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PERFORMANCE AUDIT TOOL PAT: AN EXPERT SYSTEM BASED TOOL FOR THE DETECTION AND DIAGNOSIS OF BUILDING UNDERPERFORMANCE

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INTRODUCTION

The Performance Audit Tool (PAT) will be used to automatically supervise building performance. In its final state it will be installed in Landis & Stäfa branch offices or maybe at big customers' offices. It will be run over night as a batch job having (remotely) automatic access to building data and producing a printed report of its findings..

The underperformance types to be detected include comfort issues like zone temperature and exceeded energy consumption as well. Their causes may be among others total or partial component failure, wrong parameter settings, operators' errors, undersized system capacity, changes of usage. As the PAT will not get any user input during the audit it will in most cases not be able to indicate the exact cause of an underperformance it has detected. Instead it will produce a list of possible causes.The PAT does not cover active testing or guidance of service people during testing.

In order to be applied to different buildings the Performance Audit Tool needs information about a building's structure and the building control system's configuration as well. The configuration set-up will be automated as far as possible.

The PAT is covering US and European Building Energy Management Systems (BEMS) systems. The first interfaces developed are those for the following three Landis & Stäfa systems: Visonik, System 600 and Unigyr. The MMI is therefore in german and english.

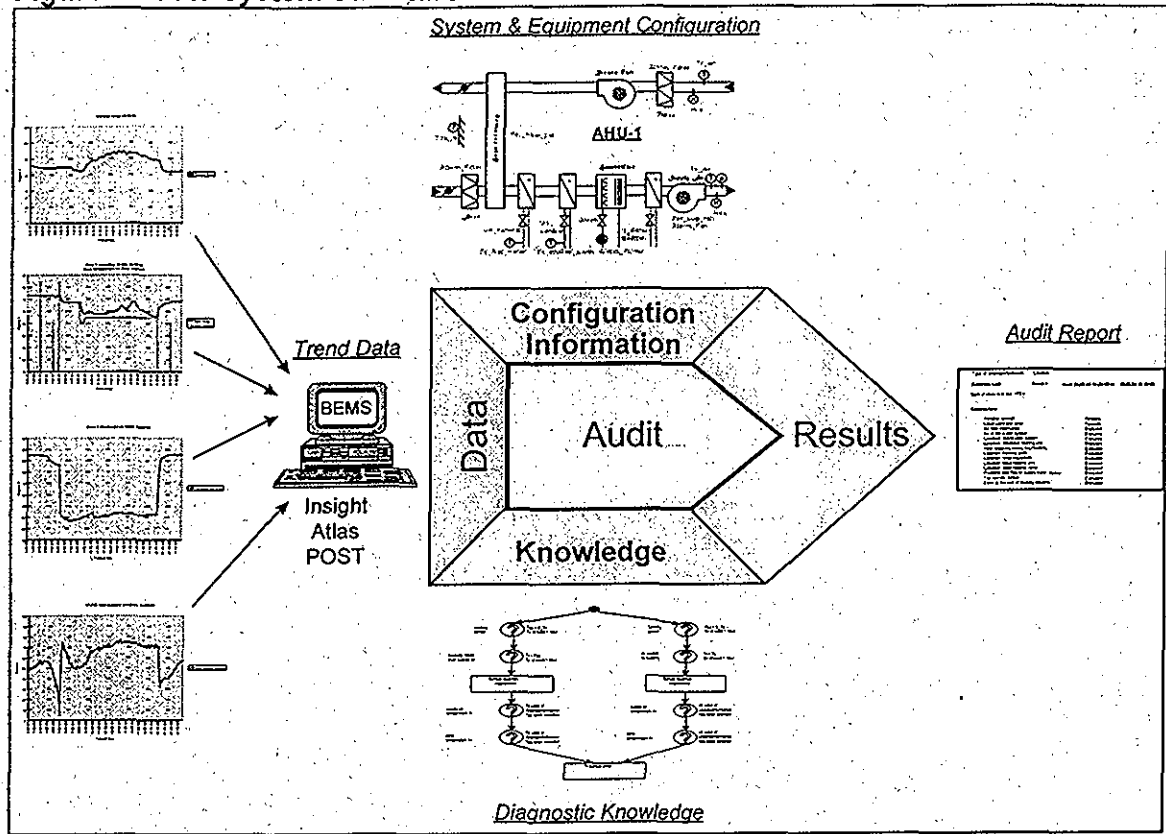
First a prototype is built with a full software framework but with limited diagnostic capabilities. This prototype has been tested in some simple cases and will be installed in some larger test sites to evaluate the cost-benefit relation.

