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Using long-term measurements of airflow, electrical power, indoor temperature and CO_2 concentration for evaluating sizing and performance of an all-air HVAC system in an office building – a case study

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Monitoring performance of heating, ventilation and air-conditioning (HVAC) during building operation enables to evaluate the appropriateness of the system's design. Such insights can help to reduce energy consumption while ensuring satisfying indoor conditions in the monitored building. Additionally, such insight can help to improve future HVAC design. The aim of this paper is to present a case study demonstrating how HVAC engineers can evaluate whether the monitored air-handling units (AHUs) were appropriately sized and performed as intended based on design requirements regarding energy-efficiency, thermal conditions and indoor air quality (IAQ). Three months of measurements of airflow, electrical power, indoor temperature and CO_2-concentrations were collected from an office building with six AHUs. The results showed that three of the AHUs were appropriately sized and satisfied the thermal condition, IAQ and energy-efficiency requirements. The remaining three AHUs were apparently appropriately sized and satisfied IAQ requirements, but they did not satisfy the required energy-efficiency and thermal conditions. The applied approach seemed to be suitable for supporting building operating managers for on-going performance monitoring as it was able to identify discrepancies from intended performance. But it remains the task for the operating personnel to identify the cause of the identified discrepancies.

Keywords: Energy Efficiency, Indoor Air Quality, Heating, ventilation and air conditioning, Thermal Comfort

Introduction

The main task of a heating, ventilation and air-conditioning (HVAC) system is to provide satisfying thermal conditions and indoor air quality (IAQ) in a building. HVAC accounts for almost 10-20% of the total energy consumption in developed countries (Pérez-Lombard *et al.* 2008). Consequently, there is a significant push for more energy-efficient HVAC systems. The European Ecodesign directive (Ivanovich and Jones 2014) is a prescriptive energy regulation that pushes for more energy-efficient HVAC components on the European market. National building codes are tightening overall building energy requirements (Heiselberg 2006) that result in to tighter energy-efficiency requirements for HVAC systems (Pérez-Lombard *et al.* 2011). The overall push for energy-efficient HVAC systems and the increasing attention for better indoor environmental quality (IEQ) place high demands on HVAC engineers' ability to provide an optimized HVAC design. Furthermore, it is a challenge for HVAC engineers to provide an optimized design within limited project time, resources and sparse available information on occupancy loads or peak-load conditions (Jacobs and Henderson 2002, Thomas and Moller 2006, Huang *et al.* 2017). By trying to meet the high demands within the imposed limitations, engineers design HVAC systems by making assumptions based on "rules of thumb" or prescriptive design guidelines that do not necessarily reflect what happens in practice (Bordass *et al.* 2004). Consequently, these assumptions can lead to sub-optimized design solutions that result in a gap between expected and actual performance (Bordass *et al.* 2004, Menezes *et al.* 2012, Zou *et al.* 2018).

To reduce the performance gap, the primary step is to monitor the HVAC during operation as to quantify the gap and to identify the underlying cause of the gap (van Dronkelaar *et al.* 2016). However, to improve the future design the obtained information needs to come back to the HVAC engineer (Bordass *et al.* 2004, Arens and Brown 2012, van Dronkelaar *et al.* 2016). Feedback between the operational stage and the design stage can be provided by measuring and analyzing data on HVAC operational performance. With the emergence of affordable sensor technologies and data analytic platforms, collecting and analyzing measurements have become more convenient (Capehart and Brambley 2014, Geng *et al.* 2019). For example, research studies within performance monitoring such as (Menezes *et al.* 2012, Göçer *et al.* 2015, Oti *et al.* 2016) demonstrated how data collected through post-occupancy evaluations and audits or via the building automation system (BAS) could be used in prediction models to determine the performance gap or integrated with the building model to close the information gap between the operational stage and the design stage. Even though the studies successfully demonstrated how to feed-forward information from the design stage to the operational stage, they did not demonstrate how information from the operational stage could be used to inform the design stage.

The aim of this paper is to present a case study demonstrating how HVAC engineers can obtain feedback from the actual performance of a system they have designed. The case study had the objective to demonstrate the collection, analysis and presentation of operational parameters of six air-handling units (AHU) in a Danish office building with an all-air HVAC system. The goal was to use measurements of airflow, electrical power, indoor temperature and CO_2-concentration from conditioned occupied spaces to evaluate: (1) Whether the studied AHUs were sized appropriately and (2) how they performed compared to design requirements.

Methods

Sizing of ventilation systems in Danish context

The typical procedure for sizing large mechanical ventilation systems can be divided into three steps: In the first step, the airflow necessary to meet thermal and IAQ requirements is determined by using building simulation models. The input variables and design requirements used in the model are usually defined in the design brief, industry guidelines such as Vorre et al. (2017) or the European Standard EN 16798-1 (2019). The airflow is determined for selected representative and critical zones and summed over the total number of zones in the building. The summed airflow is used as the design airflow that fulfils the thermal and IAQ requirements during concurrent full-load conditions. Depending on the complexity of the building design and the HVAC engineer's experience, the design value is sometimes multiplied either by a safety factor of 1.10-1.25 (Jacobs and Henderson 2002, Gorter 2012) or a diversity factor of 0.70-0.80. Multiplying with a safety factor is argued to account for changes during late design stages, contracting or operation (Nall 2015), while multiplying by a diversity factor is argued to account for the fact that full-load conditions are rare and short events.

In the second step, the pressure drop in the ventilation system is determined by sizing the duct system according to prescribed design air velocity of 4-8 m/s (Olufsen 1995) to avoid noise and high energy consumption. Furthermore, the design, control and operating conditions (e.g. operational hours, morning warm-up) of the ventilation system are modified so that the ventilation system meets the energy-efficiency requirements that are set by the Danish Building Regulation (BR18) (Ministry of Transport Building and Housing 2018). The requirements in BR18 are divided into two requirements: a prescriptive requirement and a performance requirement. The prescriptive requirement states that the maximum specific fan power (SFP_{max}) must not be more than 2100 W/(m^3/s) at maximum pressure (full-load) yield in variable-air-volume (VAV) systems. The performance requirement states that the building should not use more than the overall building energy requirement. To comply with this requirement, the yearly average SFP ($SFP_{average}$) for the VAV system, which is an average of various operating conditions in the building, is typically assumed to be 20-75% below the allowed SFP_{max}.

In the third step, the AHU is typically sized by using manufacturers' product selection software tools (Jacobs and Henderson 2002). The design airflow (from step one) and the pressure drop in the ducts (from step two) are used as input values in the software tool, and the AHU is sized so that it ensures compliance with SFP_{max} and $SFP_{average}$. The output of the selection software tool is documented in a manufacturer's datasheet, which displays the yielded SFP (denoted design SFP) for the specific AHU size during design airflow.

