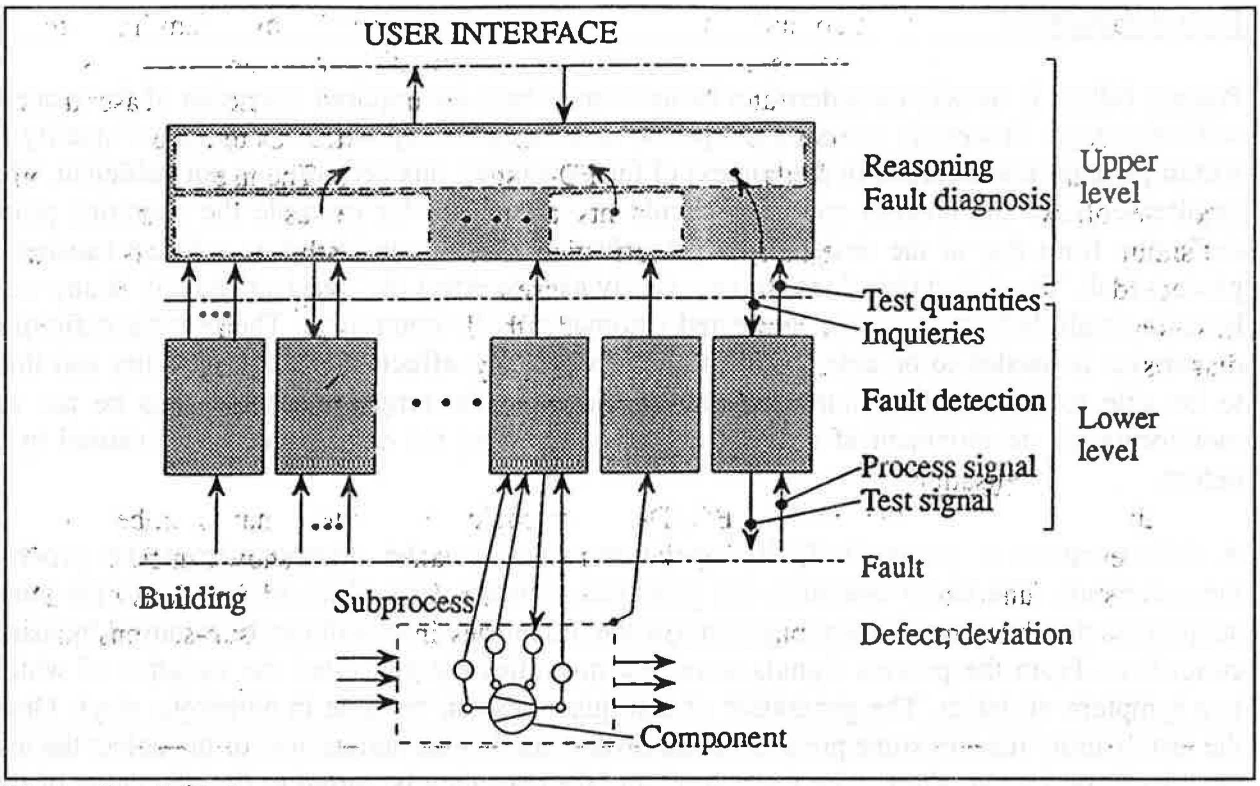

Figure 2. BOFD system structure

test signals are passed from upper level to the lower level. A lower level module can use an additional test signal that is fed out to the process for generating suitable process conditions for fault detection purposes.

For example if the parameters of some subprocess are wanted to be estimated the operator or upper level software sends an inquiry to lower level module of that subprocess utilising estimation techniques. Lower level module generates a suitable test signal and the subprocess parameters are estimated from the control signal and the process signals. As a result the parameter estimates are passed back to the upper level as test quantities.

Lower level
The methods on the lower level are modular and independent of other modules. Each module monitors a single well-defined process unit (building, subprocess, component). For one process unit there may exist several monitoring modules each of which monitors a specific defect or uses a specific method. Fault detection methods should aim at least to give good relative accuracy so that the relative changes in test quantities could be used for fault detection.

Upper level
Each lower level module generates one or more test quantities or symptoms from the measured process signals. The test quantities are passed to the upper level for reasoning. The reasoning aims at locating and finding the cause of the fault (diagnosing the defect). The output for the user is instructions and aid for correcting the defect and the fault. The reasoning may in addition to generated test quantities use also direct process signals and information gained from the user by a dialogue. If there are mutually redundant test quantities the reasoning may use only the most apparent test quantities or a set of test quantities may be combined to give the best result.

