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Enhanced Building Operation Using 'Operation Diagnostics' – A Case Study

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ABSTRACT

At former ICEBO's in 2003 and 2004 papers have been presented by the author that showed the approach and methodology of 'operation diagnostics' and 'operation prognostics' [1], [2], [3]. Within this approach, advanced visualization techniques are used to display large amounts of recorded data from the BAS and to show the information that is hidden in the data. Simulation models are used to create optimal operation data, that can be used to compare real operation and optimal operation in form of visualized 'operation patterns'. Optimization potential and even precise optimization measures regarding operation and control of buildings and systems can be identified and quantified by this methodology.

This paper shows how 'operation diagnostics' has been applied at an office building in Munich, Germany. The four storey building features extensive systems like chiller plants, free cooling, heating and cooling panels in rooms, mechanical ventilation with heating, cooling, humidification, and dehumidification, etc., that are controlled by a central building automation system. Therefore, this building is predestined for extensive optimization of operation scenarios and control strategies.

The analysis and diagnosis of more than 1 year of recorded data yielded several measures to reduce the energy consumption noticeably. The measures are realized and verified by additional measurements, performed by the 'Forschungsstelle für Energiewirtschaft (FfE)' as an independent party. The measures range from inspection and replacement of faulty sensors and actuators, customization of operation schedules, and adaptation of characteristics, to the implementation of new control strategies.

GENERAL APPROACH

Operation Diagnostics

Operation Diagnostics using multi-dimensional visualization tools allow a quick check of large amounts of recorded BEMS data of a building to get an idea about the quality of the operation as well as extensive analysis to get detailed information about the structures and background of the operation.

A first numerical plausibility check gives a rough outline of the quality and the reliability of the data. The following visual diagnosis with carpet plots allows a quick check of large time series of the data. Figure 1 shows a single carpet plot with an explanation how to read it. The visual method enables one to detect even slight indications of optimization potential.

The visualization of the data in form of scatter plots and scatter plot matrices with histograms (see Figure 2) allows detailed analysis of the correlation of operation with complex control strategies and dependencies. Further calculations profit by the brushing function implemented in the used visualization tool *Pia* [4] that enables to select and highlight data interactively in the diagram. Subsequently, numerical analysis gives the possibility to estimate optimization and saving potential.

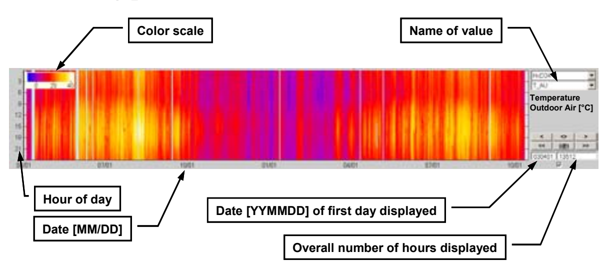

Figure 1. Example and explanation of a carpet plot that shows outdoor air temperatures for 1 ½ years.

The measures indicated by Operation Diagnostics mainly focus on optimization in the form of modified control strategies and changed parameter settings. Therefore, the measures are extremely cost-effective with pay-back times that are calculated with consulting fees only.

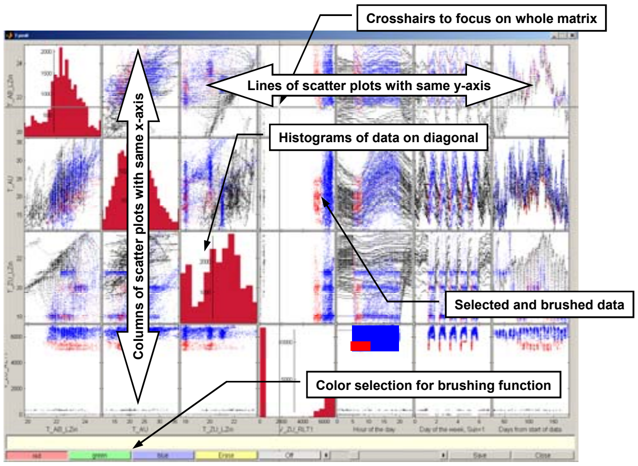

Figure 2. Example and explanation of a scatter plot matrix with histograms.

