COMPARATIVE STUDY OF VENTILATION STRATEGIES IN RESIDENTIAL APARTMENT BUILDINGS UNDER UNCERTAINTY

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ABSTRACT

In this paper, eight ventilation strategies in a typical apartment floor plan in Jeju, Korea were studied. In terms of size and floor plan, the chosen building is typical of residential buildings and consists of three bedrooms, a living room, and a kitchen. In this study, uncertainty propagation was introduced to treat the parameters which are not "deterministic" but "probabilistic" such as the stochastic nature of weather, the occupants' behavior, building components, and simulation parameters. The ranges of the uncertainty parameters were selected based on data available from literature and on-site visits. The Monte-Carlo method with Latin Hypercube Sampling (LHS) was employed for uncertainty propagation. For the simulation of ventilation phenomena, CONTAMW 2.4 was chosen. The eight ventilation strategies with varying supply air rates and air inlet locations were assessed in terms of initial investment cost, energy cost, comfort level (PD: Percentage Dissatisfied, %), and CO_2 concentration. It was found that the DCV-CO_2 (Demand Controlled Ventilation-CO_2 sensor-based) strategies save about 50% more energy than the CAV (Constant Air Volume) strategies.

INTRODUCTION

The selection of an effective ventilation strategy is important in terms of IEQ (Indoor Environmental Quality) to improve the productivity and quality of life of the occupants. The removal of contaminants and a sufficient supply of outdoor air result in improved IEQ.

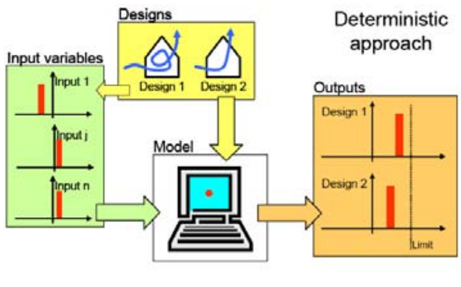
Among natural, mechanical, and hybrid ventilation schemes, mechanical ventilation including a built-in total heat exchanger known as an ERV (Energy Recovery Ventilator), which is typical in Korean residential buildings, was chosen in the study. The ERV method is classified based on the outdoor air supply rate into CAV (0.7 ACH: Air Changes per Hour, h^{-1}, Korean building code) and DCV-CO_2 methods. In addition, various ventilation strategies are possible depending on (1) the air inlet location (one air inlet in the living room only, one air inlet in the living room and another in the master bedroom) and (2) CO_2 sensor position (living room only, living room and master bedroom, or every room). This study compares 8 ventilation strategies according to the outdoor air supply rate, air inlet location, and CO_2 sensor position in terms of four assessment criteria (initial investment cost, energy cost, PD (Percentage Dissatisfied, %), and CO_2 concentration). To accomplish this, the following uncertainties should be accounted for.

- *Stochastic nature of weather*: Natural airflows have two driving forces: buoyancy and wind. Since wind speed and direction change quickly and the temperature difference between the indoors and outdoors also fluctuates diurnally as well as annually, it is difficult to quantify such influences on the ventilation rate.
- *Occupants' behavior:* As an example, the energy cost, PD, and CO_2 concentration in case 1, where the occupant spends most of his time in the master bedroom, and in case 2, where the occupant spends most of his time in the living room, may be different even if the same amount of outdoor air is supplied through the air inlet installed in the living room. Therefore, the efficiency and performance of the ventilation strategy may vary depending on the occupants' presence, the occupants' behavior, and the air inlet position.
- *Building components*: The tightness of the openings in a residential apartment building (front door and windows) is diverse, and an identical product may have a different tightness from its specification due to construction error, deterioration, and building maintenance.
- *Uncertainties in simulation parameters*: Simulation parameters such as discharge coefficient, flow coefficient, etc., used to simulate airflow phenomena inside and around the building cannot be predicted accurately. Thus, different values of such parameters have appeared in the literature (ASHRAE, 2005; de Wit, 2001; Feustel, 1990; Feustel, 1998; Grosso, 1995; Knoll, 1995; Orme, 1994; Persily, 2001; Walton & Dols, 2005). Moreover, these parameters change significantly with location and time.

