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OPERATION DIAGNOSTICS – USE OF OPERATION PATTERNS TO VERIFY AND OPTIMIZE BUILDING AND SYSTEM OPERATION

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Summary
Building energy management systems (BEMS) process a large amount of data to operate the building. Instead of using this data only to signal failures and breakdowns of systems, it can be further employed for enhanced operation diagnostics. Adequate visualization techniques can be used to describe building and system operation in form of operation patterns. Building and system operation can then be verified and optimized by comparing recorded BEMS data with the operation patterns. Simulation models (component and whole building level) can help to obtain optimal operation patterns.

Keywords: *Operation Diagnostics*, *Operation Patterns*, *Commissioning*, *BEMS data*, *Simulation*, *Optimization*.

INTRODUCTION

Building automation systems (BAS) and building energy management systems (BEMS) have been used in modern edifices for the last 2 decades. These systems measure, process, and monitor a huge amount of data to operate the building and systems more or less properly. Often, the data is only used to signal failures or breakdowns of systems or components. Further information of the data to analyze and diagnose the building operation is not used due to the lack of analysis methods and tools.

This paper shows an approach of how to apply different visualization techniques to display the information that is hidden in the recorded operation data of buildings and systems. Different diagrams and plot types are used to generate *operation patterns*. Time series of large data amounts can be realized and analyzed quickly, as well as the correlation between various operation values, the frequency of data, or other useful statistical information. These operation patterns are qualified for evaluating the quality of operation and identifying optimization potential by comparing them with optimal operation patterns. Furthermore, the quantity of optimization potential can be estimated by additional visual or numerical analysis of the deviation between optimal and real operation patterns.

Optimal operation patterns can be generated by plausible thoughts (e.g. for schedules, characteristics, etc.) or by the use of dynamic simulation for more complex operation structures and correlations. Therefore, the simulation models need to comply with some requirements given by the used simulation strategies.

This methodology has been applied for the operation diagnostic of an office building in Munich, Germany. In the first part of the paper, the general approach of using different visualization forms to display operation data is discussed. The second part describes a practical example for the performance of operation diagnostics by means of an air handling unit (AHU).

VISUALIZATION OF OPERATION DATA

Visualization Forms

The human brain is trained for transmitting information (in the form of sensory perception) into logical structures like groups or patterns, or classifying with logical structures like groups or patterns, respectively. That aids in better understanding, analyzing, and valuating the information. Recognition is a factor of importance as well. Information is easier to handle and to recall when filed into mental or real structures. The human brain uses this structuring of information fairly unconsciously, depending on talent or training. Numbers, for example, are much easier to remember by combining them in groups of two, three or four.

This study shows how to use different visualization forms to describe or monitor building operation. Nevertheless, these visualization forms have high potential in placing operation data into so-called operation patterns, which are not yet utilized within BEMS. Operation patterns should be suitable to display large amounts of data in a way that the data is still easily recognizable and comprehensible in its entirety and dependency.

Table 1 gives an overview about categories of information and adequate visualization forms. The higher the dimension of the visualization form, the more information can be obtained. The most important visualization forms for visualization of operation data and creating operation patterns are underlined and described in the following.

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Information / Visualization form	**Dimension**
time series (temperatures, schedules) • line plot • cluster plot • carpet plot	 2-dimensional 2½-dimensional 3-dimensional
correlations (dependant switching, characteristics) • scatter plot • matrix of dependent scatter plots	 2-dimensional n-dimensional
quantities (energy consumption) • characteristic values • load duration curve • cumulated load duration curve	 0-dimensional 1-dimensional 1-dimensional
statistical distribution (utilization, frequency) • histogram • pie chart	 1-dimensional 1-dimensional
states of operation • trend of demand • schematic with dynamic display	 1-dimensional 0-dimensional

Table 1. Categories of information and their respective visualization forms.

Time Series of Data

Usually, time series of data are displayed in form of *line plots* (see Figure 1 and Figure 2). Multiple sets of data can be displayed in a single diagram and, thus, be compared directly for identical time periods. The time range of the data that can be displayed in a diagram is limited by the resolution in combination with the frequency of data variation. Temperatures, for example, can be displayed only for a time range of about several weeks. Larger time ranges, in particular with high frequency, are often no longer recognizable.