Oversizing of AHUs

A mechanical ventilation system is considered oversized if it has more installed airflow capacity than required by the actual predominant operating condition. Some of the mentioned design practices specifically related to the assumption of concurrent full-load conditions, addition of safety factors to the design airflow and the assumption that $SFP_{average}$ can be 20-75% of SFP_{max} can lead to large ducts and large AHUs (Thomas and Moller 2006, Gorter 2012). As large AHUs can risk never being fully utilized during operation, they can be considered oversized. Oversizing can lead to inefficient energy use and poor control of indoor conditions in buildings (Thomas and Moller 2007). Various studies such as (EPA 1995, Crozier 2000, Thomas and Moller 2006, Gorter 2012) state that oversizing of AHU is a prevalent problem in buildings: Crozier (2000) compared the measured airflow of eighteen constant-air-volume (CAV) systems in UK and found that 88% of the ventilation systems were oversized. EPA (1995) identified that more than half of the 26 investigated buildings in USA had an oversized ventilation system which only required an actual airflow that was at least 10% below the design airflow during full-load conditions. The various studies discuss that poor design practices, such as the use of conservative “rules of thumb” and the lack of proper load estimations, are the cause of oversized systems. Consequently, oversizing of AHU can be reduced by challenging “rules of thumb” (Thomas and Moller 2007) and by proper load estimations (Gorter 2012) using guidelines (e.g. (Burdick 2012)), software tools or uncertainty analysis (e.g. (Sun *et al.* 2014)). One way to reduce oversizing in existing AHU is to select a smaller fan-motor configuration that can operate closer to the maximum efficiency for the most common predominant airflow rates (Schild and Mysen 2009). Another way is to use a variable speed drive (VSD) to vary the rotation speed of a fan according to the actual required airflow and actual pressure in the ventilation system. Even though, moderately oversized AHUs with VSDs are not problematic in terms of fan-efficiency, grossly oversized AHUs with VSDs can risk operating with very low fan-efficiency and higher energy use during part-load conditions (Hydeman *et al.* 2003). This can happen because the grossly oversized fan in the AHU operates with very low fan-speeds that generate higher noise levels and greater wear on the fan and its components (Schild and Mysen 2009). A general problem with oversized ventilation systems is that they can be more costly to install and maintain, and the space allocated for the technical rooms and shafts need to be larger. Cost calculations by Thomas and Moller (2007) shows that savings on the installation cost of 4.9-24% can be achieved by rightsizing AHUs.

The previous studies mostly focus on oversizing of AHUs as it is a more prevalent issue than undersizing. However, undersized AHU can also be problematic because it can operate at full capacity without being able to provide the required thermal conditions and IAQ (Thomas and Moller 2006).

Evaluation of sizing and performance of AHU

In the present case study, airflow and electrical power were selected for performance and sizing evaluation because they made up the design indices (design airflow and SFP_{design}) that were used in the AHU sizing procedure, described in the previous sections. The indoor temperature and CO_2-concentration were selected as they are the typical parameters used for evaluating the thermal conditions and IAQ in occupied zones (Wei *et al.* 2020).

Furthermore, following considerations were made regarding the data collection, analysis and presentation of measurements as they had an impact on end-results: Measurement validity (Was the measurement accurate and representative for the evaluation?), operational hours (Which operating hours were representative for the evaluation?) and thresholds (Which criteria should be used to evaluate the sizing and performance of the studied AHU?). The implications of these considerations on the results are discussed later in this paper.

To investigate the size and performance of the studied AHUs in the case study, the term "sizing level" was used to indicate whether the studied AHUs were "oversized", "rightsized" or "undersized". This was done by comparing the actual airflow to the design airflow. The term "performance level" was used to evaluate whether the energy-efficiency, thermal performance and IAQ performance of the studied AHUs were "poor", "acceptable" or "very good". Energy-efficiency was evaluated by using actual measurements of airflow and electrical power from the studied AHUs to determine the SFP. The measured indoor temperature and CO_2-concentration from occupied zones that were served by a particular AHU were used to evaluate the thermal conditions and IAQ. The sizing and performance of a studied AHU were considered appropriate if its sizing level was determined as “rightsized” and its performance level was determined as “acceptable” or “very good”.

Data processing and cleaning

The measurement data from the case study was processed and cleaned as to minimize the bias from measurement inaccuracy, faulty sensor readings and measurements outside of operational hours. All measurements were filtrated to only contain values logged during operational hours. The operational hours were based on the design brief and the actual HVAC system schedules. It was necessary to process and clean measurements of airflow, indoor temperature and CO_2-concentration, but nothing was observed in electrical power measurements to justify further processing of these measurements.

In the present study, the airflow measurement displayed in the BAS was not zero when the fan was turned off even though it should have been. This was likely due to air leakage from the inlet/outlet dampers. Therefore, the offset in the airflow measurement data was corrected assuming a linear relation between the supplied volumetric airflow q_v [m^3/s] and the operation of the inlet fan F [%] (Lawrence Berkeley National Laboratory and Resource Dynamics Corporation 2003) with a slope α and an intercept β as described by Equation 1:

$$q_v = \beta + \alpha \times F \quad (1)$$

The intercept should be equal to 0 m^3/s, when the fan was turned off (F = 0%), if this was not the case the intercept was subtracted from the volumetric airflow.

Temperature and CO_2 sensors that showed constant, zero or negative readings were removed from the dataset. Furthermore, a filtration method inspired by Zhou et al. (2011) was developed and applied to remove faulty temperature and CO_2 sensor readings as well as poorly calibrated sensors with biased readings. The filtration method consisted of "temporal filtration" and "spatial filtration".

"Temporal filtration" was based on statistical methods for outlier detection: Outliers ($\theta_{Outlier}$) were defined as rare sensor values that occurred in a short time span because of signal-noise related to e.g. sensor or BAS issues. In "temporal filtration" the lower (θ_{25}) and upper (θ_{75}) quartile values were derived for each sensor over the entire time span and were applied in Equation 2 to get the inter-quartile range (IQR).

$$IQR = (\theta_{75} - \theta_{25}) \tag{2}$$

The IQR was used in Equation 3 to identify outliers (Aggarwal 2013), which were filtrated from the dataset.

$$\theta_{Outlier} = \begin{cases} \theta < \theta_{25} - 1.5 \times IQR \\ \theta > \theta_{75} + 1.5 \times IQR \end{cases} \tag{3}$$

Where θ is a sensor value in a given timestep. "Temporal filtration" was only applied to temperature measurements. Equation 3 was not suitable for measurements of CO_2-concentration as it removed all peaks from the measurements. This is because CO_2-concentrations can strongly fluctuate over a short time span.

"Spatial filtration" was used to identify poorly calibrated sensors by assuming that two or more sensors should not have significantly deviating values when they were located in zones with similar conditions either on the same floor or on different floors facing the same orientation. If one of these sensors had values significantly different from the other sensors', it was removed from the dataset. The deviation was investigated by calculating the minimum, median and the maximum of each sensor and by grouping and visualizing the three indices for each sensor according to the location and orientation of the zones. If a visual inspection showed that the median of a sensor was close to the minimum or the maximum of other sensors, which were located in a zone on the same floor or different floor facing the same orientation, the deviation was assessed to be significant and the sensor was removed from the dataset.

Performance metrics

The processed dataset was used for calculating the performance metrics. The SFP was calculated from Equation 4 (Schild and Mysen 2009):

$$SFP = \frac{P}{q_v} \tag{4}$$

where q_v is the volumetric airflow [m^3/s], P is the total electrical power [W] including the power needed by the supply and return fan and SFP is the specific fan power [W/(m^3/s)]. The SFP for multiple AHUs can be calculated with Equation 4 using the summed airflow and the summed electrical power for the studied AHUs. The measured SFP (SFP_{actual}) can be calculated with Equation 4 using the measured power (P_{actual}) and the measured airflow (q_{actual}), whereas the design SFP (SFP_{design}) can be calculated using the design power (P_{design}) and the design airflow (q_{design}). q_{actual} and SFP_{actual} were normalized respectively with q_{design} and SFP_{design} using Equation 5 and 6:

$$q_n = \frac{q_{actual}}{q_{design}} \times 100 \tag{5}$$

$$SFP_n = \frac{SFP_{actual}}{SFP_{design}} \times 100 \tag{6}$$

where q_n is the normalized airflow [%] and SFP_n is the normalized SFP [%].

Data analysis and presentation

The normalized airflow, indoor temperature and CO_2-concentration were presented as cumulative distributions. The cumulative distribution of the normalized airflow was divided into two regions that were denoted as “starting-up” and “operation”. “Starting-up” depicted the percentage of time the studied AHUs were turned off (q_{actual} = 0 m^3/s) and it occurred because the determined operational hours could vary between the days of the week. Therefore, the cumulative distribution of the normalized airflow covered regions outside of the actual operational hours. This region was therefore not included in the evaluation of the sizing level. The sizing level was only evaluated for “operation” which included the operational hours the provided airflow was more than 0 m^3/s.

