https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

Factors Affecting Pollutants' Dispersion and Concentration Levels in the Built Environment

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ABSTRACT
The extent to which an individual is harmed by indoor air pollution depends on their total exposure to pollutants, the duration of exposure, and the concentration level. Various factors contribute to the concentration levels and duration of exposure to the indoor pollutant. This study approached knowledge from a multitude of disciplines (e.g., epidemiology, virology, mechanical, etc.) and showcased them from an architectural point of view. Understanding the effects of these factors on contaminant dispersion in built environments can lead to the design of healthier living spaces. Several factors contribute to contaminant dispersion and escalate health risks in the built environment. These factors are not straightforward; but rather a complex interaction between several environmental factors. Building designs, site layout, and space distribution can contribute to the concentration level and duration of exposure to the indoor pollutant. Ventilation parameters such as ventilation exchange rate, airflow distribution patterns, and their overall direction are vital in controlling and diluting the pollutants' concentration levels. The study also shows that other factors, such as relative humidity, temperature, convective transport phenomena, and furniture arrangement, significantly influence indoor airflow and pollutant dispersion. Understanding these factors is critical to eliminating or reducing occupants' exposure to indoor air pollutants found in the built environment.

Keywords: *Indoor air quality; Healthy indoors; Infection control; Contaminant dispersion; Health risks*

1. Introduction

Pollutants are the primary cause of indoor air quality (IAQ) problems [1, 2, 3, 4]. Mølhave identified indoor air pollutants as the accumulation of compounds in the indoor environment in concentrations and durations that cause adverse health problems. Indoor air is outside air brought directly either by natural, mechanical, or both to remove or reduce indoor pollutants' concentration. Indoor air pollution can be up to 650 times worse than outdoor air pollution [5, 6]. Some pollutants are produced indoors as a result of people's activities, such as cooking, respiration activities such as talking, or emitted from products used indoors, such as furnishing, and building materials [2, 7, 8]. Poor indoor air quality contributes to both short and long-term adverse health problems, including lung cancer from radon, poisoning from carbon monoxide exposure, and an increased risk of heart disease, strokes, cancer, pneumonia, colds, and other airborne infectious diseases. Moreover, indoor air pollutants negatively affect cognitive function and increase the level of sick absence and productivity. Poor indoor air quality is attributed to an average of 10% of productivity losses among office workers [7]. IAQ and its impact on building occupants depend on different factors which determine the risk level. These factors are not straightforward, but rather a complex interaction between several environmental factors, such as the quality and quantity of indoor pollutants, ventilation systems, human parameters, etc. [6, 10]. To reduce the risk level and duration of exposure, there is a need to understand and narrow down the factors that affect the level of indoor contamination concentration and those that determine the risk level. An intensive, comprehensive, and interdisciplinary systematic review was conducted to clarify the factors that may potentially affect contaminant dispersion and concentration in occupied spaces. Understanding the effects of these factors on contaminant dispersion in built-up areas could lead to the design of healthier living spaces in the future. The main challenge was that the study approached knowledge from a multitude of disciplines (e.g., epidemiology, virology, mechanical...) and showcased them from an architectural point of view. As a result, influential factors will be briefly discussed in this paper to open doors for further investigation from an architectural standpoint.

2. Building designs and site layouts

The first step in ventilation design for adequate IAQ is determining compliance with outdoor air quality standards in the region where the building exists. The building's location and ventilation should be a consideration, especially for buildings established near heavy traffic or other major outdoor sources of pollutants. According to WHO and other environmental regulatory agencies, poorly ventilated spaces result in high concentration levels of indoor pollutants [1, 3, 5, 11, 12]. Indoor concentrations of benzene range from 0.6 to 3.4 times the outdoor concentrations as a result of the accumulation of benzene from outdoor sources such as heavy traffic, nearby petrol stations or industrial sites, poor ventilation, and additional indoor sources [5]. The fresh air inlets should be located on the least polluted side of the building to reduce levels of indoor-outdoor pollutants [1, 5]. Sites with crowded tall buildings could obstruct sunlight access and fresh air on lower-level floors. A study by Lai et al. correlated floor levels to pollutant concentrations [13]. The study found that spaces located at lower levels of a building had more health risks. Another study investigated the health risk in three buildings located at different sites: sites A, B, and C [14]. The building on site A had enough space available between adjacent buildings; subsequently, it had better access to sunlight and ventilation, which resulted in lower health risks compared to the other two sites. The layout of sites B and C led to higher health risks than site A, figure .1 [14]. This conclusion was supported by an Indonesian study that reported that the risk of chest infections was higher among residents in apartments at lower levels due to a lack of sunlight and/or natural ventilation [15].

