VISION OF A VISUALIZATION TOOL FOR COMMISSIONING

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Summary. A prototype visualisation tool to display long time series of measured data was developed and tested. We report some ideas on the requirements and present our experiences from using the prototype in the evaluation of functional performance in real buildings.

Keywords: visualisation , FDD, trend data, performance monitoring.

INTRODUCTION

Few HVAC systems perform as well in practice as originally intended. There is a considerable potential for achieving better performance, by means of accurate design, good installation, rigorous commissioning and not the least proper operation and maintenance. Energy savings in the order of 5% to 15% may typically be realized by means of improved operation alone. This is already recognized by the industry, but several obstacles hamper a performance oriented approach. One such obstacle is the lack of cost-effective procedures and tools to monitor and evaluate the functional performance of HVAC-systems.

Modern building energy management systems, BEMS, comprise ample computer power, storage, bandwidth, and hundreds of sensors. Obviously, with the BEMS huge amounts of time series data can be acquired and stored. Furthermore, today's standard computers allow intensive analysis and visualization. Nevertheless, we neither see significant use of BEMS to support performance monitoring, nor considerable efforts to develop such use. In Sweden the control manufactures do not see a demand from the marketplace; on the contrary they observe little use of the tools they already provide.

Research studies, e.g. Norford et al. [1], argue for the value of graphical presentation of data. Austin [2] presents a case study and argues that Trend Analysis (based on diagrams with historical data) is a powerful tool for HVAC troubleshooting. Meyers et al. [3] present a number of case studies and conclude that data visualization can help achieve substantial improvements in energy management. Furthermore, a project in California has developed and demonstrated an Information Monitoring and Diagnostics System, IMDS [4], which comprises a data acquisition system, a data archive and a visualization tool. The project reports success. Diagnostic software tools for large commercial buildings are being developed to help detect and diagnose energy and other performance problems with building operations.[5]

We think that tools for trend analysis in standard BEMS are little used not because there is little need for such tools, but because they do not serve the operator well enough. We cannot understand why BEMS manufacturers do not add more powerful visualization and analysis tools to their products. Apparently, functional analysis HVAC-systems based on intensive trending is not used on a regular basis.

Our hypothesis is that monitoring and functional analysis of HVAC-systems can be done cost-effectively with a procedure based on:

- intensive BEMS-supported data acquisition (i.e. historical data logging)
- a powerful visualization tool focused on data analysis
- existing fault detection and diagnosis methods (FDD)
- existing tools for detailed simulations of HVAC

The economical requisite makes it a challenge to demonstrate such a procedure in everyday operation of commercial buildings. Based on our own experience of evaluation of large amounts of historical data from research experiments in the energy conservation field, and from operation of commercial buildings we presume

- the procedure would be adequate to produce the information needed to operate the HVAC-system in an energy efficient way
- the time needed to apply the procedure must be radically decreased compared to what we are aware of

Even so, our goal is to demonstrate that a procedure of this kind is indeed possible. We aim to deliver

- A working prototype of a visualization tool
- Examples from applying the procedure to support the operation of large office buildings

Thus, we concentrate on visualization and its integration with FDD and simulation tools. This project is to a large extent about man-computer interaction. Improved support for historical data logging and storage should be supplied by the control manufactures and others.

METHODS

We carry out the project in close cooperation between practitioners and academic researchers. We continuously deliver results to the organizations that operate the buildings, in which we test our procedure, and the building owner pay the project for this service. This approach ensures that the project focuses on genuine problems, which we are suited to tackle. The project comprise

- building software prototypes
- applying the evolving procedure in real buildings
- participating in the evaluation of functional performance in the formal post-acceptance step
- doing real work with the BEMS
- listen to practitioners

Requirements

Requirement analysis is a major problem when building original software. We cannot achieve our goal by just building on the tools available in contemporary BEMS products. We need to come up with something different. In that situation the potential end users are seldom able formulate specific requirements. To be useful, requirements must be founded in understandings of both the needs originating in the end activities and the limits set by the current technology. In our small project we try to circumvent the problem. The same persons take part in routine work with the BEMS, participate in commission "meetings" on the performance, apply our evolving procedure on historical data, and develop prototypes. In this way the developer himself represents the end user in the developing process. We have little written requirement specification and we keep our fingers crossed.