SYSTEM STRUCTURE

Figure 1 shows the modular structure of PAT:

- The "Data " component loads trend data from the BEMS into the PAT **trend data archive database** using existing packages like. Existing data management tools for the different BEMS are integrated at the front end of the data aquisition process. Invalid data are detected by comparing the data with upper and lower boundaries and missing data are handled.

Figure 1: PAT system structure



- The "Configuration Information" component provides a user interface to enter configuration information (e.g., points, plants, zones) into the configuration database. Part of this "set-up" module are the "point parsers" that try to extract automatically information from point names and descriptions. The configuration data are stored in a relational **configuration data base** holding data for each installation about:
  - building topology (floors, zones)
  - HVAC system (subsystem, equipment, design parameters)
  - point definitions (read from the BEMS)
  - point functions (e.g. "zone temperature")
  - connections between points and their setpoints
  - point locations (minimum: buildings, floors and zones under consideration)
  - operating schedule and holidays
  - some fixed operational and design parameters (e.g., design temperatures)
  - data storage
- The "Knowledge" component contains expert knowledge on improving building performance. Diagnostic knowledge is captured in rules forming decision trees. It is stored in a **knowledge base**. A knowledge-based system was used to capture and store the expertise on improving building performance. This knowledge-based system realised with the expert system shell Level 5 Object was embedded into "conventional" relational databases. Users will only see the database interface. Only those people maintaining the knowledge base will have to deal with the proprietary technology of the "expert system shell".

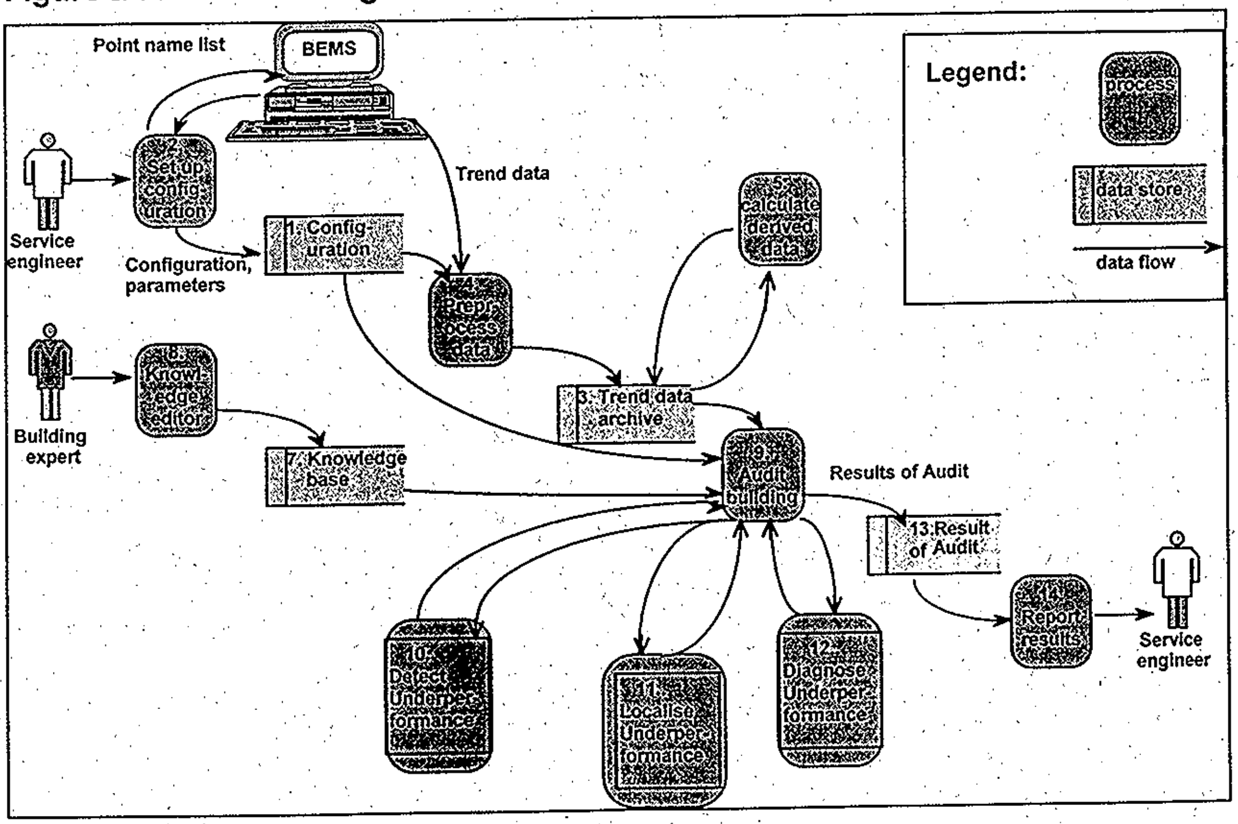
- The "Audit" component combines knowledge and configuration information to interpret and evaluate trend data. Cases of underperformance and their likely causes are exported into the result database.
- The "Results" component consists of a **result database** holding cases of underperformance and diagnostic results. It is automatically filled by the Audit component.The block transforms also the results of the audit into easy to understand audit reports.

