Infection Resilient Environments: International Best Practice

Final Report

Commissioned by the Royal Academy of Engineering

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LIST OF INFECTIOUS DISEASE DEFINITIONS

Aerosols	A collection of pathogen particles in the air.
Airborne	The airborne route (also called aerosol transmission) occurs when exhaled respiratory droplets are small enough to remain suspended in air such that they can be inhaled into the respiratory system of other people.
Contact	The contact route takes place when respiratory droplets are deposited onto surfaces that are then touched by other people who go on to touch their mouth, nose or eyes before washing or disinfecting their hands.
COVID-19	The contagious disease that is caused by the pathogen SARS-CoV-2.
Doff	Taking off PPE
Don	Putting on PPE
Droplets	The droplet route of infection involves the transfer of respiratory droplets from an infected person to the mucous membranes of a subject, i.e. respiratory droplets land in the mouth, nose or eyes of others.
Endemic	A disease that belongs to a particular people or country.
Epidemic	Disease that affects a large number of people within a community, population, or region.
Fomites	Objects or materials that are likely to carry infectious diseases.
Outbreak	Greater-than-anticipated increase in the number of endemic cases. If not quickly controlled, an outbreak can become an epidemic.
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a pathogen that is a strain of coronavirus that causes COVID-19.
Pandemic	Epidemic that has spread over multiple countries or continents.
Transmission	Action or process of passing infections onto others.

1. EXECUTIVE SUMMARY

This report examines international good practice for infection resilience in the built environment and public transport. This includes the background for infection resilience within infrastructure design in the past, and analyses the key approaches and interventions incorporated across the globe to reduce transmission of different types of infections.

Throughout history, health threats and pandemics have shaped cities and permanently shifted how the built environment is designed; many health issues have been reflected in the architecture and urban planning we experience today. The Black Death in the 14th Century affected the urban design of European societies by calling for more and larger public spaces and Cholera outbreaks in the early 19th century had a major impact on the management of waste in the streets of Paris and London. In regard to building design, Tuberculosis (TB) led to an improved understanding of germ theory which influenced the consideration of fresh air and sunlight.

The recent COVID-19 pandemic has highlighted the necessity to review how we currently design buildings, such as designing for flexibility and adaptability in all spaces to cater for future infection peaks. International standards, such as the WELL Building Standard which is used in over 120 countries, has been revised to incorporate indicators around disease transmission prevention in the introduction of the Health-Safety Rating demonstrates the re-emergence of infection resilience concepts within design practice today.

The information for international best practice was conducted from a combination of literature review, extraction of practical experience and foresight techniques. This information collated was verified with key stakeholders for each building typology to confirm how measures and guidance were implemented in practice and to provide relevant case studies. The research covers 43 countries internationally and includes representation from Europe, the Americas, Africa and Asia.

In order to describe what constitutes "best practice", the resilience of what, for whom and for what purpose are variables which must be defined to provide the appropriate framing. In this report, it assumed that, in general terms, the purpose is to maintain, as much as possible, business continuity, or the regular function of the infrastructure, while minimising the risk of transmission of infection between its users. This needs to consider the prevalent infections of the moment, and the immediate future.

However, the exact answer to the question above is different in every case, and therefore the concept of best practice is much more than a set of discrete interventions; rather the examples of those who have fared the best have a set of common approaches which influenced the decisions taken in regard to the interventions employed in their specific context. That contextual setting includes constraints of the situation, for example the available investment or the flexibility allowed to make changes to the infrastructure for legal or operational reasons. These are broadly covered in 3 themes:

- Taking an "**as low as reasonably practicable**" (ALARP) approach, where the risk is lowered as far as possible by taking the most effective set of interventions feasible; but there is an acceptance that a zero-risk scenario is not attainable. Interventions are selected from a list of "tools in the mitigation toolbox,", as described in Chapter 5, each of which can contribute towards a reduction in risk, with multiple interventions being employed at the same time1. This also helps to mitigate against uncertainty around the relative contribution of one transmission mechanism over another, as is common early in an outbreak2 or when planning for a future, unknown infection.
- **Planning for adaption**, where alterations and interventions to respond to a changing environment in future are accepted and planned for within the initial response. The science of infectious diseases is constantly being reviewed, and the scientific makeup of future infectious pathogens is likely to change, including the characteristics of their behaviour and infectiousness. This will impact the necessary response required to reduce transmission in the built environment, resulting in a need for the response to adapt accordingly.
- Integrating infection resilience within the context of **broader design decision making**, recognising that intervention decisions must be made in balance with a number of other priorities, some of which are complementary and some of which may be contradictory. For example, a large focus in infection resilience is around improved indoor air quality and, in many cases, this results in an increase in demand for mechanical ventilation systems. This is in direct tension with low-carbon operational design.

Below these principles, are a wide range of specific interventions which can be taken at different points within the building lifecycle. Within this report, these have been defined as:

- **Short term:** Immediate actions and measures that can be enacted in existing spaces. These are typically low capital cost and have a minimal impact on the existing infrastructure.
- **Medium term:** Interventions able to be implemented within the existing building fabric (e.g. retrofit) but require more capital expenditure.
- **Long term:** Decisions which require significant investment or new infrastructure or a change in common industry practice to achieve.

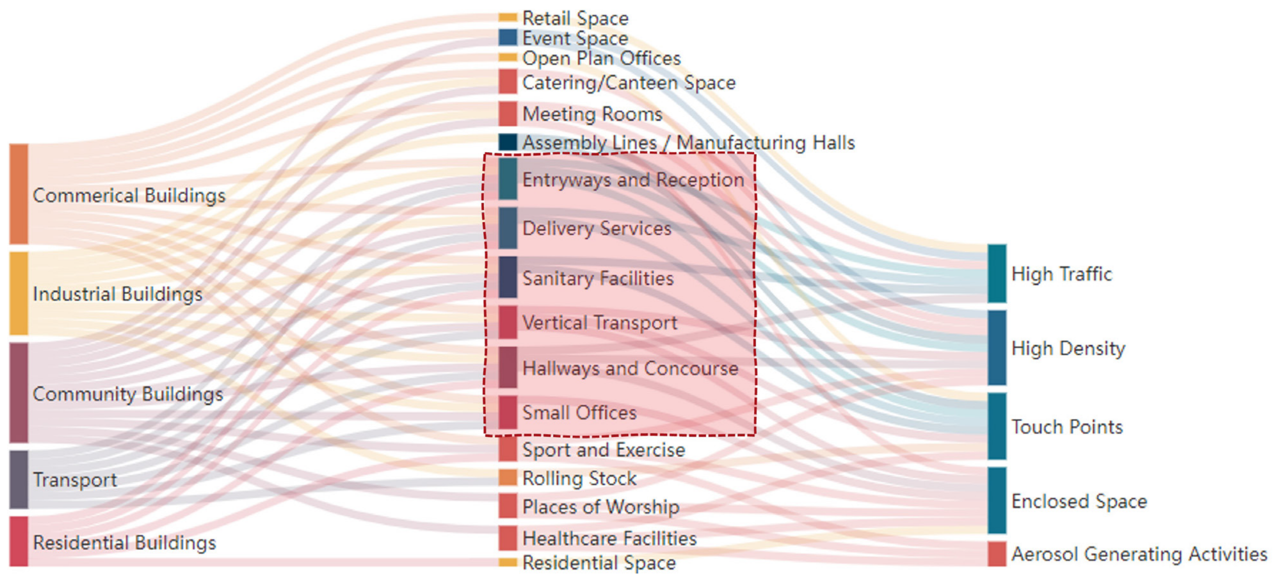
Within these interventions, the research showed that they could broadly be categorised into 2 types: those which are common across all infrastructure types, and those which are specific to the building use. Those which were use-agnostic included interventions which covered the following topics:

- **Improving indoor air quality** through increased clean air delivery rates, achieved through ventilation, increased outdoor air intake and use of filtration to reduce airborne transmission of pathogens between building users. The manner in which this is achieved will vary according to the particular context, for example determining whether the use of natural or mechanical ventilation is most appropriate or what filtration will work within an existing system.

