Sensitivity Analysis of Parameters affecting Indoor Air Quality related to HCHO and TVOC Reduction

Mi Yeon Kim[1], Hae Jin Kang[1], Jin Chul Park[2], Eon Ku Rhee[2]

[1] Graduate Program, Dept. of Architecture, Chung-Ang University, Seoul, Korea 156-756
[2] Professor, Dept. of Architecture, Chung-Ang University, Seoul, Korea 156-756

Abstract
The objective of the study is to analyze the relative performance of factors affecting indoor air quality in multi-residential buildings in Korea. A study of the factors affecting indoor air quality is essential for establishing indoor air quality management strategies effectively. To observe the indoor air quality response following a modification of a given parameter sensitivity analysis was performed. The factors examined for the analysis include; wall+ceiling paper, adhesive for wall/ceiling paper, floor material, adhesive for floor material, and ventilation rate. The experimental design system which offers main effects among the design parameters with a few experiments was used to decrease the number of experiments. The simulation for indoor air quality was undertaken using a validated equation. Then, ANOVA(Analysis of Variance) was performed to evaluate the relative importance of each parameter affecting the indoor air quality. The result of the study indicates that the indoor air quality may be influenced most by adhesive for wall/ceiling paper, followed by ventilation rate and adhesive for floor material.

Keywords: Indoor Air Quality, Sensitivity Analysis, ANOVA, Residential Building

1.Introduction

As the importance of indoor air quality is increased in Korea, recommended standards and relevant regulations have been being established. Particularly in newly built residential buildings having 100 or more units, total volatile organic compounds (TVOC) and formaldehyde (HCHO) should be measured and notified to residents mandatorily prior to occupation. In order to meet recommended standards, the designer and engineers have a tendency to apply almost all IAQ strategies such as eco-labeled interior materials, ventilation, and bake-out in addition. However careless application of IAQ strategies can lead to overuse of cost or materials ineffectively. This is due to the lack of information of relative importance of factors affecting indoor air quality and of factor characteristics. Therefore, a study of the parameters affecting indoor air quality is essential for better establishing strategies of indoor air quality improvement.

2. Research Scope and Methodology

The scope and methods of this study are summarized as follows in the order of progress of sensitivity study. However, there are no formal rules and well-defined procedure for performing sensitivity analysis for indoor air quality, because the objectives of each study are different and building description are quite complicated. In most cases, perturbation technique and sensitivity methods are being used to study the impacts of parameters on different simulation outputs, compared to a base case situation. Then, the results are interpreted and generalized so as to predict the likely response of the performance.

1) Selection of parameters of indoor air quality

Important parameters of the indoor air quality are identified and analyzed from the point of view of intensity reduction of HCHO and TVOC. In order to identify major parameters for HCHO and TVOC applicable to multi-residential buildings, relevant research was reviewed.

2) Establishing base case reference and simulations

To formulate a base case reference, a survey of multi-residential buildings located in Soul was conducted. The equation for the basis of simulation is selected. The equation is approved and used in the Ministry of Environment. In order to secure the validity of equation, actual data of several residential buildings are compared with the result of the equation.

3) ANOVA(Analysis of Variance)

To obtain the factors largely affecting HCHO and TVOC reduction, sensitivity analysis and ANOVA(analysis variance) were conducted. The system of experimental design which offers information about the main effect among the parameters with a few experiments was used to decrease the number of simulations.

3. Identification of relative importance factors applicable to multi-residential buildings

Before performing the analysis, it is essential to understand what parameters are to be studied. A list of the parameters was prepared, and they represented a variety of different factors encountered in multi-residential building design and construction. They are categorized according to applicable sequences ; design stage and construction stage. In each stage, different sub-parameters are divided as shown in Table 1. As shown in Table1, ventilation strategies can be applied in every stage. However, all strategies in terms of ventilation are integrated into total ventilation rate. Bake-out is excluded from analysis due to theoretical uncertainty and largely-fluctuated results depending on the conditions during the bake-out. Therefore, it was finally determined to include; wall+ceiling papers, adhesive for wall/ceiling papers, floor material, adhesive for floor material, ventilation rate.