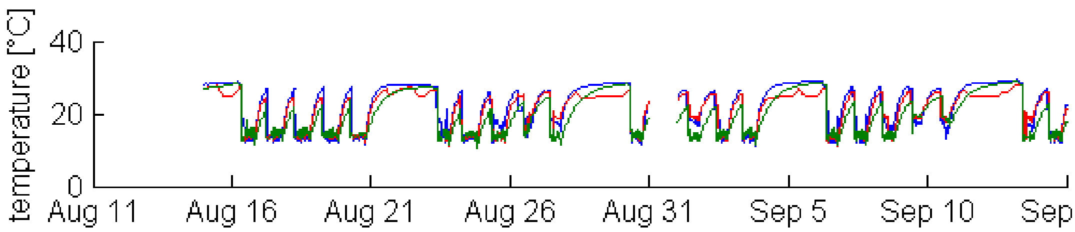

Figure 1. Line plot – Return water temperatures from cooling coils for a time range of 4 weeks; AHU 1 (green), AHU 2 (red), AHU 3 (blue).

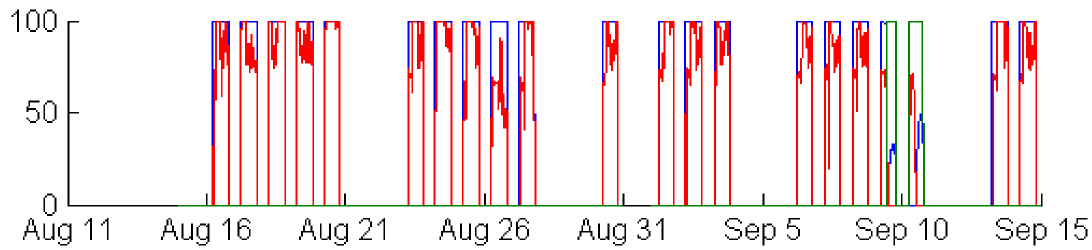

Figure 2. Line plot – Position of control valves of cooling coil (blue), heating coil (red), humidifier (green).

A different way to display time series of data is the *carpet plot*. In carpet plots the data is displayed in different colors in respect to a color scale. The data of one day is arranged in columns with the time of day from top down on the Y-axis (1 to 24 hours). The data of the following day is aligned in the right next column on the Xaxis. Carpet plots yield operation patterns that enable the viewer to recognize quickly whether the recorded operation is valid or not. Figure 3 shows the return water temperature from a cooling coil with a sampling rate of 5 minutes for the time range of four weeks.

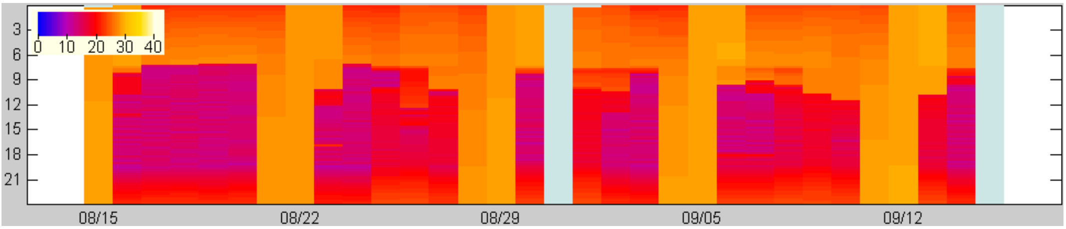

Figure 3. Carpet plot – Return water temperature from cooling coil AHU 3 for a time range of 4 weeks.

In carpet plots, large amounts of data of even an entire year can be displayed, still recognizable in its long-term course. Line plots are more suited to point out short-term course and to display absolute values.

Correlation of Data

The most important analysis of operation data is to check the correlation between different operation data or measured data. A very simple example is the check whether a building space is being heated and cooled at the same time. The correlation between the position of the heating and cooling valve can be displayed in form of a *scatter plot*. Additional correlations that can be displayed within scatter plots are room temperatures against outdoor temperature (see Figure 4), air flow rates against air quality, etc. to check and verify their correct dependency.

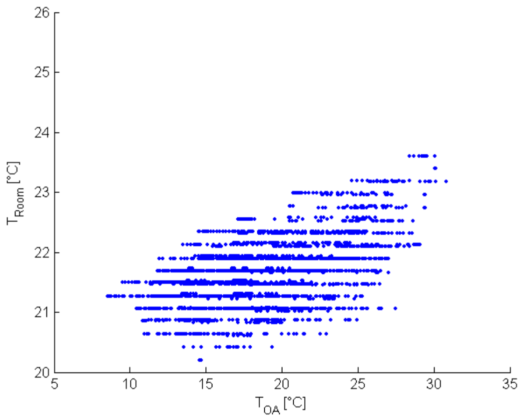

Figure 4. Scatter plot – room temperature T_{Room} against outdoor temperature T_{OA}.

More powerful analysis can be made by enlarging single scatter plots to entire matrices of dependent scatter plots. Within scatter plot matrices, the dimension of the displayed data and thus the obtained information is much higher than in any other visualization forms. Figure 5 shows the operation data of an AHU in form of a scatter plot matrix with temperatures and humidity at outdoor, and supply air conditions as well as the valve position of the humidifier. The visualization tool used to create the scatter plot matrix is provided with a brushing tool to identify and select specified operation data that is then available for further (numerical) analysis. The blue marks in Figure 5 indicate operation of the AHU during weekdays.

