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The Hong Kong Polytechnic University
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Indoor Air Quality against COVID-19 and other contamination in public places

Seminar on Indoor Air Quality in Long Term Care Settings and RCHEs

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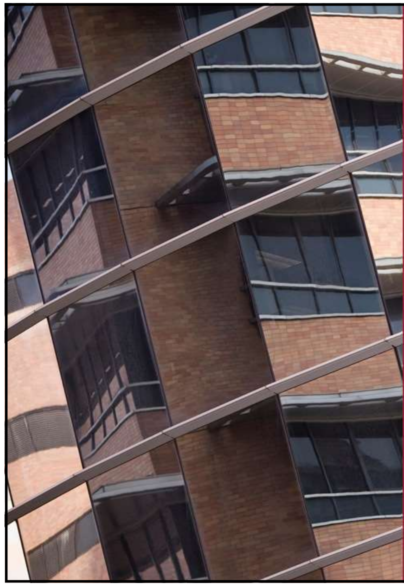
Opening Minds • Shaping the Future



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General Principles….

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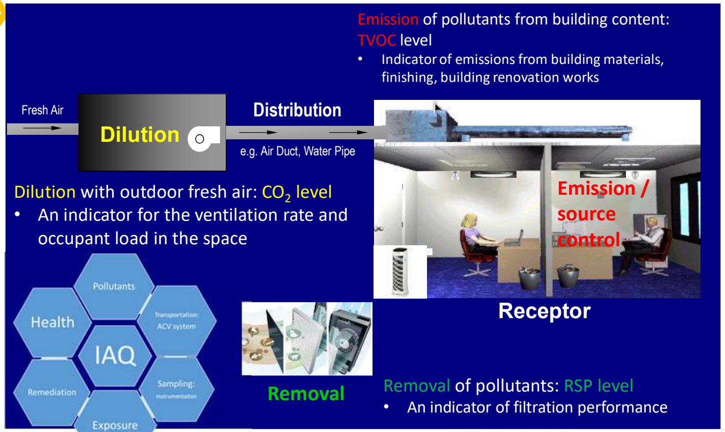
Generalization Principle

3 common IAQ control strategies



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Why study Bioaerosols?

Transmit Disease to Humans, animals
- Costs measured in billions.

Bioterrorism threats
- Regional bacterials census to differentiate normal versus suspicious fluctuations in airborne pathogens.

Influence on the environment
- Spread of organisms.

Monitoring production process
- Food and beverage, pharmaceutical, hospitals.

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Bioaerosols

Defined as organic aerosols that are alive, carry living organisms, or are released from living organisms
- *Bacteria, fungi and viruses

Natural or manmade

Range from 0.010 (small virus) to 100 microns (pollen grains)

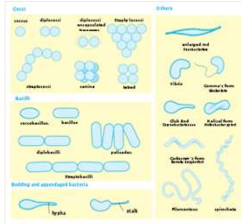
Animal dander (dogs and cats)
- Minute scales from hair, feathers or skin

Plant pollen

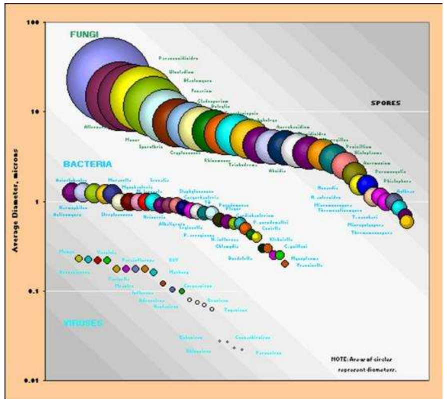
* Dust mites
- *Found in every home/office environment and impossible to get rid of them all

Bioaerosols - microbes

- Main groups of concern
  - Fungi
  - Bacteria
  - Virus



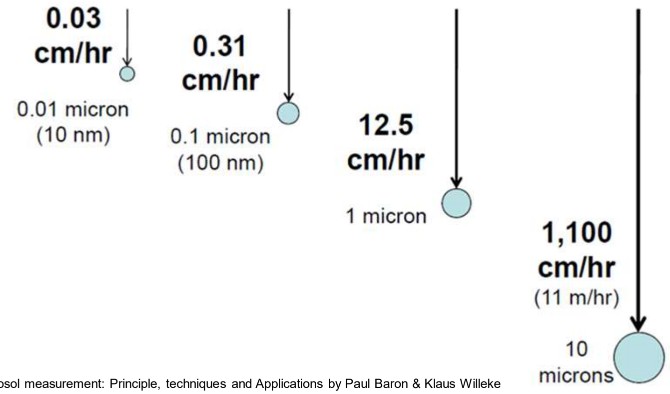
Bioaerosols



Relative size of air-borne micro-organisms

Extracted from Kolwaski (1998)

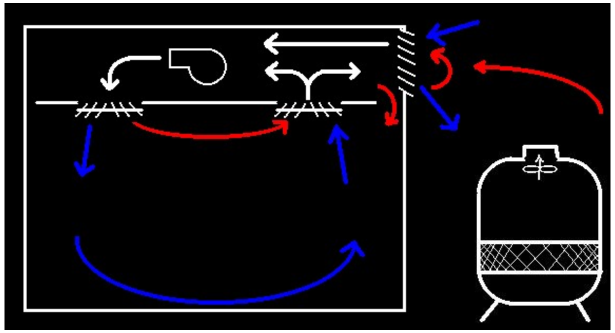
Settling velocity



Aerosol measurement: Principle, techniques and Applications by Paul Baron & Klaus Willeke

Preventing by Building Services system (I)

Clean Air



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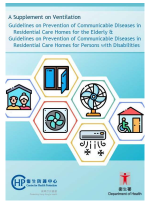
Preventing by Building Services system (II)