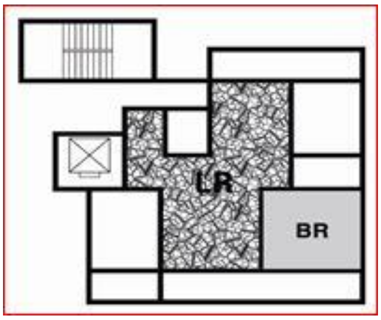
Table 1 Parameters affecting to HCHO, TVOC reduction

Applicable Stage	Category		Parameters
Design	Interior Materials	Finishing Materials	Wall+Ceiling paper
			Floor materials
			Adhesive for Wall/Ceiling paper
			Adhesive for Floor materials-
	Ventilation Strategy	Natural ventilation	Space Planning
			Opening Size & Location
		Forced Ventilation	Ventilation System
Construction	Ventilation Strategy	Natural Ventilation	Ventilation Periods, Ventilation Quantity
		Forced Ventilaton	
	Bake-out	Bake-out	Bake-out temperature, Periods

4. The base case reference for simulation

The base case model forms a very important part in the analysis because all subsequent calculation and analysis are based on the comparison with it. A base case multi-residential building has been established from a survey in Seoul. The characteristics of base case model was determined by careful examination of typical design. Brief description and the plan of the base case building is given in Table 2.

Table 2 Brief description of building and Plan

Plan 	Total Area		108.9 m^2
	LR	Volume	100.8m^3
		Wall-Ceiling Area	130.1 m^2
		Floor Area	42.0 m^2
	BR	Volume	39.4 m^3
		Wall-Ceiling Area	55.4 m^2
		Floor Area	16.4 m^2
Ventilation	Ventilation Rate		0.7/h
Outdoor Air	HCHO		6.00 mg/m^3/h
	TVOC		101.90 mg/m^3/h

The total area of the base case is 108.9 m^2. Among the space, the living room and bed room in which good level finishing materials in eco-label mark are applied are selected for sensitivity analysis. The ventilation rate is 0.7/h, the minimum standard in a multi-residential building. The outdoor HCHO and TVOC intensity was 6.00 mg/m^3/h and 101.90 mg/m^3/h.

5. Experiment Design and Simulation

To determine the relative importance of each parameter on HCHO and TVOC reduction, all other parameters should be fixed and one parameter should be changed diversely to review how the results change. However, even if the five parameters presented in Table 4 are changed in only three levels, as many as 3^5(=279) simulations will be required, making the analysis almost impossible.

Table 3 Brief description of building and Plan

Categorize	Parameters	Level		
		1	2	3
Finishing Materials	Wall+Ceiling paper	General	Good	Excellent
	Floor materials	General	Good	Excellent
	Adhesive for Wall/Ceiling paper	General	Good	Excellent
	Adhesive for Floor materials	General	Good	Excellent
Ventilation Rate		0.5/h	0.7/h	0.9/h

However, if a design of experiment called Orthogonal Arrays is used, the same results as the calculation of entire simulation can be induced by only implementing small number of simulations. According to the Orthogonal Arrays it is possible to reduce the number of simulation up to 27($L_{27}(3^{13})$). However to secure p-value in statistical analysis, the reduced number of simulation was limited to 81 as partly shown in Table 5.

Table 5 Orthogonal Arrays($L_{81}(3^{40})$)