Operation Prognostics

Operation Prognostics uses expert knowledge from the design phase of systems and buildings to develop 'Operation Patterns', that describe the dynamic behavior in a visual way. Figure 3 shows a matrix with operation patterns that describe the operation of an air handling unit (AHU). These operation patterns can be used to compare measured operation data from the BAS with data under optimal operation conditions. Optimized operation data can be produced with calibrated simulation models. Even faulty operation of systems can be simulated to obtain clues how to interpret measured data and to identify reasons for ineffective operation and to define clear measures how to optimize it.

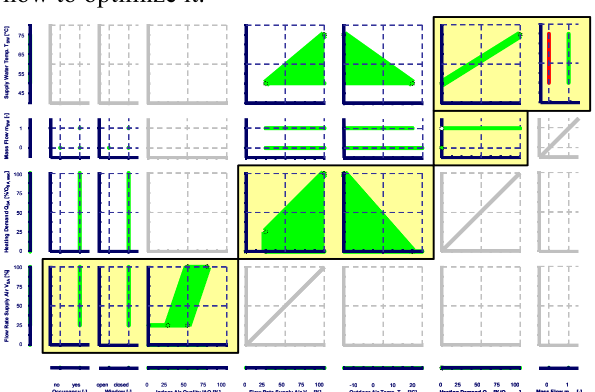

Figure 3. Example of operation patterns for an AHU.

BUILDING DESCRIPTION

Building

The office building where operation diagnostics has been applied is a 4 storey building with approx. 8.600 m² gross floor area (see Figure 4). It was constructed in 1965 and renovated in 1997. The renovation comprised the improvement of the building envelope, the replacement of major HVAC equipment, as well as the renewal of the BAS. Therefore, the building is in technically good condition.

The average energy consumption per year is 690 MWh (80 kWh/m²) for heating and 550 MWh (64 kWh/m²) for electric energy. The building comes to yearly energy costs of about 78.000 € (approx. 95.000 US$).

Figure 4. Photo of the office building Münchener Rückversicherung (Munich Re), Königinstraße 38 in Munich.

Heating System

Heating energy is supplied via district heating. Two heat exchangers, 320 kW each, transform the steam from the utility into hot water. They are located in a central heating plant room in the basement. The distribution system maintains static heating (offices south-west and offices north-east), heating coils of the AHU's, as well as central domestic hot water generation. Additionally, steam is directly used for humidification of the supply air.

Cooling System

Cooling is generated with a 300 kW screw-type chiller in combination with two cooling towers (410 kW). The cooling towers are also used for free cooling. The offices are provided with cooling panels, while technical rooms and computer cabinets are provided with fan coil units (FCU's). Cooling is also required by the cooling coils of the AHU's.

Ventilation System

Four central AHU's with capacities from 2.000 to 14.000 m³/h are installed to serve the main zones (offices, conference rooms, lobby, archives) within the building with fresh air. Except the system for the archives, all AHU's are provided with capability for heating, cooling, humidification and dehumidification. The constant air volume (CAV) systems provide two air changes per hour (2 h^{-1}) for office spaces and eight air changes per hour for conference rooms (8 h^{-1}). Ventilation air is not used for heating or cooling of the office spaces. Additional AHU's are installed to provide ventilation air for toilets, technical rooms, smoke exhaust, etc.

Building Automation System (BAS)

A direct digital control (DDC) system is installed to control and operate the central HVAC systems, as well as the room equipment like heating and cooling panels, lighting, shading devices, etc. The BAS comprise controllers with about 3.200 data points.

OPERATION DIAGNOSTICS

The application of operation diagnostics is shown exemplarily for the room behavior and the operation of the central heating system, including the district heating transfer station using date from the winter period 2004/2005. In a first step, the time series of all measured data are diagnosed to identify the quality of the data regarding missing data (outage of BAS) and faulty data (sensor calibration). This gives a first overview of the general system operation. The next step is to analyze the dependencies and correlations of different data points to diagnose the correctness and efficiency of control strategies and control settings. This leads to measures that enhance the dynamic operation of systems regarding reduced energy consumption and/or improved comfort.

Available Data Base and Data Quality

Data from the BAS has been recorded since Spring 2004. Due to limited capacity of the network only 160 of the 3200 data points could be recorded. The chosen sampling rate, also limited due to the network capacities, is 10 minutes. The recorded data points analyzed within this work include

- weather data (outdoor air temperature t_{oa}, relative outdoor humidity rh_{oa}, illumination on facades, wind velocity v_w),
- room conditions (room temperature t_{rm}, position of control valve for heating and cooling, position of room thermostat), and
- conditions of central heating system (hot water supply temperatures t_{sw}, hot water return temperatures t_{rw}, stroke of control valves).