3. Space disruption

Furthermore, in addition to the influence, the building site can have on levels of pollutant concentrations and health risks, the building's interior spatial distribution can play a significant role in maximizing pollutant spread [15, 16]. A study by Escombe et al. compared natural ventilation performance in old-fashioned designed facilities (pre-1950) to modern ones. These old buildings had higher ceilings and larger windows of 4.2 m compared to 3 m and openings of 6.6 $m^2$and 3.4 m^2, respectively. The risk of airborne contagion was significantly lower in older, spacious buildings with high ceilings and large windows. In contrast, modern buildings with low ceilings and small windows are associated with greater risk [17]. Another study that emphasizes space disruption was by Qi Zhou et al., who investigated natural ventilation performance in a building in Nanjing, China, with a central corridor and rooms on both sides figure. 2a [5]. The building had five stories, and the simulation was conducted for the third level. which had six rooms from (A) to (F), three on each side of the corridor. The rooms directly open to the corridor and have windows on the wall opposite the door figure. 2b. When the doors were opened, cross-ventilation infection risk was investigated using the computational fluid dynamics (CFD) method. The contaminated air moved from upstream rooms to downstream rooms. They found that the airflow pattern was responsible for the dispersion of airborne particles between rooms. The cross ventilation led to the dispersion of infectious particles across the entire floor. The infected individual was located in an upstream room (B), and the outdoor wind velocity was 2 m/s. When the infected individual stays at the same location in a space; the probability of catching an infection is high. The contaminated air moved from upstream rooms to downstream rooms. The downstream rooms were highly polluted. Cross infection occurred between the room with an infected individual and downstream rooms. In this scenario, keeping the doors closed or installing air curtain devices at the doorway is recommended.

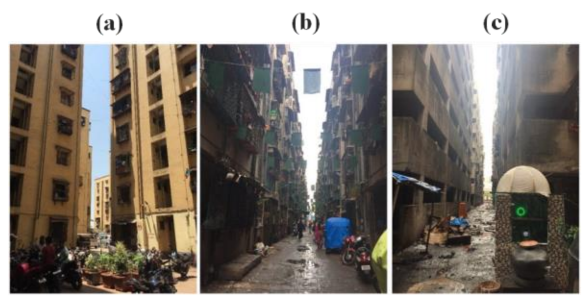

Figure 1 Shows spaces between adjacent buildings in **(a)** site A, **(b)** site B, and **(c)** site C [14].

4 .Building ventilation

Indoor ventilation strategies can play a vital role in controlling and/or diluting indoor pollutants' health risks [16, 19]. The Chartered Institution of Building Services Engineers, CIBSE, recently guided on using ventilation as a way of diluting airborne pathogens. It stated that “there is good evidence that demonstrates occupants are more at risk of catching an illness in a poorly ventilated space than in a well-ventilated one”.

Modern society spends from 80 to 90 % of its time indoors - offices, homes, schools, etc., which are either naturally, mechanically, or hybrid ventilated

[19]. The objective of any ventilation system is to supply fresh outdoor air to the occupants, removing excess heat and pollutants from the built environment [1,47]. Fresh air should be provided to the occupants' breathing zone, diluting the pollutants originating in the building and removing them from it [21]. The decision on whether to use mechanical or natural ventilation for indoor

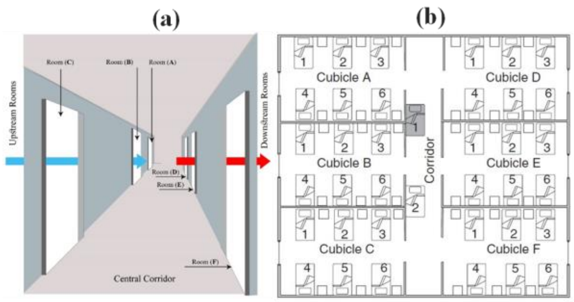

Figure 2 (a) Central corridor; **(b)** Building layout [18].