- Upgrade of **material and surface characteristics** for antimicrobial resistance, plus enhanced cleaning regimes and sanitation points, to prevent fomite transmission, where transmission occurs between building users through contaminated surfaces. This is particularly key for frequently touched surfaces such as entry gates, door handles, lift buttons and countertops.
- **Alteration of spatial configuration** to reduce occupancy density and promote physical distancing. The level to which this can be achieved typically depends on the space function, for example it may be possible to stagger worker position in an assembly line but spacing tables in a restaurant may lead to an uneconomically low number of diners for the viability of the business. This may also be something which is only employed during infection peaks and the design of the space should be flexible to allow for this during these times but sustain higher occupancies at other times.
- Addressing **waterborne transmission** through the reduction of water stagnation and transmission routes through drainage and wastewater systems.

A number of infections including Legionella and SARS-1 were demonstrated to be transmitted through the plumbing systems, typically when poorly maintained. Designs of water systems can be upgraded to reduce the risks of infrequent maintenance and thereby improve resilience, even during periods of inoccupation of a building.

- Designing to **improve collective behaviours** such as reducing use of spatially-confined lifts by promoting stair use and encouraging hand sanitation by placing handwashing or sanitation facilities within easy reach of the users.
- **Use of monitoring software** to track occupancy and air quality, adherence to sanitation schedules and maintenance, and the use of AI or other smart technology (IoT) to predict changes, conduct contact tracing, and enact preventative measures. This typically requires a high level of investment, particularly if a Building Management System (BMS) is not already being used but has been shown to be effective in improving air quality by producing the information for better, and at times automated, management of ventilation systems. It also requires training for Facilities Management (FM) staff in their function and use to be effective.



These interventions typically also relate to common space types which are present in many buildings regardless of use, such as vertical transport, hallways and entrances, small offices or sanitary facilities, as highlighted in in the diagram.

In addition to these, there were interventions highlighted by the research which were specifically addressing the use of that type of infrastructure, and therefore not typically found in other use classes. These have been split in line with the UK Planning Regulation Use Classes, as per the scope of the research. These cover 5 broad infrastructure classifications, as noted below, and described in more detail in Section 2.3:

- **Industrial (Class B):** these are characterised by very specialist use functions, depending on the exact nature of the industry involved and appropriate interventions typically change to reflect this. Examples of key interventions are linked to worker placement and management of deliveries to minimise contact between different groups of building users. Additionally, increased use of automation enables an overall reduction the number of building users within warehouses, decreasing infection risk.
- **Residential (Class C):** appropriate interventions for these buildings varied between large, multi-occupant buildings such as hotels or large high-rise blocks, which typically have more advanced building systems, such as mechanical ventilation, which can be adjusted and smaller single dwelling buildings which do not have an building manager or operator in the same way. Additionally interventions were included which allow the multi-use of space which is required as residential spaces expand to provide use for multiple functions such as work or school or in use a isolation spaces.
- **Commercial (Class E):** the COVID-19 pandemic showed these buildings to be particularly vulnerable to shutdowns or lockdowns, and key interventions for this group centre around the ability to maintain business continuity during infection peaks. These included design features for user management such as designing user routes with options for one-way systems or increased physical distancing which can be used intermittently as required.
- **Local Community (Class F)**: interventions in this class were typically split between educational facilities, which have specific requirements around child users and other public facility buildings. In schools, interventions included providing covered outdoor play and learning spaces to reduce time indoors and consideration of safeguarding measures.
- **Transport & Transport-Related Development**: The inherent nature of public transport means that it is designed to carry a large volume of people, resulting in greater opportunities for the spread of infection at key points throughout the journey, whether it is dwelling on concourses or in waiting areas, funnelling through gate lines or security checks, or travelling within high-capacity vehicles. Interventions are included which respond to these key transmission points such as contactless entry and increasing the number of aligning points to reduce "pinch points" all contribute to mitigation at these areas. plumbing systems, typically when poorly maintained. Designs of water systems can be upgraded to reduce the risks of infrequent maintenance and thereby improve resilience, even during periods of inoccupation of a building.

In order to demonstrate how the principles and the interventions can be brought together in different environments and contexts, Chapter 6 describes a range of scenarios that define how different mitigating measures could be implemented in the decision-making process.

2. INTRODUCTION

2.1 PROJECT PURPOSE

The project aims to examine interventions incorporated into the built environment or transport system to reduce transmission of infections, including technological and behavioural changes and the role, if any, of the policy and regulatory environment to enable intervention.

2.2 PROJECT OBJECTIVES

The specific objectives of the research set by the Royal Academy were:

1. To develop an understanding of how widespread, internationally, the concept is of making an environment, such as a building or transport system, less susceptible to disease transmission, how that is conceptualised and articulated, and what it is considered to entail.
2. To understand what methods exist to create infection resilient buildings and transport systems internationally.
3. To identify what constitutes best practice in infection resilient environments from an international perspective.
4. To outline emerging challenges and opportunities with significant potential impact on creating infection resilient environments.

2.3 SCOPE OF THE RESEARCH

Infrastructure Types

The research covers the following infrastructure types, which reflect specific building types as defined by UK Planning Regulation. These are:

Table 1: Infrastructure Types within Scope of Research

INFRASTRUCTURE TYPE	SPECIFIC USE CLASSES
Industrial (Class B)	• B2 General industrial • B8 Storage or distribution
Residential (Class C)	• C1 Hotels • C2 Residential institutions • C2A Secure residential institution • C3 Dwelling houses • C4 Houses in multiple occupation
Commercial (Class E)	• E(a) Display or retail sale of goods, other than hot food • E(b) Sale of food and drink for consumption • E(c) Provision of financial, professional, or other services • E(d) Indoor sport, recreation or fitness • E(e) Provision of medical or health services - not attached to consultant or practitioner • E(f) Creche, day nursery or day centre • E(g) Office, research and development, industrial processes
Local Community (Class F)	• F1 Learning and non-residential institutions including • (a) Provision of education • (b) Display of works of art • (c) Museums • (d) Public libraries or public reading rooms • (e) Public halls or exhibition halls • (f) Public worship or religious instruction • (g) Law courts • F2 Local community
Transport & Transport-Related Development	• 8 (A) Railway or light railway • 8 (B to C) Dock, pier, harbour, water transport, canal, inland navigation undertakings • 8 (F to N) Development surrounding airport • 9 (A to E) Roads, Highways, Toll roads, Tramway and road transport undertakings

Transmission Types

Infections can be transmitted in a variety of modes or transmission pathways. Understanding how infectious pathogens spread is key to improving the infection resilience aspects within the design of infrastructure.

Key transmission types considered within the research are:

Table 2: Summary of Primary Transmission Modes Considered within Research (© RAEng)

TRANSMISSION ROUTE	TRANSMISSION OCCURS IN SITUATION OF…
Direct contact transmission	Direct body contact with the tissues or fluids of an infected individual.
Surface (fomite) transmission	Inanimate objects contaminated by an infected individual that then come into contact with another.
Airborne (aerosol) transmission	Transfer of pathogens via very small particles or droplet nuclei. Very small particles may remain suspended in the air for extended periods.
Oral (ingestion) transmission.	Ingestion of pathogens from contaminated food or water.

The following transmission modes were identified in the literature and will be noted along with any trends, but do not form a significant focus in the research:

Table 3: Summary of Other Transmission Modes which are not the Primary Focus of the Research (© RAEng)

TRANSMISSION ROUTE	TRANSMISSION OCCURS IN SITUATION OF…
Vector-borne transmission	Living organisms that transfer pathogenic microorganisms including insects such as mosquitos.
Zoonosis	Diseases transferred from animal to people.
Environmental transmission	Soil, water, and vegetation containing infectious organisms transferred to people.

