Design Guide for Epidemic Resilient Natural Ventilation (NV) and Mixed-Mode Ventilation (MMV) Systems for Buildings

Guidelines for designing Epidemic Resilient Natural Ventilation (NV) and Mixed-Mode Ventilation (MMV) Systems for Buildings.

Revision log:

S/N	Brief description of changes	Revision date
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The Building and Construction Authority, Singapore has made this guide available to the public for its information and as a general guide for designing epidemic resilient natural ventilation and mixed-mode ventilation systems for buildings.

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BCA reserves the right to update this guide periodically without prior notice.

Acknowledgements

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Contents

Foreword

The COVID-19 Pandemic had an unprecedented impact on the way people live and work. Different institutions and associations such as the World Health Organization (WHO), Chartered Institution of Building Services Engineers (CIBSE), American Society for Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), and Federation of European Heating, Ventilation and Air Conditioning Association (REHVA), have released guidelines including measures to enhance ventilation and indoor air quality while reducing the potential for airborne aerosol transmission in indoor spaces. Most of these guidelines advocate for maximizing outdoor air ventilation as much as reasonably possible. However, this strategy needs to be balanced against the consequential energy demand, carbon emissions and thermal discomfort associated with higher outdoor air ventilation rates. Before the COVID-19 pandemic, indoor air quality and ventilation standards for non-healthcare premises rarely addressed infection control. Rapid revisions were made highlighting the importance of ventilation in preventing virus spread.

In standards such as ASHRAE 62.1(2022) and SS553(2021), the existing minimum rates of outdoor air ventilation for non-healthcare premises before COVID-19 were significantly lower than what is now recommended for effective infection control. These have since been updated to include additional ventilation and measures for infection control. The World Health Organization (WHO) had pre-COVID publications, including recommendations for infection control. These publications were specialized for healthcare settings, such as "Natural Ventilation for Infection Control in Healthcare Settings 2009".

Although it is well documented that Natural Ventilation (NV) or Mixed Mode Ventilation (MMV) can provide higher ventilation rates, there are additional challenges to consider. These include ventilation instability, varying effectiveness (especially in achieving even distribution in large spaces), coordination issues with air conditioning (such as thermal comfort and condensation in the case of MMV), as well as potential noise and indoor air quality issues.

In response to the pandemic, guides generally recommend maximizing outdoor air ventilation and minimizing recirculation. Openable windows and doors are advised to enhance air exchange. However, in Singapore's hot and humid climate, using cooling systems with passive openings can lead to high energy consumption and increased indoor humidity. Careful management is essential to prevent condensation and microbial growth.

ASHRAE Standard 241(2023), which focuses on the Control of Infectious Aerosols, introduces a novel ventilation rate called the "equivalent clean airflow rate per occupant" (ECAi). This updated standard recognizes that the equivalent clean airflow requirement for a space or system can be achieved not only using outdoor air but also by incorporating filtered recirculated air and air disinfected by various technologies. This flexible approach allows for compliance by implementing combinations of controls that optimize factors such as cost and energy usage, making it a favorable update compared to previous guidelines.

Before COVID-19, designing epidemic-resilient ventilation systems faced several challenges:

Lack of Guidelines: There were no specific guidelines for infection control ventilation in non-healthcare premises. This gap became notably pronounced during the onset of the COVID-19 outbreak.

Inadequate Ventilation Rates: Minimum outdoor air ventilation rates, such as those specified in ASHRAE 62.1 (2022), were significantly lower than current recommendations for infection control.

High Energy Demand: Unrestricted operation of ventilation systems, especially with opened doors and windows, led to excessive energy consumption, complicating the balance between infection control and energy use.

This design guideline was developed to address the challenges of achieving epidemic resilience in tropical climates like Singapore, where Natural Ventilation (NV) and Mixed Mode Ventilation (MMV) present viable alternatives to conventional air-conditioning. This guideline aims to determine the optimal additional ventilation rates achievable through natural ventilation or mixed-mode ventilation (via openings), rather than solely relying on the ACMV system to supply the required amount of outdoor air.

Executive Summary

The purpose of this design guide is to outline essential passive design principles and recommended strategies to help buildings adapt to NV and MMV modes, enhancing their epidemic resilience. It is intended to support architects, engineers, and the broader construction industry in integrating more effective, locally adaptable, and resilient solutions into their projects.

This guide applies to both new buildings and renovations, focusing on office spaces, retail, and preschools. It helps designers and building professionals improve NV/MMV systems for healthier indoor environments and better energy efficiency. This guideline also enhances building design to cope with future epidemic threats, creating a safer and more adaptable environment.

This guide offers recommended opening sizes to meet ventilation rate requirements for epidemic control and includes additional recommendations to enhance epidemic resiliency in the operations in office spaces, preschools, and retail environments.

Design Guideline Scope

This design guide includes the following chapters, which outline general strategies and fundamentals for controlling aerosol infection in indoor spaces, the types of ventilation utilized in this guideline, and the recommended ventilation rates under epidemic mode and normal mode with NV/MMV using openable windows for three different typologies: Office, Preschool, and Retail.

CHAPTER 1: INFECTION CONTROL IN INDOOR ENVIRONMENTS AND VENTILATION

i. General principles of infection control

CHAPTER 2: TYPES OF VENTILATION

i. Current good design practice for NV/MMV under normal operation

CHAPTER 3: GUIDANCE FOR INFECTION CONTROL

i. Flow chart for design thinking process when designing a NV/MMV building according to this guide
ii. Guidance for recommended ventilation rates under epidemic mode and normal mode with NV/MMV using openable windows for three different typologies - Office, Preschool, and Retail.
iii. Encouraged design provisions additional to the recommended ventilation rate and baseline provisions
iv. Additional considerations when designing an NV/MMV building.
v. Working example: A practical demonstration of implementation.
vi. Guidance for determining the effective opening area for various types of windows.

Normative Reference

The application of this Design Guideline references the following documents. For dated references, only the edition specified is applicable. For undated references, the latest edition of the referenced document, including any amendments, is applicable.

- ASHRAE STANDARD 241 – 2023 Control of Infection Aerosols
- ASHRAE. (2022a). ASHRAE positions on infectious Aerosols
- ASHRAE. (2002b). ASHRAE standard 62.1 ventilation and acceptable indoor air quality.
- SS553. (2021). Amendment No. 2, SS553 (2016) Code of practice for air-conditioning and mechanical ventilation in buildings
- Building Control Act 2013
- CIBSE Applications Manual AM10 Natural Ventilation in non-domestic buildings
- CIBSE Guide B2 Ventilation and air conditioning
- REHVA 2021 COVID 19 guidance version 4.1
- Approved Document F Volume 2, 2021 edition - Building Regulations 2010
- WHO Natural Ventilation for Infection Control in Health-Care Settings

Definitions of Terms

Air Conditioning (AC): Process of treating air to meet the requirements of conditioned space by controlling its temperature, humidity, cleanliness, and distribution.

Air movement device/air-mixing device: A mechanism designed to facilitate circulation and mixing of air within an indoor space, typically to improve air quality, temperature distribution, or overall comfort.

Epidemic mode: Operating a premise or building during the widespread occurrence of an infectious disease in a community at a particular time.

Effective openable area: Net free area of a window that can be opened for ventilation.

Fan-assisted natural ventilation: A system that combines the principles of natural ventilation with the assistance of fans (such as ceiling fans or wall-mounted fans) to improve ventilation within a space.

Mechanical Ventilation (MV): Ventilation provided by mechanically powered equipment such as motor-driven fans and blowers, but not by devices such as wind-driven turbine ventilators and mechanically operated windows.

Mixed Mode Ventilation (MMV): A hybrid approach to space conditioning which combines natural ventilation from operable windows or passive inlet vents (manually or automatically controlled) with mechanical systems that distribute air and offer some form of cooling.

Natural Ventilation (NV): Ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building.

Net occupiable area: Floor area of an occupiable space defined by the inside surfaces of its walls but excluding shafts, column enclosures, and other permanently enclosed, inaccessible, and unoccupiable areas. Obstructions in the space, such as furnishings, display or storage racks, and other obstructions, whether temporary or permanent, are considered part of the net occupiable area.

Occupancy rate: This guide was derived based on occupancy rates in applicable fire codes.

Openable area: Net free area of an opening.

Outdoor air: Ambient air entering the system or opening from outdoors before any air treatment.

Regularly occupied space: Enclosed areas where people normally spend time, defined as more than one hour of continuous occupancy per person per day, on average.

Types of window configuration (natural ventilation):

- Corner Opening: For zones with openings on two adjacent sides of a zone.