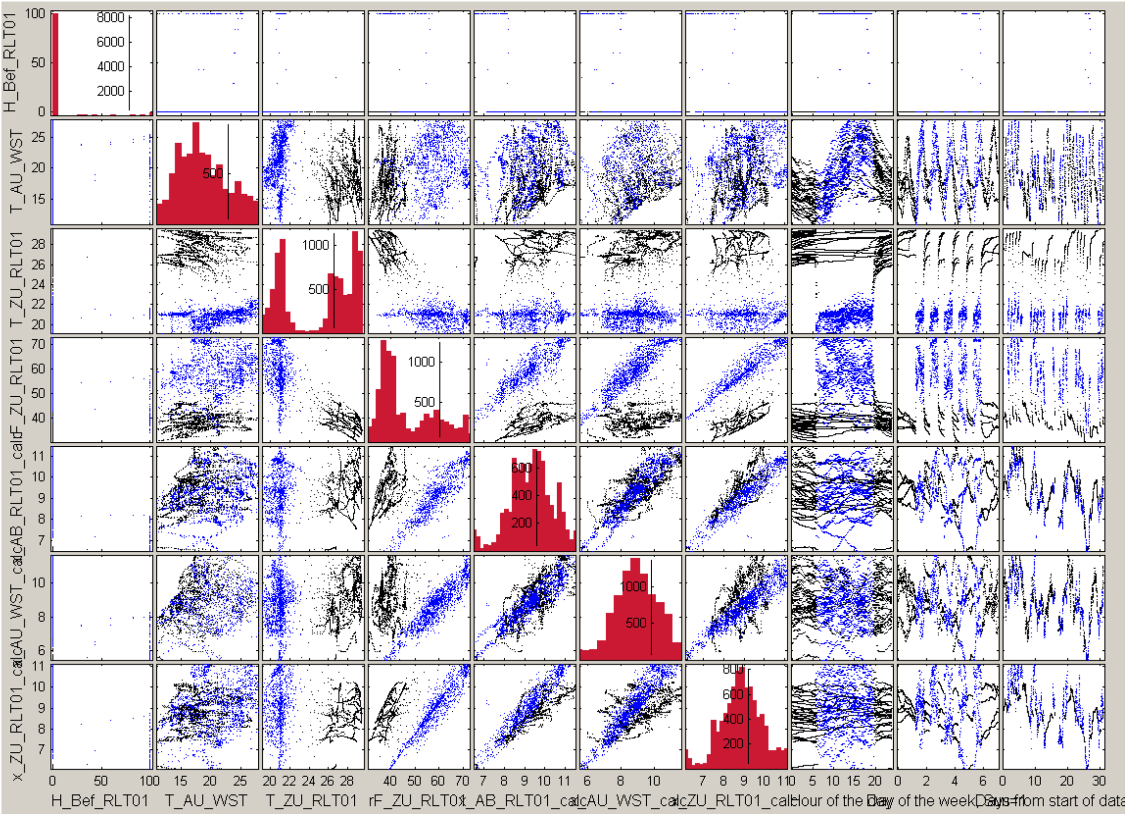

Figure 5. Matrix of dependent scatter plots – Operation data of AHU with temperatures, humidity, and valve position of humidifier; blue marks indicate operation of AHU.

Statistical Distribution of Data

Additional information can be obtained from the statistical distribution of operation data. For example, the left diagram in Figure 6 shows the frequency of the operation stage of a cold water pump. Even though it is a pump with variable speed, it does not modulate, but operates only at the maximum speed or stops. The right diagram shows the valve position of a heating circuit. It is perceptible that the valve does modulate, but opens only from 0 % to a maximum of 50 %.

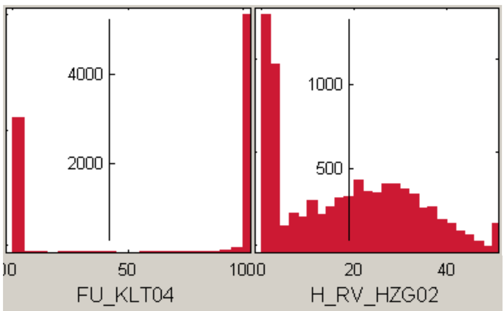

Figure 6. Histogram – Frequency of cold water pump (left); position of heating valve (right).

USE OF OPERATION PATTERNS

So far, building and system operation is documented in form of schemes and verbal descriptions of functionality and, sometimes, of performance. The schemes give only an idea about the static system assembly and do not consider dynamic behavior. The verbal descriptions often mention only coarse dependencies and therefore, leave room for individual interpretation. There is seldom system operation that is described clearly and unmistakably. Verification and optimization of dynamic operation, thus is often not performed properly due to lack of information.

