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A Sensitivity Analysis of Parameters Affecting Indoor Air Quality Related to TVOC and HCHO Reduction

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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, a 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 which identifies 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, Analysis of Variance, Residential Building, TVOC, HCHO

1. INTRODUCTION

As the importance of indoor air quality has been increased in Korea, various 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, 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 establishment of indoor air quality improvement strategies.

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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.

2.1 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 TVOC and HCHO. In order to identify major parameters for TVOC and HCHO applicable to multi-residential buildings, relevant research was reviewed.

2.2 Establishing base case reference and simulation equation

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

2.3 ANOVA(Analysis of Variance)

To obtain the major factors affecting TVOC and HCHO 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 IMPORTANT PARAMETERS APPLICABLE TO IAQ IMPROVEMENT IN MULTI-RESIDENTIAL BUILDINGS

Before performing the analysis, it is essential to understand what parameters are to be studied. A list of the parameters which represent a variety of different factors encountered in multi-residential building design and construction were identified. They were categorized according to applicable sequence; design stage and construction stage. In each stage, different sub-parameters were divided as shown in Table 1.

As shown in Table 1, 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 materials, adhesive for floor material, ventilation rate.

Table 1. Parameters affecting to TVOC/HCHO Reduction.

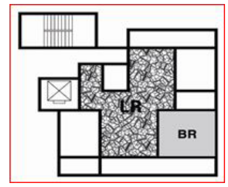
Stage	Category		Parameters
Design	Interior Materials	Finishing Materials	Wall/Ceiling Papers
			Floor materials
			Adhesive for Wall/ Ceiling Papers
			Adhesive for Floor materials
	Ventilation	Natural Ventilation Forced Ventilation	Ventilation Rate
Const-ruction	Ventilation	Natural Ventilation	
		Forced Ventilation	

4. CHARACTERISTICS OF BASE CASE MODEL

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, a prototype 33-pyung unit, were determined through careful examination of typical design. Brief description and the plan of the base case building are given in Table 2.

The total area of the base case is 108.9m2. Among the space, the living room and bedroom in which "good" level finishing materials in eco-label mark are applied are selected for sensitivity analysis. The ventilation rate is assumed 0.7/h. The outdoor TVOC and HCHO intensity was 6.00 mg/m3/h and 101.90 mg/m3/h

Table 2. Brief Description of Building and Plan

Plan	Total Area		108.9 m^2
	Living Room	Volume	100.8m^3
		Wall/Ceiling Area	130.1 m^2
		Floor Area	42.0 m^2
	Bed Room	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

5. EXPERIMENT DESIGN AND SIMULATION

The sensitivity analysis of IAQ performance was conducted for living-room and bedroom of the base model. The performance levels of each parameter were set to 3 levels (general, good, excellent) based on the HB certification system of Korean Air Cleaning Association (Table 3). The typical values of each level were assigned for the calculation.

To determine the relative importance of each parameter on TVOC and HCHO reduction, one parameter should be changed diversely to review how the results change while all other parameters are fixed. However, even if the five parameters presented in Table 3 are changed in only three levels, as many 35(=243) calculations are required, making the analysis very time-consuming. 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 81, while securing statistically significant p-value in analysis. Table 4 shows the Orthogonal Arrays used in this analysis. In each column of the orthogonal array, five parameters are arranged as follows: 2=Floor Materials; 5=Adhesive for Floor materials; 9=Wall/Ceiling Papers; 12=Adhesive for Wall/Ceiling Papers, 16=Ventilation Rate. The rest of the columns are dummies.

Table 3. Performance Levels of Parameters for Orthogonal Arrays

Category	Parameters		Level		
			1	2	3
Finishing Materials	Wall/Ceiling Papers	A	General	Good	Excellent
	Floor materials	B	General	Good	Excellent
	Adhesive for Wall/Ceiling Papers	C	General	Good	Excellent
	Adhesive for Floor materials	D	General	Good	Excellent
Ventilation Rate		E	0.5/h	0.7/h	0.9/h

Table 4. Orthogonal Array Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2
5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
7	0	0	0	0	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1
8	0	0	0	0	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2
9	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
10	0	1	1	1	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2
11	0	1	1	1	0	0	0	1	1	1	2	2	2	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0
12	0	1	1	1	0	0	0	1	1	1	2	2	2	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	1	1	1
13	0	1	1	1	1	1	1	2	2	2	0	0	0	0	0	0	1	1	1	2	2	2	1	1	1	2	2	2	0	0	0	2	2	2	0	0	0	1	1	1
14	0	1	1	1	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2	0	0	0	2	2	2	0	0	0	1	1	1	0	0	0	1	1	1	2	2	2
15	0	1	1	1	1	1	1	2	2	2	0	0	0	2	2	2	0	0	0	1	1	1	0	0	0	1	1	1	2	2	2	1	1	1	2	2	2	0	0	0
16	0	1	1	1	2	2	2	0	0	0	1	1	1	0	0	0	1	1	1	2	2	2	2	2	2	0	0	0	1	1	1	1	1	1	2	2	2	0	0	0
17	0	1	1	1	2	2	2	0	0	0	1	1	1	1	1	1	2	2	2	0	0	0	0	0	0	1	1	1	2	2	2	2	2	2	0	0	0	1	1	1
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27	0	2	2	2	2	2	2	1	1	1	0	0	0	2	2	2	1	1	1	0	0	0	1	1	1	0	0	0	2	2	2	0	0	0	2	2	2	1	1	1
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35	1	0	1	2	2	0	1	2	0	1	2	0	1	1	2	0	1	2	0	1	2	0	0	1	2	0	1	2	0	1	2	2	0	1	2	0	1	2	0	1
36	1	0	1	2	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	1	2	0	1	2	0	1	2	0	0	1	2	0	1	2	0	1	2
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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
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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
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56	2	0	2	1	0	2	1	0	2	1	0	2	1	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
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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For calculation, the equation which is used as the official test method for chamber test by the Ministry of Environment is selected. The equation is shown in <Eq.1>. Because <Eq.1> was developed to figure out the emission intensities of materials in the small chamber, <Eq.1> is re-established by implementing the binomial theorem of <Eq.2>.