43	1	1	2	0	2	0	1	0	1	2	1	2	0	0	1	2	1	2	0	2	0	1	2	0	1	0	1	2	1	2	0	1	2	0	2	0	1	0	1	2
44	1	1	2	0	2	0	1	0	1	2	1	2	0	1	2	0	2	0	1	0	1	2	0	1	2	1	2	0	2	0	1	2	0	1	0	1	2	1	2	0
45	1	1	2	0	2	0	1	0	1	2	1	2	0	2	0	1	0	1	2	1	2	0	1	2	0	2	0	1	0	1	2	0	1	2	1	2	0	2	0	1
46	1	2	0	1	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0
47	1	2	0	1	0	1	2	2	0	1	1	2	0	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1
48	1	2	0	1	0	1	2	2	0	1	1	2	0	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2
49	1	2	0	1	1	2	0	0	1	2	2	0	1	0	1	2	2	0	1	1	2	0	1	2	0	0	1	2	2	0	1	2	0	1	1	2	0	0	1	2
50	1	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	2	0	1	2	0	1	1	2	0	0	1	2	0	1	2	2	0	1	1	2	0
51	1	2	0	1	1	2	0	0	1	2	2	0	1	2	0	1	1	2	0	0	1	2	0	1	2	2	0	1	1	2	0	1	2	0	0	1	2	2	0	1
52	1	2	0	1	2	0	1	1	2	0	0	1	2	0	1	2	2	0	1	1	2	0	2	0	1	1	2	0	0	1	2	1	2	0	0	1	2	2	0	1
53	1	2	0	1	2	0	1	1	2	0	0	1	2	1	2	0	0	1	2	2	0	1	0	1	2	2	0	1	1	2	0	2	0	1	1	2	0	0	1	2
54	1	2	0	1	2	0	1	1	2	0	0	1	2	2	0	1	1	2	0	0	1	2	1	2	0	0	1	2	2	0	1	0	1	2	2	0	1	1	2	0
55	2	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1
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57	2	0	2	1	0	2	1	0	2	1	0	2	1	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0
58	2	0	2	1	1	0	2	1	0	2	1	0	2	0	2	1	0	2	1	0	2	1	1	0	2	1	0	2	1	0	2	2	1	0	2	1	0	2	1	0
59	2	0	2	1	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	2	1	0	2	1	0	2	1	0	0	2	1	0	2	1	0	2	1
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62	2	0	2	1	2	1	0	2	1	0	2	1	0	1	0	2	1	0	2	1	0	2	0	2	1	0	2	1	0	2	1	2	1	0	2	1	0	2	1	0
63	2	0	2	1	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	2	1	0	1	0	2	1	0	2	1	0	2	0	2	1	0	2	1	0	2	1
64	2	1	0	2	0	2	1	1	0	2	2	1	0	0	2	1	1	0	2	2	1	0	0	2	1	1	0	2	2	1	0	0	2	1	1	0	2	2	1	0
65	2	1	0	2	0	2	1	1	0	2	2	1	0	1	0	2	2	1	0	0	2	1	1	0	2	2	1	0	0	2	1	1	0	2	2	1	0	0	2	1
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69	2	1	0	2	1	0	2	2	1	0	0	2	1	2	1	0	0	2	1	1	0	2	0	2	1	1	0	2	2	1	0	1	0	2	2	1	0	0	2	1
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73	2	2	1	0	0	2	1	2	1	0	1	0	2	0	2	1	2	1	0	1	0	2	0	2	1	2	1	0	1	0	2	0	2	1	2	1	0	1	0	2
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79	2	2	1	0	2	1	0	1	0	2	0	2	1	0	2	1	2	1	0	1	0	2	2	1	0	1	0	2	0	2	1	1	0	2	0	2	1	2	1	0
80	2	2	1	0	2	1	0	1	0	2	0	2	1	1	0	2	0	2	1	2	1	0	0	2	1	2	1	0	1	0	2	2	1	0	1	0	2	0	2	1
81	2	2	1	0	2	1	0	1	0	2	0	2	1	2	1	0	1	0	2	0	2	1	1	0	2	0	2	1	2	1	0	0	2	1	2	1	0	1	0	2
[illegible]	B	F	■	■	D	■	■	■	A	■	■	C	■	■	■	G	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

For simulation, the equation which is used in the Ministry of Environment for chamber test is selected. The equation is shown in <Eq. 1>. Because <Eq. 1> was developed to figure out the emission intensities of material in the small chamber, < Eq. 1> is re-established by implementing the binomial theorem of < Eq. 2>.

$$EF = \frac{\left(C_t - C_{t_b.t}\right)\times Q}{A} = \frac{\left(C_t - C_{t_b.t}\right)\times nV}{A} = \left(C_t - C_{t_b.t}\right)\times q = \left(C_t - C_{t_b.t}\right)\times \frac{n}{L} \qquad \text{(Eq. 1)}$$

A	Area of materials (㎡)
Ct	HCHO and TVOC intensity during ‘t’ hours in the chamber (㎎/㎥)
Ctb,t	HCHO and TVOC intensity during ‘t’ hours in the empty chamber (㎎/㎥)
EFa	Emission intensity per area(㎎/㎡. h)
n	Ventilation rate (/hr)
Q	Ventilation rate in the chamber(㎥/h)
q	Ventilation rate per area(㎥/㎡. h)
t	‘t’ hours after starting experiment
V	Volume of the chamber(㎥)

$$C_t = \frac{\sum(EF_a \times A)}{n \times V} + C_{t_b.t} \qquad \text{(Eq. 2)}$$

A	Area of materials (㎡)
Ct	HCHO and TVOC intensity during 't' hours in the chamber (㎎/㎥)
Ctb,t	HCHO and TVOC intensity during 't' hours in the empty chamber (㎎/㎥)
EFa	Emission intensity per area(㎎/㎡ . h)
N	Ventilation rate (/hr)
Q	Ventilation rate in the chamber(㎥/h)
Q	Ventilation rate per area(㎥/㎡ . h)
T	't' hours after starting experiment
V	Volume of the chamber(㎥)

In order to secure the validity of IAQ simulation, actual indoor air quality data of several residential buildings were compared with results of < Eq. 2>. Based on the results, it was identified that differences were within 10% (0.2%-9%).