The prototype uses MS Access as database for the trend data archive, the configuration and the results. Modules handling trend and configuration data are written in Visual Basic. In order to enable the exchange of the database system with little effort those modules that are meant to run as batch jobs use ODBC access to the database. The user interface for the configuration entry was written as modules inside the MS Access database for cost reasons.

DATA FLOW AND PROCESSING

The different steps that have to be performed for a specific audit are illustrated in the data flow diagram in Fig.2. It shows the sequence of processes that has to be done.

Figure 2 : Data flow diagram



A particular Performance Audit is done in several subsequent steps

1. First the prepared relational data base holding the configuration information has to be filled with data for the building under inspection (point 1 of Fig.2).

2. A list of point names and parameters needed for fault detection and diagnosis for the specific audit is created. A service engineer has to provide

the necessary information about the configuration. Unfortunately it is not possible to retrieve automatically all the neeeded information from the BEMS point name and its technical addresses. This fact makes the engineering cost for configuration of PAT for old installation high. For each point the following information has to be known:
- point name (nonstandardised identifier given by the service engineer)
- point type (data type)
- point function (identifier for the role of the point in the system, e.g. "zone temperature")
- point location (identifies which specific equipment or system or zone the point is connected to)
- technical address (identifier for point in the system software)

For instance the measurement of "21.1" taken at 11 a.m. by the point "G'02K64'980_BAVA" becomes meaningful only if you know that "G'02K64'980_BAVA" is the internal name of "the actual zone temperature of zone 1". Such information is kept in the "configuration database" which has to be filled once for each installation

These points have to be generated additionally, if not yet needed for control, on the BEMS, and are also stored and matched with the building topology in the configuration data base (point 2).

3. After the configuration set up is completed, the acquisition of data which are defined in the configuration database can be started. They are first preprocessed to check for validity against min- and max-values, for missing data interpolation, for special yearly information like holiday (point 4) and then stored in the trend data archive (point 3). They can also be compressed if needed for long term diagnostics. Once the set-up is done data pre-processing is done automatically at regular intervals. Typical intervals for data acquisition are 10min.

4. The stored trend data can then be further processed in the "calculate derive data" block. Here other software packages (e.g. neural network) can calculate additional performance measures (point 5).

5. Then the core piece of the PAT is activated consisting of the knowledge base (point 7) and the inference component (points 10,11,12) to apply knowledge to trended data. The knowledge based system reads input data (configuration and trend data) from the databases and writes the results of the audit back to database tables. There are several key aspects how the Audit is realised:

A **first** key aspect of this approach is to write the rules for the fault detection and diagnosis in a way that they can be parameterised by configurable values stored in the configuration database.

Example: "If the outside air temperature has been above *the cooling system's design temperature* for more than *relevant time* then do not consider zones being too hot."