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

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

A	*Area of materials (m^2)*
Ct	*HCHO and TVOC intensity during 't' hours in the chamber (mg/m^3)*
$C_{tb,t}$	*HCHO and TVOC intensity during 't' hours in the empty chamber (mg/m^3)*
EFa	*Emission intensity per area($mg/m^2.h$)*
n	*Ventilation rate (/hr)*
Q	*Ventilation rate in the chamber(m^3/h)*
q	*Ventilation rate per area($m^3/m^2.h$)*
t	*'t' hours after starting experiment*
V	*Volume of the chamber(m^3)*

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 indentified that differences were within 10% (0.2 - 9%).

6. ANALYSIS OF VARIANCE(ANOVA)

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

$$P_{A_0} = \frac{Y_1+Y_2+Y_3+\cdots+Y_{27}}{27} - T_m \qquad \text{Eq.3}$$

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 coefficient of determination ρT which implies the amount of variation that is explained by independent parameter was calculated using the following equation.

$$\rho_T (\%) = SST'/SST \times 100 \qquad \text{Eq.4}$$

ρ_T *Coefficient of Determination*
SST' *Sum of Square due to parameter*
SST *Total Sum of Square*

The result of the analysis is summarized from Table 5 to Table 8. The contribution implies the change of contaminant (TVOC or HCHO) level, compared to the base case model where all the parameters are set to "good" level. The negative value indicates the increase of contamination, while the positive value infers the improvement of IAQ. The result 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 paper (59.3%(LR), 60.5%(BR)) ventilation rate(22.3%(LR), 22.4%(BR)) and floor adhesive(8.0%(LR), 7.1%(BR)). It is considered that the other parameters' contributions are small enough to be negligible.(Table 5,6,7,8)

Table 5. The contribution rate to TVOC reduction (Living Room)

Category		ρ_T (%)	Contribution to TVOC Reduction (μg/m³)		
			1	2	3
A	Wall/Ceiling papers	1.8	-90.4	-2.8	93.2
B	Adhesive for Wall/Ceiling papers-	49.9	-467.0	13.2	453.8
C	Floor materials	0.3	-46.8	8.0	38.8
D	Floor Adhesive	7.3	-171.6	-12.6	184.2
E	Ventilation Rate	31.9	-385.2	35.0	350.2

Table 6. The contribution rate to TVOC reduction (Bedroom)

Category		ρ_T (%)	Contribution to TVOC Reduction (μg/m³)		
			1	2	3
A	Wall/Ceiling papers	1.1	-69.8	-17.4	87.2
B	Adhesive for Wall/Ceiling papers-	59.3	-523.3	0.0	523.0
C	Floor materials	0.1	-20.5	-5.1	25.6
D	Floor Adhesive	8.0	-188.9	15.7	173.2
E	Ventilation Rate	22.8	-416.5	37.9	378.6

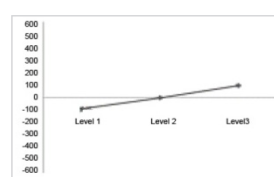
Table 7. The contribution rate to HCHO reduction Living Room)

Category		ρT (%)	Contribution to HCHO Level (μg/m³)		
			1	2	3
A	Wall/Ceiling papers	1.5	-96.8	32.4	64.4
B	Adhesive for Wall/Ceiling papers-	53.9	-112.0	-28.0	140.0
C	Floor materials	0.0	-7.2	-1.8	9.0
D	Floor Adhesive	6.4	-43.9	-6.8	50.7
E	Ventilation Rate	31.2	-83.2	7.6	75.7

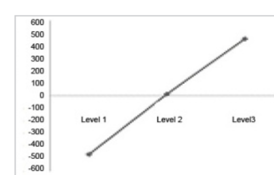
Table 8. The contribution rate to HCHO reduction (Bedroom)

Category		ρT (%)	Contribution to HCHO Level (μg/m³)		
			1	2	3
A	Wall/Ceiling papers	1.5	-96.8	32.4	64.4
B	Adhesive for Wall/Ceiling papers-	60.5	-122.1	-30.5	152.7
C	Floor materials	0.0	-7.2	-1.8	9.0
D	Floor Adhesive	7.1	-45.0	-6.4	51.4
E	Ventilation Rate	22.3	-88.9	8.1	80.8

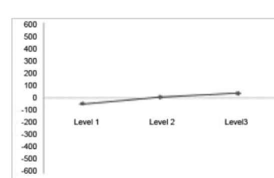
In figure 1,2,3,4, the contribution rates are illustrated in the gradient in graph. The more the factors contribute to TVOC and HCHO reduction, the steeper the gradient in inclined. In the graph, 0(zero) corresponds to the average intensity of TVOC and HCHO.