6. Analysis of variances(ANOVA)

ANOVA were conducted with the results of simulations. The relative importance of each parameter was obtained by the following equation

$$P_{A_0} = \frac{Y_1+Y_2+Y_3+\cdots+Y_{27}}{27} - T_m$$

P_{Ai}	Affections of each parameters on i level.
Y_i	HCHO or TVOC intensity of each experiment

T_m Total average of HCHO or TVOC intensity of 81 experiments

The result of the study indicates that, in terms of the contribution to TVOC reductions, adhesive for wall+ceiling paper was found to have the best contribution(49.9%(LR), 53.9%(BR)) followed by ventilation rate(31.9%(LR), 31.2%(BR)) and floor adhesive (7.3%(LR), 6.4%(BR)). As for HCHO, it was found that the contribution of reduction is greater as the following order; adhesive for wall+ceiling(59.3%(LR), 60.5%(BR)), ventilation rate(22.3%(LR), 22.4%(BR)) and floor-adhesives(8.0%(LR), 7.1%(BR)). It is considered that the other parameters' contributions are small enough to be negligible. (Table 6,7)

Table 6 The contribution rate to TVOC reduction

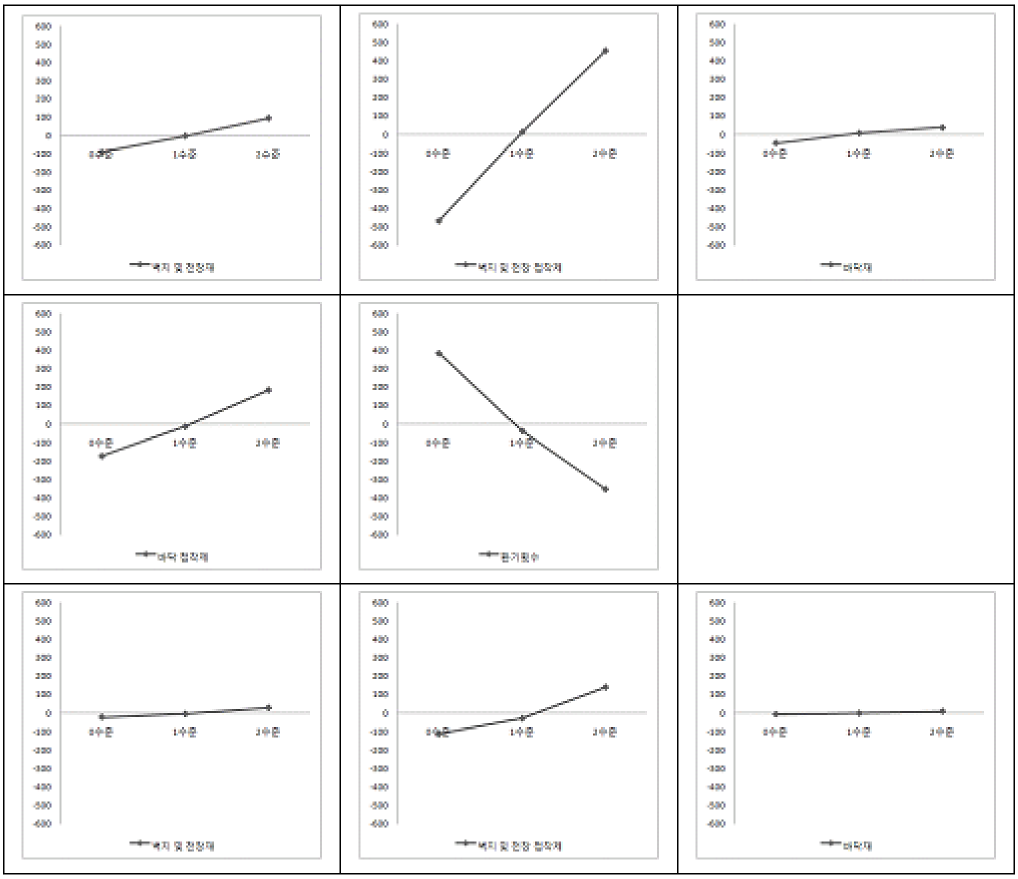
			Contribution to TVOC reduction in LR				Contribution to TVOC reduction in BR		
			0	1	2		0	1	2
A	Wall+Ceiling papers	1.8	-90.4	-2.8	93.2	1.5	96.8	-32.4	-64.4
B	Adhesive for Wall/Ceiling papers-	49.9	-467.0	13.2	453.8	59.3	-523.3	0.0	523.0
C	Floor materials	0.3	-46.8	8.0	38.8	0.1	-20.5	-5.1	25.6
D	Floor Adhesive	7.3	-171.6	-12.6	184.2	8.0	-188.9	15.7	173.2
E	Ventilation Rate	31.9	385.2	-35.0	-350.2	22.8	416.5	-37.9	-378.6