- Double opening (Cross Ventilation): For zones with openings on two opposite sides of the zone, the naturally ventilated area shall extend between the openings separated by a distance not greater than five times the height of the ceiling. For spaces with opening distances more than five times the height of the ceiling, it will be considered as single side opening.

- Single side opening: For zones with openings on only one side of the zone.

Ventilated floor area: The net occupiable floor area of the ventilation zone ventilated by the same openable area, measured from the interior surfaces of the walls, excluding permanent obstructions like shafts and columns.

Ventilation: A process of either supplying outdoor air to or removing indoor air from a space, achieved through natural or mechanical methods. This air may or may not have undergone conditioning.

Ventilation mode: Operating mode of interest for mixed-mode ventilation.

- Change-over mode (Same space, different times): Changeover mode allows open windows and air conditioning at different times in the same place.

- Concurrent Mode (Same space, same time): Concurrent mode allows open windows and air conditioning at the same time in the same space.

Ventilation Rate (ACH): Air changes per hour, which is the number of times that the total air volume in a room or space is completely removed and replaced in an hour

Acronyms

ACH	Air changes per hour
ppm	Parts per million
CFD	Computational Fluid Dynamics
TDM	Thermal Dynamic Modelling
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
WHO	World Health Organization
BCA	Building and Construction Authority
AC	Air conditioning
NV	Natural ventilation
MMV	Mixed-mode ventilation
GM	BCA Green Mark Certification
ACH	Air change per hour

CHAPTER 1

CHAPTER 1: INFECTION CONTROL IN INDOOR ENVIRONMENTS AND VENTILATION

This guide is designed for indoor environments intended for human occupancy, with a particular focus on office, retail, and preschool buildings utilizing natural ventilation or mixed-mode ventilation design strategies. Its aim is to provide recommendations for optimizing these ventilation approaches within the context of infection control.

In indoor spaces, infectious diseases can spread through droplets and aerosols. Droplets, which are larger particles expelled when coughing or sneezing, typically travel short distances less than 3 meters before falling to surfaces. Aerosols, which are smaller particles released through breathing or talking, or formed by rapid evaporation of undeposited larger exhaled particles, can remain in the air for hours, especially in poorly ventilated areas. Proper ventilation and airflow patterns play vital roles in reducing transmission by dispersing and removing these particles. Understanding these transmission mechanisms is crucial for implementing preventive measures.

This design guideline emphasizes recommendations primarily on passive design strategies for indoor transmission control. It is important to note that these recommendations are meant to complement primary control measures like occupancy reduction and distancing. According to the World Health Organization, aerosol transmission, also known as airborne transmission, involves the dispersion of very small droplets that can remain in the air for extended periods. While it's difficult to completely avoid exposure to these aerosols, the measures outlined in this document aim to reduce exposure rather than eliminate it entirely.

The measures outlined in this document aim solely to reduce exposure, not to eliminate it entirely. Complete control of exposure to airborne infection in indoor environments is challenging due to the complex flow interactions between the infected person, the exposed person, virus droplets, aerosols, and respiratory flow.

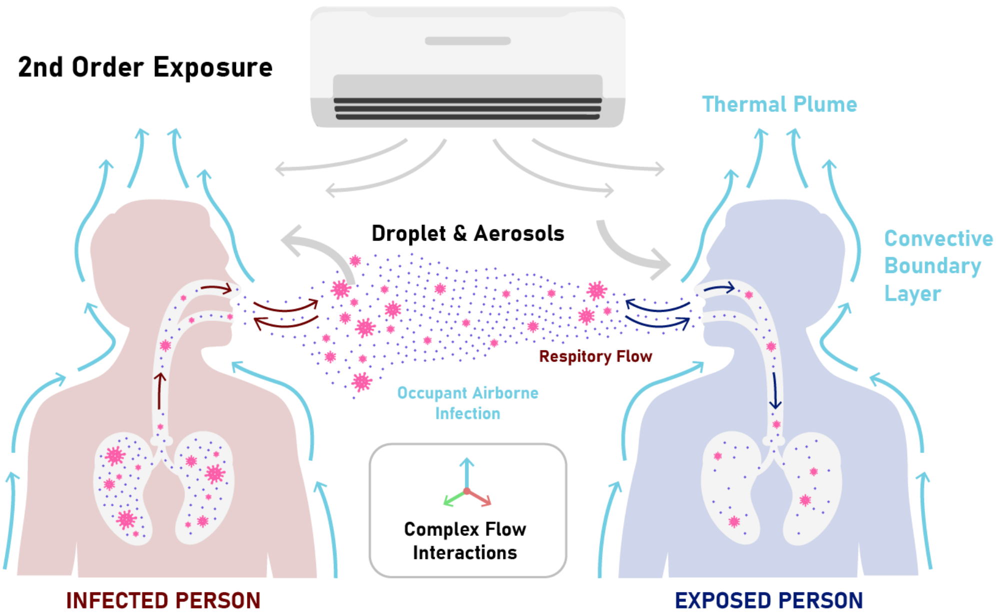


Figure 1 Infection Transmission in indoor Environments

General Principles of Infection Control

Epidemic-ready building ventilation design emphasizes indoor air dilution, air filtration, airflow management, and disinfection technologies to reduce exposure to infectious aerosols. Increasing ventilation emerges as a fundamental method for infection control during epidemic mode, effectively reducing the concentration of infectious particles. Consequently, natural ventilation (NV) and mixed-mode ventilation (MV) represent promising solutions for increasing outdoor air provision during pandemics. Buildings employing these ventilation methods are generally perceived as healthier, experiencing fewer instances of sick building syndrome, and facilitating better air circulation, thus supporting building operations amid pandemics.

Various factors influence the efficiency of natural ventilation, including opening size relative to ventilation floor area, air mixing patterns, distance from ventilated spaces to operable wall or roof openings to the outdoors, in addition to the window configuration of the ventilated space such as single-side, double side, and/or cross ventilation. Employing simulation tools such as Computational Fluid Dynamics (CFD) simulations is recommended to verify ventilation effectiveness.

It is important to note that current recommendations for natural ventilation may not be directly applicable to mixed-mode ventilation, as the prescribed percentage of openings also accounts for thermal comfort. Excessive openings in mixed-mode ventilation (concurrent mode) can lead to significant energy inefficiencies.