Ventilation

Litre/s /person	Significance	Year of concern	Expected CO_2 (ppm)	Fanger's PPD(%)
28	reduced risk of spread of viable disease, e.g. Tuberculosis	1893	500	6
17	reduce microbial pollution	1896	600	10
14	use before recirculation was allowed	before 1973	650	11
10	allows for low smoking rate	since 1989	800	15
7.5	minimum for adapted person+odour contribution from ventilation system and furnishing	1996	1000	20
2.5 - 3	adapted person	1973	2200	40
1	level of concern	-	5000	63

3.1 Three key points for achieving good ventilation

- For Residential Care Homes (RCHs) adopting mechanical ventilation, rate of fresh air replacement to attain a minimum of 10L/s/person (i.e. 0.6m³/min/person) is advised;



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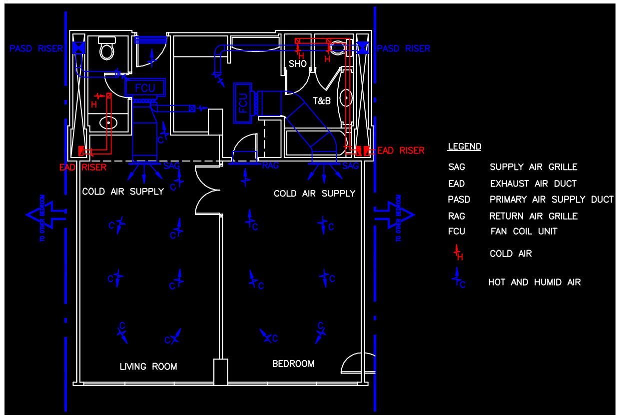
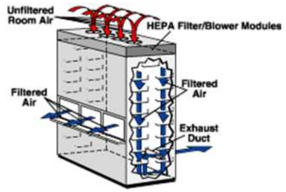
Preventing by Building Services system (III)

Ventilation (effective air distribution)

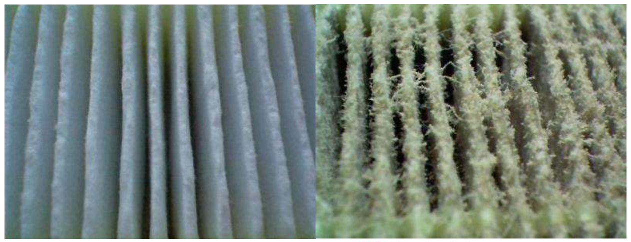


Preventing by Building Services system (IV)

Filtering (HEPA)



99.999% efficient @ 0.12μm particles



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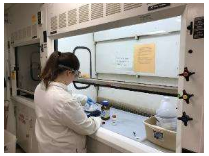
IAQ improvement methods

Local exhaust ventilation

- Chemical fume hoods to control critical emission sources of chemical vapours
- Ensure adequate removal of the pollutant
- Air cleaner with HEPA filter

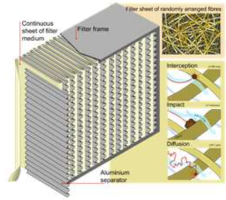
Ultraviolet light Irradiation

- Upper-room irradiation
- Duct irradiation
- Mobile irradiation system



Different types of air purification system

- High efficiency particulate air filter (HEPA)
- Ultraviolet germicidal irradiance (UVGI)
- Carbon filters
- Photocatalytic oxidation (PCO)
- Ozone oxidation
- Ionization



High risk premises

- Mask Off
- Close Proximity
- Long Term Exposure
- Enjoyable Loud Talking

Vulnerable groups

Possible outbreak if teachers are infected and their offices become a hub

Schools and Elderly Homes: Physically vulnerable segment with long-term close interaction

Any solutions?

Problems today

- COVID-19 Virus is more viable than SARS in normal thermal condition
- Transmission of the virus through carrier in air seems to be effective
- The most effective way of precaution is to cut off all possible connections between people (not desirable)
- All interpersonal activities are halt and caused damage to most schooling (classroom, teacher's office)
- Difficult to perform effective risk assessment (Hidden paths of transmission are very hard to determine)
- Situations change so rapidly. When emergency out break takes place, how to respond?
- Actual Virus test in real environmental is not desirable

What is needed?

- Simple assessment method
- Minimal disturbance to tenants and occupants
- Rapid response and deployment
- Provide all possible ways of dispersion profile
- Provide an easy-to-understand presentation of the current situation to the occupants
- Provide suggestions of remedy for effective precaution (i.e. seating plans modification, occupant allocation, operation scheduling, air purifications, system modifications)

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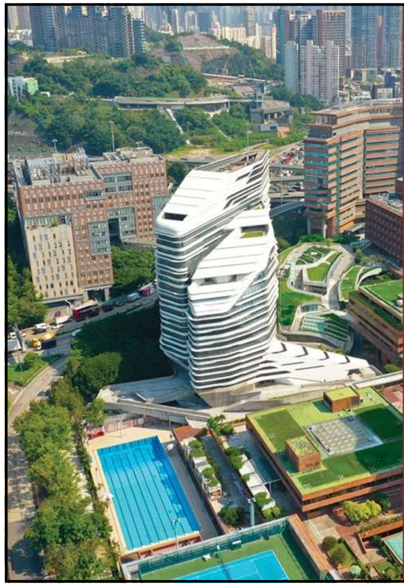

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Ventilation & Transmission

Any Technologies?

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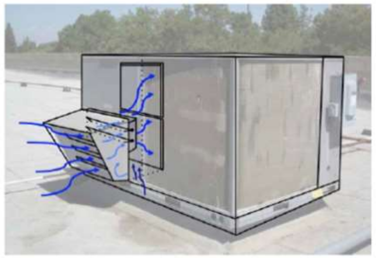
Ventilation principles

Ventilation is the supply of outdoor air to a building



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Why is building ventilation needed?