During building audit the values for "the cooling system's design temperature" and "relevant time" are read from the configuration database.

This enables the system to be configured for different buildings, as the configuration database will contain the information about the building and its building management system needed to determine the rule parameters' values. The rules themselves are not changed by the user. They have been

formulated by building experts and fed into the system. Then they are stored in the knowledge base (point 7). This expert knowledge acquisition is done before the actual audit.
The rules capture not only steady state relationships but also cause-effect relationships with a time dependency.
Field engineers will have no access to the knowledge base itself. All parameters they need to edit are stored in the configuration database.

A **second** key aspect of the design is that the depth of the audit depends on the amount of information entered into the configuration database. This means that only sections of the rules which have been enabled by setting up the required information will actually be run. Thus, a fuller description of a building will provide a more detailed and more accurate analysis of building performance. Thus initially a smaller configuration of the system with a lower set up cost can be run. To provide a more detailed analysis of the building performance this configuration can be extended incrementally.

A **third** key aspect is that the diagnosis is done in three inference steps:
i) Pre-processed data are evaluated to **detect** problem areas (cases of "underperformance"). Under-performance may concern a zone (e.g., "too cold"), a system ("simultaneous heating and cooling") or the whole building ("exceeded energy use"). Initial effort was focused on common problems with energy-intensive elements (point 10).
ii) The cause for the under-performance is isolated (**localised**) as far as possible. In most cases data is not detailed enough to identify the exact cause (point 11).
iii) A list of possible **diagnostic** messages using results from i) and ii) is created (point 12).

Localisation and diagnosis are sometimes very closely related. Mainly backward chaining is used in the above three steps.

6. The results of the Audit are written to the "result of the Audit" database (point 13).

7. Reports are simple database applications. The reports generator filters the results of the audit in order to report the same cause just once. It adds appropriate trend plots and prints a report in the user's language (point 14)

The audit is done regularly for each day once at night as batch job.

STATUS

The tool is in a prototype phase. Three modules have been implemented:

- zone
- central air handling unit (CAHU)
- chiller

The most advanced in term of rules and testing is the zone, the least one is the chiller module.
The above Table lists the relevant information for the three modules:
The first row contains the number of points needed for the detection of all the implemented underperformances. If some of these points are missing the number of detectable underperformances is reduced. The points needed for the detection may also be needed for the localisation and diagnosis.The

Table: current status of PAT capabilities

	Zone	CAHU	Chiller
number and type of *points* needed for *detection*	**9** temperatures control signals operation mode	**12** temperatures control signals operation mode humidity pressure,speed	**4** status pressure load
additional number and type of *points* needed for *localisation and diagnosis*	**12** temperatures local commands CO2	**14** temperatures operation modes alarms control signals	**9** temperatures pressures
number and type of *parameters* needed for *detection, localisation and diagnosis*	**15** identifiers thresholds schedule design parameters	**15** identifiers thresholds	**21** identifiers thresholds design parameters
number and type of *detectable underperformances* total number:36	**11 for zone** **1 for building** • too hot/too cold • too much heating/ cooling • sensor defect/ offset • draft • supply air too hot/ cold • higher energy consumption	**20 for CAHU** **1 for building** (same as for zone) • supply too hot/ cold • too humid/ dry • simultaneous heating/cooling • wrong control combinations • sensor error/ offset • exceeded energy consumption • pressure too high/low • filter blocked	**4** • evaporator pressure too low • condenser pressure too high
number of *decision trees* total number:28	**11**	**15**	**2**
number of *diagnostic rules* total number: ca. 250	**ca. 100** **plus ca. 35 for structuring**	**ca. 100** **plus ca. 35 for structuring** (same as for zone)	**ca. 15**
number of *conclusions* total number:86	**25 for detection in zone, fault cause in zone** **11 for detection in zone, fault cause in CAHU**	**41**	**9**

second row indicates the additional points that are needed if a complete diagnosis is wanted. So the total number of points is the sum of the first two rows. The third row lists the parameters needed for the audit. The crucial parameters are the thresholds. The fourth row contains the number and type of underperformances for each of the modules. Some of the underperformances appear twice like supply air too hot/cold for zone and CAHU underperformance
The knowledge is stored in the decision trees, diagnostic rules and conclusions (rows 5,6 and 7.