pollution or infection control should be based on needs, the availability of the resources, and the cost of the system to provide the best control to counteract the risks. Although advanced ventilation systems and negative pressure ventilation show a lot of potentials, they are expensive to install and maintain [16, 22, 23]. Furthermore, faulty or insufficiently maintained mechanical ventilation systems can increase the concentration and spread of contaminants in the indoor environment, as shown by the outbreak of the novel coronavirus disease that occurred in a mechanically ventilated restaurant in China [19, 24, 25]. The outbreak took place on the third floor of the restaurant, which is vented by five air conditioning units without natural ventilation. The third-floor dining area was 145 m^2; the distance between each table is about 1 m.

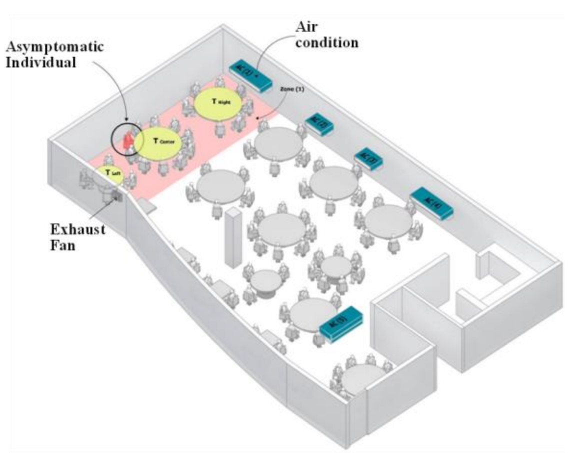

Figure 3 Guangzhou restaurant’s third floor layout [25].

Each unit vented a particular zone of the floor, figure.3. The outbreak happened in a shared ventilation zone, zone (1), The air inlet and outlet for the central air conditioner were located above the right table with a low ventilation rate of 1 L/S/P. The airflow direction is illustrated in figure .4. This air movement facilitated the dispersion of infected droplets into adjacent occupants' breathing zones. Although there was a 30.5 x 30.5 cm exhaust fan in the wall opposite the air conditioning, it was insufficient

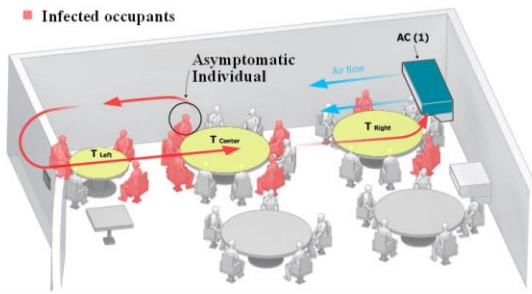

Figure 4 Guangzhou restaurant’s air movement in the shared ventilation zone, zone (1) [25].

to remove the polluted air. None of the 62 occupants at the other 12 tables located in different ventilation zones were infected. Which suggested that the alternate scenarios (touching surfaces or going to the restroom at the same time) were less likely to be the cause of infection. This study concluded that the droplet transmission was prompted by air-conditioned ventilation. The key factors for infection were low ventilation rates and the direction of the airflow [24, 25]. The furthest infection was about 4.6 m; therefore, long-range transmission is possible in poorly ventilated spaces [14, 24, 25]. Natural-ventilated buildings have been shown to reduce the risk of airborne infection [5, 17,19,18, 26]. Several researchers advocated for maximizing natural ventilation in low-resource settings for infection control [27]. Escombe et al. compared the health risk in naturally and mechanically ventilated rooms. When compared to rooms with natural ventilation, mechanically ventilated rooms with sealed windows had an even higher risk, despite being ventilated optimally according to guidelines [17]. Another mechanical and natural ventilation comparison was made by a collaborative study by Imperial College London’s Department of Infectious Diseases & Immunity. The study found that naturally ventilated environments provide high air exchange rates even on days with little wind compared to mechanically ventilated rooms. Mechanically ventilated rooms had poor absolute ventilation even at recommended air exchange rates (12 ACH) for high-risk areas and consequently had higher estimated risks of airborne contagion [17]. Any type of ventilation has three elements: ventilation airflow rate, airflow pattern (air distribution), and airflow direction. These parameters can affect the concentration and distribution of pollutants in the occupied zone [19, 26, 28, 29].