The visualization techniques mentioned above can be used to generate operation patterns that describe the functionality and performance of building and system operation in a visual way. Therefore, the theoretically possible and optimal operation data, or range of operation data, respectively, is displayed within different diagrams in form of patterns. The sum of all of these operation patterns represents a plain description of the dynamic operation and behavior of the building and systems. Operation patterns do not only define operation of systems in full-load conditions, but also within the full range of part load conditions.

Operation patterns aim two objectives. First, the given operation ranges indicate valid operation that can be compared with real operation data. Second, the operation patterns can be divided into different zones inside and outside the valid ranges, which identify specified definite clues as to causes for faulty operation, existing optimization potential, and measures to avoid and realize them, respectively.

When comparing measured operation data with operation patterns, it is important to take into account the accuracy of sensors and actuators, and hence the accuracy of specific operation states. Since data from the BAS is used to verify system operation, the operation patterns have to include sufficient fringe to consider inaccuracy of sensors without suppressing real optimization potential or even faulty operation.

System description

The use of operation patterns is shown by means of a constant flow rate air handling unit (AHU) that supplies fully conditioned air to the rooms of an office building. The scheme in Figure 7 shows the single components of the AHU (including the hydronic circuits of heating and cooling coils) as well as the related measurement and data points of the BAS. The system description gives only vague specifications concerning the operation of heat recovery, pre-heating coil, cooling coil, re-heating coil, and humidifier. Control schemes show the control logic for the system, but do not give the exact settings of set points and threshold values.

The data used for operation diagnostic for this work was recorded from mid-August through mid-September 2004, with a sampling rate of 5 minutes. Due to limited capacity of the BAS, not all of the data points shown in Figure 7 could be recorded. Nevertheless, the most important system temperatures and operation data is available.

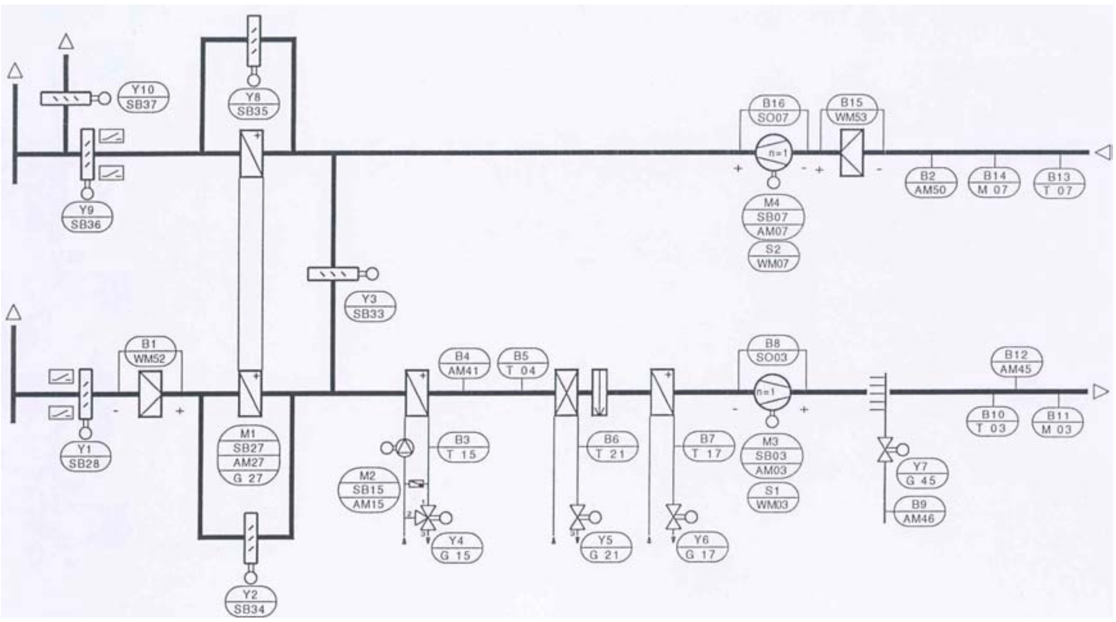

Figure 7. Scheme of air handling unit (AHU).

Operation Patterns – Operation Schedules

Since the air handling units operate only for fixed schedules during office time, the first operation pattern can be defined in form of a carpet plot (see Figure 8). The operation times of all related systems and components, such as heating and cooling coil valves and pumps, respectively, should comply with this schedule. The schedule itself should be adjusted with the actual occupancy of the building.