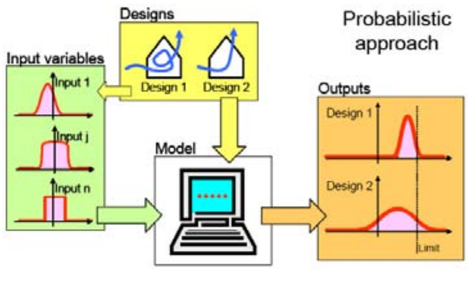
The aforementioned issues lead to difficulty in quantitatively evaluating ventilation strategies. Hence, the paper presents a probabilistic approach to estimate ventilation strategies in multi-family apartment buildings using uncertainties in relevant parameters. Uncertainty propagation is introduced to treat the parameters which are not 'deterministic' but 'probabilistic'. In the paper, significant parameters in the influence on ventilation strategies are identified, and the uncertainty range of parameters is then estimated based on the literature and on-site visits. Finally, through the Latin Hypercube Sampling (LHS) method, ventilation strategies are assessed. The paper addresses the fact that uncertainty in modeling ventilation strategies is significant and without introducing the stochastic nature of the ventilation phenomena the deterministic estimation of the ventilation strategies in residential buildings may lead to limited or false conclusions.

UNCERTAINTY ANALYSIS

When estimating a ventialtion strategy in a given situation, performing a standard deterministic simulation may hide important information. The reason for this is that the result is strongly influenced by the chosen value of input parameters which should in fact be treated as stochastic variables whose values are not deterministically obtainable but are known to be within a certain range and generally obey a certain probability distribution within that range. Fig. 1 shows the difference between the deterministic approach and the probabilistic approach. The deterministic approach executes a simulation using default values for parameters, while the probabilistic approach executes a series of simulations considering the probabilistic properties of the parameters. Although both designs in Fig. 1 comply, design 2 is regarded as better than design 1 since the output is farther from the limit (Fig. 1a). But, if the design is evaluated based on the probability of not meeting the minimum energy cost, design 1 is considered better than design 2 (Fig. 1b).



(a) deterministic approach



(b) probabilistic approach

Figure 1 Deterministic approach vs probabilistic approach (Wouters et al, 2004)

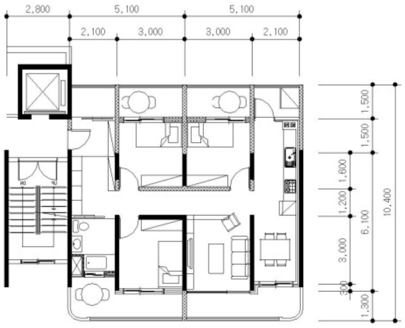
Therefore, if one treats the problem in a deterministic fashion, it could easily happen that, with a favorable set of assumptions and parameters, the design team could knowingly or unknowingly present the clients with an overly optimistic value. This will result in situations where some consultants may mislead the clients whereas other consultants would use different assumptions for the parameters leading to non-compliance of the design. This could make the performance assessment as well as code checking process erroneous, especially when inexperienced consultants are involved.

Experienced consultants will recognize the impact of their assumptions on the end result, and therefore perform a sensitivity analysis with different parameter values. This is time consuming and difficult to do in a systematic fashion. In comparing different design alternatives, the probabilistic approach delivers more meaningful information than one single or even a series of deterministic simulations.

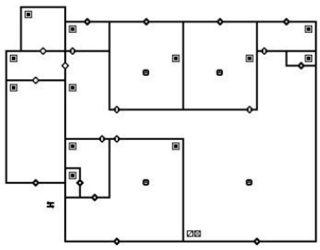
SIMULATION

Simulation model and tool

A 5-story residential building in Jeju, Korea was selected for analysis of the ventilation strategies. In terms of size and floor plan, the building is a typical of residential building. Fig. 2(a) shows the floor plan consisting of a master bedroom (MR), two additional bedrooms (BR1, BR2), a living room (LR), and a kitchen. To simulate airflow entering the building, CONTAMW 2.4 (Walton, 2005), developed by the National Institute of Standards and Technology, was used. CONTAMW 2.4 is one of several well known flow simulation programs that use the so-called nodal flow network approach. This approach has proven adequate for determining macro flow phenomena such as overall ventilation rates (Walton, 2005). The alternative way of conducting ventilation studies is to use the computationally intensive Computational Fluid Dynamics (CFD) programs. CFD is adequate if one is interested in detailed information about flow patterns around the building and inside rooms. Fortunately, the use of nodal flow simulation is appropriate for the macro ventilation outcomes of interest in this study. The use of CFD would become a bottleneck for the large number of simulation runs required for uncertainty analysis. CONTAMW 2.4 has been used extensively for the design and analysis of the indoor air quality of buildings (Walton, 2005). For the provided nodal flow network, CONTAMW predicts time histories of the airflows between nodes and time varying concentrations of indoor pollutants. In the CONTAMW model, the living room and kitchen were modeled as a single space (Fig. 2(b)). For mechanical ventilation simulation runs, winter days from Oct. 1 to Feb. 28 were chosen because most occupants in Korea make the maximum use of natural ventilation during the spring, summer, and fall seasons. In the simulation runs, all windows were assumed to be closed and indoor doors to be open. Infiltration was assumed to occur through the openings.