4.1 Ventilation airflow Rate

The ventilation rate measures how many times a volume of air within a room will be added, removed, or exchanged with fresh outdoor air. It is calculated using the air exchange rate (air changes per hour (ACH)) or ventilation rate per person (liters/second) [22]. Multiple experimental studies correlated high pollutant concentration levels to low rates of ventilation typically used in residences and offices, which aid the rapid dispersion of airborne contaminants. In the past two decades, several published studies have attempted to relate sick building syndrome (SBS) reported symptoms to their causations, finding that a low ventilation rate is among these factors. Studies have associated low ventilation rates of below 10 l/s per person with increased airborne building contaminants [29]. Although mechanical ventilation can be more reliable in delivering standard flow rates, natural ventilation generally provides higher ventilation rates. Natural ventilation, when properly designed, can be dependable and provide higher change rates at low costs [21]. It’s important to point that some studies argues that a high flow rate can heighten the risk of airborne cross-infection [30, 31].

4.2 Air distribution pattern and direction

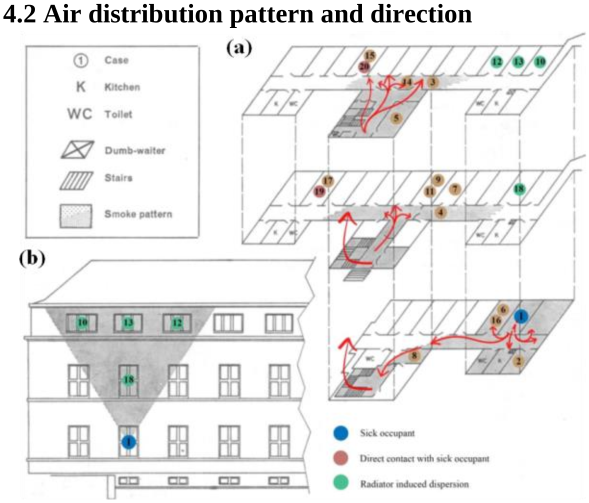

Figure 5 (a) The floor plan of the building where the airborne transmission occurred and the location of all cases. **(b)** building façade [37].

Although the outdoor air intake rate may be adequate, air distribution problems can lead to poorly ventilated areas in the building [21]. A study used a smoke test to show the airflow pattern and direction’s effects on pollutant dispersion in the built environment [32]. The floor plan of the building where the airborne transmission occurred is illustrated in figure 5a, the gray color indicates the dispersion pattern. The infectious particles spread to the adjacent rooms and then to the corridor, through a door normally kept ajar using a special device, and then into the entrance hall where occupant number 8 was. These spaces had the highest levels of concentration. After the infected particles passed through the entrance area, they flowed directly to the stairwell, which served as a chimney and conducted a dense cloud of smoke to the first and second-floor levels, where it drifted into the corridors and adjacent rooms. Ventilation for rooms and corridors was arranged by opening windows or doors. The rooms were heated by steam radiators situated beneath the windows in each room. The heaters were working when the outbreak occurred. The infected particles flow out of a partially opened window in the sick occupant’s room and then directly up the building’s facade, into the rooms where occupants’ numbers 10, 12, 13, and 18 were, Figure 5b. This flow pattern into the upper windows appeared to be caused by convection currents generated by radiators located below the windows [37]. The direction of the overall airflow can affect pollutant transport within a building or adjacent buildings. W. Kemble et al. associated high-occupied diverse spaces with high levels of pollutants and recommended that overall flow direction should move from low-occupied spaces to high-occupied ones [36]. The ideal ventilation system directs the overall airflow in a building from clean zones to dirty zones, e.g., from corridors to toilets; this role is important to prevent pollutant transmission between different spaces [21].