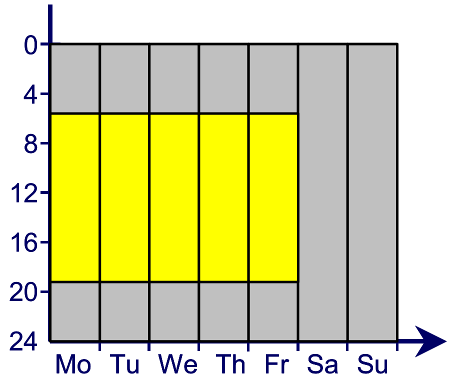

Figure 8. Operation pattern – Operation time of air handling unit (AHU) and related systems and components.

The carpet plots in Figure 9 show the same structure as the operation pattern in Figure 8. Thus, the operation times of the AHU seem to be correctly adjusted. This could be shown for all components, related to the AHU. Although the operation times are all right, the bottommost plot in Figure 9 indicates faulty operation of the cooling coil, since the valve is completely open during operation time instead of modulating.

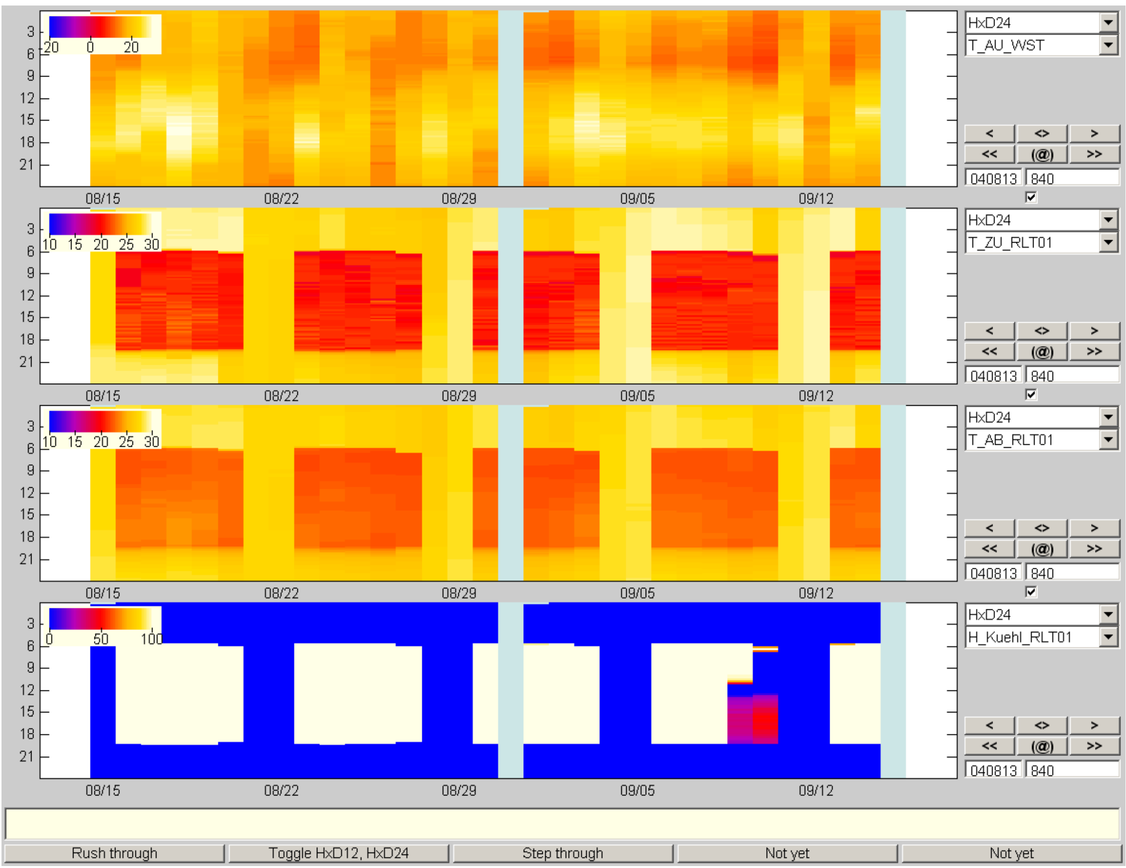

Figure 9. Carpet Plot of (i) outdoor temperature, (ii) supply air temperature AHU1, (iii) return air temperature AHU1, (iv) position of cooling coil valve AHU1 (from top down).

Operation Patterns – Operation Fields

Another way to use operation patterns is to define operation fields within a single diagram or a set of diagrams. Operation fields describe more or less general states of operation, depending on different (external) conditions. Psychrometric charts, for example, can be used to define the different AHU processes like heating, cooling, dehumidification and humidification, depending on outdoor conditions. Figure 10 shows in its left diagram a psychrometric chart with the operation fields for the four thermodynamic processes for AHUs. The right diagram shows the recorded operation data, also in a diagram where the outdoor air temperature (T_{OA}) is plotted against the absolute humidity ratio of outdoor air (x_{OA}). Since the absolute humidity ratio is not measured by the BAS, it was calculated using the outdoor temperature and relative humidity ratio. The atmospheric pressure, thereat, is assumed to be constant.

