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Method identifying oversizing of mechanical ventilation systems in office buildings using airflow and electrical power measurements

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Abstract. Heating, Ventilation and Air-Conditioning engineers face high demands from their clients to deliver reliable, optimized solutions that perform acceptably in terms of energy use and provided comfort. However, time and resources are scarce to deliver an optimized solution. To ensure that the solution works under most operation scenarios, the design is typically based on a combination of conservative rules-of-thumb, general guidelines and a large safety factor. The consequences are building service systems designed for operating conditions that never or very rarely occur leading to oversized systems. The objective of this paper was to propose a method for identifying oversized air-handling units with variable speed drives. It was demonstrated on a case study including six air-handling units in an office building. The method was able to determine that the air-handling units were not grossly oversized or undersized by comparing the measured airflow and SFP from the part- and full-load operation to the design airflow and SFP. However, the method should be extended to include additional performance criterion such as indoor climate and thermal efficiency to be able to conclusively confirm the size of the units.

1. Introduction

Mechanical ventilation systems in office buildings are designed to provide conditioned air to satisfy indoor climate and energy requirements. The typical procedure for sizing ventilation systems, specifically air-handling units (AHUs), can be divided into three steps: In the first step, the required airflow in the building is determined by using building simulation models. The input variables in the model are usually defined in the design brief or based on industry guidelines such as [1] or European Standard EN 15251:2007 [2]. But often not enough information is available, and the HVAC engineer has only a limited time to size the ventilation system [3]. Therefore, to ensure that the system fulfils design requirements, the variables are determined based on conservative rules-of-thumb or experience from previous projects [3]. The airflow is determined for selected rooms perceived to be representative of all rooms. The sum of airflows for all rooms then becomes the design airflow that is required to fulfil the indoor climate requirements during concurrent full-load condition. Sometimes a safety factor of 1.10-1.25 [3,4] is applied to the design value to account for changes during building design and operation or to accommodate morning warm-ups after night setbacks [5].

In the second step, the pressure drop in the ventilation system is determined by sizing the ductwork to avoid high noise-levels and high energy consumption. The Danish Building Regulation (BR18) [6] requires the Specific Fan Power (SFP) to be no more than 2,100 J/m³ (0.58 W/(m³/h)) at maximum pressure (full-load) yield by variable air volume (VAV) systems. Additionally, to comply with the energy frame requirements during part-load conditions, the required SFP (also denoted design SFP) is typically reduced with 20-50% below the maximum SFP from BR18.



In the third step, the design SFP is used to size the AHU along with the design airflow from step two. The AHU is sized so that the SFP is no more than the design SFP and that the fan operates with maximum fan efficiency for the design airflow.

The mentioned practice in determining the design values may lead to large ductwork and air-handling units that risk never being fully utilized during operation. Such a system is considered oversized. In general, a mechanical ventilation system is considered oversized if it has more installed airflow capacity than required by the most predominant operating condition. Thus, in this paper, size evaluation is a comparison between the design operating conditions and the actual operating conditions assuming that the intended use of the building has not significantly changed.

A study by the U.S. Environmental Protection Agency from 1995 [7] investigated 47 AHUs located in 26 commercial buildings across U.S. and identified that over half of the buildings had AHUs that were at least 10% oversized in terms of airflow during full-load condition. The oversized AHUs were in average 72% oversized and reducing oversizing to 10% could reduce fan energy with 50% [7]. Consequently, one way to do this is to select a smaller fan that operates close to the maximum fan efficiency for the most common airflow [8]. Another way is to use a variable speed drive (VSD) to vary the rotation speed of the fan according to the actual required airflow and pressure in the ventilation system. As VSDs are common in mechanical ventilation systems with VAV, moderately oversized AHUs are not an issue in terms of fan efficiency. However, grossly oversized AHUs with VSDs have the problem of operating in surge (the region of instability or stall of a fan) during part-load conditions that leads to lower total fan efficiency and higher fan energy [9]. Another problem with oversizing is the cost related to installation of the mechanical ventilation system and the space allocated for technical rooms and shafts. An expense exercise shows that savings on the installation cost of 4.9-24% can be achieved by sizing AHUs that are fully utilized in operation [10].

The available literature related to oversized HVAC primarily focuses on oversized compressors in roof-top units (RTUs): The extent of oversized RTUs [4], methods to determine oversizing and energy penalties of oversizing [11,12] and suggestions for rightsizing using stochastic modelling and uncertainty analysis [13]. However, only few studies [7,9,10] investigate the extent and problems related to oversized fans in AHUs and only [9] and [10] address oversizing issues of AHU with VSD. However, they do not explicitly state a definition of oversizing and how it can be determined. The objective of this paper was to propose and demonstrate a method to define and determine oversizing of AHUs equipped with VSDs in office buildings.