3. APPROACH AND METHODOLOGY

3.1 Project Methodology

The project has been developed over three stages, using a combination of literature review, extraction of practical experience and foresight techniques. A summary of the key activities is as follows:

STAGE 1: LITERATURE REVIEW

The literature review was the starting point for the research. Its purpose was to provide an initial background and understanding to the questions posed within the Project Objectives through review of academic articles, existing guidelines and frameworks, and grey literature. Through keyword searches on Google Scholar and a review of existing relevant research within Arup and International WELL Building Institute (IWBI), plus a follow on review of linked references, a list of 189 documents was compiled and reviewed. This information has been compiled in the references which are provided in Appendix B. This literature review highlighted a range of measures which have been implemented globally, along with a number of guidelines produced internationally. The research covers 43 countries internationally and includes representation from Europe, the Americas, Africa and Asia, plus international and regional standards and guidelines.

It also highlighted sectors or areas where there is less literature available, indicating where additional information and focus was required at the stakeholder engagement stage. The stakeholder workshops were then be used to fill in any gaps or reveal true gaps that existed for a specific building type.

The result of the literature review was a collated list of measures which have been employed internationally across the different sectors. This helped to identify where there were commonalities across the typologies which were more generic, and where measures were specifically employed related to the building use.

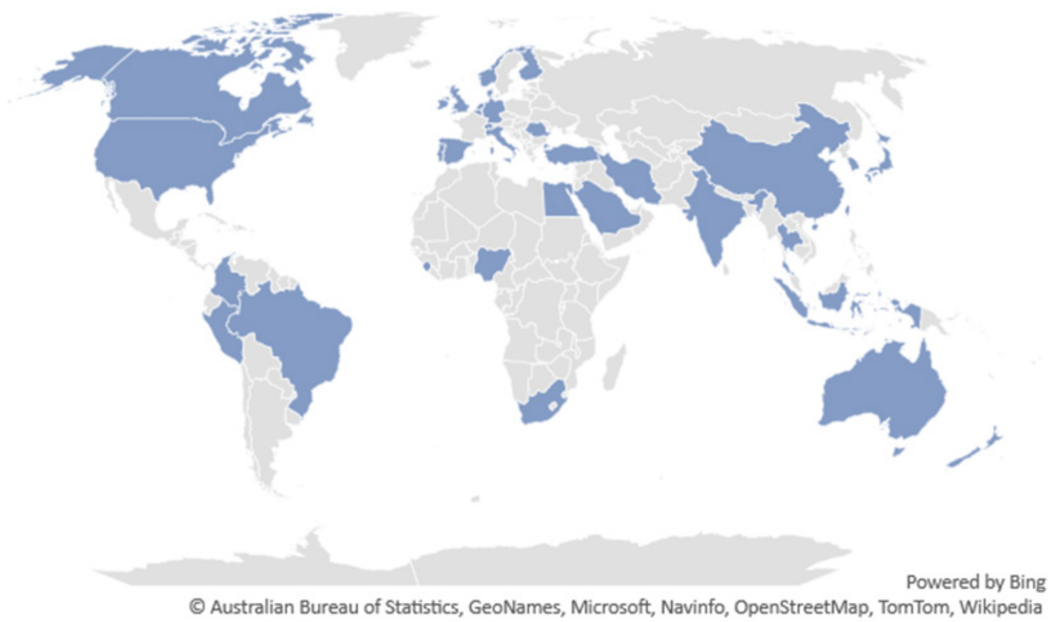


Figure 1: Origin of Country Specific Research Reviewed

STAGE 2: STAKEHOLDER ENGAGEMENT

The stakeholder consultations phase was designed with the following key objectives:

- Verify key findings from the literature review
- Fill gaps in published data through real-world practices
- Signpost to additional relevant documentation
- Provide relevant case studies

The stakeholder consultations consisted of **Key Informant Interviews** (KIIs). These were bilateral discussions to gain specific information which is held by a certain individual, potentially where they have expert knowledge or specific experience relevant to a specific area of the research subject matter.

These were followed by a series of **Participatory Workshops**, one for each building typology. These were used to gain the opinion of a group of people with experience designing, using or operating these building types.

The participant list from the consultations and the workshop structure is provided in Appendix C.

The consultations strengthened the typology-specific measures and provided a number of case studies. They also provided insight on the decision-making process employed, particularly for COVID-19, by different sectors, and the various drivers for implementation.

Consultation Summary

- 5 Workshops
- 4 Interviews
- 47 Participants
- 12 Organisations
- Representation from Europe, Africa, Asia and the Americas

STAGE 3: ANALYSIS

The final stage of the research was to bring together the findings of the two research streams from Stage 1 and Stage 2, and set the findings in response to the Project Objectives. It also draws out some of the challenges or tensions which might be found in the pursuit of improved infection resilience. Where there are specific considerations associated to specific typologies, these are noted in the relevant section. How the future of infection resilience in the built environment progresses in light of some of these challenges is also discussed, bringing in foresight analysis to the topic, and providing structure to how the measures may be implemented by decision makers in the future.

3.2 Research Approach

3.2.1 BUILDING ON EXISTING INTERNATIONAL RESEARCH

In addition to the international body of literature referenced, as noted in Section 3.1, this paper has built on the work undertaken by the IWBI in developing in the Health-Safety Rating. This was created by the IWBI Task Force on COVID-19 and Other Respiratory Infections which was convened in April 2020. This task force was composed of 16 globally acknowledged thought leaders in the role of co-chairs, and nearly 600 professional and market leaders and experts — virologists, epidemiologists and public health professionals, along with real estate professionals, architects, designers and manufacturers — from more than 30 countries. This also crowd-sourced thousands of comments during a 40-day sprint.

3.2.2 DEFINING “BEST” PRACTICE

As much of this research is emerging due to the large increase in research funding in the last two years due to the COVID-19 pandemic, it is useful to set out some definitions of Best Practice. This report includes practices which fall under the following definitions - see Table 4.

Much of this emerging research around respiratory infection transmission will fall into the “promising practice” category due to the relative youth of the research, and a changing understanding of the transmission of COVID-19, as described in Section 4.1.3. However, it is still valuable to include, particularly when set in the context of an “ALARP” approach as described in Section 5.1.1. Subsequent research will likely elevate some of these in the future. Types of infections whose transmission through the built environment are more established, such as legionella, may fall into the more validated or tested practices. These are typically already incorporated into regulation or building codes. Where newer research is being produced, for example around the SARS Cov-2 (COVID-19), due to the need to implement changes quickly, recommendations based on engineering judgement are usually peer-reviewed and published by a Professional Body, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

3.2.3 RESILIENCE OF WHAT, FOR WHOM AND FOR WHAT PURPOSE

It is also important to note that what constitutes “best” is contingent on the type of infection considered, who is being protected, and also recognises what is appropriate and affordable in a given situation. In this report, it assumed that, in general terms, the purpose is to maintain, as much as possible, business continuity or the regular function of the infrastructure, while minimising the risk of transmission of infection between its users to the prevalent infections of the moment and the immediate future.

Table 4: Types of Best Practice (adapted from: U.S. Department of Health and Human Services)[3]

Research Validated Best Practice	A strategy or intervention that has the highest degree of proven effectiveness supported by objective and comprehensive research and evaluation.
Field Tested Best Practice	A strategy or intervention that has been shown to work effectively and produce successful outcomes, and is supported to some degree by subjective and objective data sources.
Promising Practice	A strategy or intervention that has worked within one, or a type of, infrastructure and shows promise during its early stages for becoming a best practice with long-term sustainable impact. A promising practice must have some objective basis for claiming effectiveness and must have the potential for replication more widely in similar infrastructure types.

3.2.4 DETERMINATION AND CATEGORISATION OF MEASURES

The potential mitigation measures, or interventions, presented in Chapter 5 have been derived from the literature review and from the consultations. As this is a large and dynamic field and research is emerging, it is not possible to say that the list of measures is exhaustive. However, a review has been undertaken against built-environment related measures from the taxonomies developed within databases of Non-Pharmaceutical Intervention (NPIs), also known as Public Health and Social Measures (PHSMs) where available, although these were only relevant for COVID-19 measures. This included the Complexity Science Hub COVID-19 Control Strategies List (CCCSL) dataset[4] which includes data on interventions from 34 countries, and the global WHO PHSM dataset[5]. Secondary data sources from other research collating interventions have also been used as reference for completeness.