Each temperature sensor and CO_2 sensor were visualized as a cumulative distribution. Each sensor represented the thermal condition or the IAQ of an occupied zone. The cumulative distributions were grouped according to the studied AHU that served the particular zones. As to enhance the readability of the visualized cumulative distributions, the 0.05 (θ_5), 0.25 (θ_{25}), 0.75 (θ_{75}), 0.95 (θ_{95}) quantile values and median (θ_{50}) were calculated for the grouped cumulative distributions. Therefore, the quantiles represented the percentile of occupied zones (e.g. θ_{75} represented 75% of the occupied zones) that for a percentage of time had an indoor temperature or CO_2-concentration below or equal to a specific value.

A scatterplot was used to visualize the trend and relationship between the normalized airflow and the normalized SFP. The observed relation was compared visually to a regression model that is described in Equation 7 (Schild and Mysen 2009):

$$SFP_{fit} = a + b \times q_n + c \times q_n^2 + d \times q_n^3 \quad 20\% < qn < 100\% \qquad (7)$$

Where SFP_{fit} [%] is the estimated normalized SFP for an AHU operating as “normal”, “good” or “ideal” and the corresponding coefficients (*a*, *b*, *c* and *d*) listed in Table 1. The observed SFP_n was compared to SFP_{fit} as to evaluate the energy-efficiency of the studied AHUs.

Table 1. The coefficients in (7) from (Schild and Mysen 2009).

Operating conditions	a	b	c	d
Normal	1.06	-2.56	3.63	-1.13
Good	0.58	-1.50	2.66	-0.73

Ideal	0.29	-0.88	2.00	-0.40

Systems with highly efficient VSDs and static pressure reset (dynamically controlled pressure setpoint) are characterized as "ideal", whereas ventilation systems with fan-speeds that are controlled to maintain a constant static pressure are characterized as "normal" (Schild and Mysen 2009). Systems due to e.g. poor fan-efficiency, inefficient VSDs or no pressure control are characterized as worse than "normal" (Schild and Mysen 2009).

Performance and sizing evaluation

Tables 2 and 3 were used to evaluate the cumulative distribution and scatter plot as to derive the sizing level and the performance level of the studied AHUs.

Table 2. Classification of sizing level.

Sizing level & metric	Oversized	Rightsized	Undersized
Normalized airflow. Equation (5)	Operation: $q_{n,low} \leq q_n \leq 100\%$ in $\tau \leq 50\%$.	Operation: $q_{n,low} \leq q_n \leq 100\%$ in $\tau \geq 50\%$.	Operation: $q_n > 100\%$ in $\tau \geq 50\%$.

Table 3. Classification of performance level.

Performance level & metric	Poor	Acceptable	Very good
Energy-efficiency: Normalized SFP. Equation (6) and (7)	Worse than "Normal" $SFP_n > 100\%$ for $q_n \leq 100\%$.	"Normal", "Good" or Ideal" $SFP_{n,low,max} \leq SFP_n \leq 100\%$ for $q_n \leq 100\%$.	"Good" or "Ideal" $SFP_n < SFP_{n,low,max}$ for $q_n \leq 100\%$.
Thermal: Indoor temperature (T)	< 95% of occ.[a] zones: $T_{low} \leq T \leq T_{up}$ in $\tau \geq \tau_{comfort}$ and $T > T_{max,up}$ or $T < T_{min,low}$ in $\Delta\tau \leq \Delta\tau_{exceed}$	95% of occ.[a] zones: $T_{low} \leq T \leq T_{up}$ in $\tau \geq \tau_{comfort}$ and $T > T_{max,up}$ or $T < T_{min,low}$ in $\Delta\tau \leq \Delta\tau_{exceed}$	>95% of occ.[a] zones: $T_{low} \leq T \leq T_{up}$ in $\tau \geq \tau_{comfort}$ and $T > T_{max,up}$ or $T < T_{min,low}$ in $\Delta\tau \leq \Delta\tau_{exceed}$

IAQ: Indoor CO_2-concentration (CO_2)	< 95% of occ.[a] zones: $CO_2 \leq CO_{2,up}$ in $\tau \geq \tau_{comfort}$ and $CO_2 > CO_{2,max}$ in $\Delta\tau \leq \Delta\tau_{exceed}$	95% of occ.[a] zones: $CO_2 \leq CO_{2,up}$ in $\tau \geq \tau_{comfort}$ and $CO_2 > CO_{2,max}$ in $\Delta\tau \leq \Delta\tau_{exceed}$	>95% of occ.[a] zones: $CO_2 \leq CO_{2,up}$ in $\tau \geq \tau_{comfort}$ and $CO_2 > CO_{2,max}$ in $\Delta\tau \leq \Delta\tau_{exceed}$

[a]Occupied shorten to occ.

Table 2 shows the defined scheme using normalized airflow and percentage of time (τ) for identifying the sizing level of the studied AHUs. "Operation" in Table 2 refers to the region depicted in the cumulative distribution. $q_{n,low}$ [%], $SFP_{n,low,max}$ [%], T_{low} [°C], T_{up} [°C], $T_{max,up}$ [°C], $T_{min,low}$ [°C], $CO_{2,up}$ [ppm], $CO_{2,max}$ [ppm], $\tau_{comfort}$ [%] and $\Delta\tau_{exceed}$ [%] in tables 2 and 3 are the design specific requirements based on design guidelines and client requirements used for sizing the studied AHUs.

A rightsized AHU was defined to have a normalized airflow between $q_{n,low}$ and 100% in more than 50% of the time. $q_{n,low}$ could represent e.g. the minimum required airflow to satisfy thermal and IAQ requirements.

The performance level of the studied AHU was derived for each performance metric: The performance level of "energy-efficiency" was derived by visual analysis of the scatter plot and by comparing the difference between actual SFP and design SFP for q_n equal to or less than 100%. $SFP_{n,low,max}$ is defined as the boundary to distinguish an "acceptable" energy-efficient AHU from a "very good" energy-efficient AHU.

The performance metric "thermal" was evaluated by comparing the measured temperature (T) with the lower (T_{low}) and upper (T_{up}) design temperature thresholds. The performance metric "IAQ" was evaluated by comparing the measured CO_2 with the upper design threshold ($CO_{2,\,up}$). According to EN 16798-2 (2019) a certain deviation of indoor environmental requirements is acceptable as to avoid oversizing. Thus, it was defined that 95% of the occupied zones should have indoor temperatures within T_{low} and

T_{up} in $\tau_{comfort}$ percentage of time or CO_2-concentrations less than $CO_{2,\,up}$ in $\tau_{comfort}$ percentage of time. The maximum indoor temperature ($T_{max,up}$), the minimum indoor temperature ($T_{min,low}$) or the maximum CO_2-concentration ($CO_{2,\,max}$) can be exceeded less than $\Delta\tau_{exceed}$ percentage of time.

Description of the studied office building

Figure 1 shows the floor plan of the studied building which was a 16,400 m² nine story multi-tenant office building designed with three wings facing north (N), southeast (SE) and southwest (SW). The building was located near Copenhagen, Denmark.

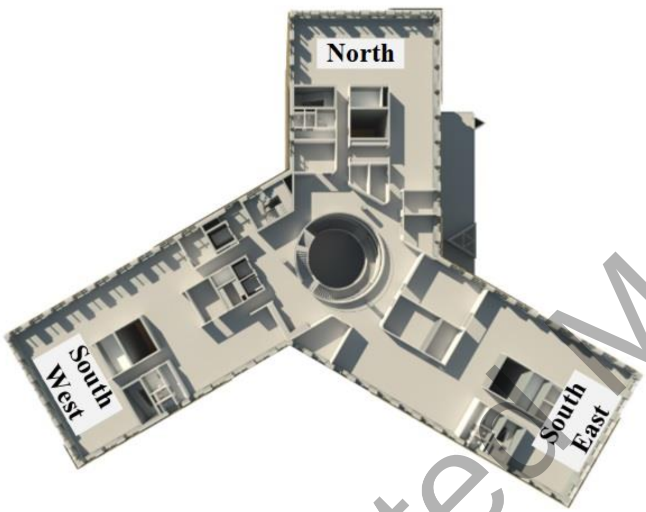

Figure 1. Floor plan of the case building and orientation of the building wings.