The allowable cost for applying this hypothetical procedure imposes severe requirements on the tools. The benefits are due mainly to a decrease in energy use. Assume 10% decrease and recognize that it should cover the cost of applying the procedure, communicating findings, deciding on action, and carrying out action. The calculation will differ depending on who applies the procedure and in which phase of the building process. The value of the procedure outcome will be higher during the post-acceptance step compared to the ordinary operation step. The cost of communicating findings and making decisions will possibly be lower if the procedure is applied in-house by the personnel who operate the building. In any case, little time will be allowed for inspection and analysis of data. What kind of requirements does that impose on the visualization tool?

The tool must be easy to implement in a new building. That is both because the cost must be low and results should be presented as early as possible during the post-acceptance step. There is simply no time to successively debug and configure.

The visual presentation of data should be perceptual effective. The user interface should be clear and free from all unnecessary details. There should be no surprises and no ambiguities. Graphics should be as simple as possible, fulfilling its purpose. We need a library of pre-defined graphs, which use easy-to-memorize conventions for line-types, symbols, colors, etc.

Results of the FDD methods should be communicated distinctly but yet in a modest way. This is because we do want to choose the sensitivity of the FDD-methods a bit aggressively and fear spurious alarms.

Interactive operations should be natural and intuitive. Response times should be short. It is certainly a demanding intellectual task to analyze the behavior of a HVAC system, especially faulty and non-optimal behavior. The user needs to concentrate on his task without being distracted by software related nuisance. Ideally, the user should not think on how to operate the tool.

Current prototypes

During the last few years we have developed a set of functions in Matlab® [6], including

- three different FDD methods for air handling units
- a simple interface to the detailed simulation program IDA
- DataBrowser, which is a graphical user interface, GUI, comprising a few tiled graphs
- pmBrush, which is a GUI, comprising a matrix of linked scatter-graphs with brushing
- functions to read text files, and miscellaneous

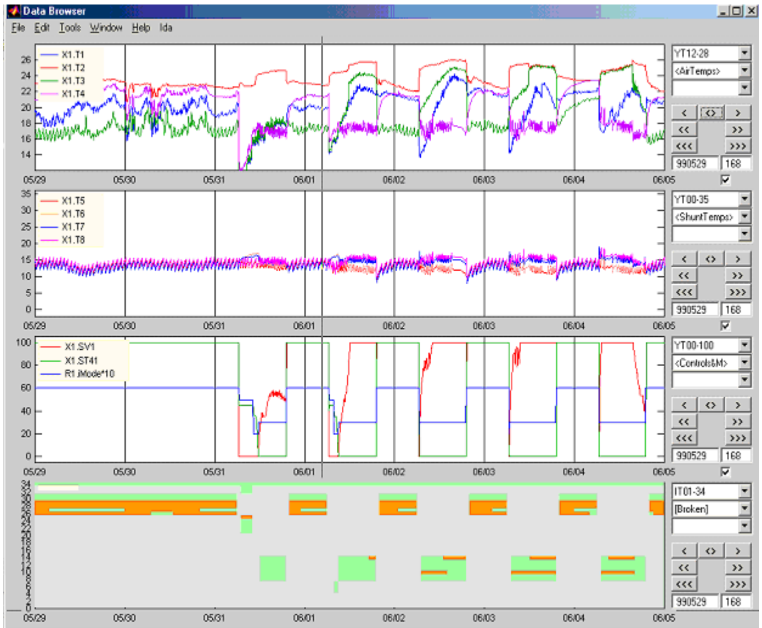

Figure 1. The primary window of the prototype, DataBrowser. Note the cross-hair, which reach all four diagrams and thus helps to check whether transients coincide. The diagrams contain seven days' worth of five-minute data from an air-handling unit in an office building. The upper diagram displays four air temperatures (ºC): outdoor, return, mixed and supply. The second diagram displays four water temperatures (ºC): supply primary side, return primary side, supply secondary side and return secondary side. The third diagram displays the control signals to the heating and cooling coil valves and to the mixing box damper. Furthermore the operational mode is indicated in this diagram. The bottom diagram displays the output of a steady state FDD-method.