2. Method

The following section presents a method to evaluate and define oversizing of AHUs based on the airflow and the electrical energy efficiency in terms of SFP.

2.1. Suggested method for evaluating oversizing based on electrical energy efficiency

The following parameters were used to evaluate oversizing based on measured airflow, measured electrical power, design airflow and design SFP. The airflow can in most cases be obtained through the building automation system (BAS) and the electrical power can be measured by clamped type power meters installed between the building power supply and the switch board belonging to the AHU. The SFP was calculated from equation (1) [8]:

$$SFP = \frac{P_{supply} + P_{return}}{q_v} \quad (1)$$

where q_v is the volumetric airflow [m^3/s], P is the electrical power [W] from the supply and return fan and SFP is the Specific Fan Power [J/m^3]. The SFP for multiple AHUs can be calculated from equation (1) using the sum of airflow and power. The measured airflow and the SFP (denoted “actual”) were normalized with the design airflow and SFP (denoted “design”) using equation (2):

$$q_n = \frac{q_{actual}}{q_{design}} \times 100, \quad SFP_n = \frac{SFP_{actual}}{SFP_{design}} \times 100 \quad (2)$$

where q_n is the normalized airflow [%] and SFP_n is the normalized SFP [%]. The normalized airflow was represented as a cumulative distribution. The distribution was divided into three regions based on the changes in the slope of the curve. Each region represented a load condition.

The methodology in AIVC Technical Note 65 [8] was used to evaluate the energy efficiency of the AHUs: The observed relation between normalized SFP and normalized airflow was compared to a regression model defined in equation (3), giving SFP_{fit} depending on the coefficients a, b, c and d.

$$SFP_{fit} = a + b \cdot q_n + c \cdot q_n^2 + d \cdot q_n^3 \quad 20\% \leq q_n \leq 100\% \quad (3)$$

SFP_{fit} represents the estimated normalized SFP, if the AHU was operating as “Ideal”, “Good” or “Normal”. The corresponding coefficients are listed in Table 1. Systems with highly efficient VSDs and static pressure reset (dynamically controlled pressure setpoint) are characterized as “Ideal” [8].

Table 1. The coefficients in equation (3) from [8].

Operating conditions	a	b	c	d
Normal	1.0547	-2.5576	3.6314	-1.1285
Good	0.5765	-1.5030	2.6557	-0.7292
Ideal	0.2869	-0.8836	1.9975	-0.4008

The range-normalized-root-mean-square-error (RN_RMSE) was used to evaluate which operating condition (SFP_{fit} ; equation (3)) fitted best with the actual operating condition (SFP_n ; equation (2)). RN_RMSE [%] was determined according to equation (4) [14]. n is the number of observations.

$$RN_RMSE = \frac{\sqrt{\frac{1}{n} \sum (SFP_n - SFP_{fit})^2}}{\max(SFP_n) - \min(SFP_n)} \times 100 \quad (4)$$

2.2. Suggested definition of oversized air-handling units with variable speed drives

Table 2 was used to evaluate AHUs as either “Grossly oversized”, “Moderately oversized”, “Rightsized” or “Undersized”. The performance criteria define the sizing conditions. The “Airflow” was evaluated based on the cumulative distribution of the normalized airflow from equation (2). The boundaries refer to the part- and full-load conditions depicted by the distribution. The “Energy efficiency” was evaluated based on the relation between the normalized SFP and airflow from equation (3). Table 2 is only valid if the investigated AHU had been commissioned correctly, and that no high air-leakage or “false” loading, such as simultaneous cooling and heating, occurred to give false impression of the actual required airflow.

Table 2. Definitions of size based on performance. Definitions are based on indices from section 2.1.

Performance criteria	Grossly oversized	Moderately oversized	Rightsized	Undersized
Airflow (Equation (2))	Part- and full-load: $50\% \leq q_n \leq 100\%$ in $\leq 50\%$ of the time.		Part- and full-load: $50\% \leq q_n \leq 100\%$ in $> 50\%$ of the time.	Part- and full-load: $q_n > 100\%$ in $> 50\%$ of the time.
Energy efficiency (Equation (3))	“Normal” or worse. $SFP_n > 100\%$ for $q_n = 100\%$.	“Good” or “Ideal”. $SFP_n < 90\%$ for $q_n = 100\%$.	“Good” or “Ideal”. $90\% \leq SFP_n \leq 100\%$ for $q_n = 100\%$.	“Normal” or worse. $SFP_n > 100\%$ for $q_n = 100\%$.