(a) Floor plan



(b) CONTAMW 2.4 model

Figure 2 Floor plan and CONTAMW 2.4 model

Ventilation strategies and assessment criteria

According to the outdoor air supply rate (CAV, DCV-CO_2), air inlet position (LR, LR+MR), and CO_2 sensor position (LR, LR+MR, every room), eight ventilation strategies were chosen, as shown in Table 1. The air inlets were usually placed in the LR or in the LR and MR, which is typical in Korea. It was assumed that CO_2 sensors could be installed in each room, because the additional cost was not high (100,000–150,000 W/ea). The CO_2 sensors were assumed to be installed in the LR, or in the LR and MR, or in the LR, MR, BR1, and BR2.

The capacity of the ERV was set at 200 CMH (Cubic Meter per Hour) for both the CAV and the DCV-CO_2 methods. When the air inlets were installed in the LR and MR, the air supply was set at 50 CMH for the MR and 150 CMH for the LR.

Table 1
Eight ventilation strategies

Ventilation Strategy ID#	Outdoor Air Supply rate	Air Inlet Position	Position of the CO_2 Sensor
1	CAV	LR	None
2	CAV	LR + MR	None
3	DCV-CO_2	LR	LR
4	DCV-CO_2	LR	LR + MR
5	DCV-CO_2	LR	LR + MR + BR1 + BR2
6	DCV-CO_2	LR + MR	LR
7	DCV-CO_2	LR + MR	LR + MR
8	DCV-CO_2	LR + MR	LR + MR + BR1 + BR2

To assess the eight ventilation strategies in Table 1, four criteria (initial investment cost, energy cost, PD, and CO_2 concentration) were selected. The initial investment cost was obtained from the data provided by two ventilation companies. The energy cost includes fan energy use and heating energy.

Fan cost data were provided by the participating company. The heating energy calculation was based on NEN 2916 (1999), which provides the calculation standard through a set of specified normative processes. All energy flows are calculated using the multiplication of the building system efficiency, generation and delivery efficiencies, and utilization factors which account for dynamic effects. For the heating energy calculations, the hourly weather data of Jeju (winter months, Oct. 1-Feb. 28) was used (TMY2,http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/). The PD was calculated using the method suggested by Fanger (1988).

For the measure of IAQ, the CO_2 concentration was selected since it is a typical contaminant generated primarily by occupants. In addition, measurement of CO_2 in occupied spaces has been widely used to evaluate the sufficiency of outdoor air supplied to indoor spaces (ASHRAE, 2005; KMOCT, 2006). The threshold of CO_2 concentration in the code was chosen to be 1,000 ppm, which is a non-mandatory but recommended value (KMOCT, 2006). The number of occupants in each room (Fig. 2) was obtained through on-site interviews and questionnaires (Table 2). The outdoor CO_2 concentration was assumed to be 380 ppm (KMA, 2006).

Uncertainty parameters

Based on literature (Walton, 2005; KMA, 2006; ASHRAE, 2001; KS, 2003; Lee, 1997; Moon, 2005) and on-site interviews using questionnaires, uncertainties in parameters influencing the ventilation strategies were identified, as shown in Table 2. The parameters include the stochastic nature of weather, occupants' behavior, building components, and simulation parameters.

The minimum, maximum, and base values of the selected parameters were then identified. Due to a lack of explicit information on the parameter distribution, normal distributions were assumed for all parameters. In other words, the lower and upper boundaries of the parameters were interpreted as a central 95% confidence interval where the base values of the parameters were mapped to the mean values of normal distributions. In addition, all the parameters were assumed to be independent of each other. It should be noted that in Table 2, wind direction is not included, but its effect is reflected in the wind pressure coefficient. The occupants' behaviors were obtained from on-site interviews and questionnaires conducted for 32 families.