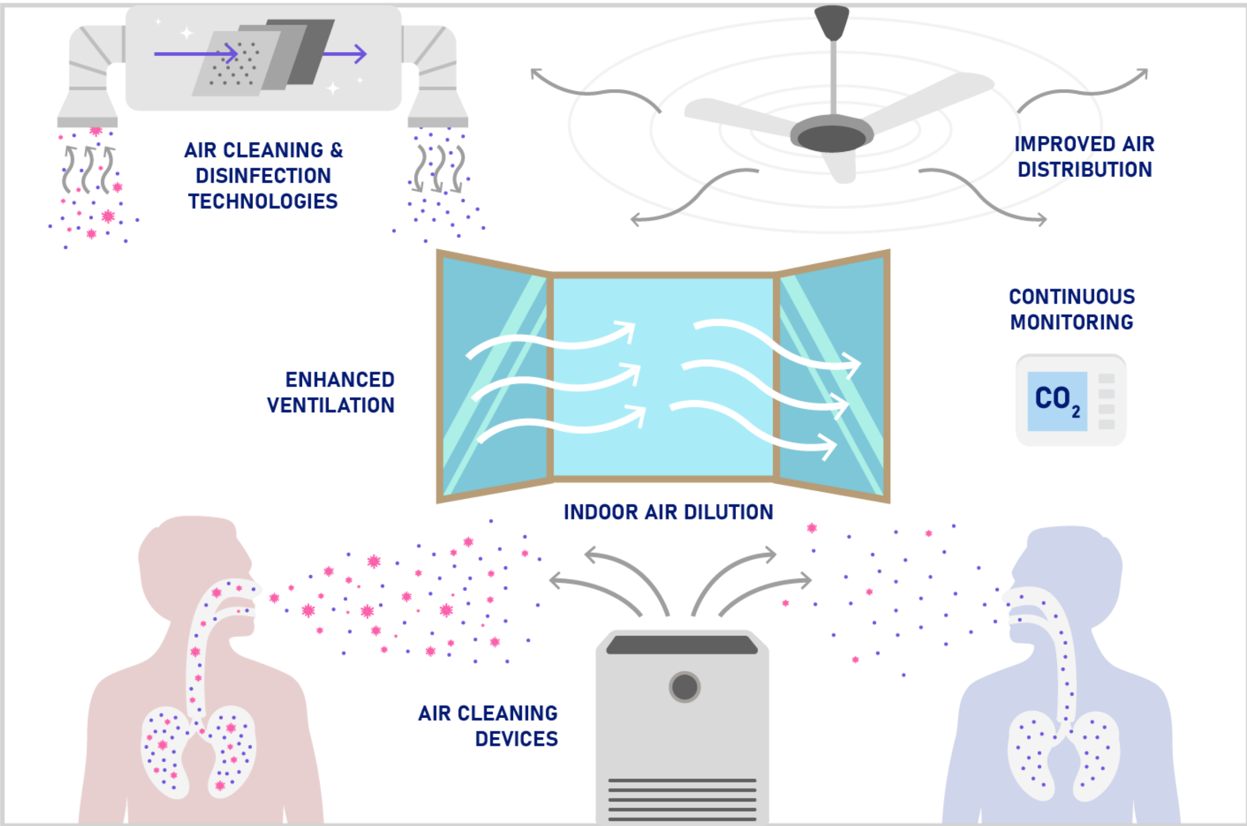


Figure 2 Infection Control Measures for Indoor Environments

CHAPTER 2

CHAPTER 2: GENERAL PRACTICES FOR NV/MMV VENTILATION

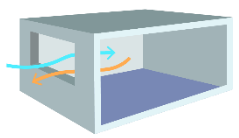
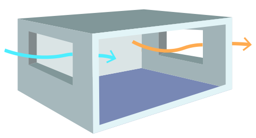
Types of NV/MMV ventilation

In a tropical climate like Singapore, Natural Ventilation (NV) and Mixed Mode Ventilation (MMV) offer viable alternatives to air conditioning. Buildings utilizing natural or mixed mode ventilation are often perceived as healthier for infection control and exhibit better indoor air quality compared to air-conditioned buildings. NV/MMV design practices are recommended by various codes and standards for different purposes. These guidelines aim to increase ventilation rates through natural or mixed-mode ventilation (via openings), reducing reliance on the ACMV system for supplying the necessary outdoor air. The image below illustrates the different methods and primary opening types that various standards use to determine the operable area and ventilation needs based on specific window configurations.

Figure 3 Types of Window Configuration

Current Good Design Practice for NV/MMV under Normal Operation

Table 1 Good Design Practice for NV/MMV

TYPE OF VENTILATION	GM 2021 / HW TECHNICAL GUIDE	Building Control Act
Single Sided Ventilation 	• The limiting depth (W) for effective ventilation is twice the floor-to-ceiling height (H) **[W≤2H]** • Limiting depth for effective single sided ventilation is **no more than 8m**. • This can be **extended to 12m with use of air movement technologies** such as ceiling fans.	• Natural ventilation shall be provided by means of one or more openable windows or other openings with an **aggregate area of not less than 5%** of the floor area of the room or space required to be ventilated. • **No part of any room or space** (other than a room in a warehouse) that is designed for natural ventilation shall be **located more than 12 metres from any window or opening** that is used to ventilate the room or space.
Cross Ventilation 	• The limiting depth(W) for effective ventilation is five times the floor-to-ceiling height (H) **[W≤5H]** • Limiting depth for effective **cross ventilation** is **15m**. This can be extended to **24m with use of air movement technologies** such as ceiling fans.	

i. Single Side Opening

For single-sided openings, it is advisable to ensure that the depth (W) for effective ventilation remains within twice the floor-to-ceiling height (H) [W ≤ 2H]. Additionally, it is recommended to restrict the depth for effective single-sided ventilation to no more than 8m. However, with the incorporation of air movement technologies such as ceiling fans, this limit can be extended to 12m.

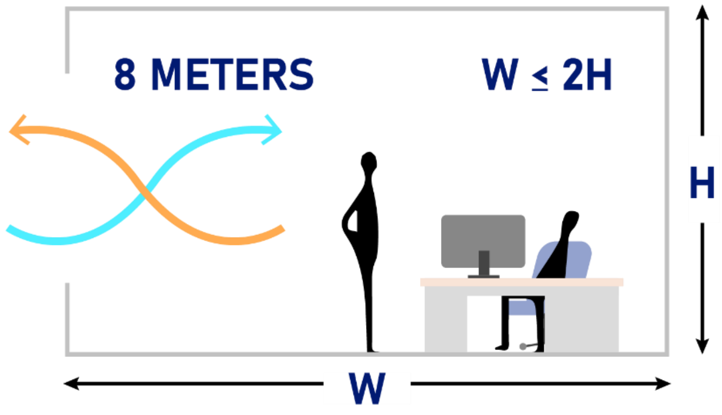


Figure 4 Single Side Opening

ii. Cross Ventilation

For cross ventilation, it is recommended to ensure that the depth (W) for effective ventilation does not surpass five times the floor-to-ceiling height (H) [W ≤ 5H]. The maximum depth for effective cross ventilation is 15m; however, this limit can be extended to 24m with the utilization of air movement technologies such as ceiling fans.

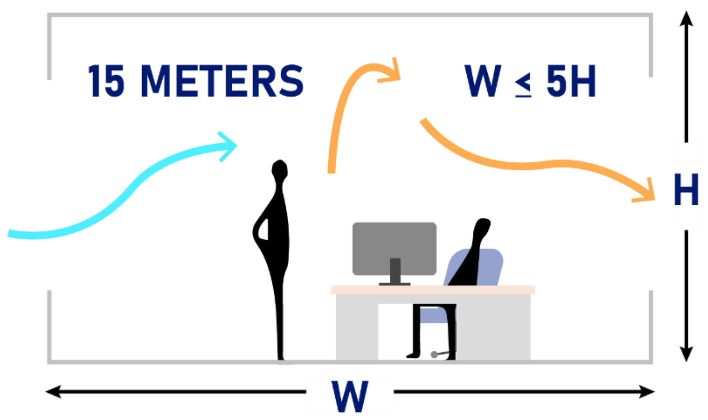


Figure 5 Cross Ventilation

iii. Minimum Opening

Natural ventilation should be provided through one or more operable windows or other openings, with a total area of at least 5% of the floor area of the room or space that requires ventilation, as specified in the Building Control Act.

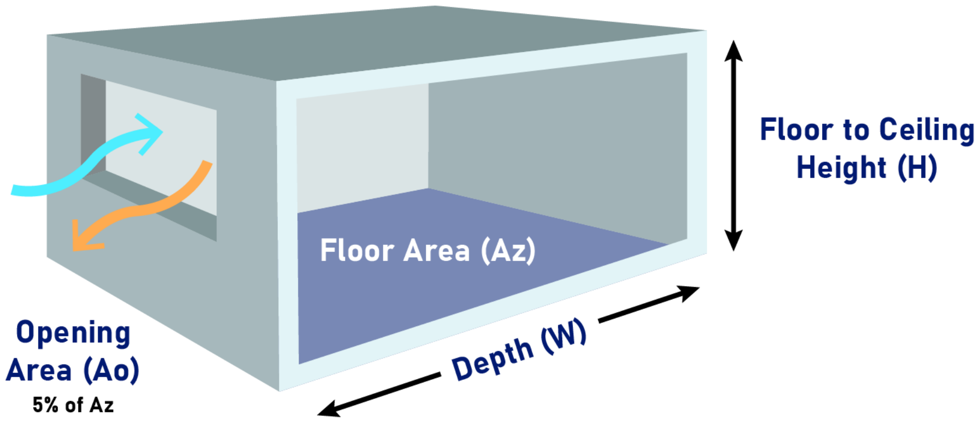


Figure 6 Illustration on effective opening area Ao and ventilated floor area Az

iv. Mixed-Mode Ventilation (MMV)

Mixed-mode ventilation, also known as hybrid ventilation, combines natural ventilation from operable windows (either manually or automatically controlled) or other passive inlet vents (such as doors) with mechanical systems to optimize thermal comfort, ventilation, and air distribution (Brager, 2006; WHO, 2009; CCIAQ, 2021). This system can be utilized in various operational modes. The following scenarios for buildings with mixed-mode ventilation were considered for the recommendations:

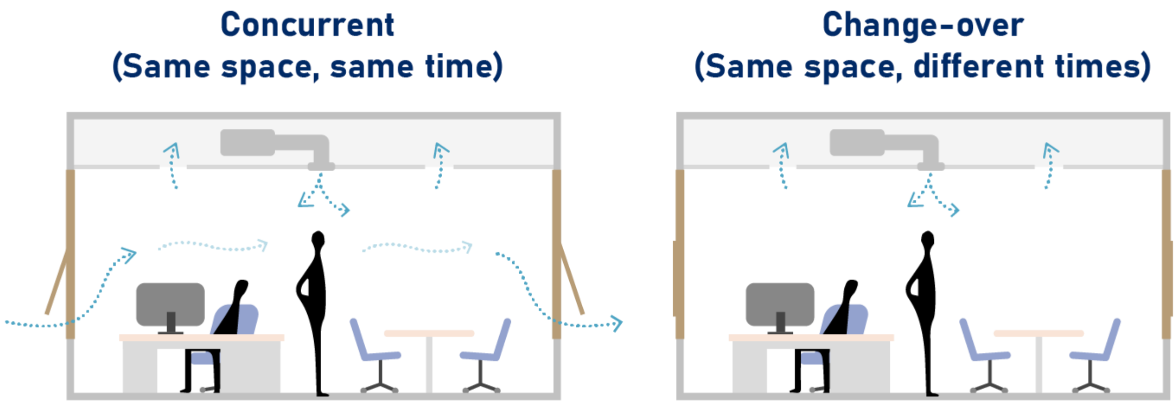
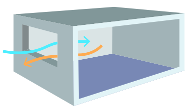
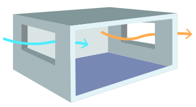
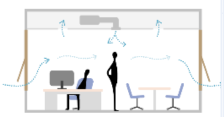


Figure 7 Operating Modes of Interest[1]

[1] Image credit: Centre for the Built Environment, UC Berkeley

The literature review identifies several benefits associated with the utilization of Natural Ventilation (NV) and Mixed Mode Ventilation (MMV) in buildings, including:

Table 2 Benefits of NV/MMV

Type of Ventilation	Strength			
Natural Ventilation (Single Side Opening) 	Simple and cost-effective method to improve indoor air quality.	Utilizes natural airflow, reducing energy consumption and costs associated with mechanical ventilation systems.		Brings in fresh outdoor air, diluting indoor pollutants and improving overall air quality.
	Natural ventilation can lead to fewer sick building syndrome symptoms. (ASHRAE Journal, 2006)	Natural Ventilation can improve indoor air quality by reducing the build-up of pollutants and odours. (WHO, 2009)		Ventilation enhancement provisions can be retrofitted to existing buildings without major modifications. (WHO, 2009)
Natural Ventilation (Cross Ventilation) 	Higher ventilation rates and air distribution within a space in comparison with single side opening.	Increases indoor air quality by promoting continuous air movement and reducing stagnant zones.	Reduces reliance on mechanical cooling systems, leading to significant energy savings.	Natural ventilation can lead to fewer sick building syndrome symptoms. (ASHRAE Journal, 2006)
Mixed-Mode Ventilation (MMV) 	Offers flexibility to switch between natural and mechanical ventilation based on environmental conditions and operation needs.	Enhances indoor air quality and reduces reliance on mechanical systems, leading to energy savings.		Can be automatically controlled for optimal efficiency.
	Improves infection control by increasing ventilation rates when needed.	Lowers overall operational costs by minimizing the use of mechanical systems and maximizing natural ventilation opportunities.		Enhances occupant health and wellbeing by providing a healthier indoor environment with better air quality and thermal comfort.

CHAPTER 3

CHAPTER 3: GUIDANCE FOR INFECTION CONTROL

This guide focuses on three building typologies: office spaces, preschools, and retail environments. Initially, the case studies were intended to cover office, commercial, and institutional spaces due to their significant impact during the pandemic. The selection was based on the higher vulnerability of occupants in childcare and preschool environments, as well as the notably higher rates of disease infection observed in these settings. Including these typologies in the case studies provides a comprehensive understanding of ventilation requirements and mitigation strategies for epidemic risk.

This section defines the recommended opening size necessary to achieve the required ventilation rates under both normal operation and epidemic mode for Office, Preschool, and Retail spaces. The recommended opening area is quantified as a percentage of the total ventilated area. For instance, if a space to be ventilated measures 100 square meters and the total recommended openable area is 2.5%, it indicates that the effective openable area of the windows should amount to 2.5 square meters.

The ventilation rate for normal operation is referenced from ASHRAE 62.1-2022, whereas for epidemic mode, it follows the guidelines of ASHRAE 241-2023.

Design Thinking Process for NV/MMV

A flow chart illustrating the design thinking process for implementing NV/MMV in epidemic resilient buildings is shown in Figure 8 below.

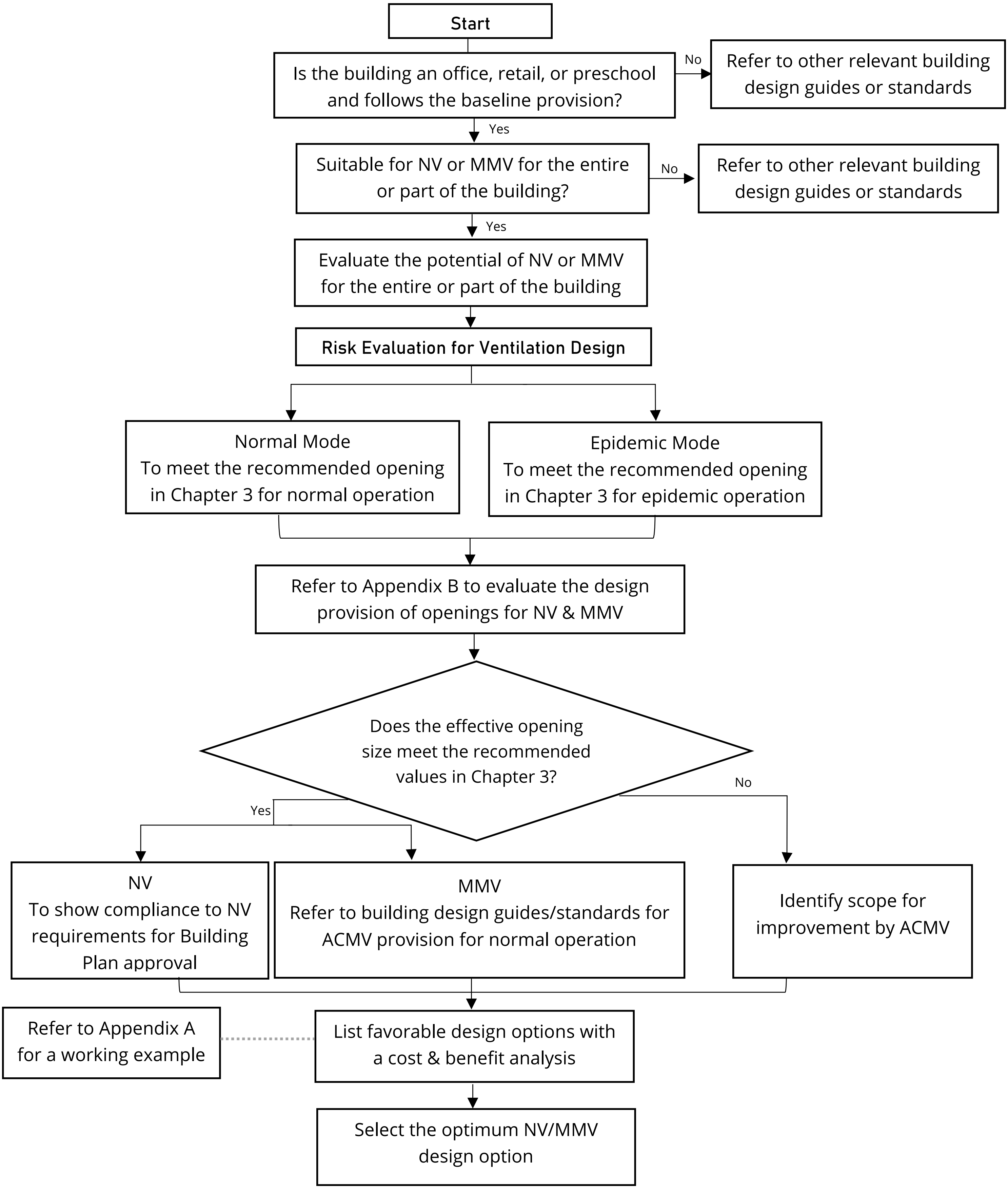


Figure 8 Design Thinking Process for Implementing NV/MMV Design Using This Guide

Guidance for Office Typology

i. Office Typology | Recommended Design Provision

With the baseline provision in place, an opening equivalent to 2.5% of the ventilated floor area is advised to meet the recommended ventilation rate for office spaces under epidemic mode operation. This guideline applies to both single side opening and cross ventilation strategies. The ventilation rate for normal operation is referenced from ASHRAE 62.1-2022, whereas for epidemic mode, it follows the guidelines of ASHRAE 241-2023.