2.3. Case study

The case study comprised an eight storey multi-tenant office building with an area of 16,400 m² located near Copenhagen. The building was constructed in 2014 and certified as a Platinum DGNB. Six mechanical ventilation systems (Table 3) heat, cool and ventilate the office areas. The ventilation operated as VAV with static pressure reset. The AHUs have rotary heat exchangers, fans with VSDs and cooling coils. The building is typically occupied from 6.00-16.00 Monday to Friday all year. Airflow measurements for the six AHUs, from January 2017 to December 2018, were extracted manually from

the building's BAS. In 2016 clamped type power meters were installed between the power supply and two switch boards supplying the mechanical ventilation systems. Measurements from these meters were collected to a cloud platform and extracted by application programming interface (API). The switch boards provided electrical power to all the components of the analysed mechanical ventilation systems, as well as the exhaust system distributed to the toilets. The electrical consumption from the exhaust system was assumed to be negligible compared to the consumption of the analysed mechanical ventilation systems. The measurements were collected at 5 min. intervals.

Table 3. Name, zone, floor and design values of the AHUs in the case building.

AHU	Zone and floor	Design airflow ³ [m ³ /h]	Design SFP ³ [J/m ³]	Switch board	Design values Switch board
VE01	West, floor: 0.-3.	24,000	1,545	TA01: VE01-03	Total airflow: 68,000 m ³ /h Average SFP ⁴ : 1,508 J/m ³
VE02	West, floor: 4.-8.	24,000	1,545		
VE03	East, floor: 0.-3.	20,000	1,419		
VE04	East, floor: 4.-8.	28,000	1,559	TA02: VE04-06	Total airflow: 61,000 m ³ /h Average SFP ⁴ : 1,523 J/m ³
VE05	North, floor: 0.-3.	15,000	1,418		
VE06	North, floor: 4.-8.	18,000	1,553		

³Design airflow and SFP for full-load condition from manufacturer's documentation.

⁴From equation (1). Power of each AHU was calculated by multiplying SFP with airflow.

3. Results

Airflow: Figure 1 shows the cumulative distribution of the normalized airflow (q_n) during working hours from 2017 to 2018. The six AHUs were lumped into two datasets TA01 (VE01-03) and TA02 (VE04-06) (Table 3). The distribution in Figure 1 was divided into three regions based on the changes in the slope of the curve for TA01 and TA02: The first region (denoted "Starting-up") occurred 16% of the time for both TA01 and TA02. This region depicts the increment of the minimum airflow to the level of airflow required in the part-load condition (denoted "Part-load"). The full-load condition (denoted "Full-load") occurred 5% of the time and is representative for the full-load condition for TA02. The full-load condition for TA01 is close to 0%. The grey area marks the lower and upper boundaries of the airflow according to the "Airflow" criterion in Table 2. The boundaries were only evaluated for regions "Part-load" and "Full-load", which occurred 84% of the time.