The building was constructed in 2014 and certified as a Platinum DGNB (DGNB 2020) office building. Six mechanical ventilation systems provided heating, cooling and ventilation to office zones on all floors. Table 4 lists the design airflow, the design SFP and the associated zones of each AHU. The design airflow was determined by simulation models of selected representative and critical zones: The ventilation rate was determined to 4 h^{-1} in office zones and 8 h^{-1} in meeting zones. This meant that $q_{n,low}$ from Table 2 was set to 50%, which is the ratio between the minimum and the maximum required airflow during operation. The threshold between "acceptable" and “very good” energy-efficiency was chosen to be 90% ($SFP_{n,low,max}$ from Table 3).

Table 4. Name, zone, floor and design values of AHUs in the case building.

AHU	Zone and floor	Design airflow[a] [m^3/s]	Design SFP[a] [W/(m^3/s)]	Switch board	Design values Switch board
VE01	SW, floor: 0.-3.	6.67	1545	TA01	Total airflow: 18.90 m^3/s Average SFP[b]: 1508 W/(m^3/s)
VE02	SW, floor: 4.-8.	6.67	1545		
VE03	SE, floor: 0.-3.	5.56	1419		
VE04	SE, floor: 4.-8.	7.78	1559	TA02	Total airflow: 16.95 m^3/s Average SFP[b]: 1523 W/(m^3/s)
VE05	N, floor: 0.-3.	4.17	1418		
VE06	N, floor: 4.-8.	5.00	1553		

[a]Design airflow and design SFP for full-load condition from manufacturer’s datasheet.

[b]Derived from Equation (4). Electrical power of an AHU was calculated by multiplying SFP with airflow.

The ventilation operated as VAV with fan-speed controlled to maintain a constant static pressure. Air was distributed to the zones via evenly distributed ceiling-mounted diffusers. Re-heaters were installed on each floor and each wing to heat the airflow, when inlet temperatures dropped below zone temperature setpoints. The AHUs were equipped with rotary heat exchangers, cooling coils and fans with VSDs. The ventilation system was designed to keep the absolute CO_2-concentration below 900 ppm ($CO_{2,\ up}$) and the temperature between 20 °C (T_{low}) to 26 °C (T_{up}) in 95% ($\tau_{comfort}$) of the time (i.e. 5% exceedance). Exceedance of temperatures below 18 °C ($T_{min,low}$) or above 27 °C ($T_{max,up}$) or exceedance of absolute CO_2-concentration above 2000 ppm ($CO_{2,\ max}$) were allowed in 1% ($\Delta\tau_{exceed}$) of the time according to the design brief. $CO_{2,\ max}$ and $T_{min,low}$ were set according to the Danish Working Environment Authority (2019).

The predominant operational hours of the AHUs and typical working hours were from 06.00-16.00 Monday to Friday, which was also in accordance with the operational hours defined in the design brief. Data on return airflow rates for all six AHUs as well as indoor temperature and CO_2-concentrations for all three wings from 4th to 8th floor were extracted from the building’s BAS (Sensors on the 7th floor SW-wing were removed as the zones were unoccupied). Measurements of floor 0 to 3 were not available. The airflow for the AHUs extracted from the BAS was calculated from the pressure rise over the fan multiplied by a fan-constant that was determined by the manufacturer (Schild and Mysen 2009). The indoor temperature and CO_2 sensors had an accuracy of ± 0.5 °C and ± 40 ppm, respectively, according to manufacturer' datasheet. The sensors were integrated in thermostats mounted in the occupied zones. No long-term measurements of electrical power were available for the AHUs through the BAS. Thus, electrical power was measured using clamped type power meters (Smappee Energy and Smappee Pro (Smappee 2019)) installed between the power supply and two switch boards (TA01 and TA02 in Table 4) supplying the mechanical ventilation systems. Placing the meter as specified ensured that the measurements included the electrical power needed for fan operation and other components such as dampers, controllers/electronics and rotary heat exchangers. The manufacturer of the power meters informed that the accuracy was less than 1%. The switch boards provided electrical power to all the components of the investigated mechanical ventilation systems as well as the exhaust system servicing toilets and copy rooms. The electrical consumption from the exhaust system were assumed to be negligible compared to the consumption of the investigated mechanical ventilation systems. The measurements were logged every 5 min. during the period from August to October 2019. The collected measurements from the studied building were prepared and presented as described in the previous sections. As high computation time of more than three minutes was experienced during the data processing and analysis of the dataset, the size of the dataset was reduced by averaging each measurement for every 15 min. The final dataset had a timestep of 15 min. and did not significantly deviate from the dataset with 5 min. timestep.

Results

Sizing level – Normalized airflow

The cumulative distribution of the normalized airflow (q_n) during operational hours from August to October 2019 is shown in Figure 2.

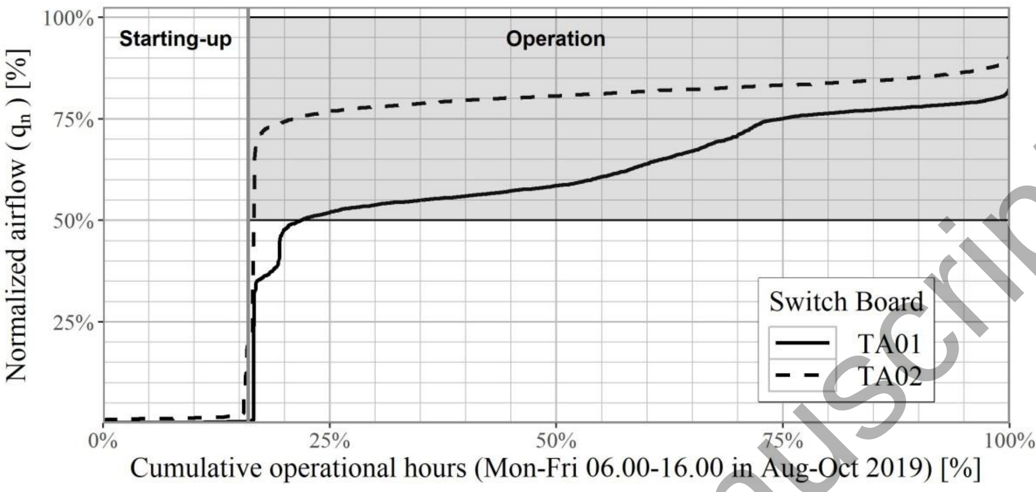

Figure 2. Cumulative distribution of q_n for TA01 and TA02.

The six AHUs were lumped into two datasets TA01 (VE01-03) and TA02 (VE04-06) according to Table 4. Figure 2 shows that both distributions of the normalized airflow for TA01 and TA02 were close to 0% for less than 16% of the time. This region is denoted as "starting-up", which is a result of the selected operational hours as not all AHUs started and stopped at the same time. The distribution of the normalized airflow for TA01 and TA02 increased to minimum 50% for more than 16% of the time. This region is denoted as "operation" and the sizing level was only evaluated for this region. The grey area marks the lower ($q_{n,low}$ = 50%) and upper boundaries (100%) of the normalized airflow according to Table 2. The normalized airflow was within 50-100% in 93% and 100% of the time during operation for respectively TA01 and TA02. According to the definition in Table 2, AHUs in both TA01 and TA02 can be considered as rightsized.

Performance level

Energy-efficiency – Normalized SFP

Figure 3 shows the relation between the normalized SFP (SFP_n) and the normalized airflow (q_n) for TA01 and TA02 for the period August to October 2019.

