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Sensitivity analysis of control strategies for mechanical ventilation in a low-energy apartment building

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Abstract. Building simulation tools are increasingly used during design of new as well as refurbishment of residential buildings. However, reliability of simulation is highly dependent on its inputs. The project investigated application of sensitivity analysis on input parameters for simulation of ten different residential ventilation control strategies. Nine strategies comprised demand control (DCV) one used constant air volume. Demand was represented by operative temperature, CO_2, relative humidity or their combinations. They were measured either in ventilation exhaust or in particular rooms. Primary energy consumption and quality of indoor environment were evaluated. A low-energy apartment of 93.8 m^2 placed in Nordhavn, Copenhagen, Denmark was used as a case study. Investigated input parameters were: heating set-point, occupancy schedule, window opening, internal heat and moisture gains, glazing area, g-value, solar shading and night ventilation. The control strategy capable of providing the best indoor climate (DCV with combination of sensors in individual rooms) was at the same time the most energy demanding. The sensitivity analysis revealed that heating setpoint and window opening were the most crucial input parameters with respect to primary energy consumption. Window opening was also the most influential factor with respect to overheating and moisture. Occupancy had a strongest effect on CO_2.

1. Introduction

Building simulation tools are being increasingly used during design of new buildings and in planning of refurbishment of existing buildings. They allow for continuous optimization of the design from its early stage. Using a simulation helps to find an optimal solution with respect to contradictory design problems like ensuring sufficient amount of daylight while limiting overheating. However, the reliability of a simulation is highly dependent on its inputs. The current practice of a “static” definition of input parameters like heating set-point, occupancy pattern or internal heat gains contributes to so-called performance gap [1]. The amount of studies where sensitivity analysis was utilized to cover a typical/possible range of input values and parameters with respect to residential ventilation is rather limited. The examples of such studies can be Van Den Bossche et al. [2] and Laverge et al. [3]. Multiple studies have used sensitivity analysis for better understanding of the energy performance in residential buildings. Brohus et al. [4] investigated the influence of occupant behaviour on energy consumption in residential buildings and a ranking of the parameters was performed using sensitivity analysis. Molin et al. [5] investigated the energy performance of newly built low-energy buildings in Sweden with a parametric study. Ioannou and Itard [6] used sensitivity analysis to study how parameters related to the building and occupancy behaviour affected the building energy consumption and thermal comfort of the occupants. The methodology for an application of sensitivity analysis on building performance was evaluated in several studies. Nguyen and Reiter [7] evaluated 9 different sensitivity methods, Yang et al. [8] compared 4 methods and Brohus et al. [4] compared 4 methods. No clear consensus exists on which method is the most suitable to study building performance, especially in relation to ventilation, however, a method by Morris [9] receives particular attention.

The main objective of the present study was to apply sensitivity analysis on input parameters for a building energy simulation to evaluate control strategies for residential mechanical ventilation.

2. Methods

2.1. Building model

A low-energy apartment building located in Nordhavn near Copenhagen, Denmark was used as a case study. A typical 3-bedroom apartment from the building with a total floor area of 93.8 m^2 (ceiling height 2.54 m) with a combined living room and kitchen, two bathrooms and a small depot (Figure 1) was modelled in IDA Indoor Climate and Energy software (IDA ICE) [10].

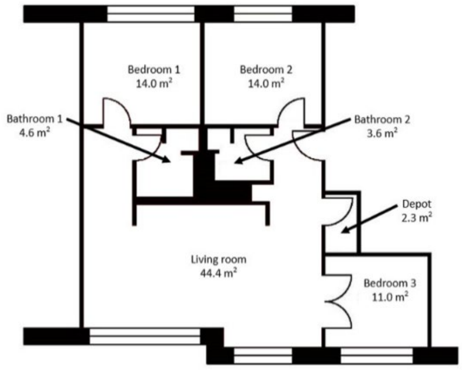

Figure 1. The floor plan of the modelled apartment

Table 1 summarizes the most important parameters of the model. The Danish design reference year [11] was used for all conducted simulations.