Table 2

Uncertain parameters and their minimum, maximum, and base values

Parameter		Min	Base	Max	References
Wind velocity (m/s)		1.10	2.15	5.20	KMA (2006)
Outdoor temperature (℃)		2.5	10.6	25.3	KMA (2006)
The number of occupants (persons)	MR	0.42	0.83	1.54	Interview (Hyun et al, 2006)
	BR1	0	0.46	1.16	
	BR2	0	0.38	0.71	
	LR	0.37	1.17	2.33	
The difference of indoor temperature (℃)	LR - MR	-2.60	0.50	1.40	Experiment
	LR - BR1	-2.60	0.50	1.40	
	LR - BR2	-2.60	0.50	1.40	
Front door leakage area (cm^2/ea)		24	41.8	248.6	ASHRAE (2001) KS (2003) Lee (1997)
The leakage area of window (cm^2/m^2)		1.9	4.3	9	ASHRAE (2001) KS (2003)
Flow exponent		0.6	0.65	0.7	Walton (2005)
C_d, Discharge coefficient		0.6	0.675	0.75	ASHRAE (2001) Lee (1997)
C_P, wind pressure coefficient		0	0.5	1	Moon (2005)
Wind speed profile exponent		0.33	0.33	0.4	Moon (2005) Walton (2005)
Local terrain constant		0.28	0.28	0.40	Moon (2005) Walton (2005)

The Latin Hypercube Sampling (LHS) Method

The Latin Hypercube Sampling (LHS) method, which is a Monte Carlo technique, was utilized for uncertainty propagation (Wyss and Jorgensen, 1998). The LHS is a form of stratified sampling. The domain of each parameter was subdivided into N disjoint intervals with equal probability mass. In each interval, a single sample was randomly drawn from the associated probability distribution. Application of this technique provides good coverage of the parameter space with relatively few samples compared to the standard brute force random sampling. More information can be found in Wyss and Jorgensen (1998). Parameter samples were generated using an LHSNORM function in the MATLAB 7.0 Statistics Toolbox and a total of 30 simulation cases were propagated. The number of generated samples is well above the value of 4 k /3 (4 k /3=21.33, where k=16 is the number of parameters) that Iman and Helton (1985) recommended as a minimum. Consequently, a total of 240 simulations (30 simulation cases * 8 ventilation strategies) were conducted for the eight ventilation strategies.

Validation of the approach

Unfortunately, no measurements of the ventilation rate reflecting the aforementioned ventilation uncertainties have been reported. Multi-family apartment buildings in Korea differ from western residential dwellings in construction, building components, and living patterns. Thus, foreign data cannot be used. The only available data from domestic literature are infiltration assessments using a blower door test (Lee *et al.*, 2007), tracer gas (Ahn, 2005; Choi *et al.*, 2006; Lee *et al.*, 2000; Yeo *et al.*, 2003), and pressure measurements (Park *et al.*, 2001). Hence, a tentative comparison was made to test our approach. For the purpose of comparison, 30 uncertainty simulations were run to simulate infiltration phenomena in addition to the 240 simulation runs which were conducted for the mechanical ventilation phenomena. The 30 simulation results (dashed line in red) are shown in Fig. 3 with the measured infiltration rates, which vary widely from 0.18 to 0.62. The minimum, average, and maximum ACH of the 30 simulation runs are 0.02, 0.22, and 0.63, respectively, which confirms the strong influence of the uncertainty in the parameters on the resulting ventilation. As shown in Fig. 3, the uncertainty propagation generated by the LHS method reasonably covers the measured infiltration rates.

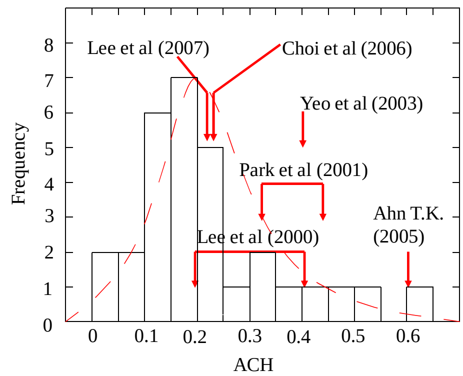


Figure 3 Comparison of the simulated and measured infiltration rates

RESULTS

Initial investment cost

Table 3 shows the initial investment costs of the ventilation strategies. The initial cost increases with an increase of the number of air inlets (LR → LR and MR) and sensors.