5. Furniture arrangement

Multiple scholars claims that furniture arrangement could have great influence on the indoor airflow and pollutant dispersion. while others rank furniture arrangement and occupant position as low impact factors to IAQ as long as they do not obstruct airflow in a space [33, 37]. A study by Cheong et al. investigated the airflow and pollutant distribution patterns a room by means of objective measurement and computational fluid dynamics (CFD) finding that room furniture greatly influences the airflow and pollutant distribution a room; and recommended that furniture not to be placed in the path of the airflow from the air supply terminal to extract terminal in the room [33, 37]. R. Zhuang et al investigated the effects of furniture arrangement on the indoor air quility [33]. The ventilation system was kept constant in all the furniture arrangements, the inlet is at the bottom of the left wall and outlet on the ceiling near the right wall figure 6a. Three different combinations of furniture layout were investigated, arrangements (A), (B), and (C) figure. 6b. the airflow and the pollutants distribution pattern were significantly different in each arrangement. The bookshelf was the source of pollutant, which was assumed to be new; and emits formaldehyde. Arrangement (A) had the least favorable performance; the concentration levels was at its highest near the occupant. As a result of the location of both the work space and the bookshelf; It was observed that the pollutant was trapped for a period of time in the occupant breathing zone before it was exhausted.

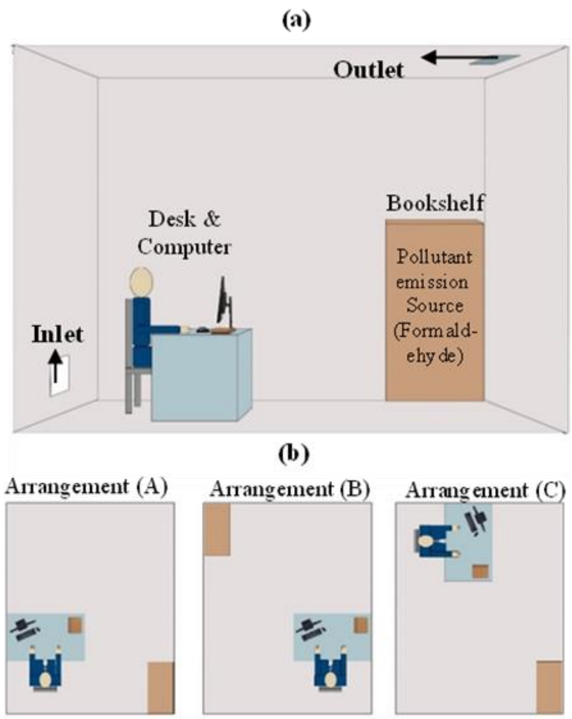

Figure 6 (a) Shows office's ventilation system, inlet located at the bottom of the left wall, and an outlet on the ceiling near the right wall. **(b)** Different combinations of furniture arrangements for an office room [33].

In arrangement (B) the pollutant source moved near the right wall. The middle part of the room had the high concentration level, still it was much less than the magnitude of pollutant concentration in the previous arrangement. As for arrangement (c) the magnitude of pollutant concentration was as high as arrangement (A), but was less in concentration near the occupants breathing zone. Arrangement (A) had an average concentration of $8.29^{-8} kg/m^3$, while (B) had $3.10^{-8} kg/m^3$, and (C) had $5.22^{-8} kg/m^3$. The study concluded that the quality of air in the occupants breathing zone could be significantly improved by adjusting the furniture layouts. It was recommended for designers to investigate furniture arrangements to reach optimal layout and achieve healthier indoor environments. designers should identify the upstream location of occupants and the downstream position for pollutants source in a space and position occupants in the upstream of the overall airflow.

6. Temperature and relative humidity (RH)

Temperature and relative humidity (RH) are major influential factors in the transmission and survivability of microorganisms [31]. In 2007, Lowen AC et al. studied the relationship between influenza virus transmission, relative humidity, and temperature. Low ambient temperatures (4°C–20°C) were found to increase influenza virus transmission and humidity levels factored in. At a higher temperature (30°C), virus transmission was eliminated regardless of relative humidity. Although the higher temperature will limit the survivability and transmission of most bacteria and fungi, it could still lead to occupants' thermal discomfort. Low relative humidity can increase the chances of microbial and spore aerosolization from surfaces and their resuscitation in indoor air [34, 36]. Several studies concluded that both RH and humidity ratio values influence the survival of viruses and bacteria as well as transmission levels. For example, high humidity levels support microbial growth due to moisture absorption by building materials [34, 35]. Lowen et al. concluded that airborne transmission of influenza virus was maximal at 20%–35% RH and poor at 50% RH. Fernstrom and Goldblatt's study on the transmission of infectious diseases found that viruses are less stable at RH 40%–70%. They both recommend that the optimum temperature to control the survival of airborne viruses such as influenza is as high as 30 °C at 50% RH [36]. Humidity is trickier than temperature. RH ranges may limit the infectivity of certain microorganisms but may cultivate others. Figure 7 shows that RH ranges may limit the infectivity of certain microorganisms but may foster others. Although a 50% RH or higher can limit the transmission of airborne gram-positive bacteria and lipid-enveloped viruses such as influenza, it may cultivate viruses without a lipid envelope. Humidity and temperature should be reviewed not only for thermal comfort but also for optimal health risks.