Table 7 The contribution rate to HCHO reduction

			Contribution to TVOC reduction in LR				Contribution to TVOC reduction in BR		
			0	1	2		0	1	2
A	Wall+Ceiling papers	1.5	96.8	-32.4	-64.4	1.5	96.8	-32.4	-64.4
B	Adhesive for Wall/Ceiling papers-	53.9	-112.0	-28.0	140.0	60.5	-122.1	-30.5	152.7

C	Floor materials	0.0	-7.2	-1.8	9.0	0.0	-7.2	-1.8	9.0
D	Floor Adhesive	6.4	-43.9	-6.8	50.7	7.1	-45.0	-6.4	51.4
E	Ventilation Rate	31.2	83.2	-7.6	-75.7	22.3	88.9	-8.1	-80.8

In figure 1, the contribution rates are illustrated in the gradient in graph. The more factors contribute to HCHO and TVOC reduction, the steeper the gradient is inclined. In the graph, 0 corresponds to the average intensity of HCHO and TVOC. Positive (+) values indicate that values are larger than the average intensity, and negative (-) values mean that values are smaller than the average intensity.



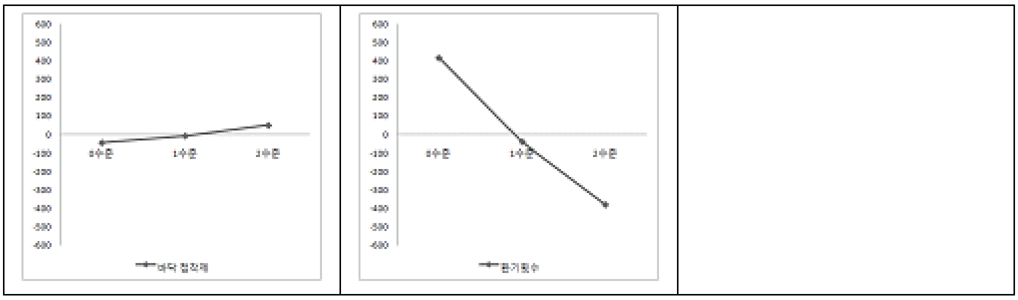


Fig. 1 Graph of the contribution rate

7. Conclusion

The objective of this study is to derive relative importance of factors which affect to reduce indoor HCHO and TVOC intensity. The HCHO/TVOC sensitivity analysis and ANOVA were conducted and the following conclusions were derived.

1) Through a literature search, the main factors affecting HCHO, TVOC are selected. The factors examined for the analysis include: wall+ceiling papers, floor materials, adhesive for wall/ceiling papers, adhesive for floor materials, ventilation rate.

2) For predicting HCHO, TVOC intensity, the equation which is approved and used by the Ministry of Environment is used. The equation is re-established because the original equation is made for testing the emission in the small chamber. The difference between equation and actual data was shown less than 10% and the reliability of the equation was secured.

3) By using orthogonal arrays, the number of simulations is reduced to 81. With the results of simulation, analysis of variance is conducted. As a results, adhesive for wall/ceiling paper was found to have the most contribution followed by ventilation rate and floor-adhesive.

Acknowledgments

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References

1. Go Eun-Hee, A Study on the Prediction of the Concentrations of Newly Built Multi-family Residential Buildings' Indoor Pollutants in Relation to the Selection of Finishing Materials, Master's Thesis, The Graduate School, Chung-Ang University, 2005

2. The number of times of ventilation in newly built multi-family residential buildings noticed to be legislated by the Ministry of Land, Transport and Marine Affairs to become effective as of January 2006.

3. The Ministry of Environment, indoor air quality process test method, 2004, p172