BOFD-system user interface
Because BOFD-system is implemented in the first hand for aiding the operator in diagnosing process faults much emphasis has to be put on designing the user interface of the BOFD-system. A building operator needs the BOFD-system to explain and reveal complex interdepencies in a

simple way, not perhaps more complicated technical systems than he already is familiar with. On the other hand the operator must be able to trust on the information the BOFD-system supplies him with and that is why the operator has to have an opportunity to check the reasoning the diagnosis is based on (explanation mechanism). In addition the operator has to have a possibility to check all the variables and calculations the BOFD-system performs. The user interface should meet the following mutually contrary requirements: the user interface has to be clear and simple but simultaneously it has to give thorough information of reasoning paths. The defects should be diagnosed exactly but too detailed diagnosis may cause the user not to notice the most apparent mistakes made by the BOFD-system. In other words: the BOFD-system should aid operator in diagnosis work but not encourage the operator to passively approve all the suggestions made by the system.

<u>BOFD-system realisation</u>

The ultimate goal in implementing a BOFD-system could be a system that is embedded in a building energy management system. This kind of system realisation is shown in figure 3. The BOFD system functions and features are added to the normal features and functions of BEMS. The BOFD modules might be a part of the normal routines in the BEMS sub-stations and the

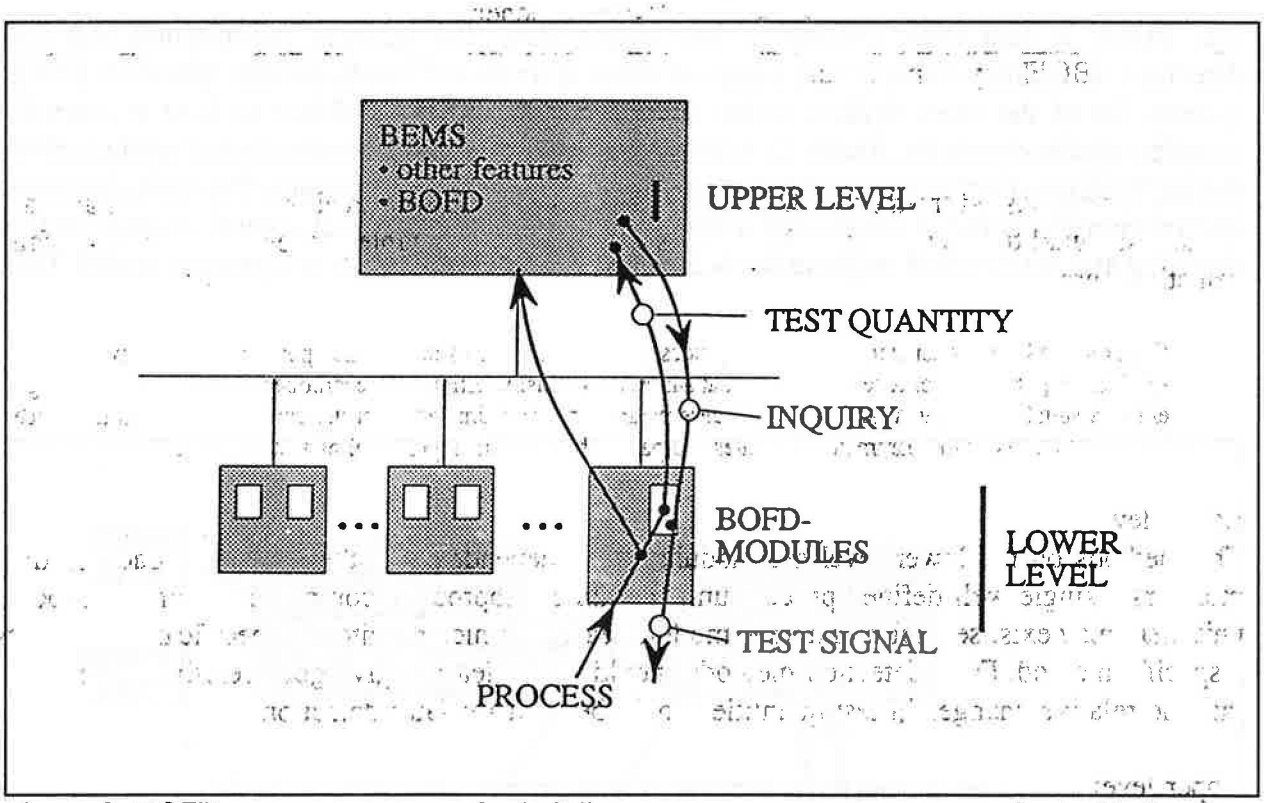

Figure 3. BOFD system as a part of a building energy management system (embedded).