Additional data is available for

- conditions of central cooling system (cold and chilled water supply temperatures t_{sw}, cold and chilled water return temperatures t_{rw}, stroke of control valves) and
- conditions of central AHU's (supply air temperatures, signals for fans and dampers, operation date for hydronic loops of heating and cooling coils).

The exact time period of the subsequently shown and analyzed data is from August 16, 2004 through March 1, 2005. Thus, mainly the winter operation is being considered in the subsequent analysis.

Unfortunately, no data for the operation of pumps is available. Additional data like temperature differences is calculated from the recorded data points.

Through the plausibility check, it was detected that several data points did not indicate correct data (see Figure 5). The heating and cooling function in room 1120, for example, was corrected only after replacement of the faulty temperature sensor in Mid-February 2005.

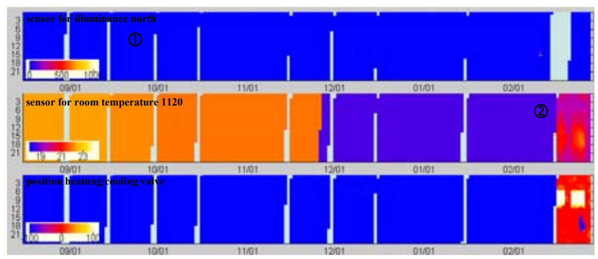

Figure 5. Time series of incorrect data points; (1) illuminance north, (2) room temperature 1120, (3) position of heating/cooling valve (from top down).

Diagnosis of Dynamic Room Behavior

Time series of operation data

First analysis shows, that the room temperatures are mostly above 20 or 21 °C during occupied periods in winter and below 26 °C in summer. This coincides with statements of the building manager that there are no major complaints from the occupants about thermal comfort. Anyhow, some rooms show temperatures above 24 °C, what is definitely too high during heating period and should be subject for further analysis.

Furthermore, a setback with lowered set points for room temperatures can be seen during unoccupied times in winter. There is no adequate setup visible for cooling in summer (see Figure 6).

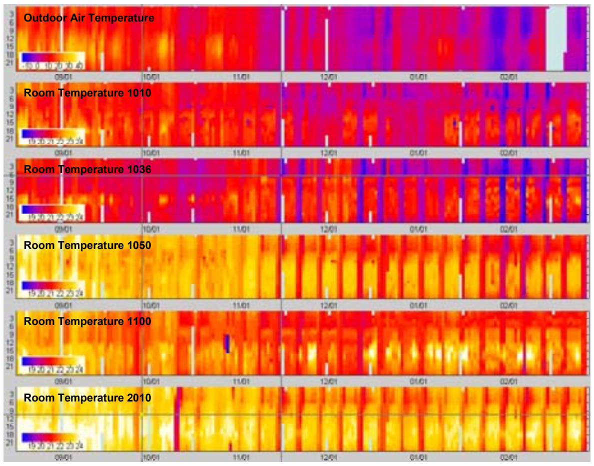

Figure 6. Time series of room temperatures (uppermost diagram shows outside air temperature, followed by room temperatures for rooms 1010, 1036, 1050, 1100, and 2010).

Figure 7 shows the time series of (1) outdoor air temperature, (2) room temperature, (3) stroke of heating and cooling valve, (4) manually set position of room thermostat (from top down) for an exemplary room (room number 1036) in form of carpet plots. The data shows regular operation with room temperatures between 21 and 23 °C during occupied times and lower room temperatures during nights and weekends. During summer time, the room is cooled (blue indicated stroke of the control valve), whereas cooling occurs mainly on afternoon.

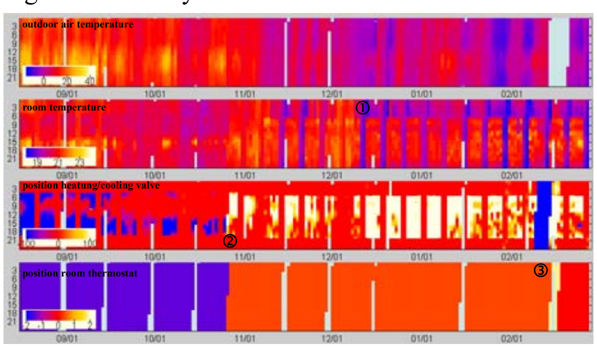

Figure 7. Time series of room conditions (room 1036).

