The Decision-making Process for Material and Ventilation Rate considering IAQ and Cost in Apartment Buildings

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ABSTRACT

Indoor air concentration is mainly affected by the emission rate of contaminants from materials and the ventilation rate. Therefore, the appropriate selection of materials and ventilation rate is an important factor for indoor air quality. The purpose of this study is to propose a method for the selection of materials and to determine an appropriate ventilation rate that can maintain the recommended guideline concentration with minimum cost. In order to achieve the objective of this research, an optimization concept for IAQ and cost was introduced, while determinative factors of IAQ and cost were deduced and their relationships were determined.

1. INTRODUCTION

Recently, as the need for a higher quality of housing has increased, the 'sick building syndrome' caused by poor indoor air quality of newly constructed apartment buildings, has become a major concern for residents of apartment buildings.

There are several methods used to resolve this matter of new apartment buildings, such as controlling the source with low-emission building materials ("Source Control"), regulating the indoor air with fresh outdoor air ("Dilution Control"), and cleaning the indoor air with air cleaning devices or decomposing chemical substances ("Air-cleaning Control") (Guo et al. 2003, Jalas 2003, Sekhar and Keong 2003). Among these methods, Air-cleaning Control is regarded as a secondary strategy for two major reasons. Firstly, air-cleaning control can increase some contaminants through chemical reactions between contaminants. Secondly, the use of a filter is insufficient for the removal of gas phase contaminants. Therefore, strategies that use low-emission building materials and ventilating rooms are regarded as more effective methods to lower the concentration of contaminants. However, using low-emission building materials is usually quite costly because of the complexity of the extra manufacturing process. This directly results in increasing house prices, which in turn conflicts with government policy of lowering apartment prices. Therefore, using building materials that are less expensive and have higher emission rates can be an economical alternative, provided there is a prerequisite guarantee that a sufficient ventilation rate will be achieved. However, a higher ventilation rate incurs a higher cost due to the requirement for larger ventilation units, ducts, and an increased use of energy.

The relationship between the source control and dilution control is the ventilation rate for maintaining the target (guideline) concentration calculated based on the amount of contaminant emissions. Due to this relationship, the material cost and ventilation cost have a reciprocal influence. Therefore, both the source control and dilution control need to be considered simultaneously and an acceptable trade-off needs to be made when a strategy for IAQ is elaborated.

The purpose of this research is to develop a decision-making process for material and ventilation rates considering IAQ and cost. For this purpose, an optimization concept for IAQ and cost was suggested, while determinative factors of IAQ and cost were determined, and the relationships between them were clarified.

2.OPTIMIZATION CONCEPT OF IAQ AND COST

The concentration levels of contaminants emitted from building materials tends to decrease over time because the levels of contaminants contained within building materials decreases during the process of emission. This means that the required ventilation rate for maintaining target concentrations at levels where IAQ problems do not occur will decrease over time. This relationship is explained in Figure 1. The upper graph of Figure 1 shows the indoor concentration of contaminants emitted from building materials, while the lower graph shows the required ventilation rate for maintaining target concentrations. Figure 1 describes two cases, where graph □ indicates the concentration levels when using building materials that have an average emission rate, while graph ② indicates the concentration levels when using building materials that have a low emission rate. To maintain target concentration in the case illustrated in graph □, the exceeded concentration level of the area A+B (on the upper graph) needs to be diluted with outdoor fresh air. Conversely, to maintain target concentration in the case illustrated in graph ②, the exceeded concentration level of the area A (on the upper graph) needs to be diluted with outdoor air. The lower graph indicates that using building materials with a low-emission rate can reduce the maximum required ventilation rate as well as the operation period of ventilation.

In terms of cost, the maximum required ventilation rate influences both the initial construction cost and the operation cost, while the operation period of ventilation influences the operation cost. Therefore, by using low-emission building materials, the initial construction cost and the cost of operating the ventilation unit, i.e. the ventilation cost, can be reduced. However, the use of low-emission building materials incurs a higher material cost.

Specifically, for materials that emit lower levels of contaminants, a higher material cost is required rather than a lower ventilation cost. Therefore, as shown in Figure 2, if an emission rate with a minimum total cost can be determined, the material and ventilation rates that satisfy indoor air quality and minimize cost can be determined.