To address the issue of appropriateness and affordability, the research presents, and distinguishes between, inventions which are “Short term”, which are those which are easy to implement, low cost and require minimal material inventions to the built environment fabric; those which are “Medium term” and able to be implemented within an existing building fabric; and “Long term” where significant investment or new infrastructure would be required to achieve these.

Short term

Immediate actions and measures that can be enacted in existing spaces

Medium term

Able to be implemented within the existing building fabric (e.g. retrofit)

Long term

Requires significant investment or new infrastructure

Figure 2: Interventions over the Building Lifecycle

3.2.5 APPLICABILITY OF INTERVENTIONS

There are some methods which are likely to apply to many different infrastructure types, including those which relate to common space types which are present in many buildings regardless of use, such as vertical transport, hallways and entrances, small offices or sanitary facilities, as shown in Figure 3.

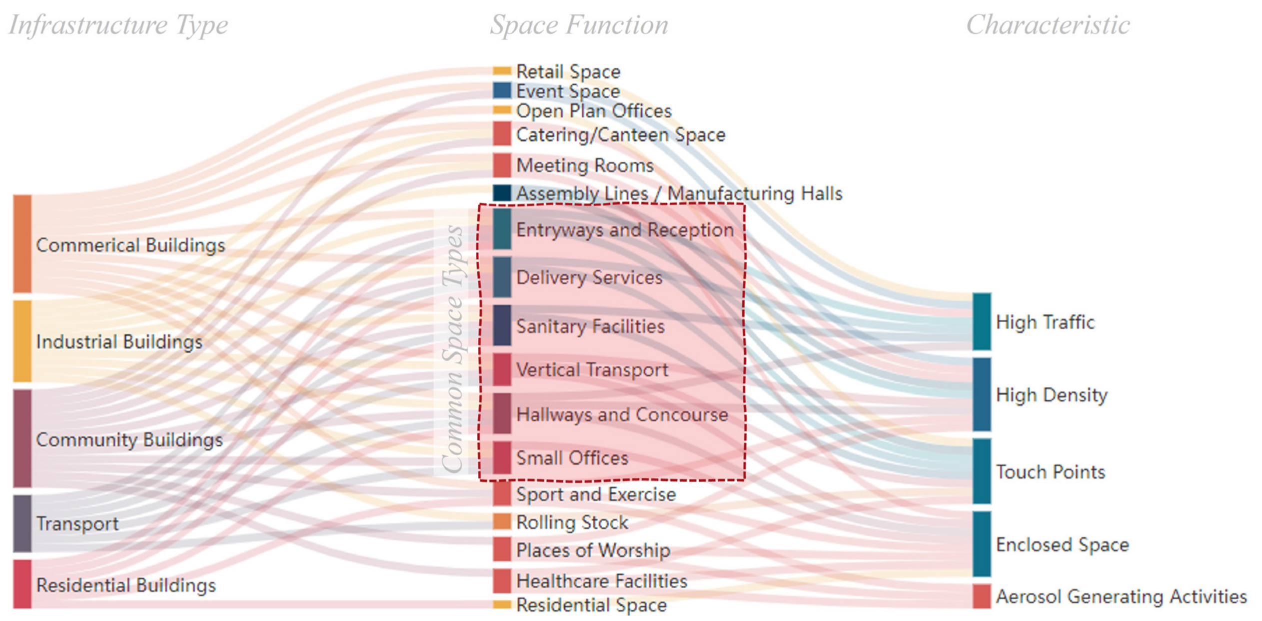


Figure 3: Common Spaces across Infrastructure Typologies

4. CONTEXT

4.1.1 BACKGROUND TO THE USE OF THE BUILT ENVIRONMENT TO REDUCE INFECTION TRANSMISSION

Throughout history, pandemics have shaped cities and permanently shifted how the built environment is designed. Many health issues have been reflected in the architecture and urban planning we experience today. This dates to the Roman Empire when rampant disease in military camps led to the installation of aqueducts, public baths and division of water and sanitation systems[6]. However, these solutions were not applied worldwide following the fall of the Roman Empire.

The Black Death in the 14th century affected the urban design of European societies by calling for the opening of more, and larger, public spaces, which provide a greater opportunity to connect with nature and reduce the feeling of isolation. Cholera outbreaks in London and Paris in the early 19th century had a major impact on the management of waste in the streets and led to the introduction of mains sewage systems which safely separated wastewater from clean water supply.

Around the same time, Tuberculosis (TB) was rife in the US, and estimated to have caused over 25% of deaths in New York City between 1810 and 1815[7]. By the end of the century, germ theory had become better understood and the recommended care was primarily environmental – fresh air and sunlight. The design of TB sanatoriums therefore started to focus on these, with a key feature of a New York centre built in 1885 being a glass enclosed deck known as a “cure porch”, and many facilities incorporating large flat roofs for sunbathing.

In wider building design outside of healthcare facilities, similar design features increasing air and light were also being implemented. Early 20th-century New York City schools were constructed with C- and H-shaped floor plans, large built-in ventilation shafts, and operable transoms in the corridors, to encourage cross-ventilation[8]. They also installed floor drains to facilitate the cleaning of bathrooms[9].

Following the SARS outbreak in Hong Kong in 2003, the Government of Hong Kong Special Administrative Region (HKSAR) set up a “Team Clean Commission”[10] to learn lessons from Amoy Gardens, a residential development where more than 300 cases were recorded (see case study below). The Commission made several policy recommendations covering both planning and design. These included that outdoor air circulation should be factored into future design practices and that planners should consider the city’s air circulation capacity and its relationship with the city’s development densities and building layouts. As noted in the case study, the primary transmission method was determined to be through the drainage. In response the Buildings Department of the HKSAR Government issued a new Practice Note for Authorised Persons[11] with a new W-trap design to prevent the drying of the water seal in the floor U trap. In addition, two important building and urban design guidelines were promulgated. The first was the Air Ventilation Assessment (AVA) Technical Circular and the other was a new chapter on city-building ventilation principles in the Hong Kong Planning Standard and Guidelines (HKPSG)[10]. While these measures have influenced design of new infrastructure in Hong Kong since then, these design features do not appear to have permeated into American and European building codes.

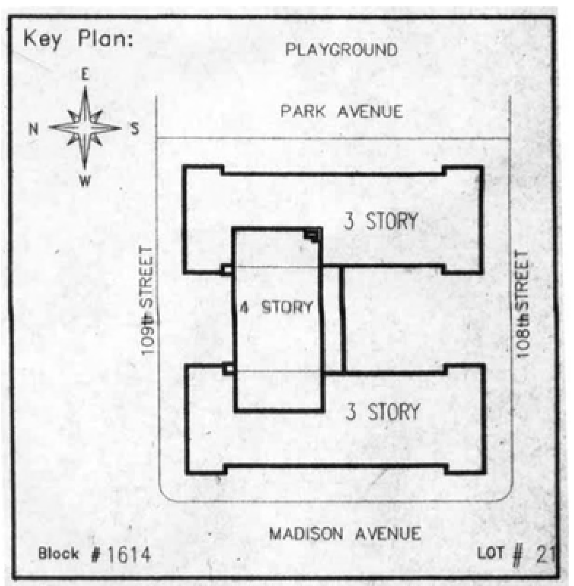


Figure 4: Example of an H-Plan School Design, New York City early 20th Century [11]

BUILT ENVIRONMENT - CASE STUDY

SPREAD OF SARS-1 IN AMOY GARDENS, HONG KONG [9,10]

Name: Amoy Gardens
Client: -
Location: Hong Kong, China

Overview

In March 2003, an outbreak of the SARS Influenza hit a residential block in Kowloon Bay in Hong Kong. Research into the spread of the disease within the block identified that it spread initially via the toilet of a flat on the 16th floor from an infected person who visited on the 14 March. By 15 April there were 321 cases of SARS in Amoy Gardens, accounting for 18% of the cases in Hong Kong.