In late October, the room thermostat was changed manually from -1 to +1 (deviation from set value for room temperature). This caused an immediate change in operation from cooling to heating mode; the room temperature increased, respectively.

In Mid-February, there was a malfunction of the heating and cooling valve that stopped room heating and forced the occupants to increase the setting of the room thermostat again. The thermostat setting was not reduced after the valve worked correctly again a few days later.

It is also remarkable, that the control valve for heating and cooling is mainly at a 100 % stroke position, what means 100 % heating or cooling capacity is provided.

Analyzing the data of several rooms with similar orientation and usage (room numbers 1036, 1050, 2036, 2050, 3036, 3050) shows, that there is no similar operation, as would be expected. The visualization of the control valve signals for heating and cooling show extremely different characteristics (see Figure 8). The different time for the change from cooling (blue) to heating (bright yellow) mode, as well as the intensity of heating and cooling (portion of blue and yellow colors) is mainly influenced by the manual and individual settings of the room thermostats.

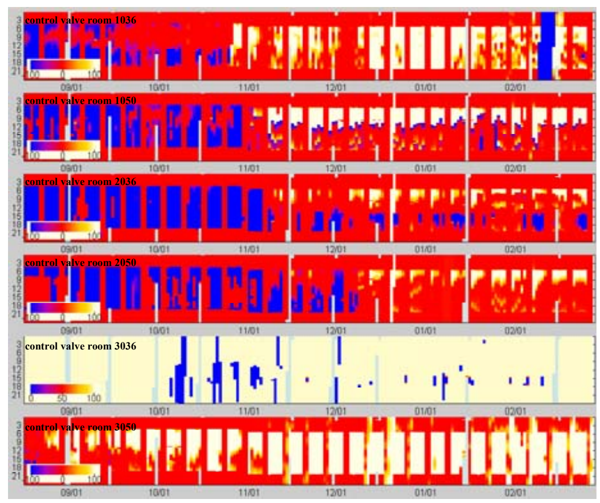

Figure 8. Time series of control valve signals for rooms 1036, 1050, 2036, 2050, 3036, 3050 (from top down).

Some rooms show a daily change from heating mode during morning to cooling mode in the afternoon (e.g. room 2036, 3rd carpet plot from top). In room 1050 (2nd carpet plot from top), heating mode even changes immediately from 100 % heating to 100 % cooling before a neutral operation accommodates. This causes needless energy consumption and should be prevented by an adequate measure.

<u>Dependencies of operation data</u>

For further analysis, the data of room 1036 is displayed in form of scatter plot matrices. Contrary to Figure 7, where time series are displayed, the same data can now be analyzed regarding its dependencies and correlation.

In the scatter plot matrix shown in Figure 9, the control valve position shows a distinct change from heating to cooling mode at an outdoor air temperature of about 10 °C (row 1 vs. column 1). The control valve position against the setting of the room thermostat and against the entire time period (columns 3 and 6) show, that the change from heating to cooling mode comes also along with the manual readjustment of the room thermostat. Thus, the obvious dependency between heating and cooling mode and an outdoor temperature of 10 °C proved to be more or less accidental. Furthermore, the stroke of the control valve (as an indicator for heating and cooling capacity, respectively) is mainly 100 % open. There occurs neither a dead band, nor a throttling range temperature between heating and cooling as should be expected. [7]

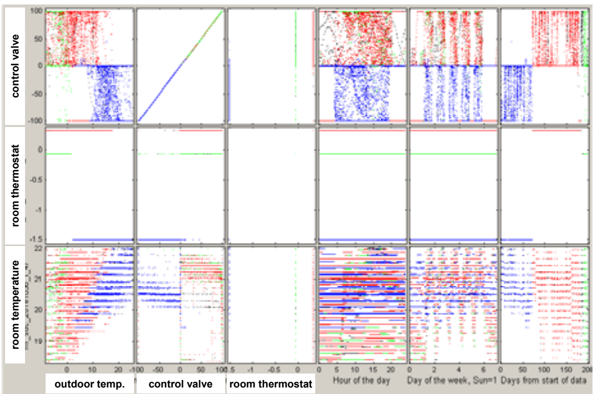

Figure 9. Scatter plot matrix for operation data room 1036 (rows: (1) control valve position, (2) adjustment of room thermostat, (3) room temperature; columns: (1) outdoor air temperature, (2) control valve position, (3) adjustment of room thermostat, (4) hour of day, (5) day of week, (6) days from start of data).