Table 3

Initial investment cost

Ventilation strategy ID# (Table 1)	Initial investment cost (Kwon)
1	750,000
2	1,100,000
3	900,000
4	1,050,000
5	1,200,000
6	1,250,000
7	1,400,000
8	1,550,000

Energy cost

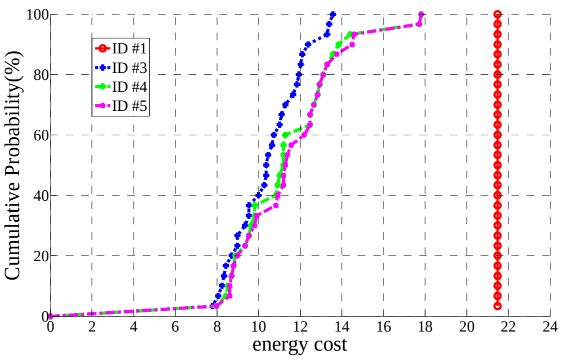
Table 4 shows the minimums, maximums, base values, average values, and standard deviations of the energy cost. The DCV-CO_2 based ventilation strategies, ID #3-8, supply the required outdoor air rate based on the sensor inputs, which leads to different energy costs between the strategies while the CAV-based strategies, IDs #1 and 2, have a constant energy cost. This means that the DCV-CO_2 methods (#3-8) are far more advantageous than the CAV methods (#1, 2) in terms of energy cost. In addition, the minimums, maximums, base values, and average values of the DCV-CO_2 methods show significant differences. This means that the simulation results may be influenced by the selected values of the uncertainty parameters.

Table 4

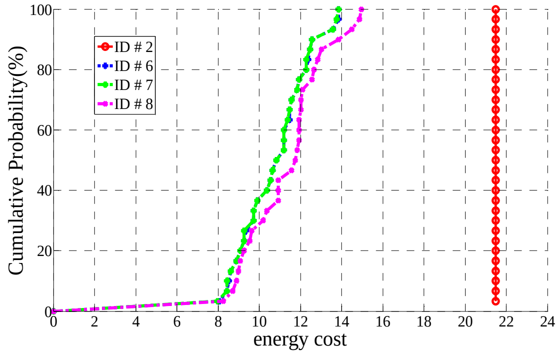
Comparison of energy cost (Kwon/year)

ID # (Table 1)	Min	Base	Max	Ave rage	Standard Deviation
1	214, 850	214, 850	214, 850	214, 850	-
2	214, 850	214, 850	214, 850	214, 850	-
3	77, 909	102, 720	135, 810	104, 807	16,525
4	79, 747	109, 160	178, 090	114, 763	25,008
5	79, 747	109, 160	178, 090	116, 356	24,945
6	80, 666	106, 400	138, 570	108, 268	16,488
7	79, 747	106, 400	138, 570	108, 084	16,517
8	82, 504	110, 080	149, 600	113, 999	18,532

Fig. 4 shows the cumulative probability of the energy cost. Fig. 4(a) compares the CAV and the DCV-CO_2 methods where air inlets are installed in the MR. It can be seen that the DCV-CO_2 methods are better than the CAV methods in terms of energy cost. The CAV methods with constant ventilation (0.7 h^{-1}) have a constant energy cost, as shown in Fig. 4. The energy costs depending on the location of the CO_2 sensors are shown in Fig. 4(a) (ID #3-5) and Fig. 4(b) (ID #6-8). The energy cost was lower when the CO_2 sensors were installed together with the air inlets, as shown in Fig 4. (ID #3, 7).



(a) Ventilation strategy ID #1 , #3, #4, and, #5



(b) Ventilation strategy ID #2, #6, #7, and, #8

Figure 4 Energy cost

The payback periods of different strategies are shown in Table 5. A simple payback method, without introducing interest rates, was chosen in the study. Table 5 shows the results classified by installation position of the air inlet. The comparisons of ID #1 and 3 and those of ID #2 and 6 show relatively short payback periods.

