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ANALYSIS OF HVAC SYSTEMS' OPERATION THROUGH GRAPHICAL VISUALIZATION OF PERFORMANCE

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ABSTRACT

Analysing measured building performance data is a complex and time-consuming process due to specific tailoring needed for each individual building and the amount of collected data. The datasets generated through continuous monitoring quickly amount to big-data levels. There are inherent difficulties in transforming and presenting these data in a coherent and comprehensible format without excessive simplification. These issues can be overcome by flattening 3-dimensional plots, i.e. representing the third axis using a colour-coded scale, resulting in so called carpet plots.

This paper presents data collected from three office buildings located in Sweden. The measurement periods range from 7 to 12 continuous months and took place between the years 2009 and 2015. Performance related data were logged for space heating, ground heating, domestic hot water, comfort cooling, process cooling, building auxiliary electricity, occupant electricity, air flow rates.

Visualizing key building performance parameters for periods of 12 months enables identification of building-specific patterns and baseline operational performance (average working week rhythm). This establishes a situation of knowing what to expect, thus facilitating easy verification of changes in control strategies and spotting of major deviations, due to e.g. climate conditions, occupant behaviour, operational faults, in terms of both energy use and indoor environment quality. Being able to verify intended operation conditions and spot major deviations opens the possibility of utilising carpet plots also for continuous building performance optimisation and ongoing commissioning, as well as fault detection and prevention.

The results of this study highlight the usefulness of using carpet plots for building performance analysis. While the work presented in this paper focused on analysing measured data through performance visualization, further research will address issues related to continuous building performance optimisation and ongoing commissioning, as well as fault detection and prevention.

KEY WORDS: building performance, visualization, case studies

1. INTRODUCTION

Analysing measured building performance data is crucial for continuously optimising performance, ongoing commissioning and even more so for fault detection and prevention. The process is complex and time-consuming due to specific tailoring needed for each individual building and the amount of collected data. The datasets generated through continuous monitoring quickly amount to big-data levels, meaning high-volume, high-velocity and/or high-variety information assets that demand cost-effective, innovative forms of information processing that enables enhanced insight, decision making, and process automation. [1]

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Data are typically logged at least hourly, commonly within intervals of 5 or 10 minutes, which results in a minimum of 8,760 entries for a single data-point. There are inherent difficulties in transforming and presenting these data in a coherent and comprehensible format without excessive simplification. Common approaches to visualizing these datasets include simple bar charts, time-series plots, and scatter plots. Three-dimensional plots are also very useful for visualizing building performance data, however can present issues when used in practice. These issues can be overcome by flattening the 3-dimensional plot, i.e. representing the third axis using a colour-coded scale, resulting in so called carpet plots. [2] Carpet plots seem to be a promising tool for facilitating the identification of building-specific patterns and baseline operational performance.

The data presented in this paper were collected from the following three office buildings: **Klassföreståndaren** (15,616 m^2 conditioned area excluding the area of the underground garage, Stockholm, Sweden – measurement period 15 May 2009 to 13 April 2010 and 5 February 2015 to 1 September 2015), **Gångaren 11** (31,809 m^2 conditioned area excluding the area of the underground garage, Stockholm, Sweden – measurement period 1 January 2011 – 31 December 2011), **Nereus Bassängkajen** (20,670 m^2 conditioned area excluding the area of the underground garage, Malmö, Sweden – measurement period 1 September 2011 – 31 August 2012). The heating, ventilation and air conditioning (HVAC) systems are similar in all buildings and comprise of air handling units (AHU) with coil heat recovery and free cooling, constant air volume (CAV) ventilation, active chilled beams and radiators. CAV ventilation requires less AHUs, sensors and motors compared to variable air volume (VAV) ventilation. Furthermore, the ductwork of the ventilation system was sized with the final pressure drop method as illustrated in Fig. 1 which requires less dampers and no sound attenuators. All these measures are meant to reduce the HVAC system's complexity and to simplify facility management. All three buildings are connected to the district heating and cooling systems.