Optimization measures

As a first step, all sensors for room temperatures should be tested and recalibrated in case of crucial deviation. Also, occupants should be informed about adequate room temperatures to avoid overheating.

To enhance operation regarding energy consumption, it was recommended to decrease the impact of the adjustment of room thermostats on the heating and cooling demand of the room. Therefore, the pitch of the thermostat should be decreased (possibly, without mentioning to the occupants).

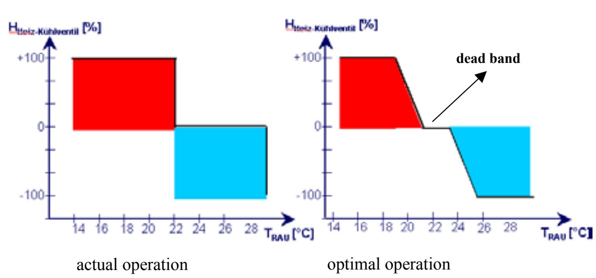

Figure 10. Operation pattern for control valve characteristic (position of control valve against air temperature), left: actual, right: optimized characteristic.

The main measure regarding the control of room behavior is to change the control settings for the heating and cooling valves. A dead band with a differential of at least 3 K would avoid the instantaneous change between heating and cooling mode (see Figure 10). Furthermore, a modified characteristic would ensure a throttling range (instead of permanently fully open valves) where only reduced heating and cooling capacity is used.

For further analysis regarding optimized control setting and exact evaluation of the possible saving potential, the room behavior has been simulated [6]. Simulated operation data is shown in Figure 11. The left scatter plots shows the heating (red) and cooling (blue) demand versus the room temperature, the right scatter plots versus the outdoor temperature, respectively. The upper row shows operation data for the control settings as it is, the lower row shows the optimized control strategy with a dead band of 3 K (from 21 °C to 24 °C).

The optimization yields energy savings of 9 % for heating and more than 30 % for cooling energy. The savings for cooling energy go along with higher room temperatures, but still below 26 °C.

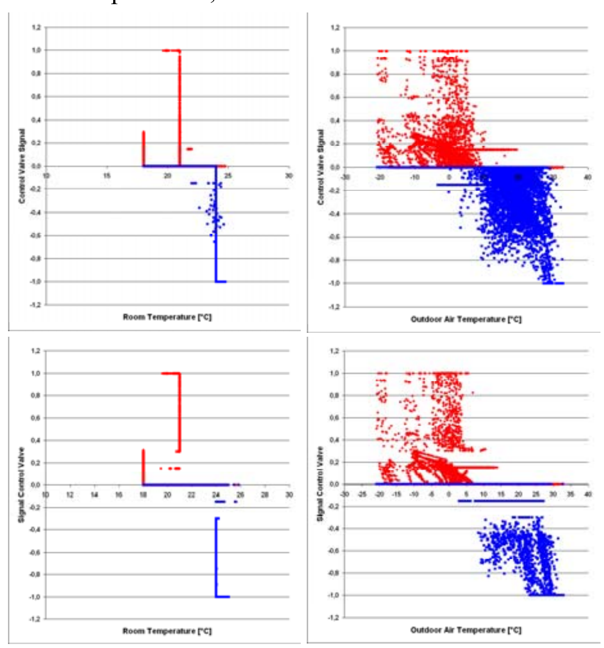

Figure 11. Scatter plots with simulated operation data showing heating/cooling demand versus room temperature (left) and outdoor air temperature (right) for valve characteristic without dead band (upper row) and with optimized valve characteristic with dead band between heating and cooling mode from 21 to 24 °C (lower row).

Diagnosis of Heating Circuits

System description / theory of operation

All rooms with same orientations are served from one independently controlled heating circuit. Figure 12 shows the functional scheme for the heating circuit 'south-west', consisting of a heating supply, a mixing valve, a pump and a heating return. Heating supply and return are connected to a manifold that is supplied with hot water from the district heating transfer station. A controller, connected to the motorized mixing valve (A), maintains the hot water supply temperature (2) depending on the outside air temperature (1).

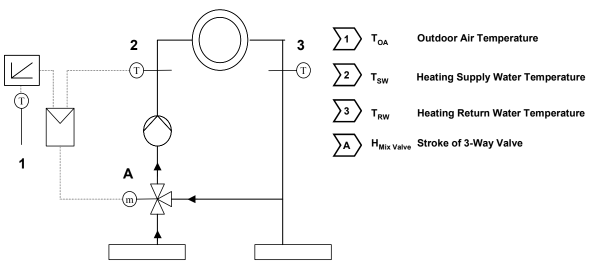

Figure 12. Functional scheme of heating circuit with measurement points.