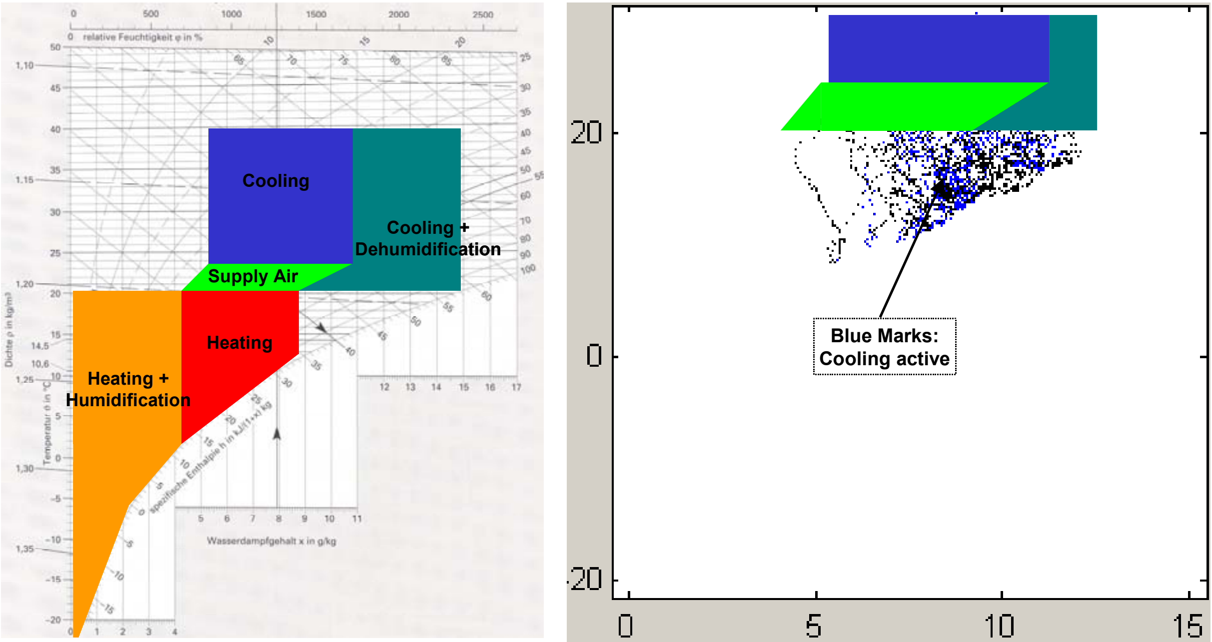

Figure 10. Operation pattern – Operation fields for AHU processes
left diagram :psychrometric chart
right diagram: corresponding scatter plot.

The blue marks in the right diagram indicate operation points where the cooling coil valve is 100 % open. In comparison with the operation fields in the psychrometric chart, it is recognizable that the cooling coil is active at conditions where neither cooling nor dehumidification is necessary. Numerical analysis of the operation data shows, that this needless operation makes up 48 % of the overall operation of the cooling coil during the observed time.

Operation Patterns – Operation Correlation

Whereas external influence caused by the occupants of a building (e.g. operation schedules) and outdoor conditions (operation fields) is often considered for optimization of system operation, the correlation of the operation of single components is seldom taken into account. Therefore, this correlation first needs to be defined in an unmistakable way. Figure 11 shows the operation pattern for the cooling coil of an AHU, depending on its use for cooling and dehumidification. The position of the cooling coil valve is used to define the operation pattern, since the signal is available on the BAS and indicates the intensity of operation. In the left diagram, the valve position is displayed against the outdoor air temperature. Also, to describe the operation due to dehumidification, the valve position is displayed against the outdoor air humidity ratio (right diagram). While the valve position is variable and depends on the outdoor air temperature for cooling only, it is completely open for dehumidification.