Table 1. Input values for the simulation model

Input	Value	Unit	Description/Source
Design power for floor heating	16.0	W/m^2	Based on building's design documentation
Specific fan power (SFP)	800	J/m^3	[12]
Heat recovery efficiency	85	%	Controls supply temperature
External wall, U-value	0.12	W/m^2/K	Concrete 150 mm, insulation 275 mm, air gap 25 mm and brick 108 mm
Glazing, U-value	0.53	W/m^2/K	Based on building's design documentation
Frame, U-value	1.80	W/m^2/K	Based on building's design documentation
Window, U-value	0.81	W/m^2/K	Frame fraction 22 %
Air leak area in internal doors	100	cm^2	All internal doors were modelled as closed

Primary energy factors of 0.6 for district heating and 1.8 for electricity corresponding to the Danish nearly zero energy building class [12] were utilized. The ventilation unit was designed according to the Danish ventilation standard DS 447 [13]. Supply air flow of 7 l/s per person and additional 0.7 l/s m^2 heated floor area resulted in maximum supply airflow of 360 m^3/h. Minimum ventilation was defined by the Building regulation requirement of a constant airflow of 0.3 l/s m^2 heated floor area. Air was supplied in the bedrooms and the living room-kitchen and exhausted from the toilet/bathroom and living room-kitchen. Supply and exhaust airflows were balanced on the apartment level.

2.2. Ventilation control strategies

Altogether ten different ventilation control strategies were investigated. The results for six of them are presented in this paper (Table 2). The strategies included simple constant volume ventilation (CAV) as well as advanced variable air volume (VAV) strategies representing demand-based control. Operative temperature (T), CO$_2$ concentration (CO$_2$), relative humidity (RH) or their combinations characterized the demand. Different positions of the sensors were considered. The sensor was positioned in the exhaust duct (indicated as "c" at the name of the strategy in Table 2) or in particular rooms (indicated as "r").

Table 2. Investigated ventilation control strategies

Strategy	Description	Airflow control settings
CAV	Minimum airflow according to Danish building regulations [12]	0.3 l/s per m^2 heated floor area 15 l/s in bathrooms and 20 l/s in kitchen
VAV (CO_2, c)	CO_2 based VAV, the sensor placed in in the exhaust duct, proportional control of fan speed	P-band = (800, 900) ppm
VAV (RH, c)	RH based VAV, the sensor placed in in the exhaust duct, proportional control of fan speed	P-band = (25, 70) %
VAV (T, c)	T based VAV, the sensor placed in in the exhaust duct, proportional control of fan speed	P-band = (23, 27) °C
VAV (CO_2-T-RH, r)	VAV based on room sensors: RH in the bathroom, CO_2 and T in the bedrooms, all three sensors in the living room-kitchen, proportional control of fan speed	P-band as for the above mentioned sensors for RH, T and CO_2
VAV (RH, r)	VAV based on room sensors: RH in the bathroom and the living room-kitchen, proportional control of fan speed	P-band = (25, 70) %

2.3. Evaluation of indoor environmental quality

Indoor environmental quality (IEQ) was evaluated using operative temperature, CO_2 concentration and relative humidity (RH). The acceptable thermal environment was defined using requirements from the Danish building regulations [12] setting the operative temperature limit to 27 °C. Standard EN 15251 [14] was used to define the limits for air quality and relative humidity: maximum CO_2 concentration 900 ppm and maximum RH 60%. The "degree hour" approach according to EN 15251 [14] was applied to assess ability of different control strategies to keep IEQ within the required limits. Degree hours Dh [°C·h], RH hours RHh [%·h] and CO_2 hours CO_2h [ppm·h] were determined for operative temperature, CO_2 concentration and RH, respectively. The limit values for Dh were determined for a scenario where the four occupied rooms were 3 °C above the limit for 5% of the year which was equal to 5256 °C·h. For the CO_2h the reference scenario was that the four occupied rooms had CO_2 concentration 200 ppm above the limit for 5% of a year resulting in 350,400 ppm·h. The reference scenario for RHh hours was 5% of a year with RH 5% above the limit for the whole apartment, which represents 2190 %·h.

2.4. Sensitivity analysis

Sensitivity analysis included the following parameters: *heating set-point, occupancy, window opening, internal heat gain, internal moisture gain, window area, solar heat gain coefficient (g-value), solar shading and night ventilation through windows in bedrooms*. Selection of the parameters was based on a literature review. The global sensitivity analysis according to Morris [9] was supplemented with "Elementary Effect" method [15] to assess the interdependency of the studied input parameters. A probability density function was assigned to each design parameter to describe the possible range of its values. Consequently, the 5th, 25th, 50th, 75th and 95th percentiles were used to define five distinct levels of each input parameter. Table 3 represents the levels for the selected design parameters (not all considered parameters are presented due to space limitations). As it can be seen in the table, some of the input parameters were broken down into sub-categories. Using a random combination of the input parameter levels, a vector representing an initial level-combination was determined. Subsequently a level of each of the design parameters was changed at a time in a randomised order, which resulted in a new vector with an unique combination of the input parameter levels. This process resulted in 11 unique vectors and thus 11 sets of input parameters for IDA ICE models for each control strategy. The sequence was repeated ten times in order to obtain reliable results [4]. The number of input variable sets per ventilation control strategy thus become 110 and for ten different control strategies, the total amount of models was 1100.