Time series of operation data

The time series displayed in Figure 13 show tendentiously the increasing heating demand with decreasing outdoor air temperatures, indicated by higher hot water supply temperatures. The mixing valve operates mainly at full stroke, what means that no return water is mixed to the supply water. The reason is, that the hot water supply temperature is already controlled and maintained with the same characteristic by the district heating transfer station. Since the heating circuit 'North-East' is the leading circuit for the supply water temperature, the circuit 'South-West' should be run with lower supply temperatures.

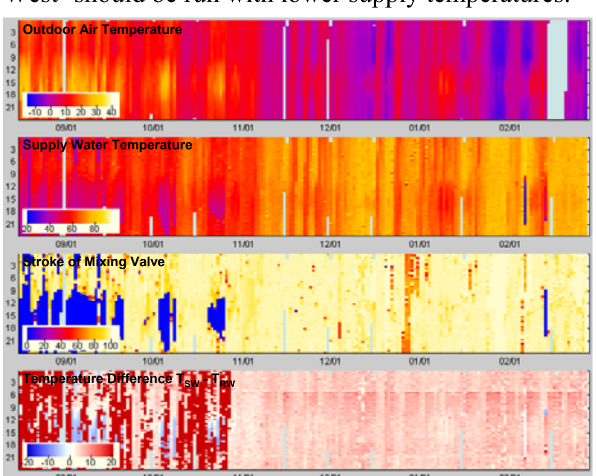

Figure 13. Time series for (1) outdoor air temperature, (2) supply water temperature, (3) stroke of mixing valve, (4) temperature difference supply return (from top down).

It is evident, that the operation of the heating circuit does not follow any setback during nights or weekends, as do the heating panels in the rooms. Another point of interest is the low temperature difference between hot water supply and return temperature. It changed dramatically near the end of October from up to 20 K (as was intended) to less than 10 K. It is not clear what caused this change.

Dependencies of operation data

Figure 14 shows the data in form of a scatter plot matrix. The green marked data indicate a closed mixing valve, thus 100 % mixing of return water. The diagrams in the second column show that this operation occurs whenever the outside air temperature is more than 17 or 18 °C. Below this outside temperature, the mixing valve is permanently and almost fully open. This should only occur, when maximum heating is demanded. The matter of fact that the temperature difference between hot water supply and return temperature is only 10 K, instead of 20 K as defined in the design documentation, (even at low outside temperatures) leads to the conclusion, that the water flow rate is higher than demanded to cover the heating demand of the building.

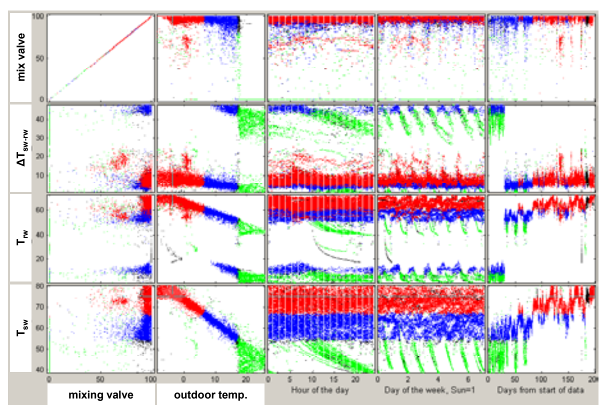

Figure 14. Scatter plot matrix for operation data of heating circuit 'South-West' (rows: (1) stroke of mixing valve, (2) temperature difference T_{sw} - T_{rw}, (3) hot water return temperature T_{rw}, (4) hot water supply temperature T_{sw}; columns: (1) stroke of mixing valve, (2) outdoor air temperature, (3) hour of day, (4) day of week, (5) days from start of data).

The characteristic of the hot water supply temperature is clearly shown in the second scatter plot in the bottom row. The hot water supply temperature increases continually with decreasing outdoor air temperatures and reaches its maximum of 80 °C at about -8 °C outdoor temperature. As mentioned before, this characteristic is not appropriate for the heating circuit 'South-West'.

Optimization measures

First of all, the analyzed heating circuit should be operated with the same setback characteristic during nights and weekends as the connected heating panels.