Table 3 Office Typology | Minimum Ventilation Recommendation

	MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 10M2/PERSON)
OFFICE	NORMAL OPERATION ASHRAE 62.1 (2022)	1.0	10
	EPIDEMIC MODE ASHRAE S241-2023	1.5	15

Table 4 Recommended opening size for the required ventilation rates (office)

MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 10M2/PERSON)	TOTAL OPENABLE AREAS ZONES AS A PERCENTAGE OF AZ (SINGLE SIDE OPENING)	TOTAL OPENABLE AREAS ZONES AS A PERCENTAGE OF AZ (DOUBLE SIDE OPENING)
NORMAL OPERATION ASHRAE 62.1 (2022)	1.0	10	2.5%	2.5%
EPIDEMIC MODE ASHRAE S241-2023	1.5	15	2.5%	2.5%

** This table is based on the result of the performance-based approach and site measurements conducted for a typical office following good design practice and the assumptions listed earlier in the design guideline in Table 5 Good Design Practice for NV/MMV*

- L/s/person = L/s/m^2 x occupancy rate (10 m^2 / person)

- (Az) Ventilated floor area

ii. Office Typology | Results & Recommendations

Design Strategy	Description
Baseline Provision / Office Typology	
Depth (W) Limit for effective ventilation	Effective ventilation is achieved when the space's depth is kept within 2.5x the floor-to-ceiling height [2] for single-side opening and 5x for double-side opening (corner openings or cross-ventilation).
Improve Air Distribution	The use of air mixing devices e.g., ceiling fans can improve air distribution and enhance thermal comfort throughout the space.

Encouraged Provision / Office Typology	
Opening Orientation	When implementing mixed-mode ventilation, it is advisable to position the openings in alignment with the prevailing wind direction. This practice has the potential to substantially enhance the air exchange rate within the space.
Double side opening	Double side opening (corner opening on adjacent facade or cross ventilation on opposite facade) is recommended as it is much more effective to improve the ventilation within a space.
Indoor Air Quality Monitoring	In an occupied space, a CO_2 level below 800ppm indicates good ventilation[3]. CO_2 sensors should be installed at the breathing zone (1.1-1.7m above the finished floor) in each ventilation zone to ensure effective monitoring. Set up the CO_2 monitoring system to trigger an audible or visual alarm when the differential CO_2 concentration surpasses the recommended levels. Furthermore, monitoring level of PM2.5 can offer valuable insights into air quality. This information helps in determining instances when natural ventilation should be avoided due to inadequate outdoor air quality, and the opening of windows be avoided

2 The floor-to-ceiling height mentioned here refers to the standard or common ceiling height, excluding high-volume spaces such as double-height areas.

3 Refer to EN 16789-1: 2019, Energy Performance of buildings – Ventilation for buildings- Part 1: Idoor environmental inut parameters for design and accessment of energy peformance of buildings addressing indoor air quanltiy, thermal environemnt, lighting and acoustics.

Guidance for Pre-school Typology

i. Preschool Typology | Recommended Design Provision

With the baseline provision in place, an opening size of 5% with single side opening, only meets the prescribed ventilation rate requirements for normal operational conditions. Therefore, achieving the recommended ventilation rates for preschools under epidemic-control scenarios with a single-sided opening remains challenging.

With the baseline provision in place, implementing cross ventilation with openings equivalent to at least 7% of the ventilated floor area in the preschool typology can achieve the recommended ventilation rates for epidemic mode operation, set at **20 L/s per person or 6.7 L/s·m²**. Hence, cross ventilation is strongly recommended for preschool settings in epidemic-control scenarios.

The ventilation rate for normal operation is referenced from ASHRAE 62.1-2022, whereas for epidemic mode, it follows the guidelines of ASHRAE 241-2023.

Table 6 Preschool Typology | Minimum Ventilation Recommendation

	MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 3 M2/PERSON)
PRESCHOOL	NORMAL OPERATION ASHRAE 62.1 (2022)	3.0	9.0
	EPIDEMIC MODE ASHRAE S241-2023	6.7	20

Table 7 Recommended opening size for the required ventilation rates (Preschool)

MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 3 M2/PERSON)	TOTAL OPENABLE AREAS ZONES AS A PERCENTAGE OF AZ (SINGLE SIDE OPENING)	TOTAL OPENABLE AREAS ZONES AS A PERCENTAGE OF AZ (DOUBLE SIDE OPENING)
NORMAL OPERATION ASHRAE 62.1 (2022)	3.0	9.0	5%	4%
EPIDEMIC MODE ASHRAE S241-2023	6.7	20	-	7%

** This table is based on the result of the performance-based approach and site measurements conducted for a typical pre-school layout following good design practice and the assumptions listed earlier in the design guideline in Table 8 Good Design Practice for NV/MMV*

- L/s/person = L/s/m² x occupancy rate (3 m²/ person)

- (Az) Ventilated floor area

ii. Preschool Typology | Results & Recommendations

Design Strategy	Description
Baseline Provision /Preschool Typology	
Cross Ventilation	Cross ventilation is strongly recommended for pre-schools.
Depth(W) Limit for effective ventilation	Effective ventilation is achieved when the space's depth is kept below 2.5x the floor-to-ceiling height [4] for cross ventilation, it can extend up to five times floor-to-ceiling height. Limiting the depth below 5x floor-to-ceiling height for double opening (cross ventilation) in the preschool typology
Improve Air Distribution	The use of air mixing devices e.g., ceiling fans improves air distribution and enhances thermal comfort within a space. Additionally, exhaust fans are beneficial in spaces where cross ventilation is not feasible, effectively improving ventilation rates.

Encouraged Provision / Preschool Typology	
Opening Orientation	When implementing mixed-mode ventilation, it is advisable to position the openings in alignment with the prevailing wind direction. This practice has the potential to substantially enhance the air exchange rate within the space.
Indoor Air Quality Monitoring	In an occupied space, a CO_2 level below 800ppm indicates good ventilation. CO_2 sensors should be installed at the breathing zone (1.1[5]m above the finished floor) in each ventilation zone to ensure effective monitoring. Set up the CO_2 monitoring system to trigger an audible or visual alarm when the differential CO_2 concentration surpasses the recommended levels. Furthermore, monitoring level of PM2.5 can offer valuable insights into air quality. This information helps in determining instances when natural ventilation should be avoided due to inadequate outdoor air quality, and the opening of windows avoided.
Air Cleaning Systems	When the required outdoor air provision under epidemic mode operation is not achievable under NV/MMV, it is recommended to employ air cleaning systems to **deliver the required Equivalent Clean Airflow Rate per Occupant (ECAi).** The assessment of infectious aerosol reduction efficiency should adhere to the

[4] *The floor-to-ceiling height mentioned here refers to the standard or common ceiling height, excluding high-volume spaces such as double-height areas.*

[5] *For preschools, it is recommended to install the CO2 monitor at 1.1 meters above the finished floor. This height accounts for the shorter stature of children, ensuring accurate readings of CO2 concentrations in their breathing zone.*

	requirements outlined in Sections 7.3.1 and 7.4.1.1 of **ASHRAE Standard 241-2023.** (*Examples of such systems include In-Duct Air Cleaning Systems, In-Room Air Cleaning Systems, In-Duct Ultraviolet Germicidal Irradiation, Upper-Room Ultraviolet Germicidal Irradiation, and other pertinent in-duct air cleaning technologies.*)

Guidance for Retail Typology

i. Retail Typology | Recommended Design Provision

With the baseline provision in place, an opening size equivalent to 7% of the ventilated floor area is advised to achieve the recommended ventilation rate for retail spaces under epidemic mode operation, which is **20 L/s/person / 4.0 L/s-m²**. The ventilation rate for normal operation is referenced from ASHRAE 62.1-2022, whereas for epidemic mode, it follows the guidelines of ASHRAE 241-2023.