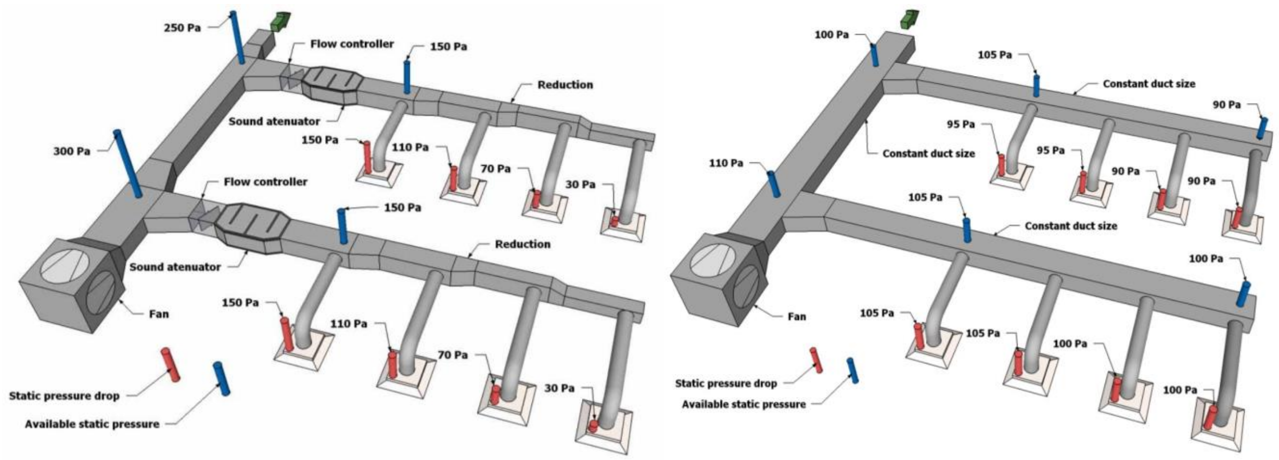

Fig. 1 Ductwork sized with the constant pressure drop method (left) and ductwork sized with the final pressure drop method (right). [3]

2. METHODS

Compliance with the Swedish building code requirements (BBR) [4] was checked for all three buildings based on measured data. Moreover, the performance of the three buildings was assessed for Green Building certification (energy performance at least 25% better than BBR requirements). In doing so, regular carpet plots have been compiled for each building. Building-specific patterns and baseline operational performance have been identified.

The measurements were logged by the building management system (BMS) installed in each building. The BMS collected performance related data for space heating, ground heating, domestic hot water, comfort cooling, process cooling, building auxiliary electricity, occupant electricity, air flow rates. The BMS's components (energy meters and sensors e.g. flow, temperature, air quality) and functions (supervisors trending all signals connected to the BMS e.g. control valves, actuators, relays, setpoints) enabled the monitoring and measuring of key building performance parameters. Measured data were analysed by regularly compiling and visualizing carpet plots. The analysis identified building-specific patterns and baseline operational performance. The utilised visualization software [5] was developed partly during the work of IEA EBC Annex 40 [6]. The carpet plots illustrate values (colour-coded according to a defined scale) of selected parameters in relation to the hour of the day (y-axis) and the day of the year (x-axis).

3. RESULTS

All three office buildings comply with BBR requirements (**Klassföreståndaren** BFS2008:6 BBR15 2008-07-01; **Gångaren 11** BFS2008:20 BBR 16 2009-02-01; **Nereus Bassängkajen** BFS2008:20 BBR 16 2009-02-01**)** and two of them comply with Green Building requirements:

- **Klassföreståndaren *2009-2010* 107** kWh/(m^2·a) BBR requirements (59 space heating, 1 domestic hot water, 18 comfort cooling, 29 building auxiliary electricity) and **82** Green Building requirements; ***2015* 86.3** kWh/(m^2·a) BBR requirements (55.9 space heating, 0.1 domestic hot water, 11.3 comfort cooling, 19 (simulated) building auxiliary electricity) and **82** Green Building requirements;
- **Gångaren 11 *2011* 62.5** kWh/(m^2·a) BBR requirements (34.8 space heating, 2.9 domestic hot water, 10.8 comfort cooling, 14 building auxiliary electricity) and **88.3** Green Building requirements;
- **Nereus Bassängkajen *2011-2012* 77.7** kWh/(m^2·a) BBR requirements (48.6 space heating, 3.2 domestic hot water, 8.7 comfort cooling, 17.2 building auxiliary electricity) and **80** Green Building requirements.

The carpet plots in Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig.7, Fig. 8 and Fig. 9 illustrate measured data for office building **Gångaren 11** during the year 2011. Similar carpet plots have been developed for all three office buildings.

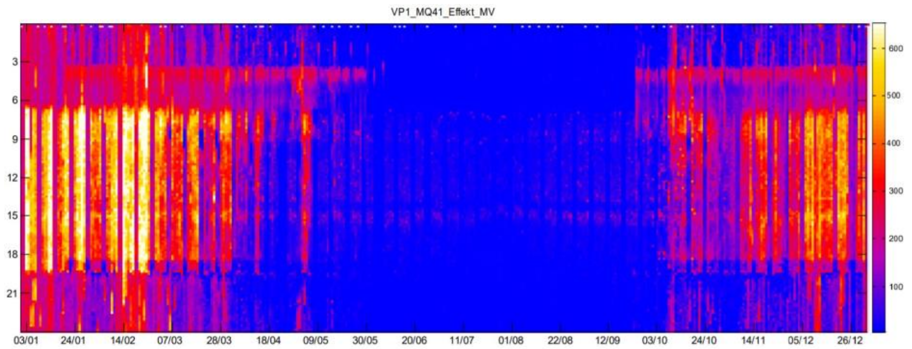

Fig. 2 Carpet plot of purchased district heating power (kW) colour-coded according to the right-hand side scale (blue means a power close to 0 kW and white means a power over 600 kW). The hours of the day according to the left-hand side scale are represented as a function of the days of the year. Domestic hot water energy use is included in district heating energy use. Ground heating energy use is included in district heating energy use, but not in BBR requirements.

Fig. 2 shows that the night setback was implemented in the middle of January and is turned off at 4 a.m. The peak demand for reheating the building after the night setback is lower compared to when AHUs are running, meaning that there will be no penalty on the district heating utility rate due to the night setback. In addition, Fig. 2 shows clear patterns, both weekly and seasonal, which is to be expected. Weekly due to the AHUs scheduled operating hours and seasonal due to the varying transmission losses due to varying outdoor temperature. During summer the measured heating power (in kW) corresponds to the heating power (in kW) for domestic hot water (Fig. 3) which is to be expected. Summer holiday influence on the heating power can be observed in Fig. 3 during July and August. In Fig. 4 periods with outdoor air temperatures higher than -8℃ and lower than +3℃ and the related impact on energy use can be visualized. Besides, the control strategy for ground heating operation could even be verified by cross-checking these data with outdoor air temperature logs.

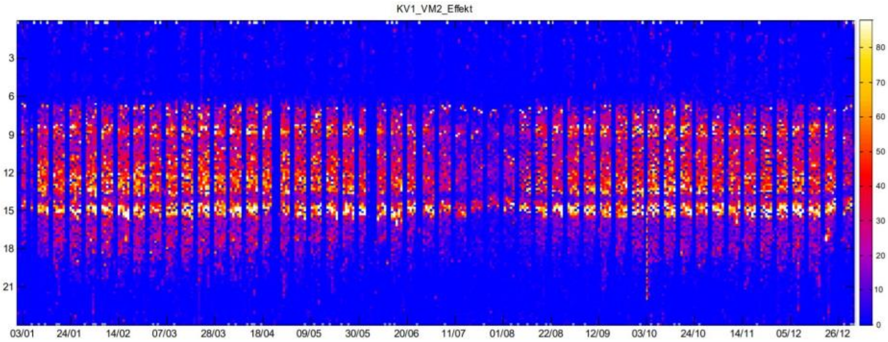

Fig. 3 Carpet plot of heating power (kW), calculated from measured water flow and temperature assuming the incoming cold water is at +10°C, for domestic hot water colour-coded according to the right-hand side scale. The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