The characteristic for supply water temperature for static heating (heating panels) should rather depend on a medial outdoor temperature than on the actual value. This would consider the thermal mass and thus the inert behavior of the building. Furthermore, the set point for the shutoff of the heating circuit could be decreased to at least 15 °C or even less.

Eventually, the characteristic for the hot water supply temperature should be modified as shown in Figure 15 to adjust the heating supply regarding the actual heating demand of this building zone.

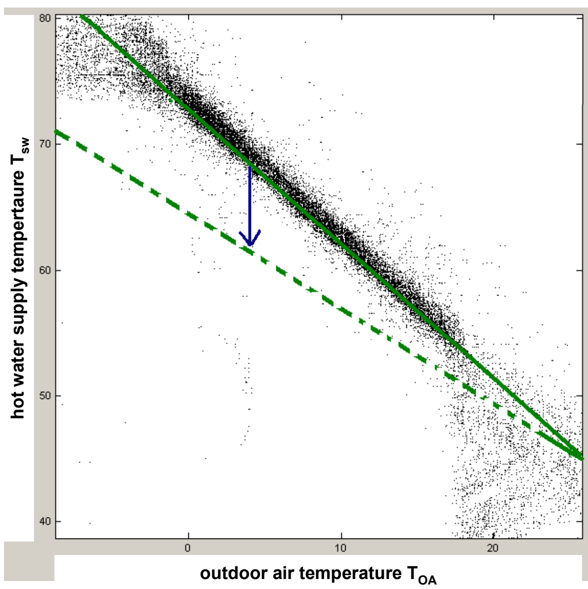

Figure 15. Characteristic of hot water supply temperature depending on outside air temperature with decreased gradient for optimization.

Diagnosis of District Heating Transfer Station

System description / theory of operation

The steam from the utility is transformed trough two parallel heat exchangers. Control valves in the condensed water return main maintain the hot water supply temperature depending on the outside air temperature, and following the heating circuit 'North-East', respectively. The second heat exchanger is activated when the first heat exchanger operates more than 5 minutes at a stroke of more than 95 %.

Time series of operation data

The correct operation of heat exchanger 1 can be seen as it operates only, when heat exchanger 2 is at its maximum capacity (see Figure 16). There is obviously no change in the order for the sequential operation between heat exchanger 1 and 2. The hot water supply temperature follows the characteristic depending the outdoor temperature, but shows no setback during nights and weekends.

Again, the temperature difference between hot water supply and return temperature is lower than the design value.

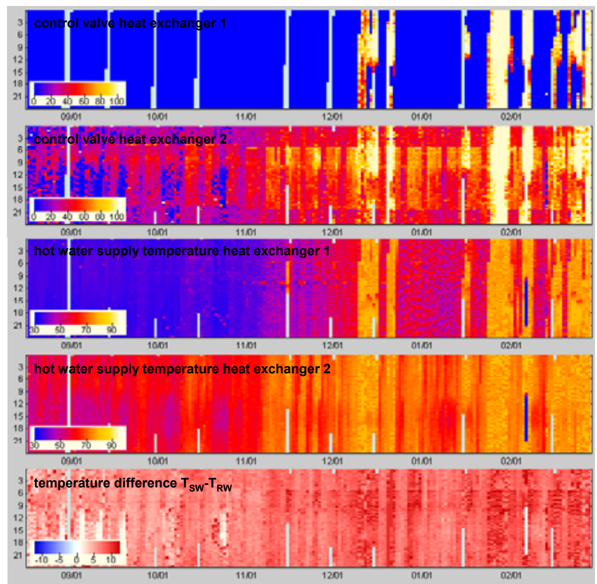

Figure 16. Time series for (1) control valve heat exchanger 1, (2) control valve heat exchanger 2, (3) hot water supply temperature heat exchanger 1, (4) hot water supply temperature heat exchanger 2, (5) temperature difference supply return (from top down).

Dependencies of operation data

The blue marked points in Figure 17 indicate operation of both heat exchangers. The analysis shows, that the second heat exchanger operates only at outdoor temperatures below 0 °C. But once in operation, it reaches its maximum capacity almost immediately.

Again, the characteristic of the hot water supply temperature depending on the outdoor air temperature can be seen clearly (4th column). Since heating capacity is also demanded for the AHU's in case of dehumidification, the control valve is still open at outdoor air temperatures above 20 and even 25 °C.