Table 9 Retail Typology | Minimum Ventilation Recommendation

	MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 5 M2/PERSON)
RETAIL	NORMAL OPERATION ASHRAE 62.1 (2022)	2.0	10
	EPIDEMIC MODE ASHRAE S241-2023	4.0	20

Table 10 Recommended opening size for the required ventilation rates (Retail)

MODE OF OPERATION	OUTDOOR AIR FLOW RATE (L/S)/M2	L/S/PERSON (OCCUPANCY RATE OF 5 M2/PERSON)	TOTAL OPENABLE AREAS ZONES AS A PERCENTAGE OF AZ (SINGLE SIDE OPENING)
NORMAL OPERATION ASHRAE 62.1 (2022)	2.0	10	4%
EPIDEMIC MODE ASHRAE S241-2023	4.0	20	7%

** This table is based on the result of the performance-based approach and site measurements conducted for a typical retail layout following good design practice and the assumptions listed earlier in the design guideline in Table 11 Good Design Practice for NV/MMV*

- L/s/person = L/s/m^2 x occupancy rate (5m^2/Person)

- (Az) Ventilated floor area

ii. Retail Typology | Results & Recommendations

Design Strategy	Description
Baseline Provision/ Retail Typology	
Depth(W) Limit for effective ventilation	Effective ventilation is achieved when the space's depth is kept below 2.5x the floor-to-ceiling height[6]. Incorporating "ventilation windows", whenever feasible, presents a valuable opportunity for retail to significantly improve their fresh air provision during epidemic scenarios.
Improve Air Distribution	The use of air mixing devices e.g., ceiling fans can improve air distribution and enhance thermal comfort throughout the space.
Encouraged Provision/ Retail Typology	
Opening Orientation	The opening orientation does not significantly impact air exchange or movement in the retail typology. This is because retail spaces with openings to naturally ventilated areas are typically linked to corridors and other protected spaces that experience lower wind exposure.
Indoor Air Quality Monitoring	In an occupied space, a CO_2 level below 800ppm indicates good ventilation. CO_2 sensors should be installed at the breathing zone (1.1-1.7m above the finished floor) in each ventilation zone to ensure effective monitoring. Set up the CO_2 monitoring system to trigger an audible or visual alarm when the differential CO_2 concentration surpasses the recommended levels. Furthermore, monitoring level of PM2.5 can offer valuable insights into air quality. This information helps in determining instances when natural ventilation should be avoided due to inadequate outdoor air quality, and the opening of windows avoided.
Additional mechanical assisted ventilation	Additional ventilation provisions through mechanical systems might be necessary to meet the recommended ventilation rates to ensure a healthy and safe indoor environment during an epidemic.

[6] *The floor-to-ceiling height mentioned here refers to the standard or common ceiling height, excluding high-volume spaces such as double-height areas.*

VENTILATION RATE ASSOCIATED WITH VARIOUS WINDOW OPENINGS

Additional studies were conducted to provide insights into the achievable ventilation rates with higher opening sizes compared to the recommended opening sizes for the three building typologies. Below are the anticipated ventilation rates corresponding to various openable areas, presented as a percentage of the ventilated floor area. It is important to note that the computation of the opening percentage depends on the specific window typology, as the effective openable area is influenced by the type of windows and their respective angles of opening. Appendix B outlines the method for calculating the effective opening area.

This table serves as a guideline to provide an understanding of the association between the percentage of opening and ventilation rate. However, it is strongly advised to conduct performance-based studies for verification. Numerous factors, such as space configuration, window type, weather conditions, window location, building type, interior layout and fit out, can influence ventilation rates through openings. Therefore, a detailed study is crucial to ensure accurate and effective ventilation design.

Table 12 Ventilation rate associated with window opening size.

Typologies / Ventilation Mode	Office (Single Side)	Office (Cross Ventilation)	Preschool (Single Side)	Preschool (Cross ventilation)	Retail (Single Side)
% opening vs ventilated floor area	VENTILATION RATES (L/S/ M2) BASED ON THERMAL DYNAMIC MODELLING (95th PERCENTILE OVER YEARLY WEATHER DATA)				
2.5%	1.78	1.89	1.56	1.81*	1.67
4%	2.67	2.89	2.41	2.57	2.50
5%	3.20*	3.44	2.8	3.11	3.25
6%	3.73	-	3.34	3.61*	3.75
7%	4.22	-	3.81	4.12	4.33

* Projected by thermal dynamic modelling result
- Not studied due to design constraint

FURTHER CONSIDERATIONS

While this guide advises on the minimum ventilation rate and window opening size for the three typologies, there are further considerations for mixed-mode ventilation in tropical areas that involves addressing various challenges and concerns to ensure effective ventilation and operation. Here are some additional considerations.

i. Rain Ingression/Wind Driven Rain

- Integrate weather control devices like overhanging ledges and rain screens with external openings. Conducting a performance-based simulation provides a check that these devices do not compromise ventilation. To increase protection against water damage from rain ingression through openable windows, it is recommended to install a waterproofing membrane on the wall adjacent to the vulnerable windows.

- Ensure proper air movement to reduce humidity build-up by incorporating ceiling fans and exhaust fans in moisture-prone areas such as kitchens and bathrooms.
- Use paint with excellent water resistance to mitigate the risk of mold and moisture in naturally ventilated rooms.
- Specify suspended non-metallic modular ceiling panels with a low water absorption rate, not exceeding 5%, to prevent water damage (Building and Construction Authority, *Green Mark 2021 Version 2.1 Maintainability Technical Reference Non-Residential Building.)*

ii. Mould Prevention

- Specify wall finishes with an anti-mold topcoat to prevent mold growth.
- Ensure material surfaces are resistant to mold growth according to standardized test methods such as UL 181, ASTM C1338, or ASTM D3273.
- Regularly check for condensation and wet spots, addressing moisture problems promptly to prevent potential issues.

iii. Haze/Dust

- Avoid opening windows when outdoor air quality is below the acceptable level (PSI > 100). During unfavorable air quality conditions, operate the building with full air conditioning to maintain a controlled indoor environment.
- Monitor PM2.5 levels to determine instances when natural ventilation should be avoided due to poor outdoor air quality, and the opening of windows avoided.

APPENDIX A WORKING EXAMPLE

i. Office space selected for working example.

The office space measures 21 meters in length and 9 meters in width, with a floor-to-ceiling height of 4 meters. It features a single side window opening (sliding window), providing a total opening area of 7.6 m^2, equivalent to 4% of the ventilated floor area.

During an influenza epidemic, the office operator is interested in implementing epidemic-mode ventilation to mitigate contagion and enhance safety measures within the workspace.

The space is designed with the following system:

- Ceiling fans (8 no's)
- Central air conditioning system

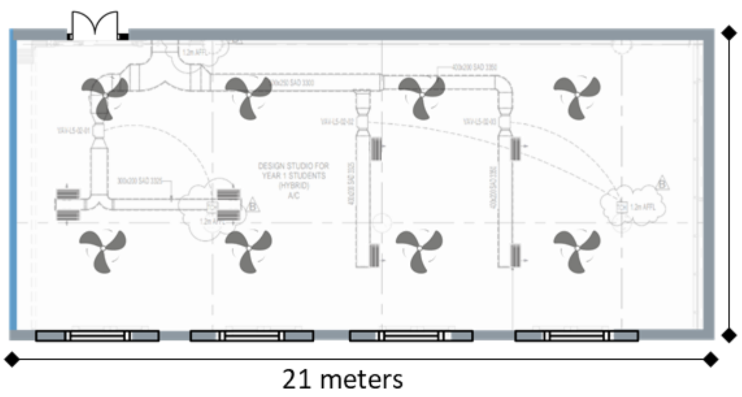


Figure 8 Office Layout

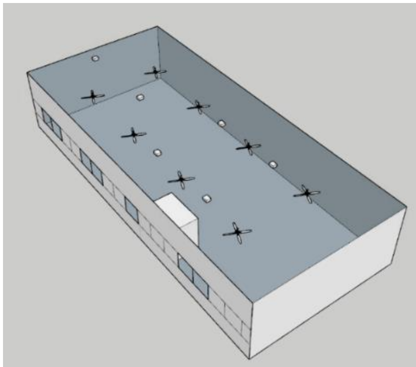


Figure 9 Office Isometric View

The office occupant density was determined in accordance with the Fire Code 2018, which allocates 1 person per 10 square meters.

Table 13 Office space parameters

Parameters	Width (m)	Depth (m)	Floor Area (m^2)	Floor to Ceiling Height(m)	Direct Opening Area	Width <2 H	Gross Window Area	Openable Area (%)
	21	9	189	4	Yes	No	7.6	4%

- Currently, the space does not meet the prescribed criteria for effective natural ventilation (Green Mark 2021 / HW 1.3) due to its **depth exceeds twice the height**, as specified. However, this limitation can be addressed by implementing air movement technologies like ceiling fans, enabling an increase in depth of up to 12 meters.