BOFD user interface and the reasoning might be realised as a part of an operator station software. In this kind of realisation the BOFD system would seem to the operator like an extended alarm handling facility in an existing BEM systems.

Functions and operation of a BOFD system can also be demonstrated with other kinds of realisations. In annex 25 one objective is to demonstrate the implementation of the BOFD-methods in conjunction with a real BEM-system. This objective can be realised with a system structure of figure 4.

REFERENCE PERFORMANCES /3/

In a general case, the performances of a process can be defined by measurable and/or nonmeasurable quantities, through a mathematical of the process. The assessment of these performances often requires the assignment of reference conditions, that serve as a support to the implementation of evaluation criteria.

In the choice of a reference condition, the following points should be kept in mind: 1) The choice of the reference condition depends on its objective. 2) The degree of detail in the choice of the reference condition depends on the available process data and models. 3) The reference condition has not necessarily to coincide with the optimal process point or with the normal operating mode of the process. 4) The reference condition should be preferably expressed by measurable signals. Otherwise, a reference mathematical model should be provided. 5) Once the objective of the reference condition has been stated, the reference condition should not depend on subjective evaluation criteria. Therefore, for the purpose of process optimisation, the reference condition would better not be an optimal operation point. 6) The use of reference characteristic quantities can simplify the information on the inner state of larger systems or sections

OPTIMAL CONTROL

The BOFD system itself consists of two major parts: the building optimisation and fault detection. In addition to these two there are other systems and issues closely related to BOFD-system. On of the most obvious is the control system and the problem of how to control a complex system optimally. Annex 25 will not concentrate in optimal control but if needed utilises the applications of optimal control in determining the reference performance. The most significant interrelationship between controlling a system, determining its optimal control strategy and/ or detecting any faults which might arise is the need to identify a system or a process model. Thus,