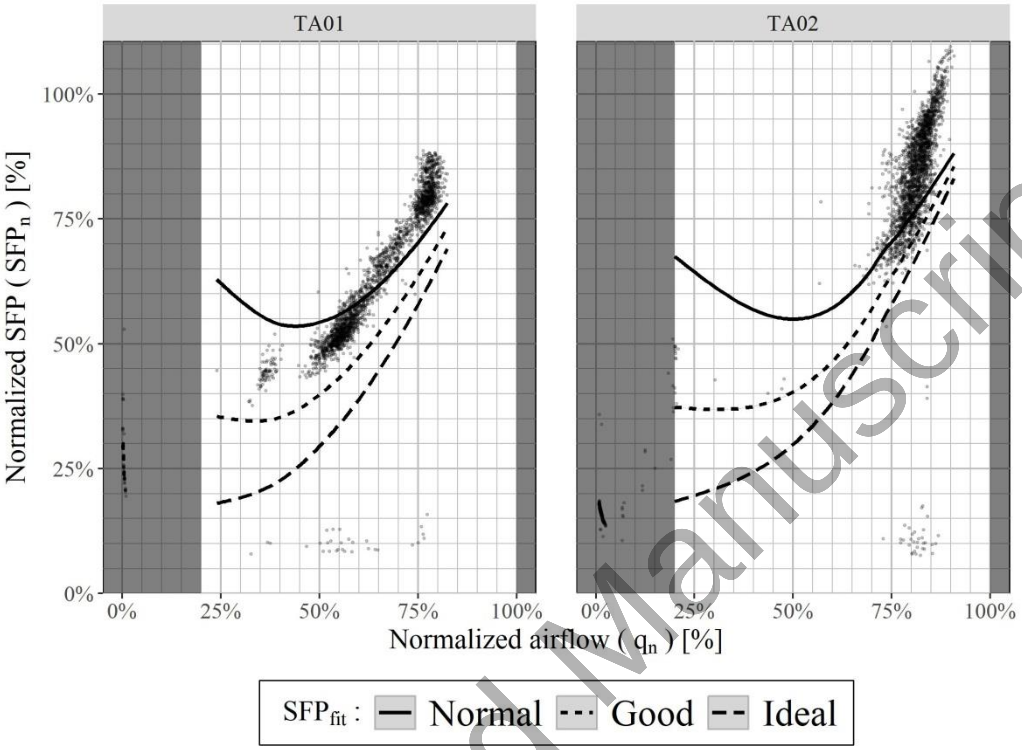

Figure 3. Scatter plot of SFP_n and q_n for Aug.-Oct. 2019. The dark region marks the values outside the boundary condition of Equation (7).

Figure 3 shows the SFP_{fit} plotted for the three operating conditions from Table 1 denoted as “normal”, “good” and “ideal”. Figure 3 shows that the normalized airflows of TA01 and TA02 were between 24-82% and 20-91%, respectively, during operational hours, and the normalized SFPs for TA01 and TA02 were between 40-88% and 60-110%, respectively, during operational hours. The datapoints for normalized SFP below 25% were considered as faulty values and therefore not included in the evaluation of the energy-efficiency of TA01 and TA02.

The maximum SFP_n for TA01 was less than 79% for q_n less than 88%. The observed relation for TA01 had a closer fit to "normal" for q_n between 55-88%, which is coincident with the region depicted as "operation" in Figure 2, and closer fit to "good" for q_n between 24-55%, which is the region depicted as "starting-up" in Figure 2. As the "operating" region of TA01 had a closer fit with "normal", TA01 was classified as "acceptable" according to "energy-efficiency" defined in Table 3.

The SFP_n for TA02 was higher than SFP_{fit} for "normal" for most of the datapoints. Moreover, the maximum SFP_n for TA02 was above 100% for q_n at 84-90%. According to the performance metric "energy-efficiency" defined in Table 3, TA02 was classified as "poor".

Thermal conditions – Indoor temperature

The cumulative distribution of the indoor temperature (T) during operational hours from August to October 2019 is shown in Figure 4.

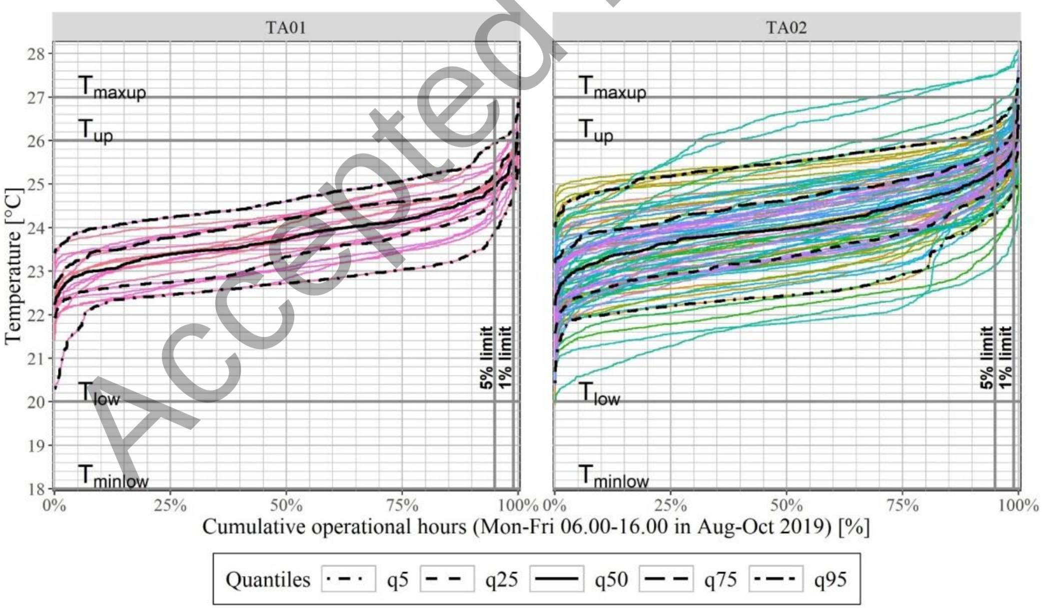

Figure 4. Cumulative distribution of temperature from each sensor (colored lines) on 4th to 8th floor for TA01 and TA02. Each sensor represents one occupied zone.

Figure 4 shows the cumulative distribution for each occupied zone and the quantiles (q_5, q_{25}, q_{50}, q_{75} and q_{95}) of the cumulative distribution. The zones grouped in TA01 were conditioned by VE02 and the zones grouped in TA02 were conditioned by VE04 and VE06 (Table 4). Indoor temperatures in all occupied zones in TA01 and TA02 were above $T_{min,low}$ and T_{low}. Figure 4 shows that the indoor temperature for all occupied zones in TA01 did not exceed $T_{max,up}$ and only less than 5% of the occupied zones exceeded T_{up} in 5% of the time. Thus, the indoor temperatures for all occupied zones on the 4th to 8th floor for TA01 were within the design requirements at least 95% of the time. For TA02 between 75-95% (~ 85%) of occupied zones had indoor temperatures less than T_{up} in 95% of the time and 5% of the zones exceeded indoor temperatures above $T_{max,up}$ more than 1% of the time. Thus, the indoor temperature was within the design requirements up to 95% of the time in 85% of the occupied zones on 4th to 8th floor for TA02. The floor and wing with the most zones that exceeded thermal design requirements were the 8th floor SE-wing. According to the performance metric "thermal" defined in Table 3, TA01 was performing "very good" and TA02 had a "poor" performance.

IAQ – Indoor CO_2-concentration

Figure 5 shows the cumulative distribution of the indoor CO_2-concentration (CO_2) during operational hours from August to October 2019.