- According to Table 1, this space requires a minimum 2.5% opening based on the prescribed criteria, equating to an opening size of 4.725m^2. The project can accomplish this by partially opening three windows to achieve the required 4.725 m^2 of effective opening.

ii. Cost Benefit Analysis (Working Example)

The primary objective is to identify a ventilation mode that meets the minimum ventilation rates required for epidemic mode while minimising the increase in energy usage and maintaining the thermal comfort within the office space.

The Thermal Dynamic Modelling used a detailed weather file containing climate patterns spanning the entire year. By considering dynamic weather conditions, this modelling approach provides a more comprehensive understanding of the effectiveness of different ventilation strategies and their implications in actual operation.

The baseline for energy consumption is based on a fully air-conditioned setup that adheres to code-compliant outdoor air (OA) requirements with a temperature set point of 24°C. In this configuration, the annual AC energy consumption is 12.5 megawatt-hours (MWh).

The baseline for outdoor air change is determined by the minimum ventilation rate necessary to operate under epidemic mode, which is calculated as 15 L/s/person (ASHRAE Standard 241-2023) /1.5 L/s per square meter (equivalent to 1.8 air changes per hour, ACH).

Thermal comfort is assessed using the Adaptive Model for Thermal Comfort (ASHRAE 55-2022), which is particularly relevant for naturally ventilated buildings such as MMV/NV scenarios. In these environments, occupants are expected to adapt to a broader range of indoor temperatures beyond the narrower comfort zones defined by the Predicted Mean Vote (PMV) model. Acceptability is measured as the percentage of hours within the acceptable limits (80%).

The following scenarios were studied and simulated through CFD and Thermal dynamic modelling.

Scenario 1 (S1): The baseline represents typical office operation with a fully air-conditioned setup, no open windows or openings, and a temperature set point of 24°C.

Scenario 2 (S2): Involves full natural ventilation with 2.5% window openings and no fans.

Scenario 3 (S3): Involves full natural ventilation with 2.5% window openings and ceiling fans.

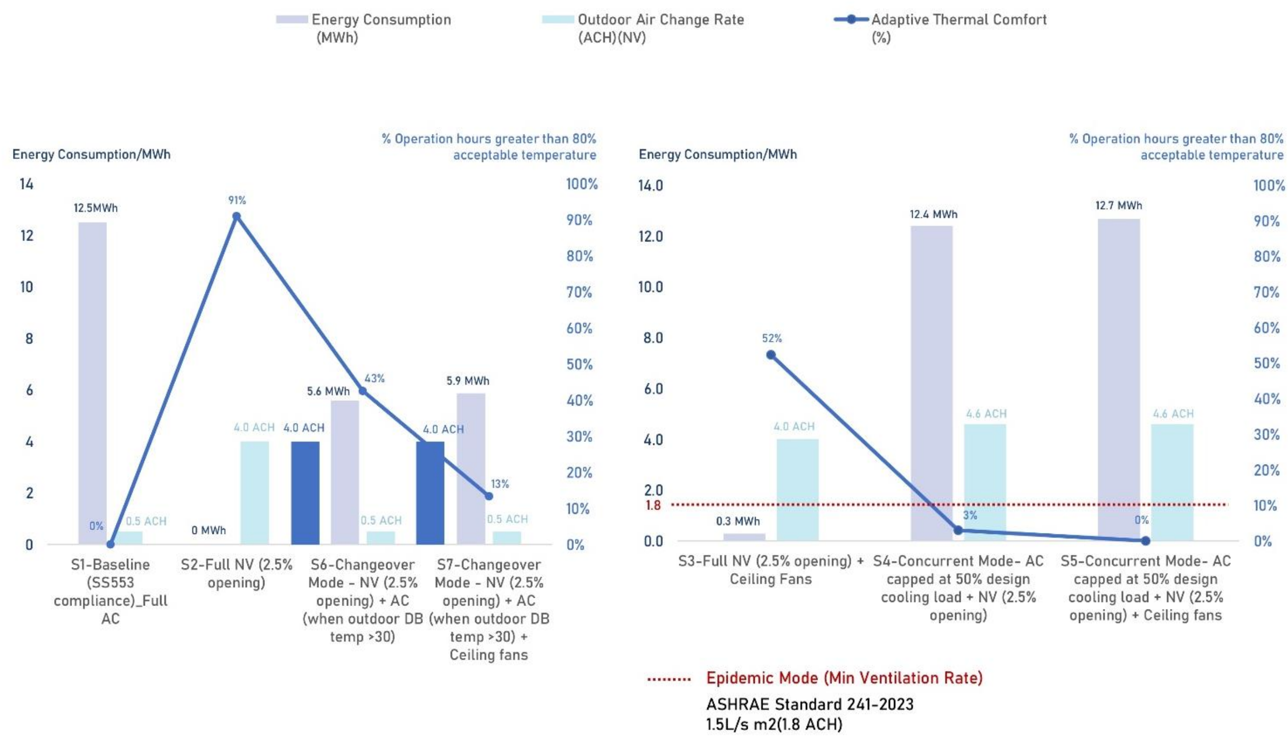
Scenario 4 (S4): Operating in concurrent mode with a cooling capacity cap of 50%, alongside 2.5% window openings, presenting an option to increase the ventilation rates without significantly impacting thermal comfort and energy efficiency.

Scenario 5 (S5): Operating in concurrent mode with a cooling capacity cap of 50%, 2.5% window openings and ceiling fans, presenting an option to increase the ventilation rates without significantly impacting thermal comfort and energy efficiency.

Scenario 6 (S6): Represents changeover mode operation, offering the opportunity to switch from AC to NV when outdoor temperature is less than 30 ̊C.
In changeover mode, windows are kept open when the outdoor air temperature is below 30°C, shifting to full air conditioning (AC) with closed windows when the outdoor temperature exceeds 30°C. The switchover can be automated or involve manual intervention, depending on the desired complexity of the building's operation.

Scenario 7 (S7): Represents changeover mode operation, offering the opportunity to switch from AC to NV and ceiling fans when outdoor temperature is less than 30℃.
In changeover mode, windows are kept open when the outdoor air temperature is below 30°C, shifting to full air conditioning (AC) with closed windows when the outdoor temperature exceeds 30°C. The switchover can be automated or involve manual intervention, depending on the desired complexity of the building's operation. Additionally, ceiling fans will be turned on when the outdoor air temperature is below 30°C and the windows are open.

iii. Result Analysis



Scenario 1 (S1): Serves as the baseline, representing a typical office space with fully air-conditioning. However, this scenario fails to meet the required fresh air standards for epidemic mode operation, delivering only 0.5 air changes per hour (ACH) and consuming 12.5 MWh per year.

Scenario 2 (S2): Involves full natural ventilation with 2.5% openings and no fans. While it requires no energy for ventilation and achieves 4.0 ACH, it significantly impacts thermal comfort, with 91% of the time exceeding acceptable limits for adaptive thermal comfort.

Scenario 3 (S3): Efficiently supplies the required fresh air for epidemic mode operation through openings. The provision of fans reduces the percentage of hours surpassing the acceptable limits for adaptive thermal comfort from 91% (S2: Full NV) to 52%. Notably, the energy required for fan operation is negligible compared to (S1).

Scenario 4 (S4): Operating in concurrent mode with a cooling capacity cap of 50% offers an option to increase the ventilation rates without significantly impacting thermal comfort and energy efficiency. This scenario achieves adequate outdoor air provision required for epidemic mode operation while utilizing nearly the same energy as (S1). Additionally, the percentage of hours exceeding acceptability limits for adaptive thermal comfort is reduced to 3%.

Scenario 5 (S5): Operating in concurrent mode with a cooling capacity cap of 50% provides an option to increase the ventilation rates without significantly impacting thermal comfort and energy efficiency. In this scenario, adequate outdoor air required for epidemic mode operation is achieved while utilizing nearly the same energy as (S1). Additionally, the inclusion of fans reduces the percentage of hours exceeding acceptability limits for thermal comfort from 3% to 0% compared to (S4).

Scenario 6 (S6): Changeover mode operation offers the chance to improve outdoor air provision while cutting energy consumption by 56% compared to full AC operation (S1). Although the average outdoor air change rates exceed the epidemic mode operation requirements, the thermal comfort is negatively affected, with 43% of the hours exceeding the acceptability limits for adaptive thermal comfort. However, it's important to note that in these scenarios, outdoor air change rates only meet epidemic mode requirements when the windows are open. Therefore, Changeover mode cannot be considered a pandemic control mode since it fails to provide the necessary ventilation rates for epidemic control when the windows are closed.