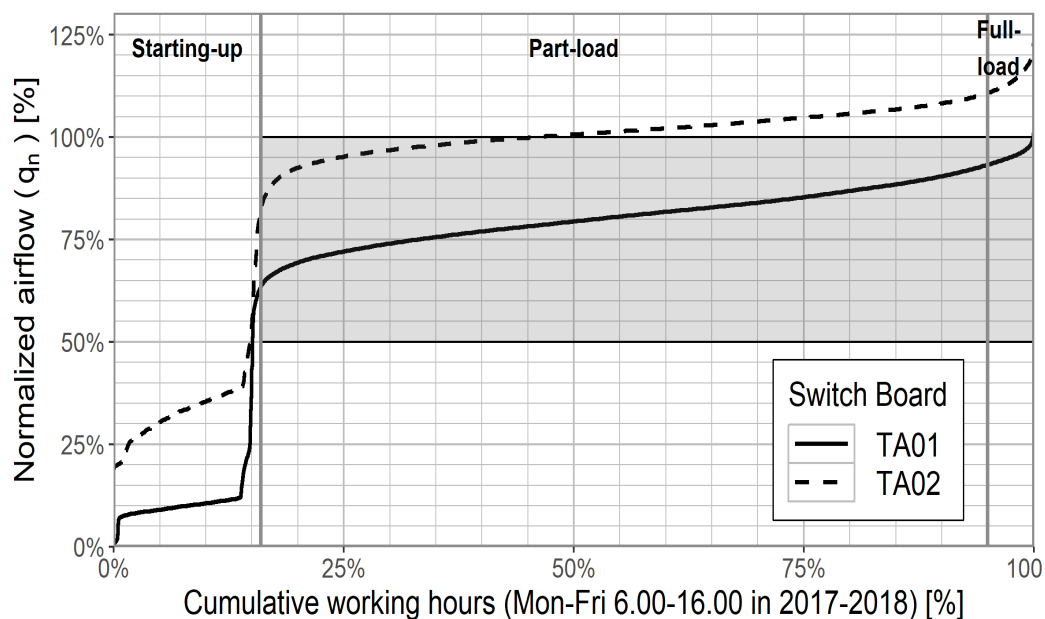


Figure 1. Cumulative distribution of q_n for TA01 and TA02 in 2017-18.

Energy efficiency: Figure 2 shows the relation between the normalized SFP (SFP_n) and the normalized airflow (q_n) for the two datasets in 2017-18. SFP_{fit} for the three operating conditions from Table 1 are depicted as curves denoted as “Normal”, “Good” and “Ideal”. The observed relations between the normalized SFP and airflow for TA01 and TA02 have a nonlinear relation corresponding to “Good” or “Ideal”. The values diverging significantly from this relation can be due to faulty sensor data (Figure 2). They were included in the calculation of RN_RMSE as they did not change the results significantly.

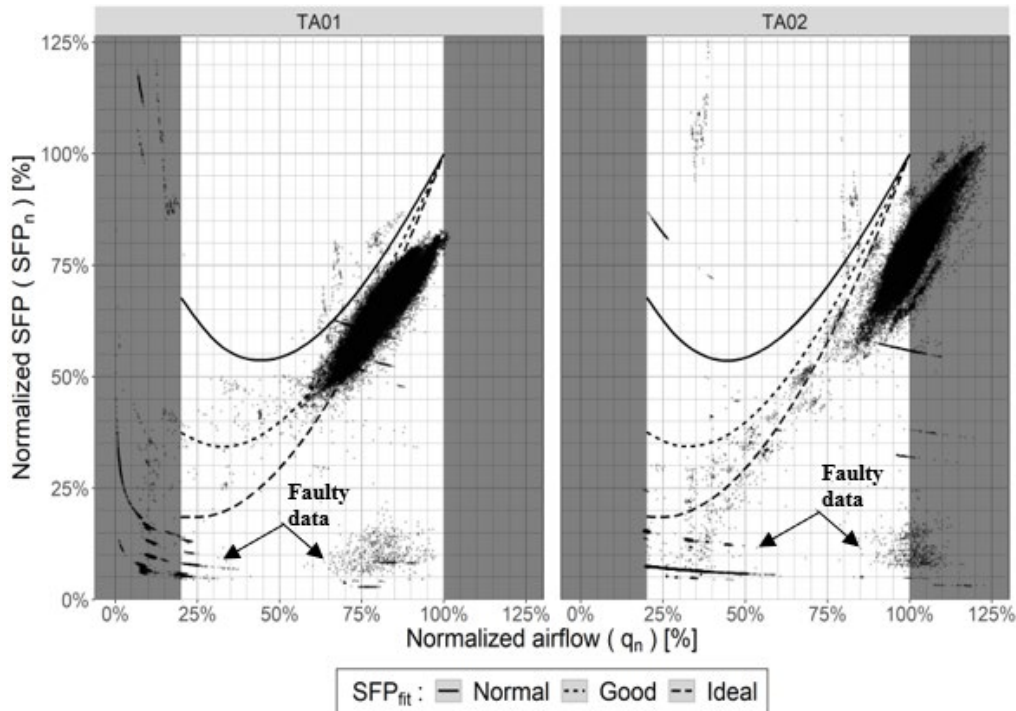


Figure 2. Relation between SFP_n and q_n in 2017-18. The dark area marks values outside the boundary condition of equation (3). The arrows denote faulty sensor data.

Table 4. RN_RMSE from (4) between SFP_n and SFP_{fit} .

Operating condition	TA01	TA02
Normal	18%	28%
Good	13%	21%
Ideal	11%	17%

TA01: Based on the “Airflow” criterion in Table 2, TA01 was rightsized because the cumulative distribution of TA01 was within the grey area all the time (Figure 1). Figure 2 shows that SFP_n of TA01 was not more than 90% for q_n equal to 100% and that the lowest RN_RMSE in Table 4 was for the operating condition “Ideal”. Based on the “Energy efficiency” criterion TA01 was moderately oversized.