Ensure comfort and satisfaction

- Remove odor
- Avoid stuffiness

Maintain overall indoor air quality

- Remove indoor air pollutants (e.g., formaldehyde emitted from building materials, furnishings)

Support health and productivity of occupants

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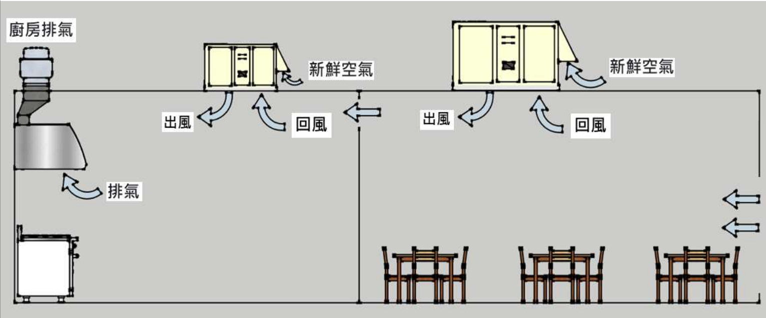
How does ventilation work?



換氣率 (Air Change Rate) = $\frac{\text{每小時每人立方米新鮮空氣 (m}^3\text{/hour/person fresh air) x 人數 (person)}}{\text{餐廳的體積 (m}^3\text{)}}$

Standard requirement

HEALTH REQUIREMENTS FOR THE ISSUE OF PROVISIONAL GENERAL/LIGHT REFRESHEMENT RESTAURANT LICENCE

STANDARD REQUIREMENTS

1. **Ventilation** : When natural ventilation is insufficient (i.e., where openings and windows to the open air are less than 1/10th of the floor area), a ventilating system shall be provided to give not less than 17 cubic metres of outside air per hour for each person that the premises are designed to accommodate. A ventilating system, which shall be independent of any ventilating system provided for the seating accommodation, shall be provided for the kitchens and toilet rooms of the premises.

2. **Toilets** : At least one toilet compartment, one urinal and one wash-hand basin shall be provided on the premises for the use of customers and staff. If the premises are designed to accommodate more than 25 customers, at least 50% of the provision required for the issue of a full licence have been provided.

A Guide to Application for Restaurant Licences (fehd.gov.hk)

How to calculate the Air Change Per Hour (ACH)?

Use	Factor used in determining the population
Seating Area	1 m^2/person
Food Room Area	4.5 m^2/person
Dancing Area	0.75 m^2/person

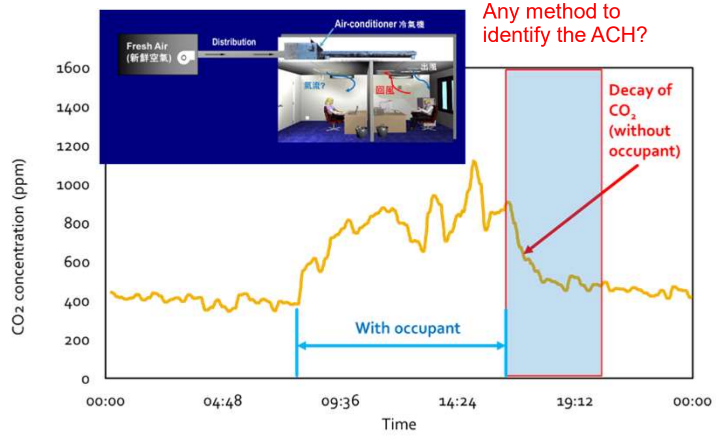
Air Change per Hour (ACH)

$$= \frac{\text{Number of occupants (person) x fresh air quantity (m}^3\text{/h/person)}}{\text{Volume of the space (m}^3\text{)}}$$

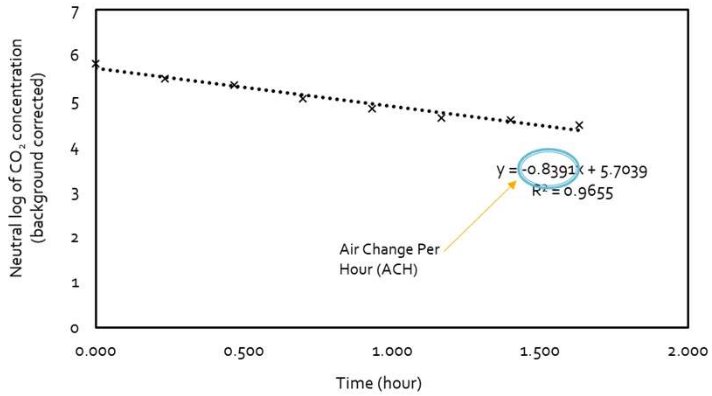
換氣率 (Air Change Rate) = $\frac{\text{每小時每人立方米新鮮空氣 (m}^3\text{/hour/person fresh air) x 人數 (person)}}{\text{餐廳的體積 (m}^3\text{)}}$

How to calculate ventilation rate? What is decay test?

Any method to identify the ACH?



Ventilation (ACH) calculation



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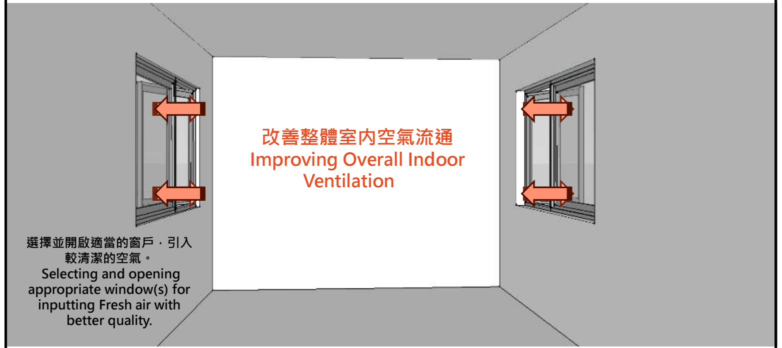
Identification of air path