Scenario 7 (S7): Changeover mode operation offers the chance to improve outdoor air provision while cutting energy consumption by 56% compared to (S1). In this scenario, the average outdoor air change rates exceed epidemic mode operation requirements, however thermal comfort is negatively impacted. Nevertheless, the inclusion of fans can reduce the percentage of hours exceeding acceptability limits for adaptive thermal comfort from 43% to 13%. However, it's important to note that in these scenarios, outdoor air change rates only meet epidemic mode requirements when the windows are open. Therefore, Changeover mode cannot be considered a pandemic control mode since it fails to provide the necessary ventilation rates for epidemic control when the windows are closed.

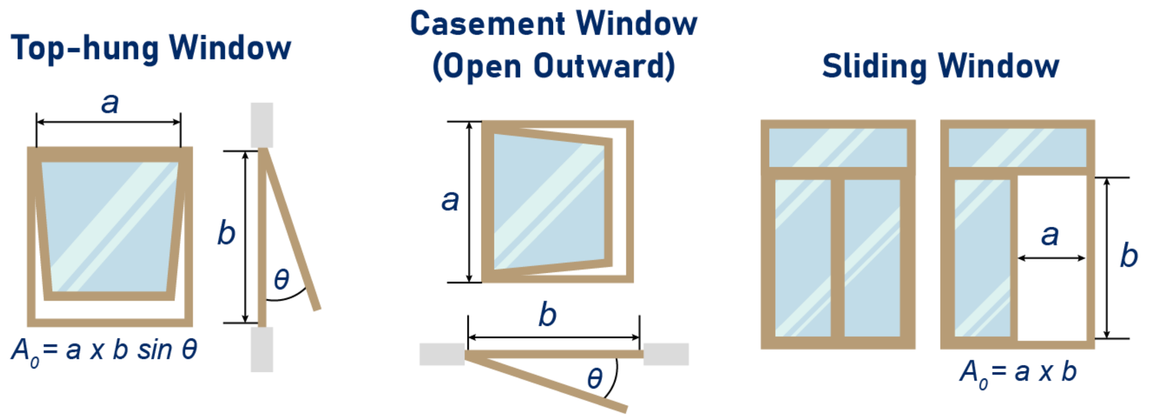
In summary, operating in concurrent mode with full AC can achieve required ventilation rates for epidemic mode operation but significantly increases energy consumption. Despite the higher fresh air ventilation rates, thermal comfort is still acceptable. Alternatively, employing a cooling capacity cap of 50% in concurrent mode allows for increased ventilation without severely affecting energy efficiency and thermal comfort. The inclusion of fans can further decrease the hours where thermal comfort exceeds acceptable limits from 3% to 0%.

This working example serves to demonstrate potential solutions capable of achieving the ventilation rate necessary for epidemic building control without comprising thermal comfort or increasing energy consumption significantly. However, it does not imply that the concurrent mode is recommended for regular operation. A comprehensive study associated with the design should also be conducted.

APPENDIX B EFFECTIVE OPENING AREA FOR VARIOUS TYPES OF WINDOWS

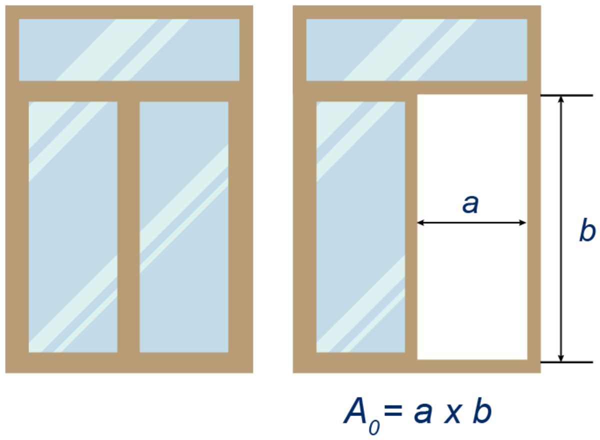
i. Types of Windows

Below are the calculation methods to determine the effective opening area for different window types. Alternatively, reference can be made to the acceptable solutions specified in the Approved Documents to determine the effective opening area.



Sliding Window

A sliding window is a window that opens by sliding horizontally along a top and bottom track in the window frame

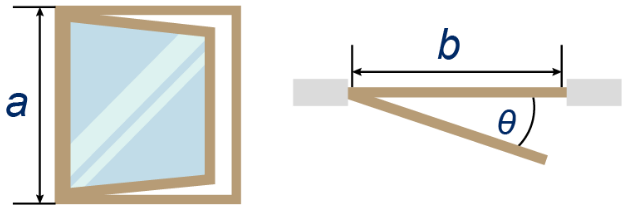


A_0 = *Effective Opening (sqm)*

$A_0 = a \times b$

Casement Window

The term 'casement' typically refers to windows featuring a hinged, glazed 'sash' that opens either from the sides (side-hung), top (top-hung), or bottom (bottom-hung)



A_0 = *Effective Opening (sqm)*

$A_0 = a \times b \sin \theta$

Below is an illustration of calculating the effective opening by considering the window type and the angles of opening.

- Window type: sliding window
- Total length of the space: 10 meters
- Total depth of the space: 8 meters

To calculate the effective window opening, following these steps:

1. Determine the ventilated floor area:

Calculate the area to be ventilated in square meters (sqm) by determining the total area of the space intended for ventilation.

Ventilated floor area = Total length x Total depth
= 10 meters x 10 meters
= 100 sqm

2. Determine the effective opening area:

Refer to the tables provided for each building typology to determine the required openable areas per typology and ventilation mode (normal operation or pandemic mode). These tables outline recommended openable areas based on specific building typologies and corresponding ventilation strategies.

For the office typology, the minimum opening is 2.5% over the ventilated floor area.

Area of the effective opening = Recommended opening size (%) x Ventilated floor area
= 2.5% x 100 sqm
= 2.5 sqm

3. Identify the window opening type and the angle of opening:

Identify the type of windows being used, considering that different window typologies have varying percentages of effective openings. This helps determine the actual size or proportion of the windows that can be opened for ventilation.

In this case, as it is a sliding window, the window opening size is equivalent to the effective opening area, i.e., 2 sqm.

4. Adjustments and Compliance:

Depending on the window design and specific factors like the presence of window grilles or restrictions on opening size, make further adjustments as necessary. Follow the guidelines provided by the window manufacturer to ensure proper functionality and compliance.

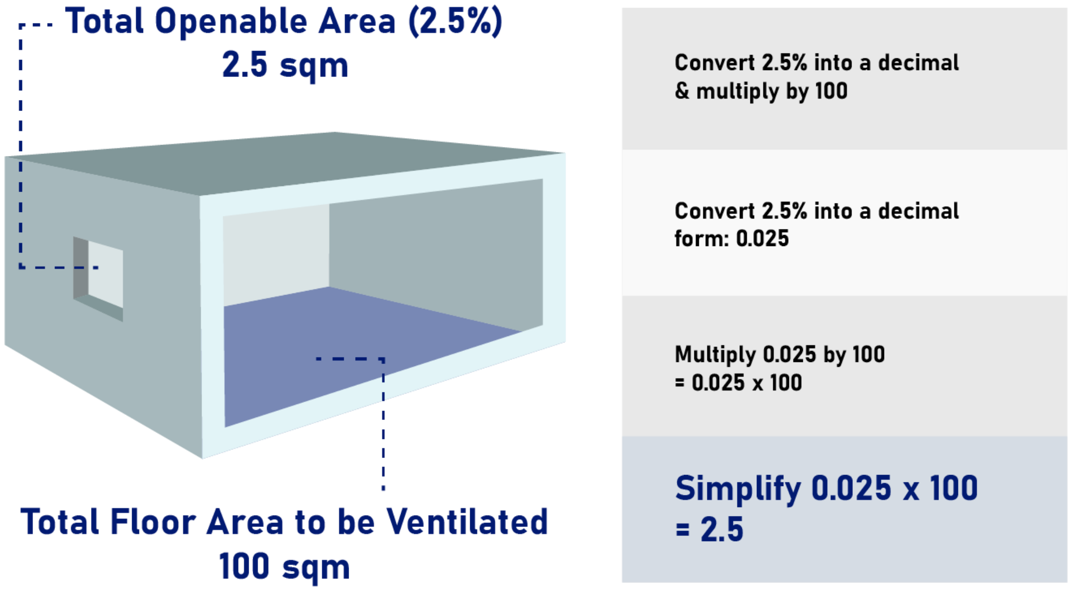


Figure 10 Example of Openable Area Calculation

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