TA02: TA02 was undersized, based on the “Airflow” criterion, as the cumulative distribution of TA02 was outside of the grey area in 55% of the time. However, based on the “Energy efficiency” criterion TA02 was rightsized as the lowest RN_RMSE in Table 4 was for the operating condition “Ideal” and that SFP_n was not more than 95% for q_n equal to 100% (Figure 2).

4. Discussion

In overall the method was able to demonstrate that TA01 and TA02 was not grossly oversized or undersized. As an example, if TA02 was only evaluated based on the normalized airflow, it would have been evaluated to be undersized. However, including energy efficiency as an additional performance criterion, it was possible to determine that TA02 was not undersized. However, the method cannot

conclusively confirm if TA02 was rightsized. Another limitation with the method was about determining if TA01 was moderately oversized or rightsized. Additional performance criteria should be provided in the definition in Table 2 to conclusively confirm the size of an AHU: The method should be extended to include an evaluation of the thermal efficiency of the AHUs to identify how the operation of the heat recovery is affected by the size of the AHU. Furthermore, the method should include an investigation of the thermal indoor climate and air quality provided by the ventilation system. Evaluation of the installation and operational costs of oversized, rightsized and undersized AHUs are also an important part of the analysis. Moreover, the boundaries defined in Table 2 for “Airflow” and “Energy efficiency” need to be further improved based on more case studies of AHUs with VSDs to help determine a common characteristic of each different sizes of AHUs. The robustness of the method should also be evaluated such as, how measurement uncertainty or temporary changes in operation or malfunctioning in the system or sensors can affect the results.

The presented method is part of a broader investigation that has the intention of evaluating if a certain design practice is consistently resulting in oversized AHUs. Oversizing is costly and identifying and eliminating design practices that lead to oversizing can be a great competitive advantage for construction companies, as they can deliver a less costly solution that still satisfies the requirements from the clients. Moreover, it would reduce energy and resources wasted on constructing oversized systems. On the other hand, moderately oversized ventilation systems may bring certain benefits as they work with reduced pressure drop, which reduces energy consumption and noise during operation. The unused capacity also safeguards the operation from unexpected changes in the ventilation requirements. The methodology can also be used to evaluate the operation and control strategy of the mechanical ventilation system as part of an ongoing commissioning process. If AHUs are identified as grossly oversized the energy efficiency can be improved either by replacing the fan in the AHU with a smaller sized fan or improving the control strategy e.g. by implementing static pressure reset [9].

5. Conclusion

A method was demonstrated on a case study of six mechanical ventilation systems in a Danish office building. The method was based on two-year measurements collected by the building automation system as well as on measurements from internet connected power meters. The method was able to determine that the AHUs were not grossly oversized or undersized by comparing the measured airflow and SFP from part- and full-load operation to the design airflow and SFP. However, the method should be extended to include additional performance criterion such as indoor climate and thermal efficiency to be able to conclusively confirm the size of the AHUs.

References

- [1] Vorre H M, Wagner H M, Maagaard E S, Noyé P, Lyng L N and Mortensen L 2017 Branchevejledning for indeklimaberegninger (Copenhagen InnoBYG) 52.
- [2] EN-15251 2017 52.
- [3] Jacobs P and Henderson H 2002 State-of-the-art review whole building, building envelope and HVAC component and system simulation and design tool (Virginia) 239.
- [4] Gorter L J 2012 *Energy Eng.* **109** 59–75.
- [5] Nall H D 2018 *ASHRAE Journal* **57** 48–51.
- [6] Building regulations 2018 (BR18) (Ministry of Transport, Building and Housing) 1–137.
- [7] EPA 1995 EPA 430-R-95-002 (Washington, DC Air and Radiation 6202J) 45.
- [8] Schild P and Mysen M 2009 Technical Note AIVC 65 (Air Infiltration and Ventilation Centre).
- [9] Hydeman M, Taylor S, Stein J, Kolderup E and Tong H 2003 Report P500-03-082-A-11 (CEC) 212.
- [10] Thomas P and Moller S 2007 HVAC system size: Getting it right (Brisbane) 13.
- [11] Djunaedy E, van den Wymelenberg K, Acker B and Thimmana H 2011 *Energy Build.* **43** 468–75.
- [12] Woradechjumroen D, Yu Y, Li H, Yu D and Yang H 2014 *Energy Build.* **69** 131–43.
- [13] Sun Y, Gu L, Jeff Wu F C and Augenbroe G 2014 *Energy Build.* **81** 243–52.
- [14] Chakraborty D and Elzarka H 2018 *J. Build. Perform. Simul.* **11** 433–48.