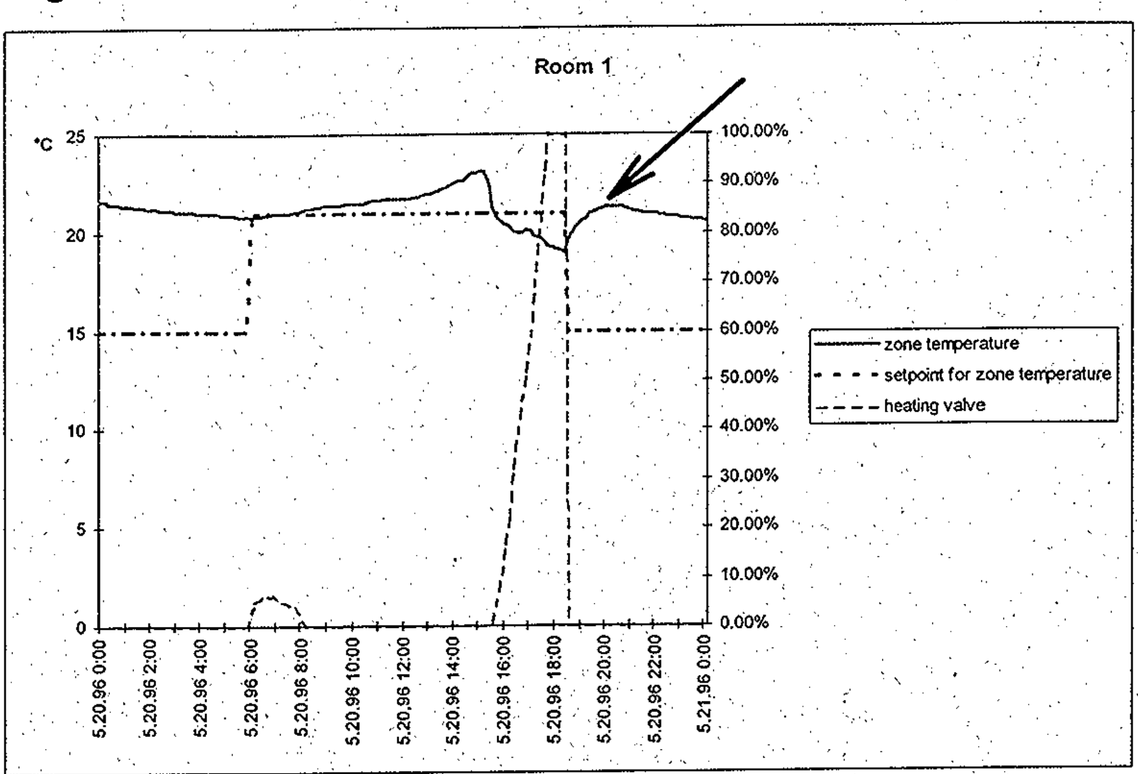
EXAMPLE

Landis & Gyr headquarter, building 2K Test set-up

Building 2K is an office building located on the Landis & Gyr area in Zug. The building is equipped with radiator heating. Some zones however are fully air conditioned. Their ventilation system is used for both heating and cooling. The supervised installation controls 2 rooms with radiator heating and one conference room conditioned by the ventilation system. Collection of test data started in February 1996. At the moment the building is no longer audited. Totally data of 22 points for the three zones were collected. So not enough information was at hand in order to carry out a full audit of a zone. The correct conclusions are marked bold. The search for the correct conclusion was done by the user. Data missing means that not enough data were available for making a statement about the posssibility of this conclusion.