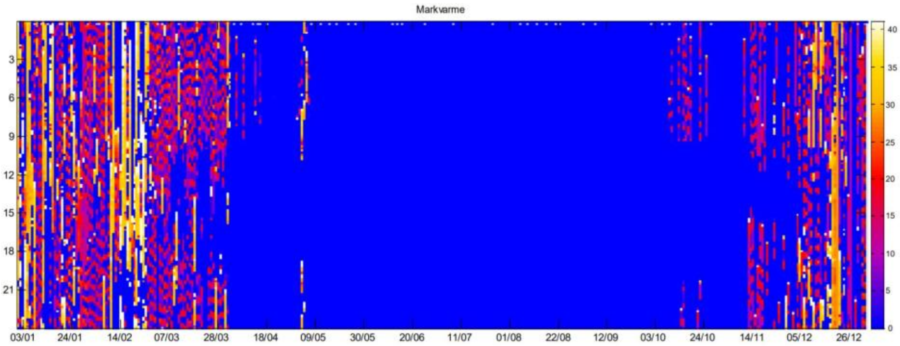

Fig. 4 Carpet plot of ground heating power (kW) colour-coded according to the right-hand side scale. The ground heating system is turned off during blue periods (outdoor air temperature higher than +3℃). The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

District cooling includes the sum of process cooling and comfort cooling. Because of no foreseen individual energy meter, the amount of process cooling is determined by considering purchased district cooling in periods when all comfort cooling is turned off i.e. when the cooling system and cooling coil valves are closed. Fig. 5 shows cooling peaks during the night which is due to occupants manually starting the AHUs outside scheduled operating hours, thus also starting the cooling system. It could be argued whether the cooling system is needed during nights and thus if there is room for improving the control strategy. Similar, during summer mornings there is, for the same reason as above, a cooling peak that may influence the utility rate. This realisation could lead to the proposal of possible improvements such as preventing district cooling during the first hour after AHUs start-up and using only the free cooling system.

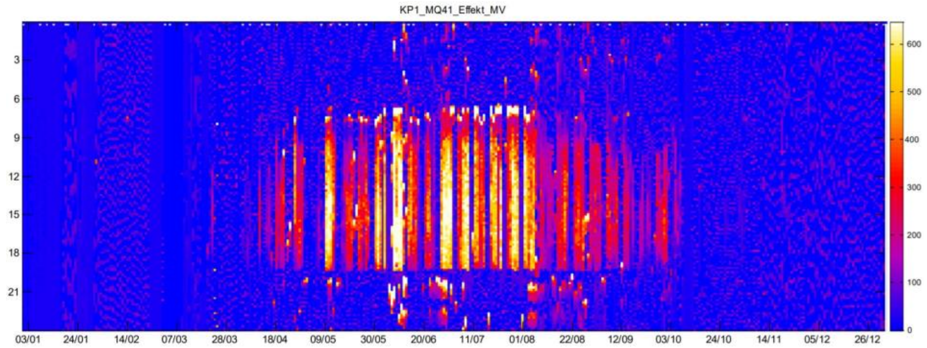

Fig. 5 Carpet plot of the purchased district cooling power (kW) colour-coded according to the right-hand side scale (blue means a power close to 0 kW, white means a power of more than 600 kW). The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

Fig. 6 shows that the process cooling system is oscillating somewhat during some periods. This is not a major problem in and of itself but can cause some extra wear on the equipment.