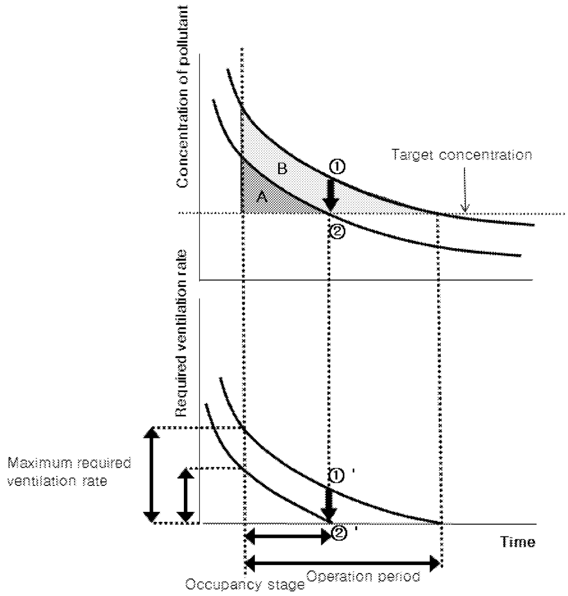

Figure 1: Variation concentration and required ventilation rate according to elapsed time

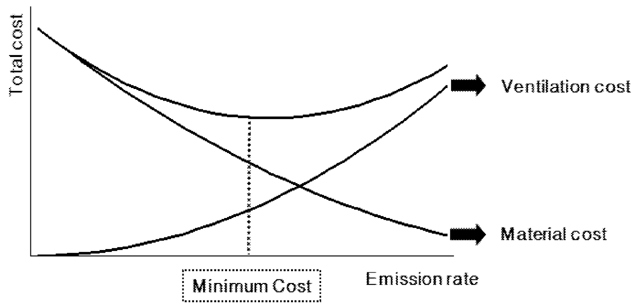

Figure 2: Relationship between emission rate and ventilation cost/material cost.

3. DETERMINATIVE FACTORS OF IAQ AND COST

3.1 Determinative Factors of IAQ

The concentration level of indoor air contaminants is the most important indicator determining whether IAQ is sufficient. Usually, such levels are controlled so that they do not exceed the guideline concentration for each contaminant. Concentration levels of indoor air contaminants are determined by the ventilation rate and the emission rate emitted from the main source. Thus, the contaminant type, the concentration level of the contaminant, and the ventilation rate are key elements that must be considered.

Types of contaminants in apartment buildings need to be considered in terms of two stages, the pre-occupancy stage and the post-occupancy stage. CO_2 is emitted from the human body through the process of respiration. Therefore, IAQ in the post-occupancy stage is affected not only by VOC levels and HCHO emitted from building materials but also by CO_2 emitted through respiration.

The level of contaminants emitted from building materials is determined by both the emission rate and the built area. Even if a material has a low emission rate, if it is located within a large built area, it could have a considerable influence upon the IAQ. Similarly, even if a material has a high emission rate, if it is within a small built area it could have only a slight influence on the IAQ. The level of contaminants emitted from the building occupants is determined by the CO_2 emission rate per person and the number of occupants.

The ventilation rate is also one of the key determinative factors of IAQ. The indoor air concentration of contaminants is determined after the contaminants have been emitted and have diluted with the fresh outdoor air. Here, a higher ventilation rate results in a lower indoor air concentration.

3.2Determinative Factors of Cost related with Determinative Factors of IAQ

In this paper, only the costs for installing the materials and the ventilation unit and the cost for operating the ventilation unit are considered. The cost for materials is determined by the unit cost and the construction area of the materials. The cost for ventilation is determined by the ventilation unit cost and the operation period of the ventilation unit. The relationship between the determinative factors of IAQ and the determinative factors of cost is shown in Figure 3.

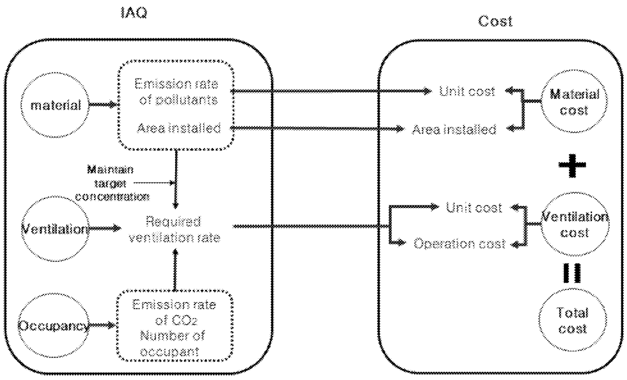

Figure 3: Determinative factors of IAQ and cost.