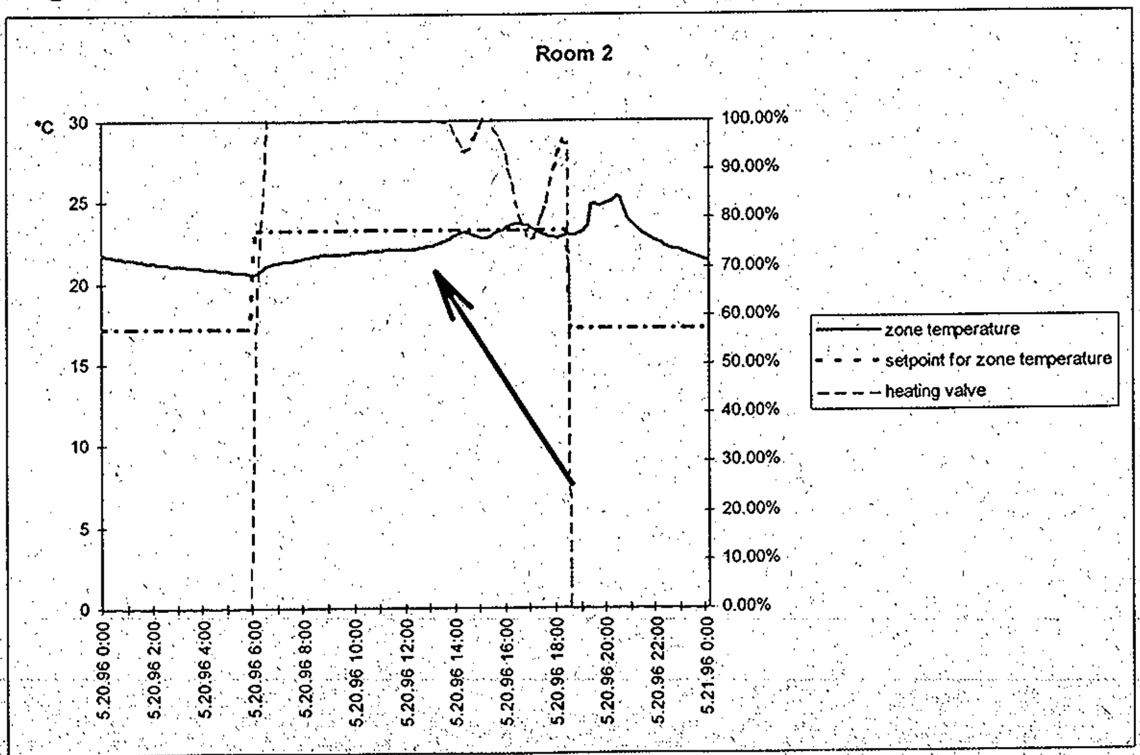
Underperformance	zone	Start	End	Comment	Conclusion	
Zone too cold	room 1	20.05.96 16:20	20.05.96 18:30	Sum of error in K min: 173.4	**window opened**	Possible
					controller does not open heating valve	Possible
Zone too cold	room 2	20.05.96 06:00	20.05.96 15:50	Sum of error in K min: 779.8	location: distribution system	Possible
					location: local heating valve	Possible
					location: local equipment	Possible
					zone at the end of heating capacity	Possible
					air in the water system	Possible
					location: electrical heating unit	Data missing
					location: heat recovery works insufficiently	Data missing
					location: heating plant	Data missing
					location: control problem	Data missing

Figure 1 : Measured data from 2K, room 1



As room 1 is not conditioned the only way to reduce the zone temperature is opening the window. This seems to have happened in the afternoon.
The second conclusion seems to be correct, too. The controller needs quite a long time to open the heating valve. Generally, control is slow in building 2K.

Figure 2 : Measured data from 2K, room 2



Room 2 shows heating problems during the whole winter season. The zone temperature follows more or less the outside air temperature. The heating capacity for this zone seems not to be sufficient.

OUTLOOK

In order to assess the usability of this tool, it is forseen to install the tool at two bigger testsites, one in Switzerland and one in Germany. The first one will use if fully implemented, ca. 100 points for the audit, the second one ca. 300. The number of points will be augmented for the two cases gradually. Both objects consist of several central air handling units and zones. No chillers will be *supervised. The following points will be considered:*

first priority: friendlyness of the tool for new users

cost for engineering and commissioning

- data acquisition
- configuration information
- *choice of parameters settings*
- knowledge about the tool

usefulness of the on-line operation

- false alarms and missed faults
- impact on the building owner
- acceptance of the operator
- cost/ benefit relation

second priority: maintenance and revisions of the existing knowledgebase for zones and central air handling units

development of a new module for a central warm water heating unit

third priority: improvement of the user friendlyness