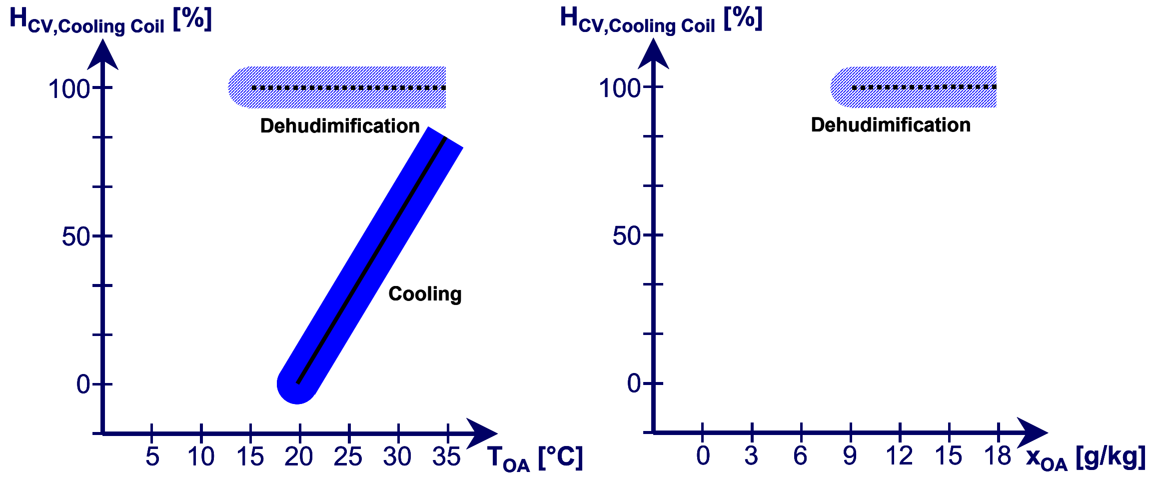

Figure 11. Operation pattern – Position of cooling coil valve for cooling and dehumidification.

Figure 12 shows the corresponding operation data of the cooling coil valve against the outdoor air temperature (left diagram) and against the outdoor air humidity ratio (right diagram). Comparing the displayed operation data with the operation patterns from Figure 11 proves correct operation for cooling (variable valve position only at outdoor air temperatures above 20 °C), but incorrect operation for dehumidification (open valve at outdoor air humidity below 8 g/kg).

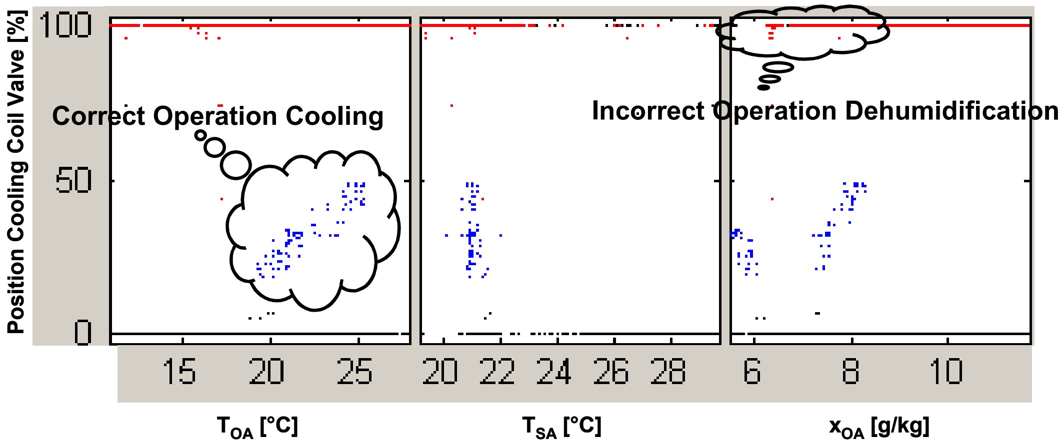

Figure 12. Operation pattern – Verification position of cooling coil valve for cooling and dehumidification.

Much more information can be obtained using extended scatter plot matrices as shown in Figure 13. The displayed operation data of supply air conditions, heating and cooling coils depending on outdoor conditions show several effects that allow enhanced diagnostics of the system operation such as (see numbers in Figure 13):

① Throttle valve for cooling coil hardly operates at part load conditions.
② Heating and cooling coil are in operation at the same time (red marked operation points).
③ Throttle valve for heating valve is used mainly to full capacity.
④ No rise in supply air temperature at increasing outdoor air temperatures.

In this paper, only a few points are mentioned that have been detected by operation diagnostics of several AHUs, heating systems, chillers, etc. The main issues found did not cause complaints of occupants or even faulty operation and, therefore, probably would never have been recognized. Several systems did not use their full capacity (e.g. chiller temperatures, use of free cooling, etc.), and therefore caused higher energy consumption. The energy saving potential that is estimated to be about 10 to 15 % has not yet been verified by measurements.