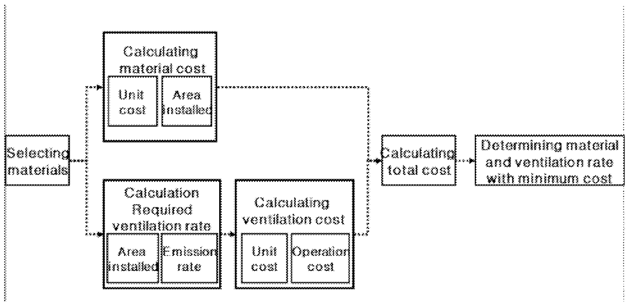

Figure 4: Basic flow for determining material and ventilation rate with minimum cost.

Firstly, the contaminant emission rate influences the material unit cost. For example, low-emission rate materials have a tendency to be more expensive. Secondly, the ventilation rate influences the ventilation unit cost and the operation cost. For example, a higher ventilation rate requires a larger ventilation unit cost and energy cost.

4. DECISION-MAKING PROCESS FOR MATERIAL AND VENTILATION RATE

In order to determine the materials and ventilation rates considering IAQ and cost, the materials must first be selected and a ventilation rate must be calculated that is able to maintain the guideline concentration levels. The total cost, as the sum of the material cost and ventilation cost, is then calculated based on the selected materials and the calculated ventilation rate. Subsequently, the total cost of each alternative needs to be compared in order to determine the alternative with the minimum total cost. Through this process, materials and ventilation rates can be determined. The schematic flow of this process is illustrated in Figure 4.

4.1 Calculation of the required Ventilation Rate

4.1.1 The required Ventilation Rate for Contaminants emitted from Materials

The relationship between the emission rates of contaminants, the ventilation rate and the concentration level can be determined as follows:

$$C_{in} = \frac{\dot{M}}{Q} + C_{out} \quad (1)$$

where:
C_{in}: Indoor contaminants concentration, $\mu g/m^3$
C_{in}: Outdoor contaminants concentration, $\mu g/m^3$
$\dot{M}$: Contaminants emission rate from the material, $\mu g/h$
Q: Ventilation rate, m^3/h

If there is more than one material, the emission rate ($\dot{M}$) can be defined as follows:

$$\dot{M} = \sum_i E_i(t) A_i \quad (2)$$

where:
$\dot{M}$: Contaminants emission rate from the materials, $\mu g/h$
$E_i(t)$: Contaminants emission rate from the material i per unit area, $\mu g/m^2h$
A_i: Area of material i, m^2

The contaminant emission rate usually decreases by elapsed time. This directly reflects on the ventilation rate required to maintain the guideline concentration. Therefore, the variation of emission rate according to elapsed time needs to be considered. In this paper, the "first-order decay model" [1] is applied as follows:

$$E(t) = E_0 \times e^{-kt} \quad (3)$$

where:
$E(t)$: Contaminants emission rate from the material i per unit area, $\mu g/m^2h$
k: Decay constant
t: Time, h
Substituting Eq. (2) and (3) into Eq. (1), we obtain Eq. (4):

$$C_{in} = \frac{Q \times C_{out} + \sum_i (E_{0,i}(t) \times e^{-k_i t} \times A_i)}{Q} \quad (4)$$

The required ventilation rate for contaminants emitted from materials can be calculated as follows:

$$Q_{req,material} = \frac{\sum_i (E_{0,i}(t) \times e^{-k_i t} \times A_i)}{(C_{target} - C_{out})} \quad (5)$$

where:
$Q_{req,material}$: Required ventilation rate for contaminants emitted from materials, m^3/h
C_{target}: Target concentration of the room, usually guideline concentration, $\mu g/m^3$

4.1.2 The required Ventilation Rate for CO_2 emitted from human respiration

The rate of CO_2 emitted from human respiration varies according to the strength of the activity carried out rather than with the elapse of time. ASHRAE suggests that the minimum ventilation rate per person should be 25 $m^3/h \cdot person$ [2]. Therefore, the required ventilation rate for CO_2 emitted from human respiration can be calculated as follows:

$$Q_{req,CO2} = \alpha \times N_{occupied} \quad (6)$$

where:
$Q_{req,CO2}$: Required ventilation rate for CO_2 emitted from human respiration m^3/h
α: Required ventilation rate per person, $m^3/h \cdot person$
$N_{occupied}$: Number of occupant, person

4.1.3 The combined required Ventilation Rate

The required ventilation rate for materials usually decreases with elapsed time. Conversely, the required ventilation rate for CO_2 is constant. And, because the required ventilation rate for the material is generally larger than that required for the ventilation rate for CO_2 in the early stage of emission, the two graphs intersect at some point (t1), as shown in Figure 5.