Table 5

payback period (Year)

	Comparison of	Payback period (year)
Air Inlet Position (LR)	ID #3 with #1	1.4
	ID #4 with #1	3.0
	ID #5 with #1	4.6
Air Inlet Position (LR+MR)	ID #6 with #2	1.4
	ID #7 with #2	2.8
	ID #8 with #2	4.5

Percentage Dissatisfied (PD)

Table 6 shows the PD values of the ventilation strategies. It suggests that the uncertain parameters should be carefully selected since there are significant differences between the minimums, maximums, base values, and average values.

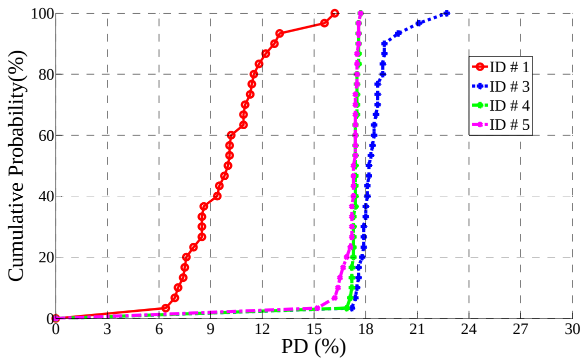
The PD is inversely proportional to the energy cost. In other words, the CAV method constantly supplies a sufficient air flow rate and is more advantageous than the DCV-CO_2 method in terms of PD. Obviously, the DCV-CO_2 method is advantageous in terms of energy, because the rooms are kept under a specified limit (1,000 ppm).

Based on the comparisons of ID #3-5 and ID #6-8, the influence of the number of CO_2 sensors on PD is not significant.

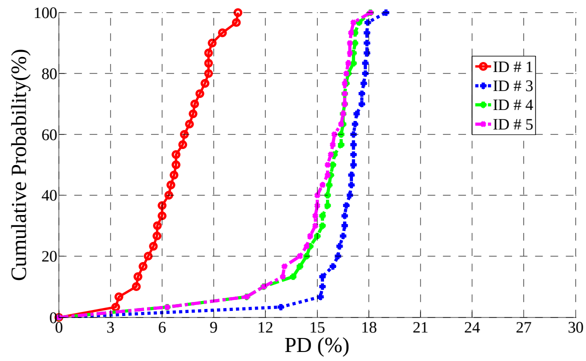
Fig. 5 shows the PD in the LR and MR. The CAV methods are more advantageous than the DCV-CO_2 methods in terms of PD. The PD in BR1 and BR2 are not presented in this paper but are similar to the results shown in Fig. 5. It is most advantageous when the CO_2 sensors are installed in each room (ID #5 and 8), regardless of the air inlet position (ID #3 vs. #5, ID #6 vs. #8).

Table 6
Comparison of PD (%)