Table 3. Examples of input parameter levels used in the sensitivity analysis; abbreviations: ML: Moisture load, IL: Internal load, KT: Kitchen, LR: Living room, T: Toilet, BR: Bedroom

Parameter	**Room**	**Input parameter level**				
		1	**2**	**3**	**4**	**5**
Heating set-point [°C]	-	18.30	21.00	22.50	23.50	25.10
Occupancy [persons]	-	1	2	3	4	5
Occupancy load [met]	KT/LR	0.90	0.96	1.20	1.63	2.52
Occupancy load [met]	BR	0.73	0.83	0.90	0.98	1.10
Window opening angle [°]	BR	3	7	9	15	28
ML-Cooking dinner [kg/load]	KT/LR	0.36	0.64	0.96	1.43	2.54
ML-Dishwashing [kg/day]	KT/LR	0.07	0.11	0.15	0.21	0.33
ML-Shower load [min]	T	5	6	8	10	15
IL-TV&DVD [W]	KT/LR	35	66	102	160	305
IL -Vacuum cleaning [W]	BR, KT/LR	1090	1155	1200	1245	1310
Glazing area/heated floor area [%]	-	0.15	0.19	0.22	0.25	0.29
Solar shading factor [-]	-	0.64	0.73	0.80	0.87	0.96
Glazing g-value [-]	-	0.60	0.64	0.67	0.70	0.74

According to Saltelli et al. [15] the Elementary Effects (EE) was defined as

$$\mathrm{EE}(x_{1,} \dots, x_k) = \frac{y(x_1, x_2, \dots, x_{i-1}, x_i + \Delta, x_{i+1}, \dots, x_k) - y(x_1, \dots, x_k)}{\Delta} \quad (1)$$

where $y(x_1, \dots, x_k)$ is the result of the model before the design parameter was changed, x_i is the level of the design parameter and Δ is the level change of the design parameter. The sensitivity of a particular simulation model to a change in particular design parameter was quantified by the mean value (μ) calculated from the corresponding EE values. The standard deviation of μ (σ) was used to assess interdependence among the studied design parameters.

3. Results and discussion

Results of the sensitivity analysis related to the primary energy consumption are shown in Figure 2 (left). The most advanced control strategy unitizing sensors placed in individual rooms, VAV (CO_2-T-RH, r), had the highest median energy consumption (heating and for ventilation). The third largest consumption was associated with simple CAV strategy. This strategy was also associated with the highest variance of the energy consumption related to the variance in the input parameters. The lowest median energy consumption was observed for CO_2 based strategy with the sensor placed in the exhaust (VAV (CO_2, c)). Regarding provided indoor environmental quality, all strategies were able to ensure the required levels of RH. Median RHh for all tested strategies was about 1600 %·h lower than the limit value. The VAV (CO_2, c) strategy showed the highest spread of the results related to the variance in the input parameters. Results regarding thermal environment indicated the same trend. Median Dh was about 4600 °C·h below the limit. All strategies were in general able to reduce overheating, while the results of the VAV (CO_2, c) strategy varied the most. Figure 2 (right) shows results regarding CO_2h. VAV (CO_2, c) strategy performs the worst in terms of indoor air quality (median CO_2h is very close to the limit). The reason for such poor performance is a placement of the CO_2 sensor centrally in the exhaust, which obviously underestimates CO_2 concentrations in particular rooms. The CAV and VAV (CO2-T-RH, r) strategies showed the best results regarding indoor air quality, while having the highest and the second highest energy consumption, respectively.

Results of Elementary Effects analysis for primary energy consumption for the CAV strategy are shown in Figure 3. The heating set-point had the largest influence as the primary energy consumption increased with more than 4 kWh/(m^2 year) for each level-change in the set-point (for levels see Table 3). Window opening had the second largest influence followed by glazing size.