Wall/Ceiling papers



Adhesive for Wall/Ceiling papers-



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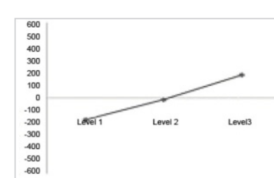
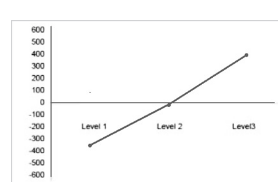
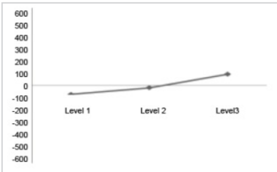


Floor Adhesive

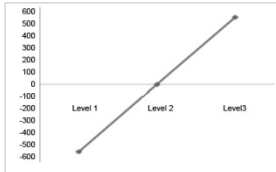


Ventilation Rate

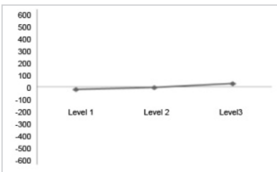
Figure 1. TVOC Reduction Contribution (Living Room)



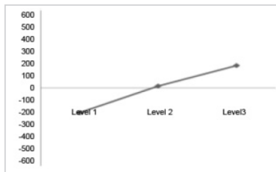
Wall/Ceiling papers



Adhesive for Wall/Ceiling papers-



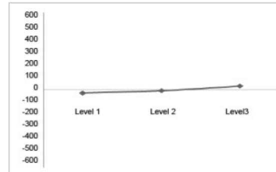
Floor materials



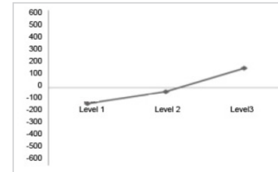
Floor Adhesive

Ventilation Rate

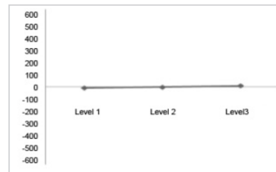
Figure 2. TVOC Reduction Contribution (Bed Room)



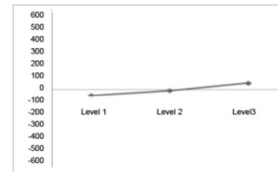
Wall/Ceiling papers



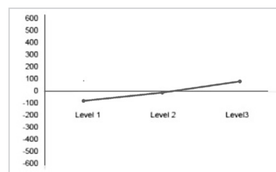
Adhesive for Wall/Ceiling papers-



Floor materials

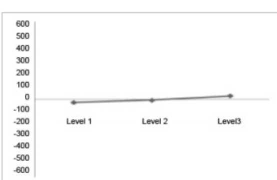


Floor Adhesive

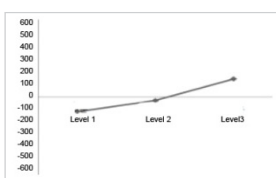


Ventilation Rate

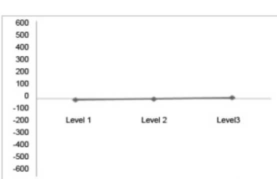
Figure 4. HCHO Reduction Contribution (Bed Room)



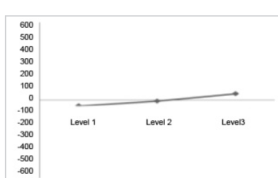
Wall/Ceiling papers



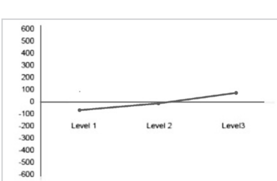
Adhesive for Wall/Ceiling papers-



Floor materials



Floor Adhesive



Ventilation Rate

Figure 3. HCHO Reduction Contribution (Living Room)

7. CONCLUSION

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

1) Through a literature search, the main factors affecting TVOC and HCHO 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 TVOC and HCHO intensity, the equation which is used as the official test method for chamber test by the Ministry of Environment is selected. The equation is re-established because the original equation is made for testing the emission in the small chamber. The differences between equation and actual data were 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(TVOC : 49.9%(LR), 53.9%(BR), HCHO : 59.3%(LR), 60.5%(BR)) was found to have the most contribution followed by ventilation rate(TVOC : 31.9%(LR), 31.2%(BR), HCHO : 22.3%(LR), 22.4%(BR)) and floor-adhesive. (TVOC : 7.3%(LR), 6.4%(BR), HCHO : 8.0%(LR), 7.1%(BR))

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