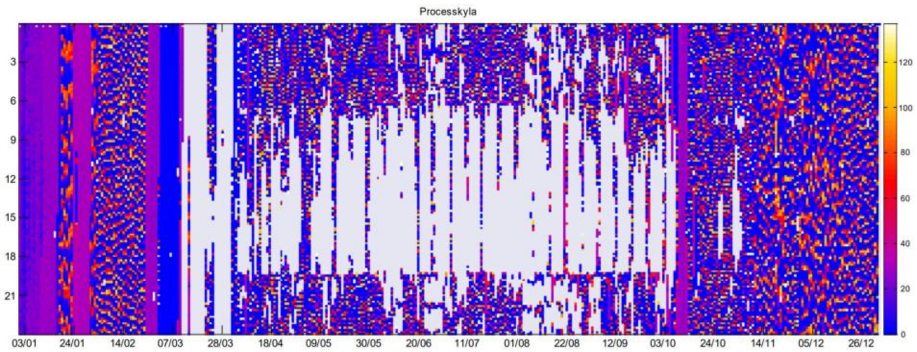

Fig. 6 Carpet plot of the process cooling power (kW) colour-coded according to the right-hand side scale. Comfort cooling, faulty and missing measurements are coloured grey. The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

When visualizing the carpet plot in Fig. 7 a clear correlation can be made to the working hours and inherently the scheduled and extra hours operation of fans and pumps belonging to building services. Note that elevator energy use is not included in the plotted values.

It can be seen in Fig. 8 that in the morning and evening, some air handling units are running outside “scheduled operating hours” because occupants activated the "extended operation" by pressing any of the buttons located on each office floor. On top, Fig. 8 shows lower air flow rate during February corresponding to a deliberate control feature i.e. lowering the air flow rate during low outdoor temperature. Lastly, Fig. 8 displays that the AHUs are running during October nights which is not expected. This was supposedly due to some “forgotten” night cooling feature that remained active from summertime.

Based on carpet plots like in Fig. 8 and Fig. 9, deviations in the values of air flow rate and indoor air temperature can be evaluated. This would enable an analysis of actual indoor environment quality throughout the operational phase.

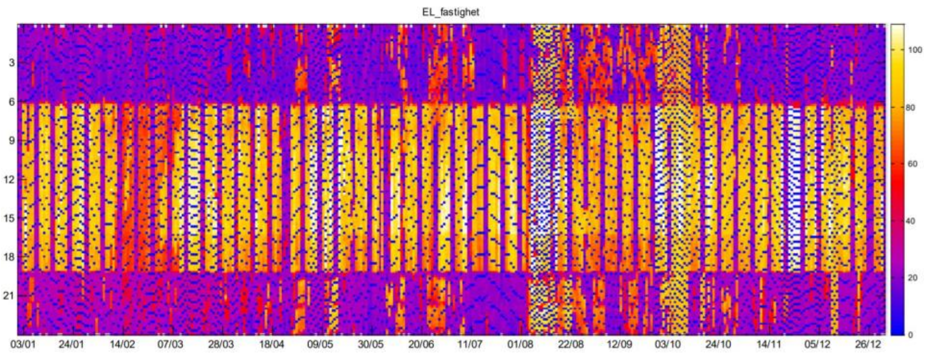

Fig. 7 Carpet plot of building auxiliary electricity power (kW) colour-coded according to the right-hand side scale. The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