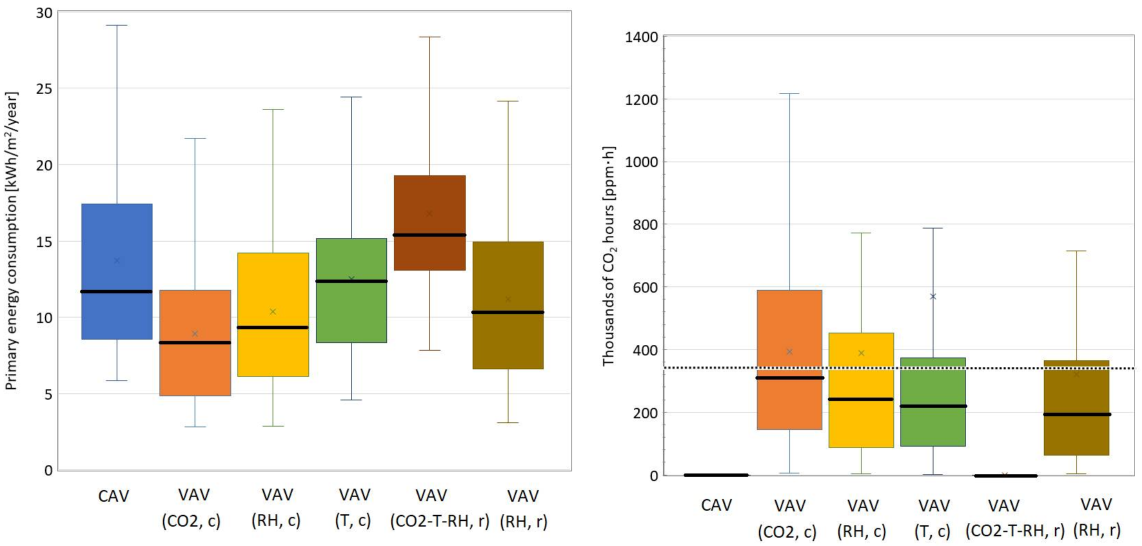

Figure 2. (Left) Primary energy consumption for selected control strategies, (Right) CO$_2$h for selected control strategies; black horizontal lines indicate the median, dotted line indicates the CO$_2$h limit

For the remaining input parameters the change of energy consumption per level-change was smaller than 1.0 kWh/(m^2 year). The three most influential design parameters had a low standard deviation σ (indicated by the green colour in Figure 3), thus they were not dependent on the remaining input parameters.

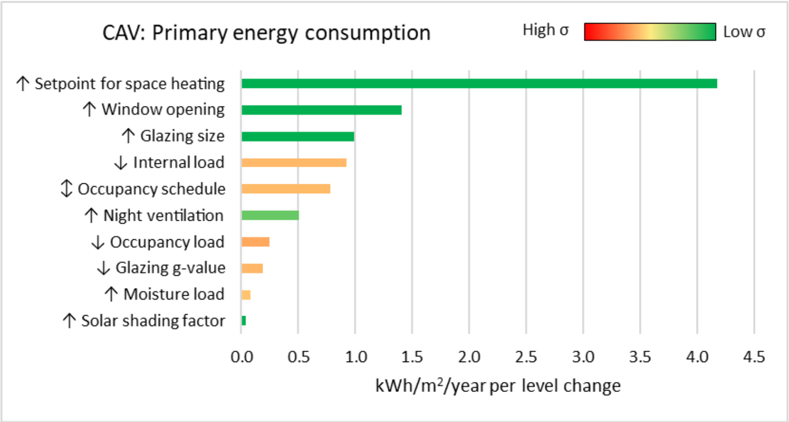

Figure 3. Results from Elementary Effects analysis for CAV strategy; parameters are ranked according to sensitivity μ regarding primary energy consumption, σ indicates how dependent the influence of the parameter was to the remaining parameters, the arrows indicate whether a higher level of the parameter is proportional (↑), inversely proportional (↓) or a combination (↕)

The analysis of all results showed that set-point for space heating had the highest overall influence on the primary energy consumption for the strategies investigated. It was followed by window opening and glazing size. When considering overheating (Dh), the window opening was the most influential factor for all strategies, followed by night ventilation and internal heat load. Window opening was also the most influential factor when considering relative humidity levels in the apartment (RHh). The second most influential input parameter was moisture load and the third night ventilation. For most control strategies, the occupancy load was the input parameter with most influence on CO_2 concentrations (CO_2h), followed by window opening. The results of the study agree with findings of Brohus et al. [4] who identified space heating and occupancy load as most influential input parameters regarding energy consumption. In addition, the present results indicate that the definition of window opening is a crucial factor influencing results regarding both energy consumption and, more importantly, indoor environmental quality. At the same time, the definition of occupancy patterns as well as window opening behaviour in the simulation models is a complex issue. Both processes are driven by human behaviour and their correct representation requires probabilistic approach [16], which may be difficult to apply in design practice. Alternatively, sets of pre-defined values for crucial parameters generated using probabilistic approach can be provided for designers in practice.

4. Conclusions

Sensitivity analysis identified heating set-point and window opening as the most crucial input parameters with respect to the primary energy consumption. Window opening was also the most influential factor with respect to overheating and moisture. Occupancy had a strongest effect on CO_2 concentration. The control strategy providing best indoor environment was associated with the highest energy consumption.

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