通風系統 Ventilation System :
渠漏解決師
優質的室內環境
Quality Indoor Environment

窗戶
Window at Light Well
開 OPEN / 關 CLOSE



By Leaky Drain Busters: HKIE, CIBSE, BSOME, CIPHE

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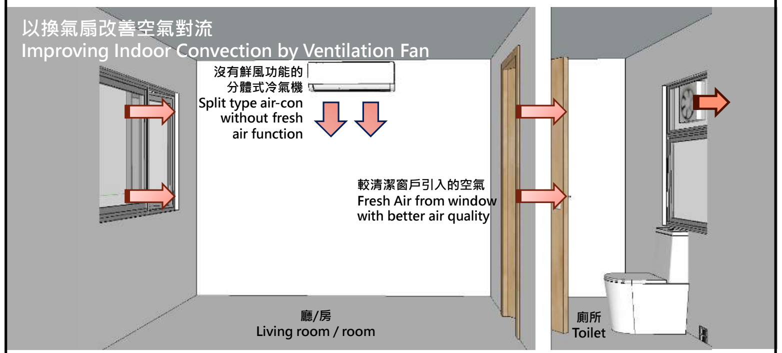
Identification of air path

通風系統 Ventilation System :
渠漏解決師
優質的室內環境
Quality Indoor Environment

換氣扇
Air-Conditioner
開 ON / 關 OFF

窗戶
Window at Light Well
開 ON / 關 OFF

廁所門
Toilet Door
開 OPEN / 關 CLOSE



By Leaky Drain Busters: HKIE, CIBSE, BSOME, CIPHE

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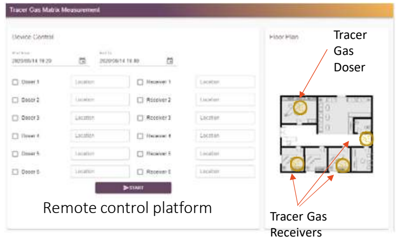
Ventilation and identification of pathogen transmission path



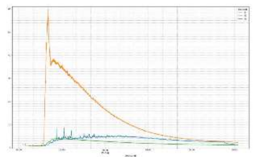
Remote control platform

Tracer Gas Matrix Surveying System

- Rapid deployment for instant response
- Minimal training required for deployment
- Remote real time analysis possible
- Environmentally friendly R134A applied as easily available tracer gas

- ACH analysis by Decay Mode
- Cross Flow/Contamination analysis by Matrix Mode (Multi-Dosers/Receivers Sycnchronized Dosing Matrix)

Real Time Tracer Gas Profile at 3 defined locations



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Tracer gas matrix measurement

Pathogen Source Dispersion Analysis
Contaminants Apportionment Analysis

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Benefits of tracer gas system

- Applicable to special situation, for instant during a pandemic, to conduct monitoring in wet market and restaurants where transmissions are observed, even clean-up has been done
- Once the equipment is set-up, the system will release and track the tracer gas **remotely** without the presence of technician. Much less manpower and time are needed
- **No personnel is required** to be on-site. Data will be automatically transmitted to server for analysis
- Compare to traditional method which takes about half a day to collect and analysis the data, this **new approach takes only 2 hours** to report the pathogenic bioaerosol dispersion pathway

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An example – video (8:13-10:00)

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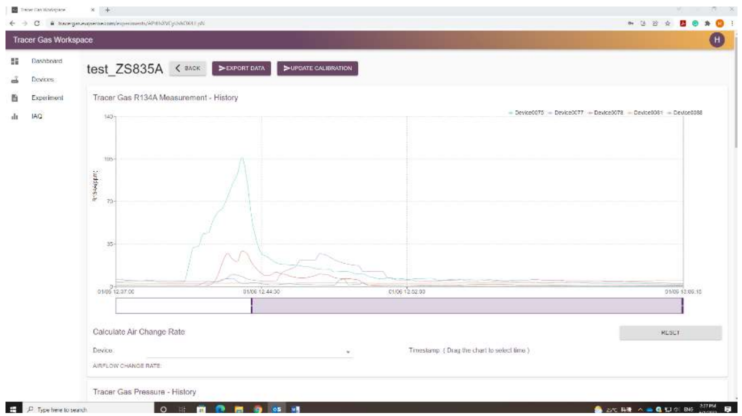
Results



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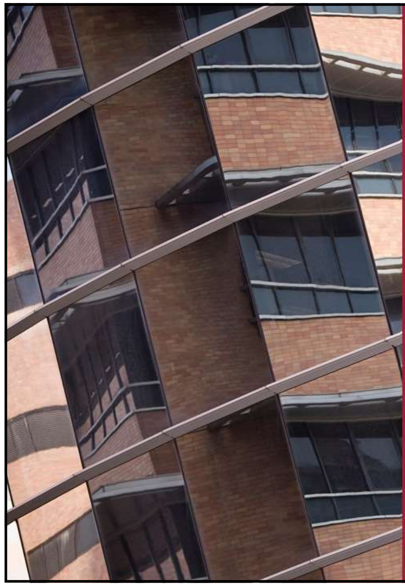

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On-stage Air Flow Analysis

Hong Kong Philharmonic Orchestra

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HK Philharmonic Orchestra On-stage Air Flow Analysis

- Determine the spreading path of potential pathogen from any player on stage
- Determine the potential risk level for other occupants on stage
- Determine the ventilation rate of the current system settings
- Help defining an optimized seating plan to minimize risk level
- Determine the best way of deployment of air purifiers if necessary
- Determine the best arrangement of barrier settings
- Evaluate the risk level at the common areas where the players may gather
- Define all possible measures that could provide a safe environment for the next performance

https://pc.watch.impress.co.jp/docs/news/1282701.html

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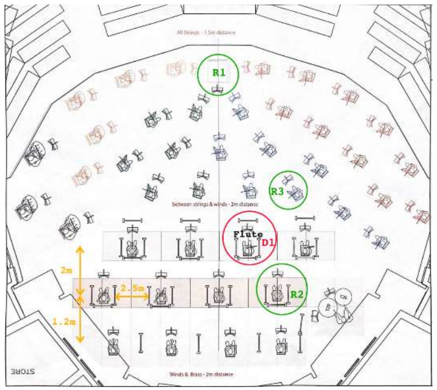
Testing Individual Barrier Setting