Studies undertaken after the outbreak suggested that the plumbing and ventilation systems interacted to transmit the virus throughout the block. The WHO environmental team determined through odour detection and smoke tests that aerosolised infected particles from the sanitation systems were drawn up through the floor drains with dry U-traps, assisted by the negative pressure caused by the bathroom fans. These were then transmitted through re-entrant spaces to other flats.

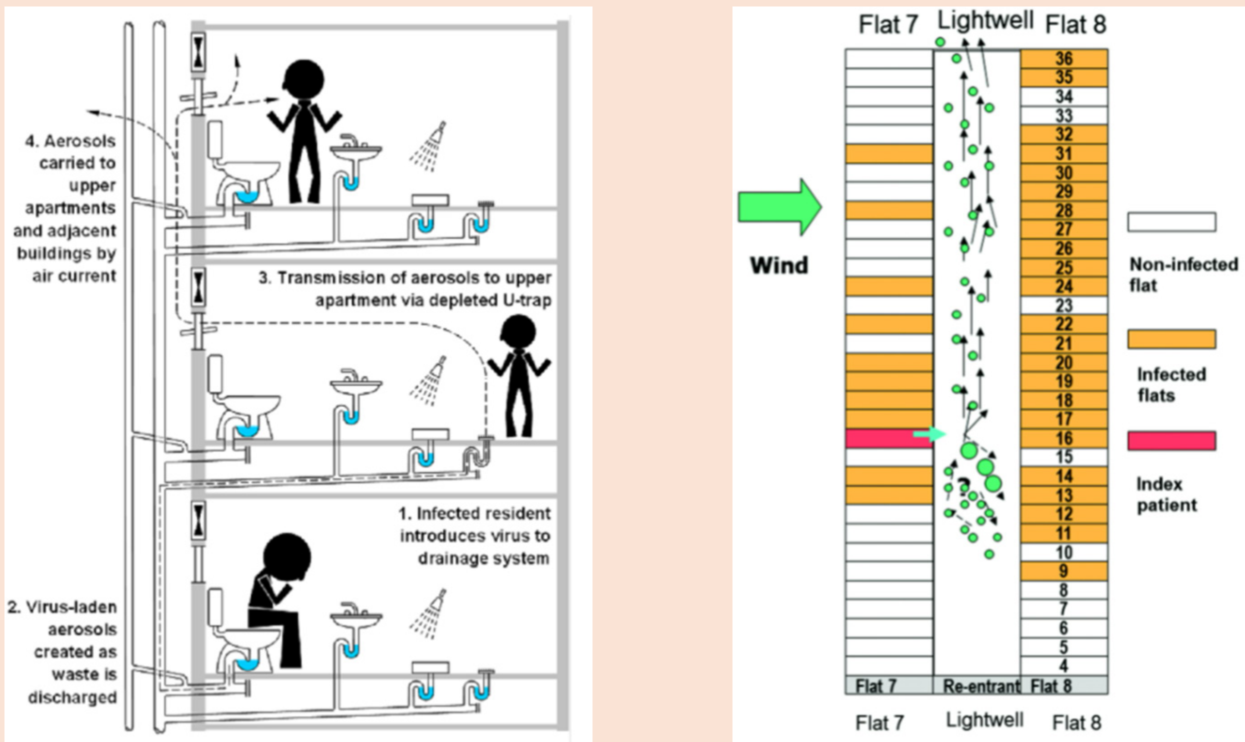


Figure 5: Example of aerosolised infected particles being drawn up through the floor drains with dry U-traps (left), aerosolised particles being transmitted through re-entrant spaces (right)[9, 10]

More recently, infection prevention guidance for buildings has focussed on the HVAC (heating ventilation and air conditioning) space. Prior to the COVID-19 pandemic, ASHRAE[12], the WHO[13], the Facility Guideline Institute (FGI)[14] and others had published guidance on the role of ventilation in infection prevention, primarily in healthcare facilities.

Research published in the US in 2013 used probabilistic methods to model relative risk of influenza infection in an office environment, using epidemiological data such as droplet size from studies in healthcare facilities, combined with a Wells-Riley model for risk. The equation was modified to account for removal of infectious particles by air recirculating through different standards of filters using ASHRAE Standard 52.2. The study showed decreasing relative risk with increasing levels of HVAC filtration (MERV 4–16 then HEPA), and that MERV 13-16 produced the greatest risk reductions at a lower operational cost than the equivalent outdoor air ventilation. Medium efficiency filters (MERV 7-11) were less expensive to operate but appeared less effective in the reduction of disease transmission.[15]

Over the past 2 years, due to the COVID-19 pandemic, guidance on the impact of ventilation on infection transmission for all indoor spaces has been published by organisations globally such as the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (SHASE)[16], Australian Health Protection Principal Committee (AHPPC)[17], the Architectural Society of China, the Chinese Association of Refrigeration[18] and the European Centre for Disease Prevention and Control[19]. This is reflective of a wider recognition of disease transmission within the built environment as an important design criteria. A further illustration of this increased focus can be seen in a statistic from the International Well Building Institute (IWBI). In February 2020 there were approximately 500-million square feet of buildings registered and certified under the WELL Building Standard (WELL). By mid-March 2022 this had increased to over 3.15 billion square feet, representing an increase of over six fold in certified spaces globally. The standard continues to become more widespread, currently enrolling nearly 5.7 million square feet of space every day. The introduction of the Health-Safety Rating also demonstrated a shift from criteria which measure healthy buildings, to ones which also incorporate disease transmission prevention.

This is an important shift, as there are a host of specific mitigation measures in building design that have been used in healthcare facilities for decades to control infectious diseases and help hospitals stay operational and safe, but are not necessarily applicable for wider infrastructure. An example of this is negative pressurisation, where isolation rooms are negatively pressurised to prevent the spread of infectious particles to adjacent rooms[20]. These are not generally either cost effective or useful in more general situations in which the infected person is not identified, and therefore not separated from other building users.

A study which reviewed research done on coronavirus outbreaks in indoor environments over the past 20 years showed that of studies which were done prior to COVID-19, 7 out of 8 studies were done in a hospital setting but of the 6 carried out looking at transmission of SARS-Cov-2, all were in non-healthcare settings, including ships, restaurants and workplaces[21] (note this review was published in August 2020).

In addition to the built environment playing a role in spreading disease, in some specific cases it can “create” diseases[6]. The bacteria Legionella that causes Legionnaires disease was discovered in 1976[22] and found to be primarily transmitted through the heating and cooling systems of buildings[23]. To date research into Legionella has been published by at least 19 countries worldwide including France, Japan, Israel and Singapore[19]. Key mitigation measures to reduce the risk of Legionella growth and spread which can be implemented by building designers, owners and managers are typically included in building regulation or other legislation (such as Health and Safety Laws). Regulation covering mitigation of Legionella applies in Europe, China, USA, New Zealand, Australia, Russia, Dubai and Singapore, with South American countries typically referencing the US Standard, ASHRAE 188. A key gap appears to be in Africa, where legislation only applies in South Africa.

It is important to consider the distinction between infectious risks that remain as a constant endemic threat in the context of the built environment such as Legionnaires Disease, against the requirement for preparation for novel infectious risks of future pandemics.

Credit: Asian Development Bank

4.1.2 PUBLIC HEALTH STRATEGIES GLOBALLY

In the wake of SARS and MERS, many Asian countries put more pandemic preparedness planning in place, but these were typically focussed on wider public health measures, rather than specifically on building interventions.

For example, since 2003, Singapore has implemented a number of measures to strengthen their capacity to respond to public health crises, including building capacity in infection disease research and diagnostics; building the National Centre for Infectious Diseases, the National Public Health Laboratory, and more biosafety level 3 laboratories; and investing in building expertise in infectious disease clinical research. In addition, capacity building in the health system was undertaken, including expanding the number of negative pressure isolation beds, stockpiling of PPE and training staff in its correct use. There were also a number of institutional measures implemented, such as the establishment of formal platforms for multi-Ministry and cross-agency coordination[30].