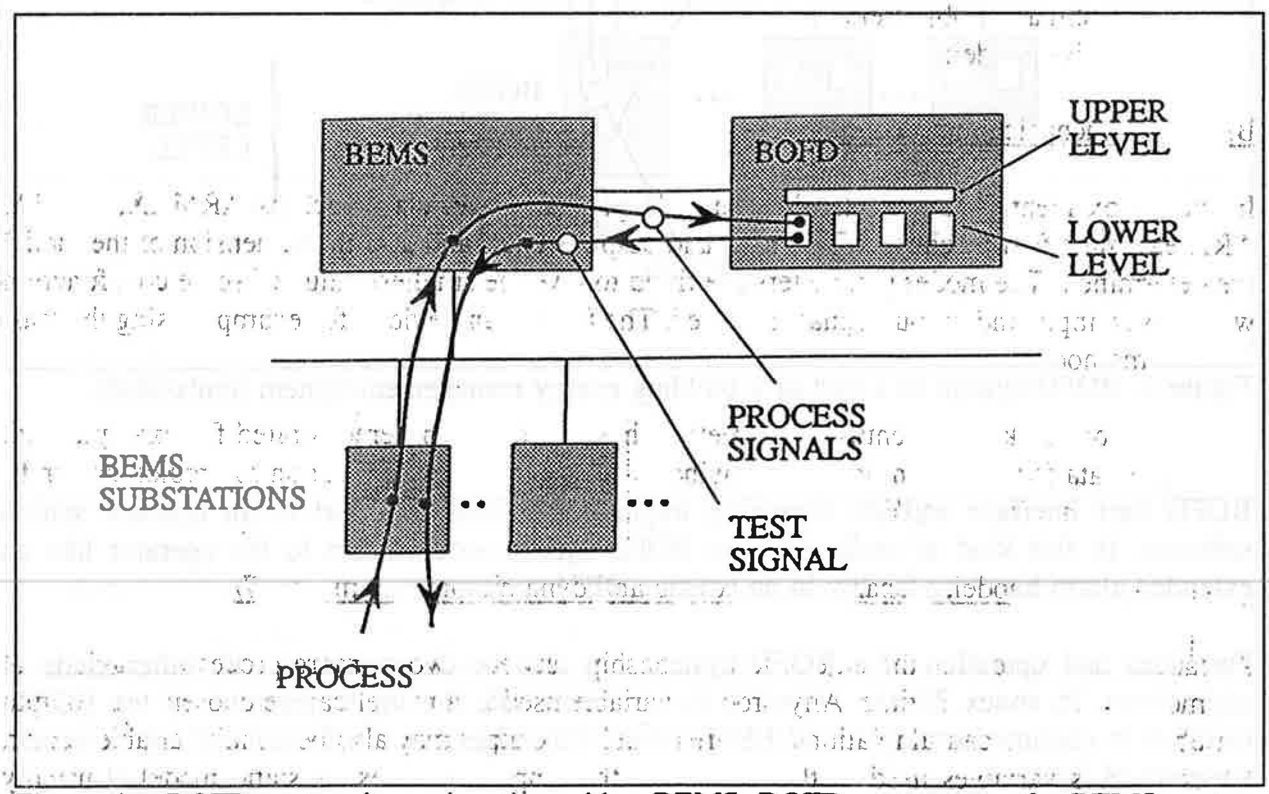

Figure 4. BOFD-system in conjunction with a BEMS. BOFD system uses the BEMS system process signal data base.

a major portion of the research that needs to be done in Annex 25 involves identifying appropriate HVAC/building system models, determining how and when they should be "updated" in real time, and then using these models in optimization and fault detection studies involving both laboratory simulation and the control of real building system. /4/

BUILDING OPTIMISATION AND FAULT DIAGNOSIS METHODS

Model based fault diagnosis methods

Model based fault diagnosis utilises models of process units (processes, subprocess, components) when diagnosing a defect or a fault. A process unit can be modelled to describe the normal operation of the process or the operation of a faulty process.

The model of a normally operating process deviates from the real process when the process gets a defect, i.e. the process goes into a failure mode. The utilising of a model of normally operating process unit reveals all the defects in theory but it does not separate one defect from another. The reasoning aiming at diagnosis must be done elsewhere. To ease the reasoning task process models can be made as fault selective as possible, i.e. a part of the reasoning is done already in the process model.

To use a model of defective process one must know the fault modes well in beforehand and no unknown fault modes are assumed to exist. Each separate fault mode must to be modelled separately. The utilising of a model of faulty process is restricted thus to cases where the process and its defects or failure modes are well known.

In Annex 25 the following model based approaches have been chosen for BOFD-method development:
- black-box identification
- a static or dynamic process model or a characteristic curve
- state estimators/observers
- qualitative modelling

Black-box identification method

In black-box identification methods a suitable general model class such as ARMAX, ARMA, ARX etc. must first be chosen. The input and output signals and also the dimension of the model are determined. The model parameters are fitted to give the smallest value of some cost function when given input and output signals are used. The fitting can be done for example using the least squares method.

The usage of black box identification method has this far been demonstrated for example with simulated data for detection of an open window /5/ and with an application to predict air-conditioning load in a building /6/.

A static process model, a characteristic curve and dynamic process model /7/

A static model describes the algebraic relationship between two or more process variables that are measured at the same time. Any process variable used in a model can be chosen as an output variable because no causal relationships are modelled. Output may also be a multivariable vector. Other process variables used in the model are then input variables. A static model is usually presented in a form of

$$y_{|t}=f_{|t}(x_1,x_2,...,x_n) \quad ... (1)$$

where the function f defines the model structure and the variables (x_i, i=1..n) define the input signals and y is the output signal. All the signals are measured at time t.

A static process model can be used to describe a process if the process dynamic is fast compared to the fault detection system sampling interval. Pumps, fans, mixers and valves are examples of processes of this kind. A static model is sufficient also in cases where the steady state condition of the process gives enough information for the fault detection.

A process can be modelled using characteristic curve which is a graphical representation of an algebraic equation. When using a characteristic curve the structure of model equation

$$y=f(x_1,x_2,...,x_n) \quad ... (2)$$

is not known and the relationship between input and output variables is given in graphical form. Compared with the algebraic model the characteristic curve is more understandable to a normal user than the algebraic model. An algebraic model is, however, easier to use in numerical calculations.

Static process models and characteristic curves have been demonstrated with data measured from a district heating substation control valve operation /7/.

State estimators and observers /8/

Fault detection using state observers and estimators e.g. Kalman filters, is being discussed in the literature since several years. Applications are reported e.g. in /9/, /10/ and /11/.This fault detection technique is based on a mathematical model. The model output is compared with the process output to generate a so called residual as fault indicating signal. A key problem with this technique is the robustness to model uncertainties. Without special care modelling errors will cause a nonzero residual and therefore false alarms.