Experimental condition

Doser: Flute player

Receiver
- R1 – 54: conductor
- R2 – 55: back-right
- R3 – 56: front-left

Tracer gas operation
- Release at: 10:56:10
- Stop at: 11:07:01



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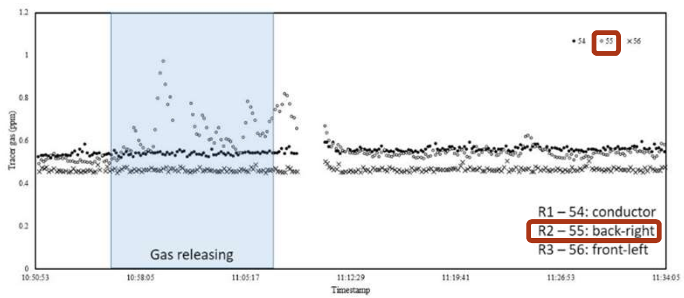
Tracer gas profile with Individual Barrier



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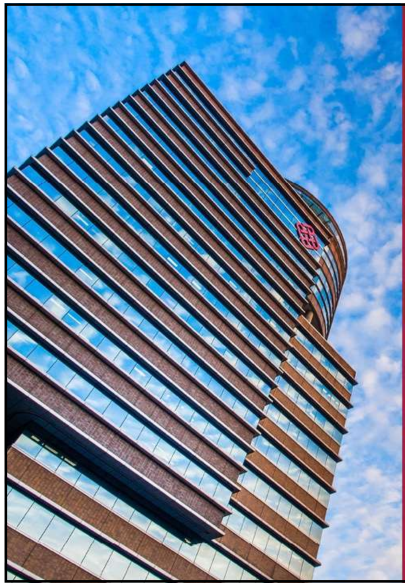

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Ventilation evaluation in health-care settings

Cheung Fat Home for Elderly

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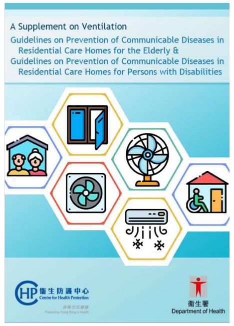
啟迪思維 • 成就未來

Background

- Good ventilation schemes and infection control strategies are essential to prevent long-distance transmission and COVID-19 outbreaks among occupants of the residential care homes
- Without technical background, misuse of and mispositioned means of ventilation could ***enhance the dispersion of virus and worsen the outbreak***



Scope of work

- Understand the current ventilation issues and outbreak situation during COVID-19 pandemic
- Inspect the existing ventilation system
- Conduct air change rate assessment of specified areas if necessary
- Evaluate the airflow pattern and stagnant air zone using tracer gas experiment

Tracer gas experiment conducted at Cheung Fat Home for the Elderly

Tracer gas system

Site of experiment

Location

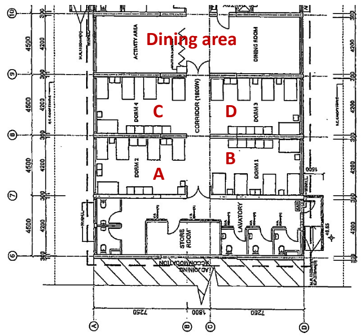
- G/F female wing

Aim

- To identify the dispersion of tracer gas (proxy of airborne virus) from one cubicle to another

Gas release rate

- 6L/min for 10 min



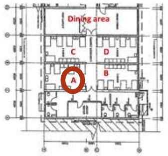
Scenario 1

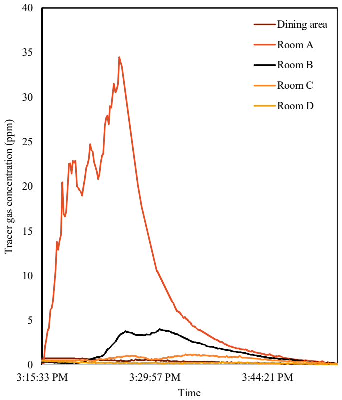
Emission location
- Room A

Ventilation
- Exhaust fan only

Detected location
- Room B & C

Results
- When tracer gas was released in Room A, it was detected in Room B (higher conc.) and Room C (lower conc.) approximately 6 mins after the emission. Tracer gas detected in Room B was 3.8 times higher than that in Room C. No observable changes were found in the tracer gas levels in Room D and the Dining area.





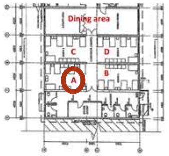
Scenario 2

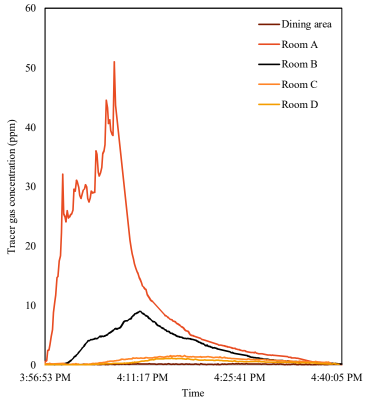
Emission location
- Room A

Ventilation
- Exhaust fan + Fan

Detected location
- All rooms

Results
- When tracer gas was released in Room A with fan on, it was detected in Room B approximately 4 mins after the emission, which was higher than that in scenario 1. Tracer gas was later detected in both Room C & D. No observable changes were found in the tracer gas levels in the Dining area.





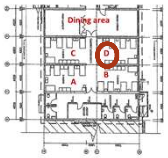
Scenario 3

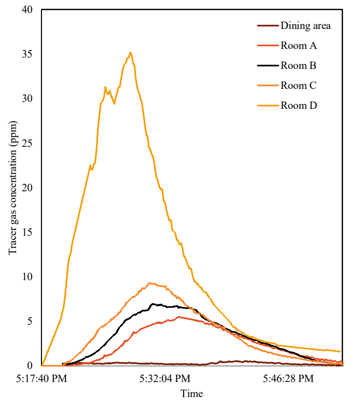
Emission location
- Room D

Ventilation
- Exhaust fan + Fan

Detected location
- All rooms

Results
- When tracer gas was released in Room D with fan on, it was detected in all Rooms approximately 3 mins after the emission, with Room C the highest and Room A the lowest. No observable changes were found in the tracer gas levels in the Dining area.