These functions are joined by a name, Pia, and by using a common data-structure. Figure 1 shows the GUI of DataBrowser, which in this case contains four graphs, each with its group of controls. Optionally the graphs may be synchronized. The user chooses among predefined graphs in a drop down combo box. DataBrowser features three types of charts; line chart, timetable chart with patches, and the 2D carpet plot (see Figure 2).

In Pia names, i.e. short text strings, are the only way to address data point and charts. The data points get their names from the BEMS and the user assign names to the charts.

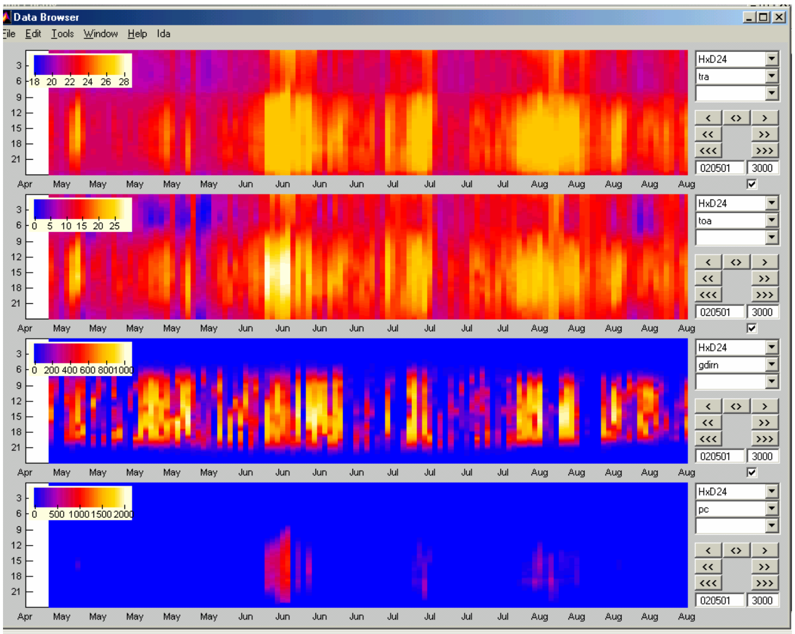

Figure 2. An example of a 2D carpet plot, which shows a number of outputs from simulations of a hospital room outside Stockholm. The quantities shown are from the top; the return air temperature (ºC), the outdoor air temperature (ºC), the direct solar radiation (W/m2) and the required cooling power to the zone (W). The diagrams contain four months' worth of five-minute data (i.e. 35 000 values in each of the four diagrams). Each "column" represents one day. Only a few seconds has to be spent analyzing the diagrams to realize:

1) that the return air temperature seldom goes higher than +26ºC, 2) the warm period in the middle of June, 3) that the sun radiation may be as powerful in August as in June, 4) that the cooling system operates very seldom.