The state estimator approach has been applied in Annex 25 this far to a simple boiler model in /8/.

Qualitative modelling /12/

Qualitative reasoning or qualitative physics is a new area of research that deals with the technical implementation of human approach to diagnosis. Operators and service engineers of processes like for example heating and ventilating plants, are found to diagnose faults in a way that differs from the purely statistical as well as from the quantitative model based approaches. Studies have indicated that human operators make use of a hierarchically organised mental representation of the plant when diagnosing a fault that they cannot immediately and intuitively recognize by their experiences. An important characteristic of this mental representation is the incorporation of qualitative models to describe the behaviour of the components, their relations to each other and the functionality of the overall plant.

Qualitative modelling has been chosen as one of the diagnosis approaches in annex 25. It has been discussed and demonstrated in /12/ and /13/. The processes were respectively heat pump system and laboratory scale air conditioning system.

SYSTEMS AND PROCESSES AND THEIR TYPICAL FAULTS

One of the main tasks in the preparation phase work of the Annex 25 was to start gathering a database of typical faults in typical HVAC systems. The database will be used for selecting the faults and components to be studied during the annex working phase.

The typical subsystems selected for annex 25 reference systems are:

- heating system /14/, which consists of a heat generation subprocess and a radiator network. The heat generation subprocess can be either oil burner or district heating substation /15/.
- chillers /16/ and heat pumps /17/
- air conditioning system /18/
- thermal storage system /19/

1. Example page of the chiller system typical faults database

IEA Annex 25, subtask P2 — March 1992

Subsystem : Refrigeration

Component : Compressor

Symptom	Failure	Cause	Remedies
Compressor noisy and/or knocking	High suction pressure.	Liquid flood-back to compressor: -Expansion valve opens too far.	Check superheat and expansion valve bulb attachment.
		- Expansion valve stuck in open condition.	Repair or replace.
	High suction pressure.	Broken suction valves.	Replace.
	Rotation.	Incorrect direction of rotation.	Invert the direction of rotation.
	High discharge pressure.	Coil clogged.	Clean coil.

The database gathering for typical faults in systems mentioned above have been started and in all cases there exists a list of the typical faults. The lists are however quite extensive and some further work must be done in order to prioritize the components or faults according to their importance. In the work different methodologies like HAZOP analysis and FME-analysis have been used. In table 1 /20/ there is an example of the typical faults of a chiller system. In table 2 /21/ there is an example of prioritizing a component with regard to a set of criteria.

Table 2. Calculating the priority of a component with regard to a set of criteria.

component: heat exchanger HE2 component number: 318

characteristic:	evaluation	weight
warm water or heat must be available some fault causes that habitant notices the effect of the fault within 10 minutes	3	33
energy consumption some fault causes that a lot of energy is wasted	3	20
serviceability repairing of some fault requires tools and break of more than 2 days in operation	3	25
Service man available repairing some fault needs a special staff	3	12
Spare parts available getting the spare parts may take two weeks	3	5
Probability of fault fault occurs once a 15 years	1	5

total importance = 3*33 + 3*20 + 3*25 + 3*12 + 3*5 + 1*5 = 290

The prioritized list of the components and their faults is used to select the components and subprocess in which the failure is most serious or the right functioning is most important. On the same basis also the failure types to be considered in the Annex will be chosen. The data base will also be used as starting point in developing fault diagnosis algorithms and rules for reasoning the fault. Also the data base serves the developing the user interface of a fault diagnosis system and gives instructions for recovering of the fault situation and for repairing it. The data base gathering work continues during the annex.

DISCUSSION

The work in Annex 25 will continue on gathering the data bases on the most important faults and components. The database information should be prioritized so that the work could be concentrated the most efficiently. The prioritizing work is difficult because there exists no generally approved method to assess an importance of a component in a system. Different approaches will be applied according to the nature and kind of the subsystem in question. However, in spite of the method used, the prioritized list will give an expert view of where to focus the effort in annex 25.

Another main task during the next 6 - 12 months is to get the first experiences of applying some BOFD-approach in method development. Using the four different approaches and utilising a real process data, experimental data or simulated process data in these 'first trials' a lot of practical information is gained. Discussing these trials - results, problems and possibilities - in the next meeting will again help each participant further in his or her own method by giving some comparative information of advantages and disadvantages of the approaches and by helping in avoiding the pitfalls in the method development work.

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