Summary of results

- Air change rate of the room with washroom ranged from 3.1 to 3.5 h^{-1}
- When the door opened to the dining area was closed, tracer gas could not reach the dining area
- Using fan to enhance air movement may escalate the dispersion of tracer gas
- The dispersion from Room D (and Room C) at the back was more widespread than from Room A (and Room B) in the front

Suggestions

- Immediate isolation of suspected/ infected cases
- Quarantine closed contacts
- Keep the door closed in case of an outbreak
- Use partition to separate the cubicles
- Use exhaust fan
- Stop using fan to reduce the spread of airborne virus
- Proper use of personal protective equipment (e.g. N95 with fit test)
- Enhance cleaning of ventilation equipment

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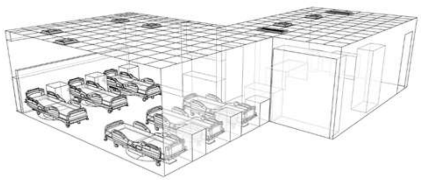
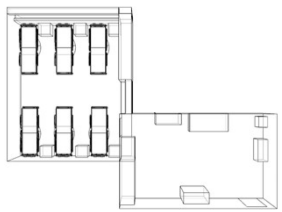
Ventilation evaluation in health-care settings

Mock-up general inpatient ward

Background

- Spatial and temporal evaluations of the dispersion of airborne pathogens in general inpatient ward
- To identify the appropriate management practices for minimizing airborne transmission
- 15-point wireless sensor network using a novel tracer gas system was constructed in a mock-up of a six-bed hospital inpatient ward cubicle with a connected nursing station





Case scenarios

Case	Ventilation rate	Door opening
Full ventilation control case	100%; ACH = 6 h^{-1}	Wide-open
Door-side ventilation only	50% (door-side only); ACH = 3 h^{-1}	Wide-open
Wall-side ventilation only	50% (wall-side only); ACH = 3 h^{-1}	Wide-open
Half-open door	100%; ACH = 6 h^{-1}	Half-open by 30°

Summary of results

- Enhancing air dispersion to achieve a lower average airborne pathogen concentration may lead to airborne transmission to a wider extent
- Localization of tracer gas near the emission location can minimize the spread of airborne pathogens and provide more protection to other patients in the ward as well as the HCWs in the nursing station
- Although a higher ventilation rate could remove the tracer gas (or the contaminants) faster, it did not guarantee lower tracer gas concentrations in the breathing zones of the susceptible patients (i.e. with a higher ACH, more dispersion was observed)
- Some forms of physical barriers may protect the susceptible patients or HCWs against airborne infection, however, the effectiveness depends on the location of emission, the position of the susceptible individual and the scheme of ventilation
- **Case-by-case evaluation is necessary**

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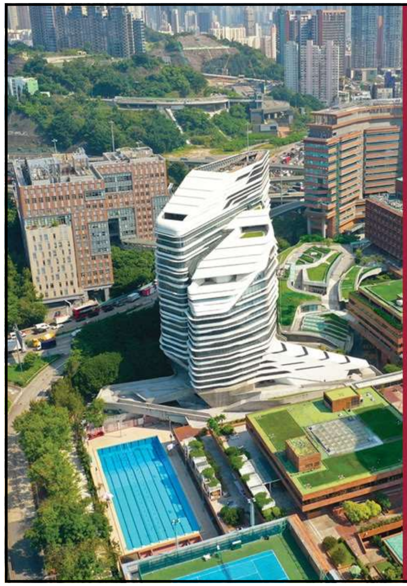

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Effective Ventilation Strategies for Mitigating Infection Risks in Hospitals

醫院環境的疾病感染風險與高效通風策略研究

Opening Minds • Shaping the Future

Project aims

- Understand the spatial distribution of pathogenic bioaerosols in **General Human Occupied Areas (GHOAs)**
- Identify the temporal influence of possible combinations of **control** and **operational** parameters on the **estimation of infection risk** within the mechanically ventilated enclosure in hospital
- Evaluate and update current **air change requirements (ACH)** in hospital
- Provide **proper ventilation strategies** which mitigate the risk of airborne infection transmission (for GHOAs)

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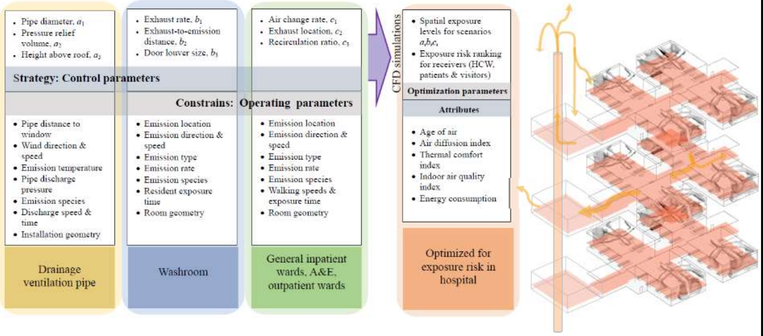
What we need to take care of?

Air flow should never go from **dirty** to clean



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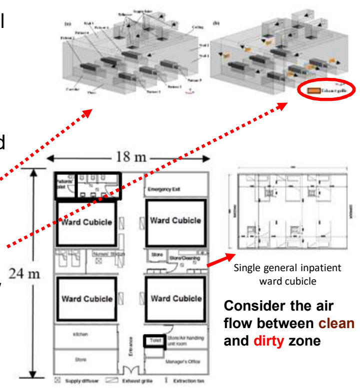
Hospitals layout and ventilation strategies data collection

- Arrangement drawings and technical details of GHOAs in hospitals (e.g. dimensions, ventilation rates and outlet locations)
- 27 ventilation scenarios for general inpatient ward (the most complicated one) will be simulated using
  - (a) **ach** (3, 9 and 13h^{-1})
  - (b) **exhaust locations**
    - EXISTING: no exhaust
    - low level exhaust near the beds
    - low level exhaust on the window side; and
  - (c) **recirculation ratios** (10, 30 and 50%)