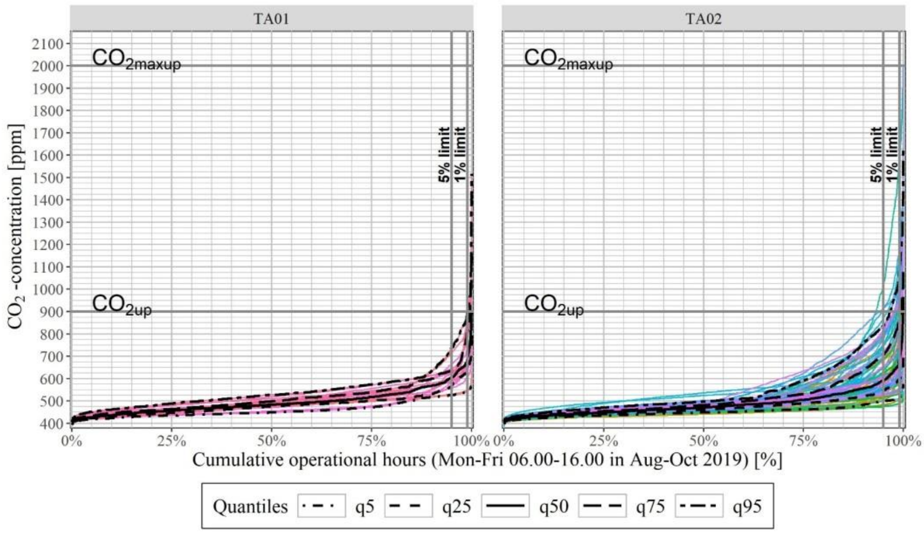

Figure 5. Cumulative distribution of CO_2 from each sensor (colored lines) on 4th to 8th floor for TA01 and TA02. Each sensor represents an occupied zone.

Figure 5 is organized in similar way as Figure 4. Figure 5 shows that for TA01 the CO_2-concentration for all occupied zones on the 4th to 8th floor was below $CO_{2,up}$ in 99% of the time and $CO_{2,max}$ was never exceeded. For TA02, approximately 99% of occupied zones were less than $CO_{2,max}$ in 95% of the time and $CO_{2,max}$ was never exceeded. According to the performance metric "IAQ" defined in Table 3, TA01 and TA02 were performing "very good".

Discussion

Evaluation of the sizing and performance level of the studied AHUs

The objective of this case study was to demonstrate an approach to collect, analyze and present long-term measurements as to evaluate: (1) Whether the studied AHUs were appropriately sized (sizing level) and (2) how they performed compared to design requirements (performance level). The study was conducted on an office building with six AHUs lumped into two datasets TA01 (VE01-03) and TA02 (VE04-06).

The first question related to the sizing level was answered using the defined scheme in Table 2. As TA01 and TA02 operated within 50-100% of the design airflow in at least 93% of the time during operational hours, the sizing levels for TA01 and TA02 were determined as rightsized. Therefore, according to the scheme in Table 2 the AHUs were sized appropriately.

The second question related to the performance level aimed to determine how the investigated AHUs performed regarding energy-efficiency, thermal condition and IAQ compared to the design requirements that were setup as a scheme in Table 3. TA01 was classified as “very good” regarding “thermal” and “IAQ” as well as “acceptable” regarding “energy-efficiency”. As TA01 was operating with fan-speed that was controlled to maintain constant pressure, it was based on Schild and Mysen (2009) expected that the observed relation between SFP_n and q_n had a closer fit to the SFP_{fit} for “normal”. Figure 3 also shows that TA01 during operation was closer to “normal”. In overall, the TA01 was appropriately sized and had an “acceptable” energy-efficiency and provided a “very good” thermal condition and IAQ.

TA02 was classified as “poor” regarding “thermal” and “energy-efficiency” and “very good” regarding “IAQ”. Thus, even though TA02 was rightsized, it was not able to meet the required thermal conditions and required energy-efficiency. There can be several explanations to this discrepancy: Results from Figure 3 suggest that TA02 was operating with a higher energy consumption (higher SFP), meaning that the pressure drop in the system was higher than expected or the fan-motor efficiency was low. Figure 4 also shows that 15% of the occupied zones exceeded upper temperature thresholds, which could suggest that the ventilation system could not provide the required thermal conditions. The high pressure drop and exceedance of upper temperature thresholds could point towards three main reasons for the discrepancy: (1) Inappropriate design assumptions leading to underestimation of the pressure drop in the ventilation system (Olufsen 1995, Hyvärinen and Kärki 1996, Hydeman *et al.* 2003) and underestimation of cooling loads in the occupied zones (e.g. due to underestimation of solar radiation, occupancy load or overestimation of solar shading). (2) Inappropriate operational procedure such as high pressure setpoints or high temperature setpoints (overheating), poor balancing of dampers, faulty VAV damper signal or poor temperature control at zone level (Hyvärinen and Kärki 1996). (3) Building use had changed from the intended use e.g. higher occupancy load because of changes to zone layout.

The demonstrated approach could not explicitly identify which of the main three reasons mentioned caused the observed discrepancy for TA02. This was because the demonstrated approach evaluated the performance of the ventilation system on a system level (i.e. AHU), and it did not provide any detailed information about the performance of ventilation components (e.g. dampers, filters), measured pressure drops in the ventilation system or applied temperature setpoints in occupied zones. Such an approach is according to IEA-EBC Annex 25 (Hyvärinen and Kärki 1996) classified as a top-down approach for building performance evaluation, i.e. an approach which is a starting point for performance evaluation and which can indicate whether there is a discrepancy that can justify the necessity for further investigation to identify the cause of the discrepancy. The IEA-EBC Annex 25 further described that further investigation should focus on the most probable reason for the discrepancy.

Thus far, the applied approach in the case study revealed that there was a significant performance discrepancy for TA02 that justified further investigations to uncover which of the presented three reasons could explain this discrepancy. The first reason was related to building design, while the second and third reasons were both related to building operation. A further investigation should first determine whether the discrepancy was related to the building operation: As previously explained, TA02 was a grouping of VE04-06, therefore the performance discrepancy could be due to one or more of these AHUs. Additionally, further investigation should pay special attention to zones on the 8th floor SE-wing conditioned by VE04 as it had the most zones exceeding upper temperature thresholds. The investigation can include e.g. audits of the mechanical ventilation system (e.g. checking setpoints, control settings and components) as well as comparing actual use (e.g. occupancy load) to the intended use to identify whether the building was used as intended. If these investigations showed that building operation (reason two and three) was not the cause of the observed discrepancy, then it could be concluded that TA02 was inappropriately sized i.e. design airflow was based on poor assumptions and was not enough to meet the upper temperature thresholds during actual operation. However, further actions would still be needed to identify what design assumptions resulted into undersizing of TA02.

Providing feedback on building operation

The case study represented a top-down approach that provided feedback on the operation of the studied AHUs. It was able to indicate to HVAC engineers whether there was an agreement between sizing and performance level. This was observed for TA01. The approach was also suitable for on-going performance monitoring to inform building operating managers whether it is necessary to conduct further investigations of the operational conditions that are causing poor thermal conditions and high energy consumption. This was observed for TA02.

Providing feedback to building design

The case study demonstrated the application, outcome and challenges related to collection, analysis and presentation of long-term measurements for evaluating the sizing and performance of the studied AHUs. The feedback to HVAC engineers, provided by the approach, first becomes valuable when the approach is applied to multiple office buildings as to investigate and provide evidence on whether a certain design practice is consistently resulting in undersized or oversized AHUs. Oversizing is costly and identifying and eliminating design practices that lead to oversizing can be a great competitive advantage for e.g. contractors as they can deliver a less costly solution that still satisfies the requirements from the clients. To illustrate this, Table 5 presents a cost estimation: In the example, TA01, with the volumetric airflow of 18.90 m^3/s (Table 4), was assumed to be 15% oversized. If TA01 was sized with a reduced airflow of 15% (16.10 m^3/s), the cost difference would be DKK 1,288,000 (USD 190,680) (Table 5).

Table 5. Example of cost difference between oversized and rightsized TA01.