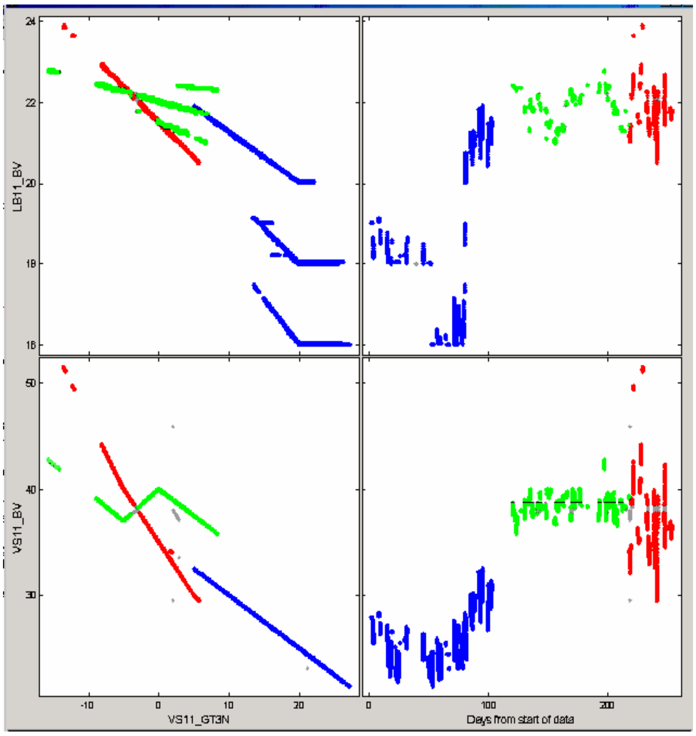

Figure 3. An example of a scatter-plot matrix. The two left hand plots shows set values as function of the ambient temperature for the supply air temperature and a heating water temperature, respectively. The two right hand plots show the same data as function of time. One set values have been changed several times.

Applying our evolving procedure

We have applied the evolving procedure in a few buildings during the last few years:

- Skanska headquater, one airhandling unit, Mar 1998 – Jun 1999, 40 data points, quarterly evaluations, research project, FDD [7,8]
- Stockholm Court house, Nov 2001 – on-going, 50 data points, quarterly evaluations, semi-commercial, on-going commissioning [9,10]
- St. Goran hospital in Stockholm, district heating substation and air handling unit, 30 data points, Feb 2004 – Apr 2004, semi-commercial, on-going commissioning
- Katsan, new office building with innovative HVAC-system, 180 data points, May 2003 – on-going, research project, on-going commissioning and detailed simulation

- Kista Entré, new office building, 500+ data points, Jun 2003 – on-going, semi-commercial and research project, performance analysis during the post-acceptance step and more.

We have typically prepared quarterly reports with lots of graphs, arrows pointing at anomalies, and short texts. In some cases we have written reports, which cover longer periods of time. We have not yet found a method for continuous communication of result to the building operator.

Data acquisition has been cumbersome and thus expensive in every project. In all projects the trendlogs have been defined interactively point by point. This requires many actions and is pretty error prone. There are typically no tools to output readable lists of "loggable" points or trend logs.

In every project we have encountered anomalies, some more severe than other. We have seen nighttime cooling in the middle of the winter; cooling of exhaust air because a heat recovery loop was operating in summer; heat recovery systems operating with only a small fraction of the effectiveness they were supposed to; numerous oscillating valves; and more.

Participating in performance evaluation meetings

In Sweden during the pos-acceptance step there are "performance evaluation meetings" chaired by the commissioning authority. Representatives from the commissioning team, the builder, subcontractors, the building owner, and the operating team participate in the meeting. In Kista Entré two such meetings were held; one devoted to winter and one to summer performance. A large part of these meetings was devoted to analysis of function by inspections of graphs, which where prepared in advance by the control contractor. For each meeting there were approx. fifty graphs, displaying a couple of day worth of data for various sets of points. The graphs were of the kind BEMS often produce: one graph per sheet, one y-axis and one time-axis; and several points of different physical unit. There was one or a couple of graphs per subsystem. These graphs are not easy to read and one may always question whether the days picked are representative.

At the end of the "winter meeting" we displayed graphs on request with a data projector. We had prepared nearly one hundred line graphs and together we were able resolve some remaining problems.

RESULTS AND DISCUSSION

We have applied our evolving procedure in a number of projects over the last few years. It causes an encouraging interest and in most cases the effort pays off in form of uncovered anomalies in the HVAC-systems. However, it is difficult to report on meaningful quantitative results. That is mainly because of two reasons. The exposure of an anomaly may be a bit awkward to someone and often it is not entirely clear whether it was known before we spotted it. Secondly, we have neither done usability studies on the prototype, nor measured the time we have spent with specific tasks. We will discuss the lesson learned so far.

The basic browsing of synchronized graphs in combination with the large cross-hair, which covers all graphs, is very useful. Separate graphs for flow rates, control signals, temperatures, etc. are easier to read than one graph with all quantities. Browsing the time series by discrete steps along the time axis is better than continuous scrolling. For example, if the graph depicts one day with midday in the centre switching to next day with midday in the centre by one click of the mouse is better than scrolling. The tick marks of the time axis remain in place and it may be assumed that the start and stop of the apparatus occur in the place on the screen.