Layout of general inpatient ward

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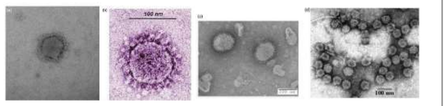
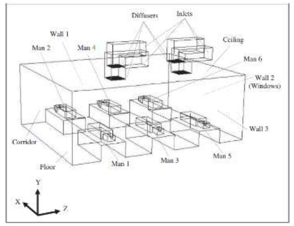
CFD simulations for mitigating infection risks

- A typical semi-enclosed six-bed general ward -7.5 m (L) x 6m (W) x 2.7 m (H)
- 3 respiratory viruses (MERS-CoV, SARS-CoV and H1N1 influenza virus)
- Computational fluid dynamics (CFD) simulation of airflow field and virus dispersion inside the ward with various ACH


Electron micrograph of reference viruses. (a) MERS-CoV19 (b) SARS-CoV20 (c) H1N1 influenza virus21 and (d) Bacteriophage Phi X174



CFD configurations of a six-bed general ward cubicle

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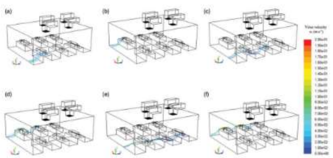
Reference: Yu, H.C., Mui, K.W., Wong, L.T. and Chu, H.S., 2017. Ventilation of general hospital wards for mitigating infection risks of three kinds of viruses including Middle East respiratory syndrome coronavirus. *Indoor and Built Environment*, *26*(4), pp.514-527.

Potential risks of cross infection with through air pathways

- Patients staying on the same side of an infected patient, especially the one located next to the corridor (i.e. Man 1 or Man 2), would have a higher chance of cross infection
- Two different virus pathway flows in the simulation due to the asymmetric diffuser locations
- The virus moved along floor surface of the ward but in cases shown in Figure d and f, virus would pass over nearby patients' heads, then flew to the corridor [Figure c and e]


MERS-CoV pathways for six source locations with ach=6 h^{-1} (a) Man 1, (b) Man 2, (c) Man 3, (d) Man 4, (e) Man 5 and (f) Man 6

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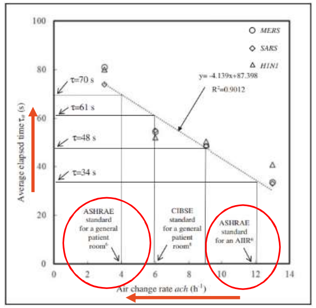
Optimal ACH for hospital

- The average elapsed time against ACH could be significantly shortened by increasing the air change rate in the ward
- The elapsed time doubled when ACH dropped from 12 to 4 h^{-1}, and thus doubling the potential inhalation risk
- Based on the median value in accordance with both ASHRAE and CIBSE standards, the maximum ACH in a general hospital ward should be *9 h^{-1} (elapsed time=48 s)* for the needs of maximizing energy efficiency and minimizing infection risk



Average elapsed time with various design standards. AIIR: airborne infection isolation room

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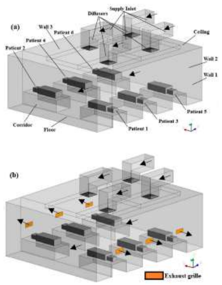
The use of local exhaust grilles for infection risk mitigation

- To evaluate the combined impacts of air change rate and exhaust airflow rate on the airflow and infection risk distributions of droplet nuclei of size 0.167 μm (i.e. MERS-CoV) within an air-conditioned general inpatient ward cubicle using CFD
- To develop a simple yet cost-effective ventilation system design that can minimize the risk of infection in an existing hospital ward



Inpatient ward cubicle with patients: (a) without exhaust grilles; (b) with local exhaust grilles

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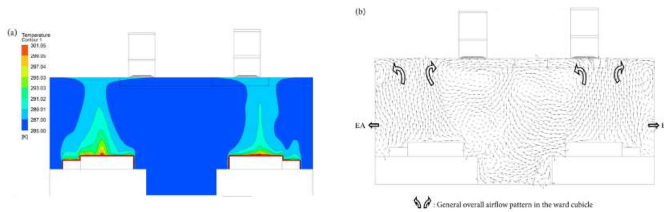
Reference: Satheesan, M.K., Mui, K.W., and Wong, L.T., 2020. A numerical study of ventilation strategies for infection risk mitigation in general inpatient wards. *Building Simulation*, 13, pp. 887-896.

Use of local exhaust grilles

- Local exhaust grilles not only facilitated the removal of a portion of exhaled virus particles but also tended to increase the particle deposition in the source patient's body and thereby reduced the residual viral load present in the air



Simulation results of ward cubicle with exhaust grilles at 6ACH and exhaust air (EA)=50%: (a) temperature distribution; (b) velocity vector plot

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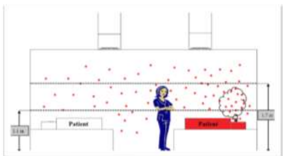
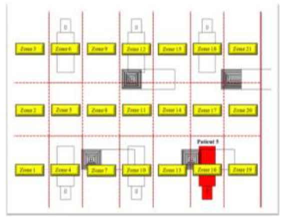
Airborne pathogens suspended in the air

- An infected patient (patient 5) sneezes one time to expel 10,000 particles from the mouth at an exhalation velocity of 50 m/s
- The spatial and temporal distribution of particles is evaluated at ward users breathing height
- The amount of time each particle spends in different breathing zones is determined from the moment it is expelled from the source location
- Four different ACH ($3h^{-1}$, $6h^{-1}$, $9h^{-1}$, $13h^{-1}$) and two exhaust flow rates (10%, 50% of supply air) are considered
- 100% virus-free air is considered with / without recirculation