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1) Sparks, E. et al(2000), IAQX Version 1.0&Risk Version 1.5 User's Guide, US EPA, pp.32-34.

2) ASHRAE(2004), ASHRAE Standard 62-2004: Ventilation for Acceptable Indoor Air Quality, ASHRAE.

Therefore, the combined required ventilation rate is determined to be the maximum value of the required ventilation rate for the material and the required ventilation rate for CO2. The combined required ventilation rate can be defined as follows:

$$Q_{req} = \max\left(Q_{req,material}, Q_{req,CO2}\right) \quad (7)$$

where:
Q_{req}: Combined required ventilation rate, m^3/h

The practical ventilation rate considering the operation of the ventilation unit can be determined from Eq. (7). According to regulations for ventilation in apartment buildings, the installation of a ventilation unit with 3 airflow rate steps is obligatory. In this case, a low airflow rate can be set for the required ventilation rate for CO2, a high airflow rate can be set for the initial required ventilation rate, and a middle airflow rate can be set for the required ventilation rate in order to minimize area A+B (as shown in Figure 6).

4.2Calculation of Material Cost and Ventilation Cost

The material cost can be calculated by multiplying the unit cost of the material by the construction area as follows:

$$MC = \sum_i UC_{i,material} \times A_i \quad (8)$$

where:
MC: Material cost
$UC_{i,material}$: Unit cost of material i
A_i: Area of material i, m^2

The ventilation cost can be calculated by totaling the initial cost and operation cost as follows:

$$VC = IC + OC \quad (9)$$

where:
VC: Ventilation cost
IC: Initial cost
OC: Operation cost

When calculating the operation cost(OC), the period of operation is from t(a) when occupancy

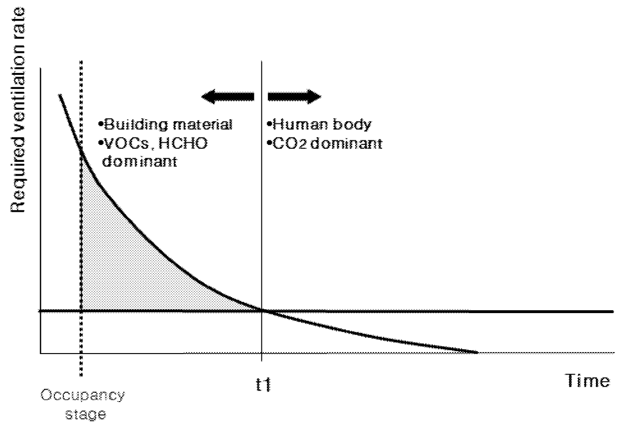

Figure 5: Required ventilation rate for materials and CO2

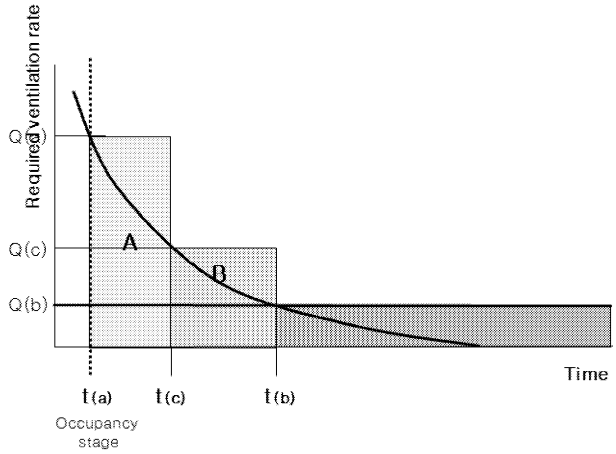

Figure 6: Ventilation rate considering operation steps of ventilation unit.