	TA01 Oversized	TA01 Rightsized
Volumetric airflow [m^3/s]	18.90	16.10
Component and installation cost[a]	DKK 8,694,000 (USD 1,287,090)	DKK 7,406,000 (USD 1,096,410)
Cost difference	DKK 1,288,000 (USD 190,680)	

[a]From the official Danish price database (Molio 2019)

Moreover, rightsized ventilation systems use less materials (e.g. smaller duct size and smaller AHU components) and take up less space in the building compared to oversized systems. On the other hand, moderately oversized ventilation systems (mainly ventilation components and ducts) may bring certain benefits as they work with reduced pressure drop, which reduces energy consumption and noise during operation (Terkildsen and Svendsen 2013). The unused capacity also safeguards the operation from unexpected changes in the ventilation requirements.

Limitations regarding collection of long-term measurements in the case study

It was possible to collect the necessary data from the studied building, but three significant limitations were identified for the used dataset. The first limitation was related to the duration of the time period covered by the dataset, which only captured the period from August to October 2019. To investigate the reliability of the used dataset related to airflow and electrical power, the dataset for a two-year period used in the preliminary study by Khan et al. (2019) was processed and analyzed according to the method of this paper. Results are presented in Figures 6 and 7.

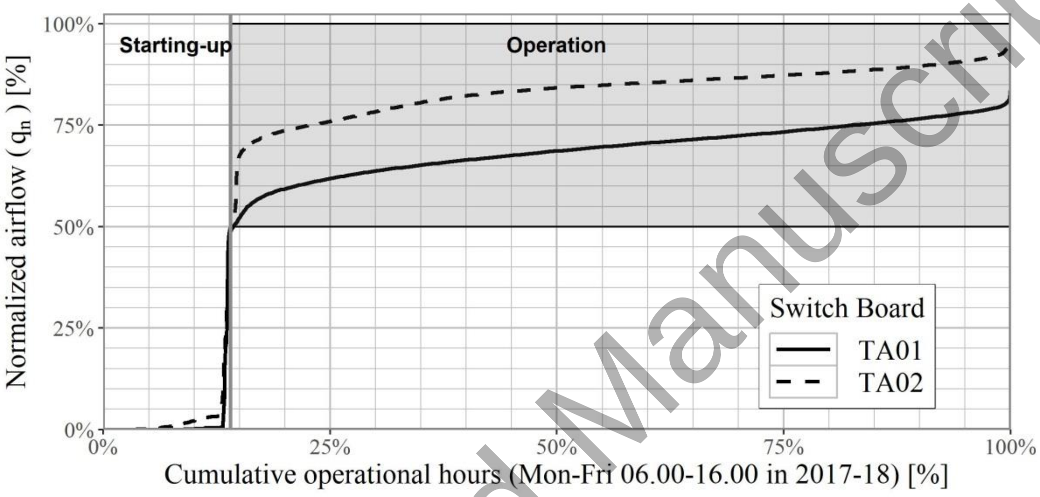

Figure 6. Cumulative distribution of q_n for TA01 and TA02 for 2017-18.

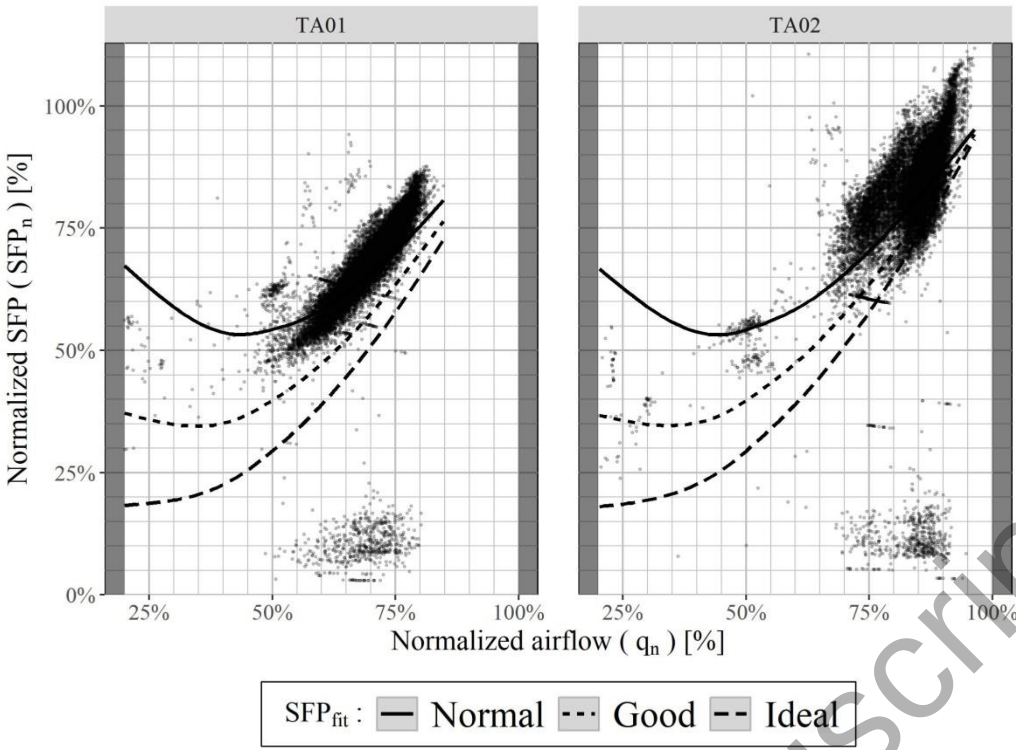

Figure 7. Scatter plot of SFP_n and q_n for 2017-18. If q_n was less than 20%, the datapoint was assumed to be faulty and was removed. The dark region marks the values outside the boundary condition of equation (7).

Figures 6 and 7 for the two-year dataset were only slightly different from figures 2 and 3 for the three-month dataset: E.g. Figure 6 shows that "starting-up" took up 14% of the operational hours instead of 16% shown in Figure 2. Both figures 6 and 2 show TA01 and TA02 to be rightsized as q_n was within the threshold defined in Table 2. Figure 7 and 3 show that the observed relations between SFP_n and q_n for TA01 was closer to "normal" and that SFP_n was less than 100% for q_n less than 83%. Figure 7 shows a similar trend for TA02 as in Figure 3, i.e. that TA02 was above "normal" and exceeded SFP_n above 100% for q_n at 84-95%. Thus, same conclusions are derived based on the two-year and the three-month dataset, i.e. that TA01 can be classified as "acceptable" and TA02 as "poor" related to energy-efficiency.

It was not possible to perform a similar investigation of the indoor temperature and CO_2 measurements due to lack of year-long data. Thus, conclusions regarding the thermal conditions and IAQ would have had a stronger validity and reliability if they were based on year-long dataset that captured the seasonal changes.

The second limitation was due to lack of data on indoor temperature and CO_2 measurements for zones on floor 0 to 3, which were conditioned by VE01, VE03 and VE05. Thus, the conclusions made regarding thermal conditions and IAQ did not include these occupied zones. However, as more than 50% of the occupied spaces were represented in the case study, the conclusions were still representative for the studied building.

The third limitation was related to the grouping of the six AHUs in two groups, which was due to the placement of electrical power meters. Due to this constraint, it was not possible to distinguish between the good and poor performing AHUs within the groups. This limitation could have been eliminated by installing meters for each AHU, but this can be costly (Guerra-Santin and Tweed 2015).

Limitations regarding the analysis and evaluation of long-term measurement in the case study

It was necessary that measurements of airflow, electrical power, indoor temperature and CO_2-concenterations had a high enough accuracy and precision as not to impact the conclusions derived based on these measurements. Therefore, this would require BAS sensors or meters to be appropriately maintained to insure valid and reliable measurements, which is not always the case in actual buildings (van Dronkelaar *et al.* 2016). The preliminary study by Khan et al. (2019) is an example of how lack of appropriate filtration and correction of airflow measurements produced significantly different results compared to the present case study. Thus, measurements need to be critically evaluated prior use. The best option would be to compare measurements from BAS to reference measurements with calibrated sensors to eliminate any systematic offset or measurement errors. However, this would be a time-consuming process and practically impossible if the demonstrated approach was intended to be used on multiple buildings. Thus, the second-best option was to reduce sensor offsets or outliers with use of filtration and correction techniques such as proposed by this paper or (Ding *et al.* 2005, Zhou *et al.* 2011).