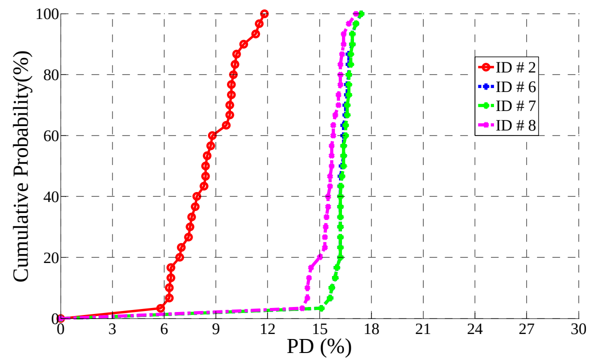
ID #	Room	Min	Base	Max	Average	Standard Deviation
1	MR	6.4	9.8	16.2	10.1	2.4
	BR 1	0.0	9.1	12.4	9.1	2.4
	BR 2	0.0	9.0	12.7	8.8	2.4
	LR	3.3	6.7	10.4	6.9	1.9
	Average	**2.4**	**8.7**	**12.9**	**8.7**	**2.3**
2	MR	5.8	8.2	11.8	8.6	1.7
	BR 1	0.0	9.1	12.6	9.0	2.5
	BR 2	0.0	8.7	12.7	8.7	2.4
	LR	4.1	7.6	11.0	7.6	1.8
	Average	**2.5**	**8.4**	**12.0**	**8.5**	**2.1**
3	MR	17.2	18.1	22.7	18.5	1.1
	BR 1	0.0	17.4	19.6	17.2	3.5
	BR 2	0.0	16.9	18.9	16.7	3.3
	LR	12.9	17.3	19.0	16.9	1.2
	Average	**7.5**	**17.4**	**20.1**	**17.3**	**2.3**
4	MR	16.9	17.6	17.7	17.4	0.2
	BR 1	0.0	16.5	19.6	15.9	3.4
	BR 2	0.0	16.9	17.6	15.8	3.2
	LR	6.3	15.6	18.1	15.4	2.3
	Average	**5.8**	**16.7**	**18.3**	**16.1**	**2.3**
5	MR	15.2	17.6	17.7	17.2	0.5
	BR 1	0.0	16.5	17.6	15.7	3.3
	BR 2	0.0	16.9	17.6	15.6	3.2
	LR	6.3	15.6	18.1	15.2	2.3
	Average	**5.4**	**16.7**	**17.8**	**15.9**	**2.3**
6	MR	15.1	16.1	17.4	16.4	0.4
	BR 1	0.0	17.4	19.6	17.1	3.5
	BR 2	0.0	18.1	19.3	16.7	3.3
	LR	15.0	16.9	19.4	17.2	0.9
	Average	**7.5**	**17.1**	**18.9**	**16.9**	**2.0**
7	MR	15.1	16.1	17.4	16.4	0.5
	BR 1	0.0	17.4	19.6	17.1	3.5
	BR 2	0.0	18.1	19.3	16.7	3.3
	LR	15.0	16.9	19.4	17.2	0.9
	Average	**7.5**	**17.1**	**18.9**	**16.9**	**2.1**
8	MR	14.0	15.6	17.1	15.6	0.8
	BR 1	0.0	17.4	17.6	16.3	3.2
	BR 2	0.0	16.9	17.6	16.1	3.2
	LR	13.0	16.2	19.0	16.2	1.2
	Average	**16.5**	**16.6**	**17.8**	**16.1**	**2.1**



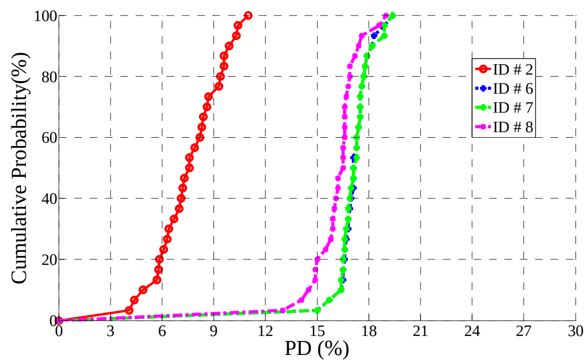
(a) Ventilation strategy ID #1, #3, #4, and #5-MR



(b) Ventilation strategy #1, #3, #4, and #5-LR



(c) Ventilation strategy #2, #6, #7, and #8-MR



(d) Ventilation strategy ID #2, #6, #7, and #8-LR
Figure 5 PD

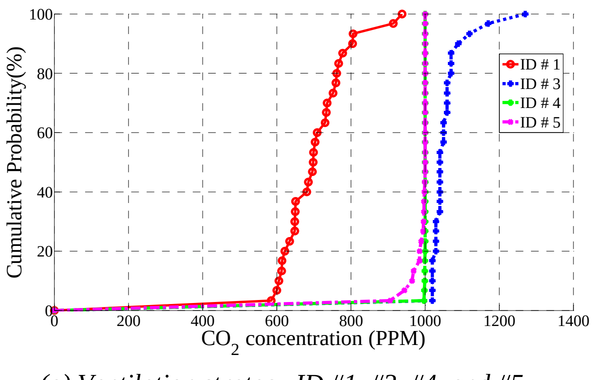
CO_2 concentration

Table 7 shows the CO_2 concentration (ppm) in each room. There are significant differences among the minimums, maximums, base values, and average values, as with the energy cost (Table 4) and PD (Table 6).