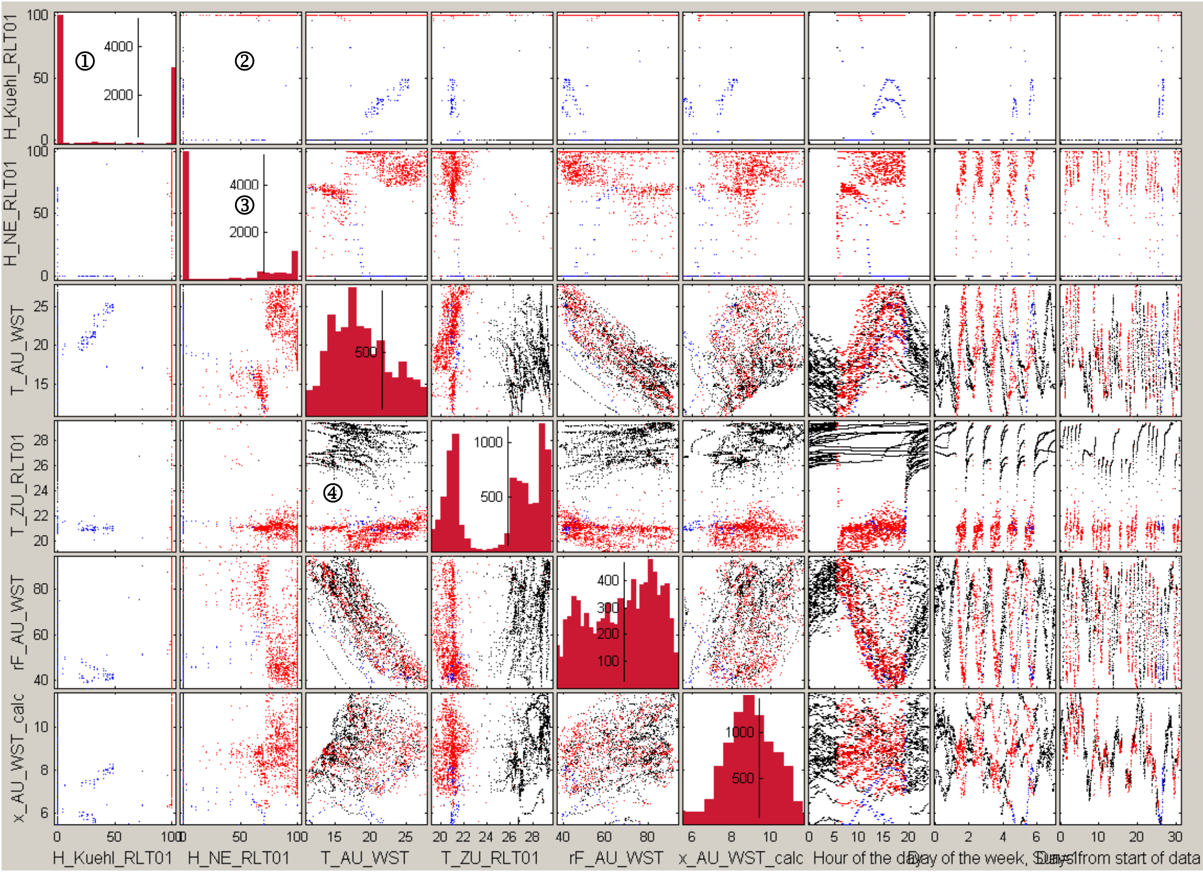

Figure 13. Operation pattern – Heating and cooling of supply air.

DISCUSSION AND CONCLUSIONS

Operation patterns in fact are visible expert rules. Numerical expert rules, as known so far, are more or less black box models which give messages of whether the tested operation data is valid or not. The expert rules themselves cannot be tested easily. Thus, it is crucial to set up clear mathematically defined rules.

The approach of using operation patterns avoids this difficulty by using visual means. Even complex rules can be described by a set of a few operation patterns that are easily recognizable. By bringing recorded operation data into the form of operation patterns, the operation of buildings and systems can be checked and verified.

Operation patterns that have been created already in the design phase of systems can be used for initial commissioning. Within the approach of operation diagnostics, it is usually necessary to develop operation patterns based on available information from design documents, system and component descriptions, and knowledge from the operation personnel.

Initial optimization can be done by considering the general correlations of systems operation when setting up suitable sets of operation patterns. Further optimization can be carried out using simulation models. To do so, it is necessary to have exact models of the systems which are able to consider control systems and control strategies. To attain adequate results that can later be compared with operation data, it is recommended to use models that are calibrated with manufacturers' data.

One of the main difficulties when applying operation diagnostics is the limited performance of BAS. Despite this, the data that could be used for operation diagnostics is already processed in the systems, the access to the data and the possibilities to record the data in an adequate format is often extremely limited.

Within a new research project, commencing in September 2004, the approach of using operation patterns for operation diagnostics will be applied at up to 15 additional buildings in Germany. It is further intended to develop sets of typicals with operation patterns for common HVAC systems that can be tuned to the systems during the design phase. These operation patterns, together with schemes and short verbal description, then give a clear description of the functionality and the performance of systems that can be used for bidding, testing and balancing, initial commissioning, hand over, and ongoing commissioning as well.

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