stage starts to t(b) when the required ventilation rate for material is equal to the required ventilation rate for CO2. The operation cost is calculated by multiplying the power consumption by the rate. Here, the power consumption can be calculated as follows.

$$P = \frac{\left(\int_{t(a)}^{t(b)} Q_{req}\,dt\right) \times H}{3600 \times 102 \times \eta_{fan}} \quad (10)$$

where:
P: Power, kWh
H: Head, $cmWG$
η_{fan}: Efficiency of fan, $\%$
t(a): Start of occupancy stage
t(b):Time for $Q_{req,material} = Q_{req,CO2}$

In the case where the airflow rate is controlled by 3 steps, the power consumption can be calculated as follows:

$$P = \frac{\left(Q(a) \times (t(c) - t(a)) + Q(c) \times (t(b) - t(c))\right)}{3600 \times 102 \times \eta_{fan}} \quad (11)$$

where:

$Q(a)$: Maximum required ventilation rate, m^3/h
$Q(c)$: Middle airflow rate, m^3/h
$t(a)$: Start of Occupancy stage
$t(b)$: Time for $Q_{req,material} = Q_{req,CO2}$
$t(c)$: Time for operating with middle airflow rate, m^3/h
η_{fan}: Efficiency of fan, %

Synthetically, the decision-making process for the material and ventilation rate with the minimum cost is shown as Figure 7.

5. CONCLUSION

A decision-making process was developed in this study for material and ventilation rate considering IAQ and cost. Formaldehyde and VOCs are major indoor contaminants emitted during the pre-occupancy stage and CO_2 can be a major contaminant emitted during the post-occupancy stage. Construction companies must therefore take into consideration the concentration level of these contaminants. It is widely known that selecting low-emission rate building materials and applying the appropriate ventilation rates are the most efficient methods for improving indoor air quality. However, using low-emission rate building materials can increase the initial construction cost. In this study, an optimization concept for IAQ and cost was suggested and the relationship between the determinative factors of IAQ and cost was presented.

- While the emission rates of building material contaminants is in inverse proportion to the material cost, the emission rates of building material contaminants is in proportion to the ventilation cost.
- Because of the CO_2 emitted from human respiration, contaminant types in apartment buildings need to be divided into the pre-occupancy stage and the post-occupancy stage. The determinative factors of IAQ are the emission rate and the construction area of the materials, the CO_2 emission rate and the number of occupants, and the ventilation rate.
- The determinative factors of cost are the unit cost and the construction area of materials, as well as the unit cost and the operation cost of the ventilation unit.
- The decision-making process for the material and ventilation rate considering IAQ and cost was developed as shown in Figure 7.

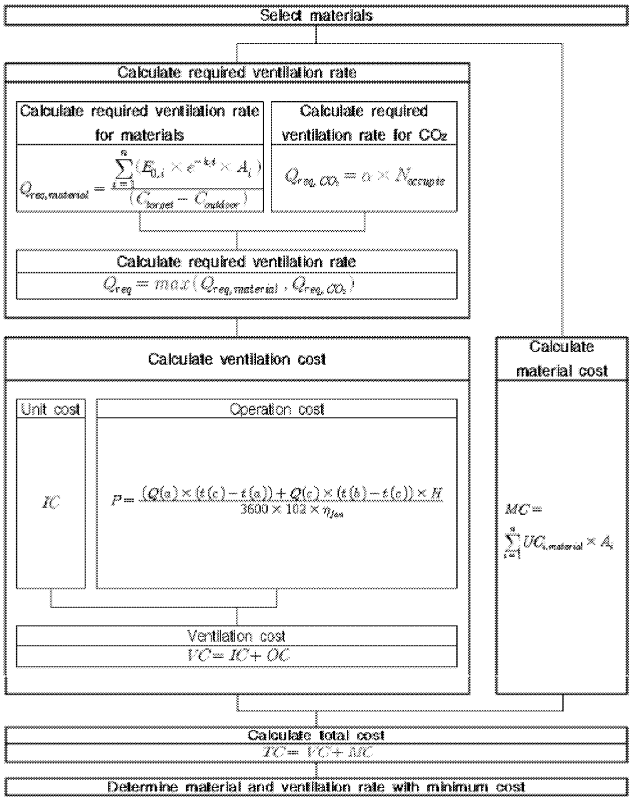

Figure 7: Decision-making process for material and ventilation rate considering IAQ and cost

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