Similarly, South Korea had a “National Crisis Management System” in place which allowed them to issue a “Blue Alert Level” and establish a joint response system as soon as they had one suspected case in early January 2020[31] Use of AI technologies also played a role in their strategy following the MERS outbreak in 2015.

The use of innovative technologies also featured in China’s response to the COVID-19 pandemic. For example: AI was used in the medical screening of more than 93% of Shanghai residents to enhance the speed of decision making, Baidu big data was used in China to identify clusters of infected people and a combination of 5G and drone technology was used in Chinese transport systems to identify violations of public health laws put in place. Similarly, robotics and autonomous vehicles were used for city sanitisation in Wuhan.

Clinical information sharing has also been identified as key to an effective response, for example in the 2014 Ebola outbreak in West Africa where scientists, clinicians, health workers and data analysts from around the world shared information to help prevent the spread of the diseases.

4.1.3 RECENT FOCUS OF HEALTH IN INFRASTRUCTURE DESIGN

There has been a lot of research done through various research institutions, bodies and companies about the relationship between health and the built environment[24,25,26]. It is now understood that the built environment significantly affects the public's health[27] and wellbeing, both physical and mental.

Studies have found that in North America and Europe people spend 90 percent of their time indoors[28]. In some places, and in some seasons, that 90 percent is actually an underestimate[26]. The prevalence of infrastructure in people's lives makes the impact that it has on their health all the more paramount. The built environment has an impact on an individual's long-term health including chronic ailments and morbidity factors such as asthma, obesity and depressive disorders that can be worsened by any number of variables in the built environment, including level of physical activity, community interaction, level of daylight, and fresh clean air quality. In the past 20 years, there has been an increase into research into "healthy" buildings, and in the past 10 years two certification programmes have been developed, the previously mentioned WELL Standard, and fitwel® which was developed by the Center for Active Design. Both of these are growing in popularity and uptake. This report focuses solely on infectious diseases which are caused by spreading microscopic germs from one individual to another. However, this does not detract from the important research that is being done within the overall sphere of health and the built environment, and many of the measures which help prevent transmission of infection will also provide co-benefits to alleviation of chronic ailments.

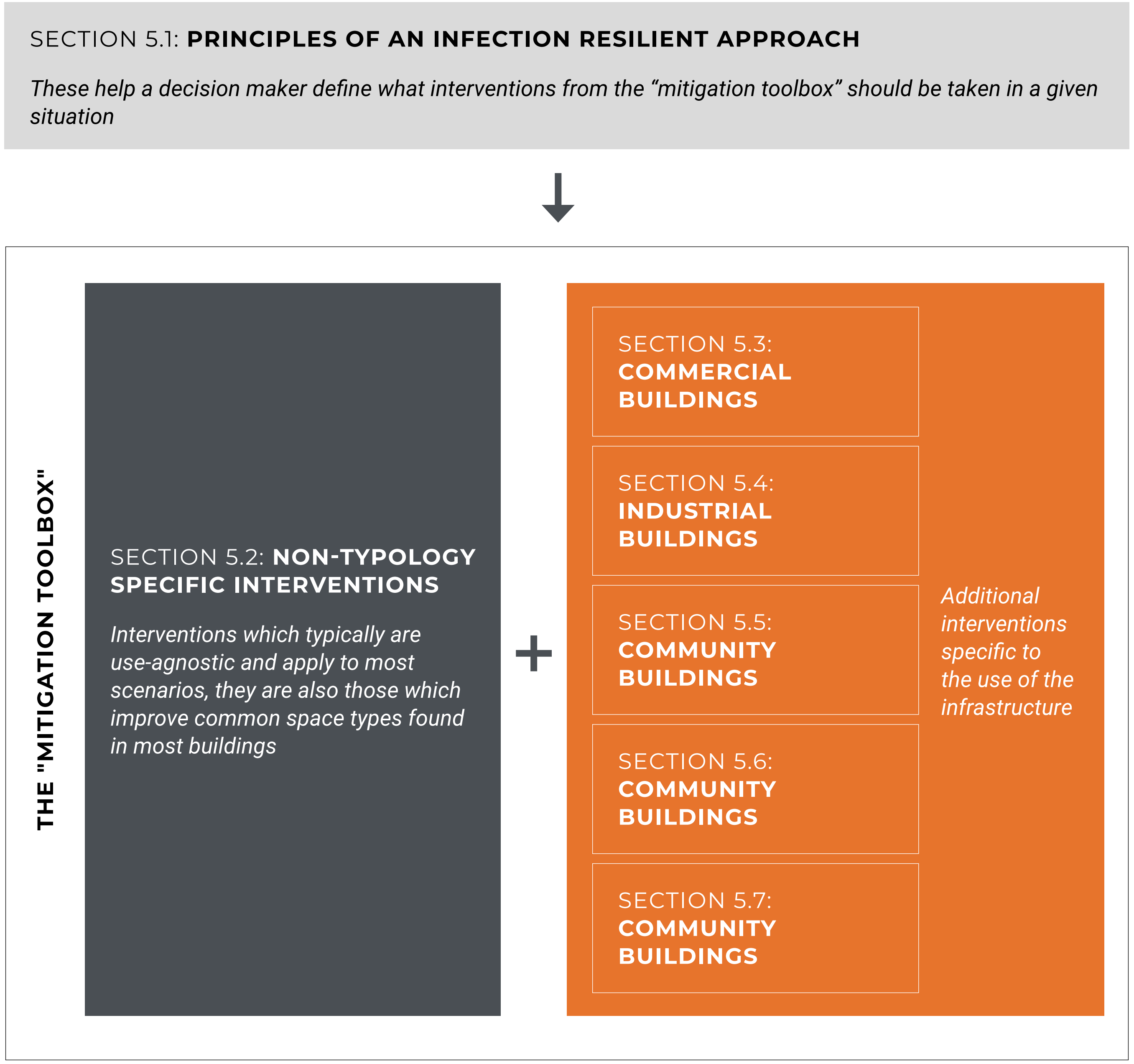
4.1.4 RESPONSE TO COVID-19 AND STATUS OF EVIDENCE

Existing infection resilience measures in the built environment varies globally, often based on lived experience and sharing of good practice based on historic events. COVID-19 has highlighted that more can be done in many of our indoor environments to improve them for infection resilience. Whilst this report is intended to cover international best practice for infectious diseases as described in Section 3.2, it should be noted that due to the timing of the COVID-19 pandemic and the impact it had on the world a significant proportion of recent research about infectious diseases and the built environment is heavily biased towards COVID-19. This does not mean that these measures are not applicable to other respiratory and infectious diseases and have been referenced to show the source of all information for all measures.

Studies, and the data, supporting infection transmission of COVID-19 are still ongoing, and as with any emerging health crisis the scientific understanding of the disease is improving all the time. It took over a year to conclude that airborne transmission was the primary transmission route of COVID-19[29] and the understanding of the specifics of the transmission of COVID-19 are constantly evolving, with some studies from early in the pandemic already being outdated. The time of issue of this report should be noted to ensure that the practitioner is applying the most recent scientific understanding to the applicable infectious disease.

5. INFECTION RESILIENCE METHODS

This chapter presents the methods to improve infection resilience in the built environment, highlighted by the research. It is split into the following sections, connected as shown in the following diagram:



5.1 Principles of an Infection Resilience Approach

As described in Section 3.2.3, the resilience of what, for whom and for what purpose are variables which must be defined to provide the appropriate framing. As noted in general terms, the purpose is to maintain, as much as possible, business continuity or the regular function of the infrastructure, while minimising the risk of transmission of infection between its users. This must recognise the prevalent infections of the moment, and the immediate future.

However, the exact answer to the question above is different in every case, therefore the concept of best practice is much more than a set of discrete interventions; rather the examples of those who have fared the best have a set of common approaches which influenced the decisions taken in regard to the interventions employed. These decisions were also set within the constraints of the situation, for example the available investment, or the flexibility allowed to make changes to the infrastructure for legal or operational reasons.