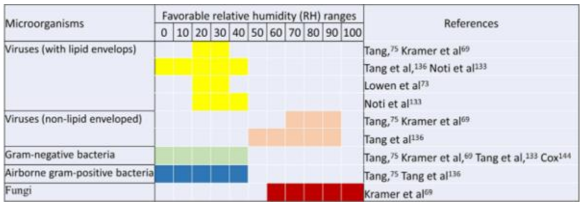

Figure 7 Favorable relative-humidity ranges for different microorganisms [34].

7 .Conclusion

Several factors affect the concentration and distribution of contaminants in the occupied zone. The building site can have a great impact on occupants' health, especially sites established near major outdoor sources of pollutants. Ventilation systems should be located far away from contaminated sources of emissions. Lack of Sunlight access was correlated with health risks. Sites with tall and small sky view factors can block sunlight from accessing the space. Spacious buildings with high ceilings and large openings were found to provide better indoor air quality and reduce health risks. The distribution of interior space affects the airflow pattern and, if poorly designed, can lead to the dispersion of infectious particles across the entire floor. Humidity and temperature should be reviewed not only for thermal comfort but also for optimal health risk. It was recommended that the optimum temperature to control the survival of airborne viruses such as influenza is as high as 30 °C at 50% RH. Ventilation plays a vital role in controlling and diluting indoor pollutants. Occupants are more susceptible to catching an illness in a poorly ventilated space than in a well-ventilated one. The ventilation system should be selected with care. Malfunctioning and inadequate mechanical ventilation systems can increase the concentration and level of spread of contaminants in the indoor environment. Mechanically ventilated rooms can have a greater risk, despite being ventilated optimally according to guidelines, compared to naturally ventilated rooms. Natural ventilated buildings were found to be effective in reducing indoor pollutants and were recommended by multiple scholars for infection control in limited resource settings. Natural ventilation can provide high air exchange rates, even on days with little wind compared to mechanical ventilation. A high ventilation rate can dilute indoor pollution levels and reduce the risk of infection. Air distribution problems can lead to certain areas in the building being poorly ventilated even with adequate ventilation rates. Inlet and outlet location are the main driving forces for the air distribution pattern in a space. A good air distribution pattern supplies air to all parts of the occupied zone without the presence of stagnant zones. It was recommended for designers to investigate furniture arrangements to achieve an optimal layout and achieve a healthier indoor environment. Designers should identify the upstream and downstream positions of pollutant sources in a space and place occupants upstream of the overall airflow .

7 .Recommendations

Designers should consider how factors such as building location, design, space layout, temperature, relative humidity, and furniture layout can affect indoor air quality. Fresh air intakes should be located on the least polluted side of the building because pollutant concentrations tend to be higher at street level. When designing buildings near heavy traffic, designers should choose a ventilation technique that achieves all airflow at a higher level where pollutant concentrations tend to be lower. Higher ceilings and larger openings should be used by designers to reduce health concerns in the indoor environment. Designers should exert careful consideration when it comes to ventilation because it is a crucial element of indoor air quality and health hazards. The decision on whether to use mechanical or natural ventilation for indoor pollution or infection control should be based on needs, the availability of the resources, and the cost of the system to provide the best control to counteract the risks. Designers should consider the airflow pattern of each space individually and ensure that fresh air reaches the occupants' breathing zone. To prevent pollutants from spreading from one room to another, the entire flow of the facility should be considered. The overall flow direction should move from low-occupied spaces to highly occupied ones, and from clean to dirty zones. In limited resource settings, natural ventilation is considered among the most effective environmental measures to reduce indoor-associated health risks. Finally, humidity and temperature should be assessed not only from a thermal comfort perspective but from a health perspective as well, to minimize health hazards.

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