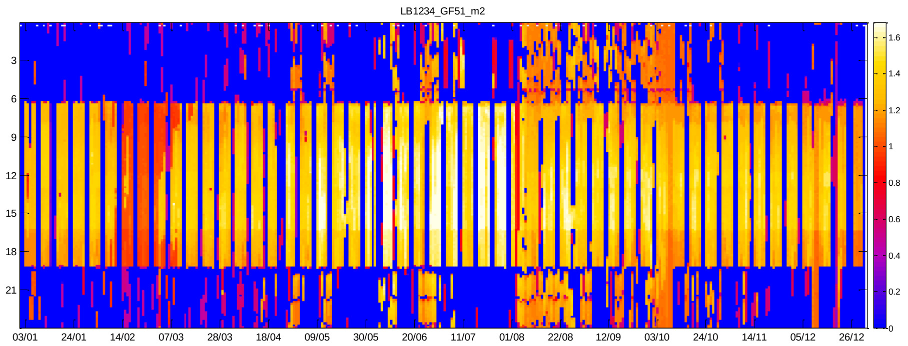

Fig. 8 Carpet plot of supply air flow l/(s·m^2) for all AHUs. The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

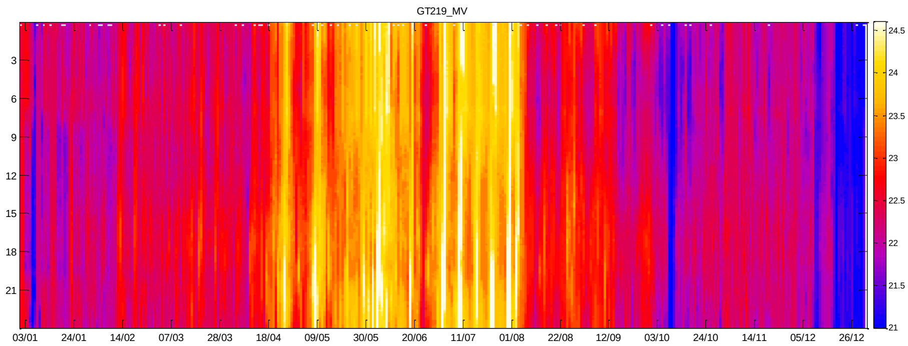

Fig. 9 Carpet plot of landscape office indoor air temperature at the top floor. The hours of the day according to the left-hand side scale are shown as a function of the days of the year.

4. DISCUSSION

In general, the building-specific patterns resembled for all three office buildings. Outdoor climate conditions and occupant behaviour had similar impact on energy use and indoor environment quality (e.g. changes in outdoor air temperature, space occupancy before or after working hours). Operational faults and building

functions (e.g. restaurant) though have a more stochastic impact on energy use and indoor environment quality.
Visualizing key building performance parameters for periods of 12 months enables identification of building-specific patterns and baseline operational performance (average working week rhythm). This establishes a situation of knowing what to expect, thus facilitating easy verification of changes in control strategies and spotting of major deviations, due to e.g. climate conditions, occupant behaviour, operational faults, in terms of both energy use and indoor environment quality.

Being able to verify intended operation conditions and spot major deviations opens the possibility of utilising carpet plots for continuous building performance optimisation and ongoing commissioning, as well as fault detection and prevention.

It should be acknowledged that at times even the BMS's components (e.g. energy meters, sensors) fail in operation (e.g. faulty measurements, lost data for certain periods). In some cases the measuring equipment has low resolution which might be misleading when visualized in carpet plots e.g. data visualized in Fig. 6 and Fig. 7 seems to be oscillating (blue dots) when in reality there were no 0 kW values. These facts stress the importance of selecting adequate and reliable measuring equipment and of regularly checking the equipment's status for preventing long periods with faulty or missing data.

5. CONCLUSIONS

By analysing measured data through graphical visualization of key building performance parameters, building-specific patterns and baseline operational performance could be identified. Carpet plots were found to have convincing potential for performance visualization and could be further utilized in building performance management practices e.g. continuous building performance optimisation, ongoing commissioning, fault detection and prevention.

The results of this study highlight the usefulness of using carpet plots for building performance analysis. While the work presented in this paper focused on analysing measured data through performance visualization, further research will address issues related to continuous building performance optimisation and ongoing commissioning, as well as fault detection and prevention.

6. ACKNOWLEDGEMENTS

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