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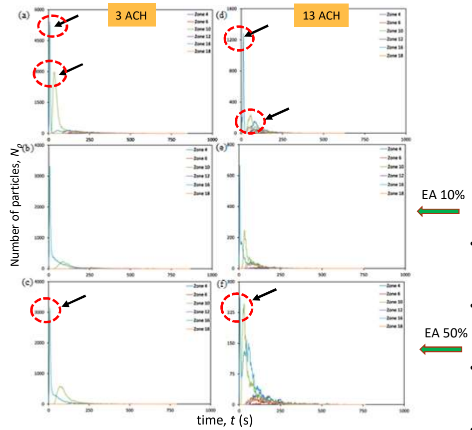
Effect of ACH



Patient Zones (4,6,10,12,16,18)

- Maximum number of pathogen presence is in the zone directly above the source patient
- The dispersion of pathogens towards other patient zones over time is also apparent
- At 13 h^{-1}, there is a greater reduction in the number of pathogens compared to 3 h^{-1}
- Significant reduction is noted at an air change rate of 13 h^{-1} and an exhaust flow rate of 50%

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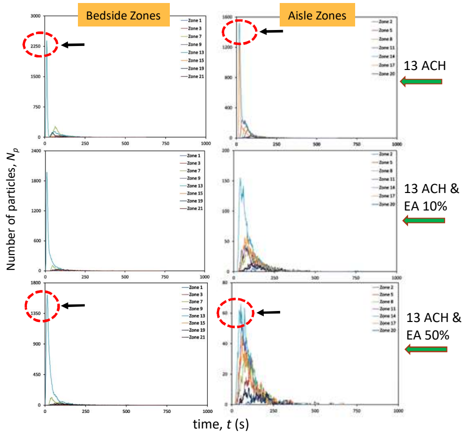
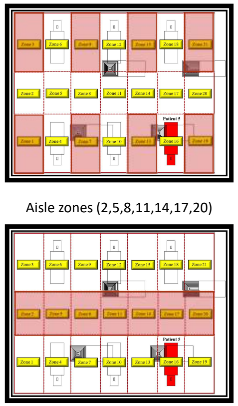
Exposure in different zones





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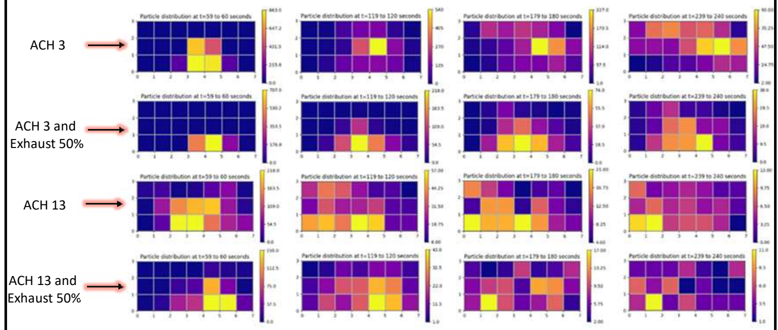
Pathogen distribution



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Coupling of CFD with genetic algorithm (GA)

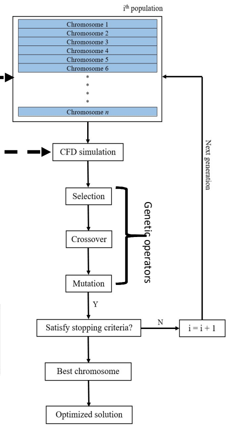
Parameters (Genes)

i. Infected patients [1-6]
ii. Air change per hour (h^{-1}) [3,6,9,13]
iii. Number of supply diffusers [3,4,6]
iv. Size of supply diffusers (m^2) [0.09, 0.36]
v. Number of exhaust grilles [0,4,6]
vi. Size of exhaust grilles (m^2) [0.0225, 0.04, 0.1]
vii. Exhaust flow rate (% of supply air) [0, 10, 30, 50]
viii. Exhaust height from floor (m) [0.8, 1.1, 1.4, 1.7]

Fitness function CFD

Fitness score D_i

$$D_i = \sum_{j=1}^{n} d_j; j \neq i$$



where D_i accounts for the pathogens deposited on other patients due to the exhalation activity of infected patient i, d_j is the particle deposited on patient j and n is the total number of patients in the ward cubicle.

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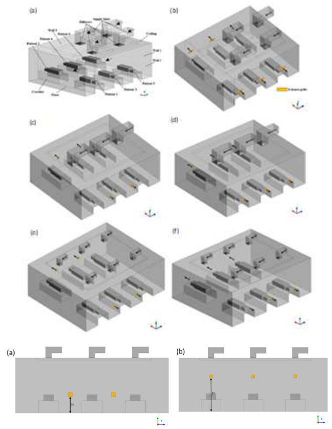
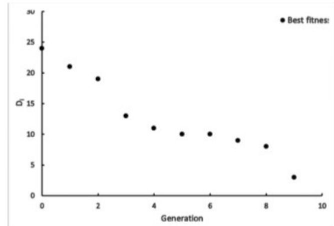
Results of CFD-GA (Example)





Parameters								Fitness Score
i	ii	iii	iv	v	vi	vii	viii	D_i
2	6	3	0.36	4	0.04	30	0.8	3

i. Infected patient	v. Number of exhaust grilles
ii. Air changes per hour (h^{-1})	vi. Size of exhaust grilles (m^2)
iii. Number of supply diffusers	vii. Exhaust flow rate (% of supply air)
iv. Size of supply diffusers (m^2)	viii. Exhaust height from floor (m)

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Final note:

Framework for ventilation and infection risk evaluation at elderly care homes

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Assessment steps

1. Walk through inspection of critical areas
2. Identify ventilation assessment scenarios based on operational practice
3. Ventilation assessment using tracer gas to identify:
   - The air change rate of specific areas
   - The dispersion of airborne pathogen
   - Proper ventilation strategies for mitigating the infection risk

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Recommendations

Some examples:

- Enhancing the capability of the ventilation
- Relocating the fresh air supply and exhaust
- Replacing/ repairing faulty ventilation system
- Replacing/ cleaning air filter
- Alternative means of ventilation

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Thank you very much! Any questions?

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