Considerations related to operational hours and thresholds

The design requirements related to thermal conditions and IAQ such as $CO_{2,up}$ and T_{up} from Table 3 are basically fixed as they were determined by design and briefing documents. However, the threshold for energy-efficiency $SFP_{n,low,max}$ from Table 3 and the threshold for sizing $q_{n,low}$ from Table 2 were selected with following considerations in mind:

$q_{n,low}$ was set to 50% for the studied building as it was the ratio between the minimum and maximum design airflow specified in design documentations. However, one could argue if this threshold could have been set to a higher threshold instead, such as $q_{n,low}$ = 65%. If $q_{n,low}$ was changed to 65%, the rightsized area (grey area) in Figure 2 would be 65-100%. The cumulative distribution of q_n for both TA01 and TA02 would therefore be outside of the grey area more than 50% of the time, which would mean that TA01 and TA02 would be classified as oversized. If this was the case, the conclusion for at least TA01 (as the performance was "acceptable" and "very good") would have been that the particular AHUs could have been sized with a 15% reduction in the design airflow (i.e. the difference between 65% ($q_{n,low}$) and the minimum normalized airflow [q_n = 50%] during "operation"). This difference could also be interpreted as the risk a client or HVAC engineer was willing to take to reduce equipment sizing and installation cost. This risk could be assessed by simulation studies to investigate which implications it would have if the size of the AHU was reduced with 15%.

As the energy-efficiency was evaluated by comparing the maximum SFP_n to $SFP_{n,low,max}$ and 100% as well as by comparing the observed relation of SFP_n with SFP_{fit}, changing $SFP_{n,low,max}$ would not have yielded any different results because the determining factor for "energy-efficiency" was the result obtained by comparing to SFP_{fit}.

Another consideration that had an impact on conclusions regarding thermal and IAQ was related to the operational hours. The sizing and performance level should only be investigated for hours, where the AHU was operating during working hours. The operational hours for the studied building was selected from 06.00 – 16.00, which represented the typical working hours of the occupants and operational hours of the AHUs. This operational hour did not differ significantly from the operational and working hours defined in the design brief. Alternatively, approaches for mapping occupancy schedule such as (Duarte *et al.* 2013, Pedersen *et al.* 2017, Zou *et al.* 2017, Obrien *et al.* 2019) could be deployed to determine working hours.

Improvement of the demonstrated approach and application to other buildings

The applied approach can be further improved by including a performance metric that describes the thermal energy-efficiency including the thermal efficiency of the heat exchanger and the heating and cooling energy provided by the re-heaters and the coils. Monitoring thermal energy-efficiency could have revealed faults related to i.a. imbalanced supply and return airflow that could affect the thermal efficiency of the heat exchanger or reveal whether there was simultaneous heating and cooling of the provided airflow. Additionally, instead of relying on proxies such as indoor temperature and CO_2-concentration to evaluate on occupant comfort, occupants actual comfort evaluation could be included via post-occupancy surveys (Loftness *et al.* 2009) or occupant voting systems (Konis 2013). Other IEQ parameters such as relative humidity and measured noise levels from the ventilation system should also be included as part of the IEQ evaluation.

To apply the approach demonstrated in the present case study to other building types or ventilation systems, the definitions and thresholds provided in tables 2 and 3 needs to be refined. For example, the approach can be deployed to evaluate AHU performance in buildings that rely on heating or cooling from radiant systems. This would mean that the upper or lower threshold for “thermal” performance in Table 3 can be excluded as the AHU would provide IAQ and either heating or cooling. The approach in the case study can also be applied for mechanically ventilated buildings that operate with fan-speeds regulated with or without VSDs or as CAV. If the AHU is operating as CAV than q_n should be set to 90% as recommended by Schild and Mysen (2009) as this is the lowest threshold to maintain high fan-efficiency. The approach can also be applied to buildings with a combination of mechanical and natural ventilation, if it is modified to include additional measurement about i.a. when natural ventilation or mechanical ventilation provides the measured indoor conditions.

Furthermore, the approach relied on visual analysis to evaluate the performance of AHUs. But visual analysis can be computationally heavy to generate, and it can take time to manually analyze and evaluate each plot from multiple AHUs or buildings. Therefore, it can be advised to only extract the bounds needed in tables 2 and 3 and to determine a regression model for the observed SFP_{n} as to compare it to the fitted SFP_{n} using range normalized root mean squared error like in (Khan *et al.* 2019) as to evaluate the performance of AHUs. However, the strength of visual analysis lies on providing a detail view of AHU performance and sizing across a range of loading conditions which can be useful in context of general exploration (Munzner 2014) and evaluation of HVAC performance (Yang and Ergan 2016).

Contribution to existing research on HVAC performance and sizing evaluation

This paper contributes to two relevant research domains: 1) HVAC performance visualization and 2) HVAC sizing and performance evaluation.

Existing scientific work on HVAC performance visualization for monitoring, fault detection such as (Masoero *et al.* 2010, Granderson *et al.* 2011, O'Donnell *et al.* 2013, Cizik and Cooper 2017) mostly focus on visualization of energy data. Few studies such as (Masoero *et al.* 2010, Georgescu and Mezic 2014) include thermal and indoor air quality measurements along with energy data as part of HVAC performance evaluation (Tisov *et al.* 2016). Thus, the case study contributed to how long-term measurements of AHU regarding energy, thermal conditions and IAQ could be visualized as to support on-going monitoring to identify whether there is a discrepancy in operational performance. But the demonstrated approach was not able to explicitly identify the cause of the observed discrepancy in operational performance. Identifying the cause of an observed discrepancy is a common limitation of top-down approaches (Hyvärinen and Kärki 1996, Kim and Katipamula 2018). So-called bottom-up approaches using more advance data collection and analysis approaches relying on models or algorithms for detecting AHU component failures such as (Xiao and Wang 2009, Yu *et al.* 2014, Abdelalim *et al.* 2017) are ablet to determine the cause of a discrepancy. But currently the advance techniques are not able to estimate what impact an identified fault have on a building's energy consumption and IEQ (Kim and Katipamula 2018). Furthermore, as the methods are typically based on machine learning techniques, they are currently difficult to implement in existing buildings as they require additional sensor measurements (Kim and Katipamula 2018) and can be costly and time-consuming to configure to a particular building (Hong *et al.* 2020).

Existing scientific work on HVAC sizing and performance mainly focus on how to right-size or to identify and prevent oversizing related to chillers, plants or rooftop units such as (Djunaedy *et al.* 2011, Gorter 2012, Woradechjumroen *et al.* 2014, Wang *et al.* 2015). Studies focusing on AHU rightsizing and oversizing such as (EPA 1995, Crozier 2000, Thomas and Moller 2006) evaluate the sizing and performance level based on airflow and energy-efficiency, however they do not include an evaluation on the thermal conditions and IAQ even though they mention how these are affected by grossly oversized AHUs. Thus, the present case study included thermal condition and IAQ performance evaluation in relation to size evaluation of AHU as to provide information to HVAC engineers on how the AHU size effect indoor conditions.

Conclusion

The present case study demonstrated an approach for collecting, analyzing and presenting long-term measurements of airflow, energy (specific fan power), indoor temperature and CO_2-concentration to determine whether an air-handling unit (AHU) was sized appropriately and how it performed compared to design requirements. The case study was conducted on an all-air office building that had six AHUs. The demonstrated approach identified that all the AHUs were appropriately sized and performed very well compared to design requirements regarding indoor air quality. Half of the AHUs performed acceptably compared to design requirements regarding energy-efficiency and thermal conditions, whereas the other half performed poorly. The discrepancy between design requirements and actual operation was discussed to be either due to inappropriate design assumptions, inappropriate operational procedure or inappropriate use of the building. The approach was useful to reveal that there was a discrepancy in the operational performance of the studied AHUs. But further steps are necessary to identify the cause of the identified discrepancy.

Acknowledgements

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