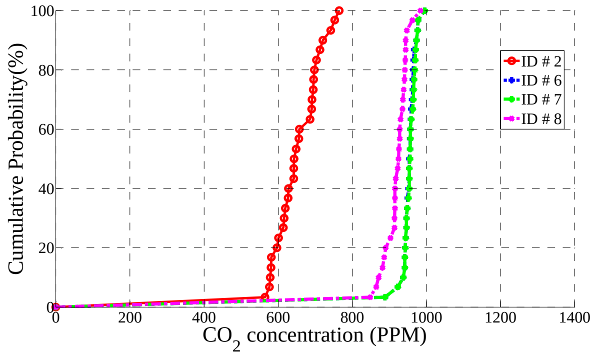
As shown in Fig. 6, the CAV methods are more advantageous in terms of CO_2 concentration than the DCV-CO_2 methods since the CAV methods constantly supply sufficient outdoor air, while the DCV-CO_2 methods only control the indoor CO_2 concentration to be not greater than 1,000 ppm. Fig. 6 shows the CO_2 concentration in the MR according to location of the CO_2 sensors (LR (ID #3, 6), LR+ MR(ID #4, 7), and each room(ID #5, 8)). The ventilation strategies IDs #5 and 8 are excellent, but only marginally different from IDs #3, 4, 6, and 7.

Table 7
Comparison of CO_2 Concentration (ppm)

ID #	Measurement Position	Min	Base	Max	Average	Standard Deviation
1	MR	585	692	938	708	86
	BR1	582	668	793	681	62
	BR2	570	663	809	672	60
	LR	561	636	745	648	53
	Average	575	665	821	677	65
2	MR	585	641	765	655	56
	BR1	579	667	800	679	62
	BR2	567	661	810	669	60
	LR	560	634	746	645	53
	Average	573	651	780	662	58
3	MR	1020	1050	1270	1058	51
	BR1	1000	1030	1120	1034	27
	BR2	998	1020	1070	1025	15
	LR	996	998	1000	1000	1
	Average	1004	1025	1115	1029	24
4	MR	997	1000	1000	1000	1
	BR1	749	984	1100	978	61
	BR2	765	978	1030	969	50
	LR	736	951	983	945	51
	Average	812	978	1028	973	41
5	MR	906	1000	1000	991	20
	BR1	749	984	1000	967	52
	BR2	765	978	1000	959	48
	LR	736	951	977	935	49
	Average	789	978	994	963	42
6	MR	889	946	996	954	19
	BR1	1000	1030	1120	1035	27
	BR2	1000	1030	1080	1025	17
	LR	996	1000	1000	999	1
	Average	971	1002	1049	1003	16
7	MR	889	946	996	955	19
	BR1	1000	1030	1120	1036	26
	BR2	1000	1030	1080	1026	18
	LR	997	1000	1000	1000	1
	Average	972	1002	1049	1004	16
8	MR	849	922	984	921	29
	BR1	956	1000	1000	993	11
	BR2	900	998	1000	985	23
	LR	883	972	991	962	24
	Average	897	973	994	965	22



(a) Ventilation strategy ID #1, #3, #4, and #5



(b) Ventilation strategy ID #2, #6, #7, and #8
Figure 6 CO_2 concentration (MR)

CONCLUSIONS AND FUTURE WORK

The premise underlying this work is that in assessing ventilation strategies in residential dwellings, uncertainty should be taken into account. Thus, a probabilistic approach was applied which is capable of capturing the stochastic characteristics of ventilation phenomena.

It was shown that the CAV methods (#1, 2) are more advantageous than the DCV-CO_2 methods (#3-8) in terms of initial cost. The DCV-CO_2 methods are more advantageous in terms of energy cost, and the investment payback periods are very short. The CAV methods, on the other hand, are advantageous in terms of PD and CO_2 concentration because they constantly supply sufficient outdoor air.

In the case of the DCV-CO_2 methods, the energy cost, PD, and CO_2 concentration were compared according to the position of the CO_2 sensors. The energy cost is the lowest when a CO_2 sensor is installed together with an air inlet (see ID #3 and 7 in Table 4). In other words, it is recommended to install the sensors and the air inlets at the same locations. In terms of PD, it is advantageous for the sensor to be installed in each room, but the differences are not significant when they were compared according to the A, B, and C categories suggested by Fanger (1988). It was also found that there is a marginal difference in the CO_2 concentration depending on the position of the sensor. Conclusively, the quantitative appraisal of the uncertainty in eight ventilation strategies (1) yields more complete and therefore, more meaningful information, (2) contributes to more rational design decisions, and (3) will help to improve confidence in simulation results. Following this successful application of uncertainty propagation to eight ventilation strategies, future studies may include:

- *Uncertainty analysis for different floor plans and climates*: Applying the proposed Monte Carlo method to various floor plans such as two bedroom, three bedroom, and four bedroom apartment units as well as different climates.

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