Additionally, future infection threats may present different primary transmission mechanisms which require different, and potentially conflicting, public health strategies in the built environment. For example, a recent foresight planning exercise undertaken by Arup and the WHO[32,(8)] presented 4 possible scenarios in order to identify threats and opportunities, and shift from a reactive to a proactive approach to address infectious threats. These scenarios were developed using a morphological approach to scenario development which considered combinations of potential projections of 20 factors, covering pathogen and host characteristics, public health and social measures, and contextual factors. The worst of these, dubbed "Here Comes Trouble", posits a new Zika strain emerging simultaneously with the COVID-19 pandemic which renders current public health responses ineffective.

In order to best respond to the varied and complex context which exists across the built environment and a volatile and uncertain future, these approaches can be defined in 3 themes:

5.1.1 AS LOW AS REASONABLY PRACTICABLE

Taking an "as low as reasonably practicable" (ALARP)[33] approach, where the risk is lowered as far as possible by taking the most effective set of interventions feasible, accepting that they will not eliminate risk completely.[33,34,35]

Interventions are selected from a list of "tools in the mitigation toolbox," each of which can contribute towards a reduction in risk, with multiple interventions being employed at the same time.[33] This is also termed a "layered" approach, and in the context of the COVID-19 pandemic has been recommended by the CDC in the USA[33,] and the WHO; more globally.[36] This approach helps to mitigate against uncertainty around the relative contribution of one transmission mechanism over another, as is common early in an outbreak[2] and equally when planning for a future, unknown infection.

For example, the relative contribution of different transmission routes in the spread of COVID-19 is very much situation-dependent in determining whether one transmission route or another is dominant. Therefore, the measures which are the most applicable for a given building depend on the specific contextual constraints and the level of investment available.[33]

5.1.2 PLANNING FOR ADAPTION

Integrating interventions in a way that future alterations and interventions to respond to a changing environment are accepted and planned for within the initial response.

This is a shift from previous commercial thinking which discouraged over-investment in unlikely alternative scenarios in the quest for efficient and cost-effective practices.[37] Adaptable buildings and dynamic systems will maximise efficiency and resilience in the future[38,] and where this has been considered in response to infection outbreaks, it has allowed improved continuity of function[39], particularly during new infection peaks. Additionally, the science of infectious diseases is constantly being reviewed and the scientific makeup of future infectious pathogens is likely to change, including the characteristics of their behaviour and infectiousness. This will impact the necessary response required to reduce transmission in the built environment, resulting in a need for the response to adapt accordingly. The IWBI recent publication, “Prevention + Preparedness, Resilience + Recovery”[40], notes the changing research landscape and how this relates to the development of standards, stating it requires a “flexible, adaptive approach to translating research to practice and to ongoing feedback from stakeholders, subject matter experts and the projects themselves”.

5.1.3 INTEGRATION WITHIN BROADER DESIGN DECISION MAKING

Integrating infection resilience within the context of broader design decision making, recognising that intervention decisions must be made in balance with a number of other priorities, some of which are complementary and some of which may be contradictory. The latter are explored further in Chapter 7. In order to achieve resilience, where the normal function of the built environment not just continues, but even improves, measures for infection resilience must be taken holistically with other design criteria.

5.2 Non-Typology Specific Key Findings

5.2.1 SUMMARY

The research has highlighted a number of interventions which are applicable across most types of infrastructure. These include:

- **Improving air quality through improved ventilation, increased outdoor air intake and use of filtration.**
- **Use of monitoring software to track occupancy and air quality, including use of AI or other smart technology (IoT) to predict changes and enact preventative measures.**
- **Alteration of material and surface characteristics for antimicrobial resistance.**
- **Alteration of spatial configuration to reduce occupancy density and promote physical distancing.**
- **Reducing water stagnation and transmission routes through drainage systems.**
- **Designing to improve collective behaviours such as reducing use of confined lifts by promoting stair use, and encouraging hand sanitation.**

Each of these can be achieved through a series of measures over the short, medium and long term as described in Section 3.2.2, which are highlighted in each section.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.2

Improved indoor air quality (IAQ)

Some diseases are passed through airborne transmission, including respiratory diseases such as COVID-19, SARS-1, Influenza and Tuberculosis (TB)[41]. Other non-respiratory airborne infections include Chicken Pox, Mumps, Measles, and vector borne diseases such as Hantavirus Pulmonary Syndrome, found in North and South America[42] which is most commonly spread through breathing in dust that is contaminated with rodent urine or droppings[43].

Improving indoor air quality (IAQ) is one of the key measures used globally to mitigate against airborne transmission of diseases; for example it is a core area of IWBI's Health Safety Rating which is used in 109 countries in over 33,000 buildings[44].

Air quality can be improved through:

- Improving natural or mechanical ventilation systems
- Increase air cleaning, through filtration or disinfection (e.g. UV-C)
- Controlling humidity
- Taking actions from monitoring proxy indicators such as Carbon Dioxide Levels (CO_2)

While these are presented separately, the recommendations are not standalone and should be considered in combination. For example ASHRAE's COVID-19 guidance in the US recommends using Clean Air Delivery Rate (CADR)[45] as a metric, where the air change rate (ACH, air changes per hour), room volume and filtration capacity is considered together.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.2.1

Improved indoor air quality (IAQ) - Ventilation systems

Improved ventilation can be either **mechanical** or **natural**; the selection of which is appropriate will depend on the existing system, building size, use, availability and suitability of plant. **Air stagnation** can concentrate airborne viruses or dust, so it is critical to keep indoor air as refreshed as possible.

Natural ventilation is the difference in atmospheric pressures caused by wind, from one façade to another, and from internal to external pressure. As pressure caused by wind cannot be guaranteed, a stable air change rate cannot be guaranteed in fully naturally ventilated buildings. Windows and louvres are passageways for fresh air to enter, and exhaust air to exit buildings. In general, adequately ventilated spaces are spaces that have an equivalent of 4% of floor area as operable window area[46].

Ventilation can be improved in naturally ventilated buildings through the use of passive design approaches that rely on air buoyancy effects as well as wind pressure, such as the stack effect to increase airflow, and positioning of openings (vents, doors and windows) to encourage cross-ventilation.[47]

Due to this **short fall in stable wind pressure**, guidance from the Lancet COVID-19 Commission Task Force on Safe Work, Safe School and Safe Travel recommends that it is used for auxiliary purposes, as the design can't guarantee constant ventilation rates. However, these systems may deliver more outdoor air and are much lower cost to implement. They therefore may be more appropriate in many scenarios, either where the scale doesn't require mechanical ventilation, such as in residential housing, or where the cost to upgrade existing systems is a significant constraint, such as in large portfolios of aging public infrastructure[48].

POTENTIAL MEASURES - NATURAL VENTILATION

Short-term

- Encourage opening of windows to allow for maximum ventilation.[48]
- Increase natural ventilation with enhancement by fans, to increase effectiveness of open windows.[49]
- Reposition outdoor air dampers to avoid transmission of potentially pathogen-laden exhaust air from indoor spaces.[(2)]
- Consider in any analysis the actual Free Area of the openings which takes into account any solid components within the opening such as window frames and mosquito nets.

Medium-term

- Reposition supply and exhaust diffusers to create directional air flow.[33]
- Retrofit buildings to include natural ventilation measures such as ensuring inoperable windows can open, and installing trickle vents in windows to allow for permanent access to fresh air.[(1)]

Long-term

- Incorporate passive design strategies into design such as new, larger windows (where safe to do so from a fall risk perspective)[(5)]
- Update building layouts to improve outdoor air delivery rates or to allow for natural cross-ventilation, such as U-shaped buildings[50].

This section references research from Denmark, USA, Taiwan, and global data from the Lancet COVID-19 Commission Task Force on Safe Work, Safe School and Safe Travel.