Optimization measures

Subsequent to the optimizations in each of the heating circuits, the characteristic of the primary hot water supply temperature should be verified and perhaps modified. Furthermore, frequent changes of the order of the sequence for the heat exchangers should be considered to avoid unbalanced fouling.

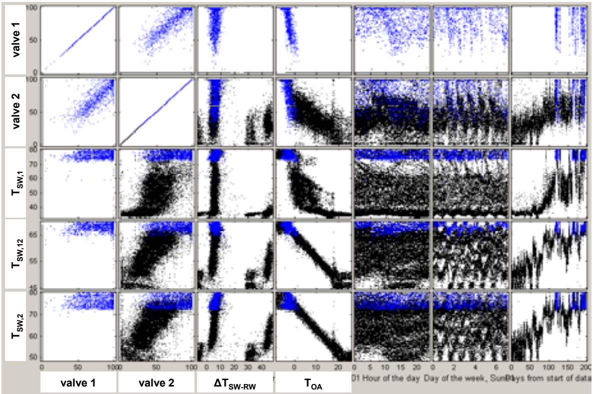

Figure 17. Scatter plot matrix for operation data of district heating transfer station (rows: (1) stroke of control valve heat exchanger 1, (2) stroke of control valve heat exchanger 1, (3) hot water supply temperature at heat exchanger 1, (4) mixed hot water supply temperature (heat exchanger 1/2), (5) hot water supply temperature at heat exchanger 2; columns: (1) stroke of control valve heat exchanger 1, (2) stroke of control valve heat exchanger 2, (3) temperature difference T_{sw} - T_{rw}, (4) outdoor air temperature, (5) hour of day, (6) day of week, (7) days from start of data).

CONCLUSIONS

The analysis of operation data for the office building of the *Münchener Rückversicherung* proved the possibilities and performance of Operation Diagnostics. The visual way to verify data enables to detect even slight indications of wrong or not optimized operation. The multi-dimensional scatter plot matrices show further clues to identify the reasons and to define adequate measures. Further numerical analysis of the data yield energy and cost savings for the recommended measures.

Additionally to the results and measures discussed before, cooling and ventilation systems have been diagnosed as well. Following measures and advices were given to enhance the building and system operation:

- adaptation of operating times for AHU's in accordance with occupied periods,
- enhanced control strategy for dehumidification of supply air in AHU's,
- reduction of chiller running time due to optimized free cooling operation,
- enhanced effectiveness of chiller operation due to maximum utilization of available capacity with higher temperature differences.

An overall saving potential of about 12 % has been calculated for this building. This includes reduction of heating demand, as well as reduction of electric energy used for the chiller plant, pumps, and fans. Electricity used for lighting and equipment was not subject to this study. Since the optimization measures comprise only measures without investments, the payback time calculated with consulting fees would be less than 2 years (since it is a research project, there have been no fees for the building owner). This result will be further verified by the monitoring, performed by the 'Forschungsstelle für Energiewirtschaft (FfE)'.

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REFERENCES

[1] Baumann, O. 2003. *Operation Diagnostics – Verification and Optimization of Building and System Operation by Multi-Dimensional Visualization of BEMS Data*, ICEBO – International Conference for Enhanced Building Operations, October 13-15, 2003, Berkeley CA, USA.

[2] Baumann, O. 2003. *Design and Optimization of Control Strategies and Parameters by Building and System Simulation*, ICEBO – International Conference for Enhanced Building Operations, October 13-15, 2003, Berkeley CA, USA.

[3] Baumann, O. 2004. *Operation Diagnostics – Use of Operation Patterns to Verify and Optimize Building and System Operation*, ICEBO – International Conference for Enhanced Building Operations, October 18-19, 2004, Paris, France.

[4] Isakson, P. 2004. *Pia-Manuals*, Department of Building Sciences, Royal Institute of Technology Stockholm (KTH), Sweden.

[5] Schmit, T. 2004. *Betriebsdiagnose: Analyse von GLT-Betriebsdaten zur Optimierung der Automationsfunktionen in einem Bürogebäude*, Diploma Thesis, Ebert-Ingenieure München, Munich University of Applied Science.

[6] Kadar, P. 2005. *Erstellung und Verifizierung von Betriebsmustern zur Beschreibung von Raumtypicals*, Diploma Thesis, Ebert-Ingenieure München, University of Applied Science Pinkafeld/Burgenland, Austria.

[7] ASHRAE. *2005 Handbook of Fundamentals*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 2005, Atlanta GA, USA.