We have found that the color coded carpet plots very effectively display long time series of signals with a diurnal pattern. For example, one year of hourly data for an electrical load fits easily in a rectangle of 120 by 40 mm and in a glance one gets the whole picture. These plots are especially well suited to communicate details in the results of yearly simulations.

The matrix of scatter graphs in combination with brushing is very effective for checking whether control algorithms are implemented correctly (see Figure 3).

Showing data from periods when the apparatus of interest is not in operation may be very confusing - scatter graphs may even become useless. Thus, hiding non-operation data should be easy.

The effort to set up the tool for a specific project should be minimal. There are many reasons. If not, it will simply not fit in the budget of the project. Furtermore, it is important to start producing results early in the post-acceptance step. It is contra-productive to successively improve and modify the design of algorithms and reports over a long period of time. It diverts the mind of the user from the real task. Comparing reports becomes more difficult because there will be many versions. Our current prototype features some function with do not need any configuration, e.g. the color coded carpet plot. We overuse them.

Matlab® is well suited for building prototypes of analysis and visualization tools of this kind. We would probably not have been able to build these tools with Fortran, C++, or Visual Basic. Our applications are adequate in speed and responsiveness. Furthermore, they handle large set of data well. We see no reason to look for another programming language.

The prototype, Pia, exhibits some obvious shortcomings. It is burdensome to configure line graphs. Remembering all those names of data points and graphs creates a large burden on the user. The lists of names become too long. However, Pia accepts wildcards in search operations. There is no mechanism in Pia to recall operation made by the user. Thus, the user needs to repeat operation over and over again. Pia operates on a batch of time series data with constant time step. Pia is made up of a set of functions, which are not integrated well enough. This is especially true for the FDD-functions.

PIA VERSION 2.0

Pia has proved itself useful and we see no better alternative. Furthermore, we have a long wish list with new features. However, it's becoming increasingly more difficult to further develop the code. We break existing code when adding new features. There are even a couple of valuable features, which are broken definitely. Matlab is being developed successively and the latest version offers a better support for GUI-building, object oriented programming, and making stand-alone applications. Thus, we more and more often think of a new version of Pia. Currently, we vision its major new characteristics to be:

- integrated automatic fault detection, the output of which should be presented in a special picture made up of patches. Each subsystem and major components should be represented by a patch. The color of the patch should signal the state of the underlying subsystem. A severe fault would make the patch red. The picture would resemble the heat-map that http://www.smartmoney.com uses to picture the stock market (Figure 4). This picture could be the top layer of the user interface.

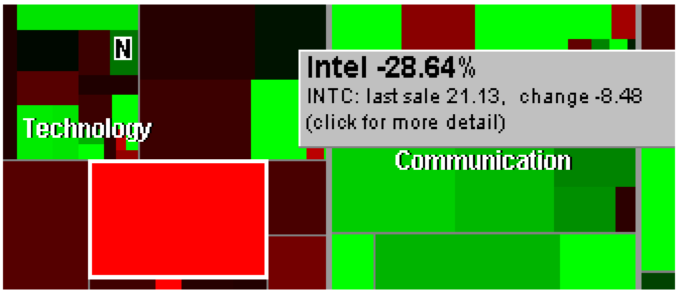

Figure 4. Part of an heat map used by SmartMoney.com to show changes in a stock exchange (http://www.smartmoney.com)

- drilldown: there should exists ample options to find more details. For example, right-clicking should produce a context-menu with some alternatives to display related data in more detailed graphs.
- the screen should typically hold a few windows containing linked graphs. Selecting a point in one graph should optionally (?) highlight the corresponding points in the other graphs.
- some kind of macro feature, which allows the user to record a sequence of graphs and replay them preferably for selectable period of time and for a another subsystem of the same kind. For example, the user should be able to record an inspection tour of an air-handling unit and then by clicking the mouse walk that tour for other air-handling units and other periods in time.
- integration with a database (SQL?) holding trend-data

- items like data points, graphs, etc. should have a name and a number of attributes. It should be possible to search and sort according to name and attribute values. Currently, it easier to find a report on the other side of the globe by using Google, than finding a graph I defined a couple of month ago. I tested by searching for "piette tools emerging lbnl".
- some clever way to configure the system. It would probably be fruitful to focus on "functional units" of the HVAC-system rather than on graphs.

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