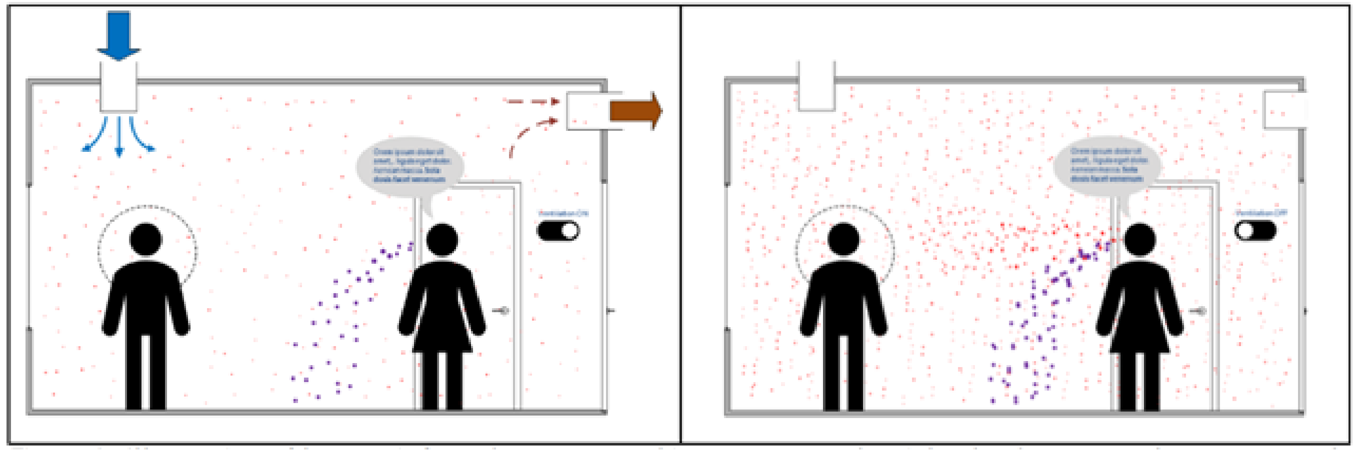


Figure 6: Illustration from the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) of how an infected person (speaking woman on the right) leads to aerosol exposure (red spikes) in the breathing zone of another person (man on the left in this case). Large droplet exhalation is marked with purple spikes. When the room is ventilated with a mixed mode ventilation system, the number of virus laden particles in the breathing zone is much lower than when the ventilation system is off. Left figure: ventilation system on, right figure: ventilation system off.

Adjustments or improvements to the **mechanical ventilation systems** can create improvements in indoor air quality (IAQ) with a higher degree of control than in naturally ventilated buildings. Well-maintained HVAC systems, including air-conditioning units, securely filter large droplets. However, aerosols (small droplets and droplet nuclei) can spread through HVAC systems within a building or vehicle and stand-alone air-conditioning units if the air is recirculated. Ventilation systems which **maximise outdoor air delivery** or **eliminate recirculation of unfiltered air** therefore reduce indoor infection transmissions. However, after long periods of vacancy, systems often require re-commissioning to ensure they are performing at the optimal level[51].

POTENTIAL MEASURES - MECHANICAL VENTILATION

Short-term

- Disable any energy saving settings such as demand-controlled ventilation while the building is in use.[52]
- Increase ventilation or clean air exchange to a maximum air change rate to provide as much protection to infectious disease transmission.[(1),(2)] (e.g., ventilating for longer hours, changing the setpoint for demand-controlled ventilation systems).[53]
- Provide training to FM teams, to improve understanding on the impact HVAC systems have on disease prevention and to ensure that changes to ventilation systems are implemented effectively.[(6)]
- Undertake an assessment of HVAC installations and specifications to understand the CADR provided by the systems, and potential modifications to system controls to increase supply of outdoor air, to understand if there is a shortfall in the CADR which may need to be mitigated by portable air cleaning (see section below). This should include reviewing whether commissioning was adequately carried out.[(1),(6),54]
- Create a Pandemic Readiness Guideline relevant to mechanical ventilation systems to enable FM teams to be able to respond to new infection peaks or threats.[55]
- If toilets have separate control equipment for ventilation, consider creating an under-pressure for these spaces (see link to Section 5.2.5 on waterborne transmission).[56]

Medium-term

- Retrofit more energy efficient HVAC infrastructure that has more adaptive controls to enable response to occupant needs, and to incorporate pandemic response “modes”.[(6)]
- Install “mouse-mesh” to prevent rodents entering buildings via vents and ducts and mitigate the risk of airborne pathogens being distributed through the mechanical system which have emanated from droppings or urine.[57]

Long-term

- Allow for increased footprint of plant for HVAC systems to encourage maximised ventilation in future. This will involve increased distribution capacity (ductwork / number of grilles) to serve all spaces adequately as functions and floorplate partitions change.[(1)]
- Invest in air change modelling and airflow pattern design within the building environment design of new buildings so that airpaths consider infection resilience and are updated to improve pathogen removal.[58]

This section references research using data from Europe, USA, China and the WHO.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.2.2

Improved indoor air quality (IAQ) - Filtration and disinfection

Filtration or other evidence-based air cleaning treatment helps improve the quality of recirculated air, but the impact is dependent on the quality of the filter. Guidance on recommended filter quality varies globally with a Minimum Efficiency Report Value (MERV) 13 filter or higher recommended by ASHRAE[59] and MERV 14 (F8 or ISO ePM1 70-80%) by the Singapore National Environment Agency[60]. However in all cases for existing systems, it is recognised that the maximum MERV value which can be used in a system is determined by the flow which the HVAC system can maintain across it.[61]

Portable air cleaners have also been recommended in situations where the existing HVAC system is not sufficient to achieve sufficient ventilation. Public Health Ontario recommends their use as a "supportive" measure to improve indoor air quality[62] and the Food and Environmental Hygiene Department of Hong Kong has produced a list of approved air filters which comply with their Prevention and Control of Disease (Requirements and Directions) (Business and Premises) Regulation (Cap.599F)[63] to help businesses select an appropriate unit for the floor area.

POTENTIAL MEASURES - FILTRATION

Short-term

- Ensure maintenance personnel inspect existing filters in HVAC systems to verify that they do not need replacement or upgrading.[{1},{6}]
- Use portable air cleaners with HEPA filtration where no filtration capacity exists within the existing mechanical ventilation system, or where it provides an insufficient CADR.[64]

Medium-term

- Install or upgrade filtration within the existing system, if possible to at least the standard of MERV 13.[65]
- Improve or include fan filtration for centralised plant.[66]

Long-term

- Allow for increased footprint of plant when designing HVAC systems to encourage flexibility and allow for future filtration technologies to be incorporated.

This section references research using data from the USA, Signapore, Canada and Hong Kong.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.2.3

Improved indoor air quality (IAQ) - Carbon dioxide levels as a proxy for air quality

Carbon dioxide (CO_2) concentrations can be used as a proxy for ventilation rates, and installation of sensors to enable real time monitoring is a recommended strategy to ensure ventilation systems are performing as intended. High CO_2 levels are an indicator of inadequate ventilation or potential overcrowding; the direct correlation between CO_2 levels and risk of exposure to viruses has not been well established, as risk can also be affected by other factors such as compliance with safe distancing, proper mask-wearing, and the presence of infected persons.[67]

Nonetheless, CO_2 levels below 800ppm are recommended in spaces where there are high levels of physical activity, continuous talking or singing. This level is consistent across a number of countries including both the UK HSE[68], the CDC (USA)[33], REHVA (Europe) and Singapore's National Environment Agency. CO_2 levels which are consistently above 1100ppm could demonstrate poor ventilation; however these levels should not be used to denote "safe" levels, rather as indicative values of effectiveness of a ventilation system.[68,69]

High CO_2 levels are an indicator of inadequate ventilation or potential overcrowding; the direct correlation between CO_2 levels and risk of exposure to viruses has not been well established, as risk can also be affected by other factors such as compliance with safe distancing, proper mask-wearing, and the presence of infected persons.[67]

POTENTIAL MEASURES - CARBON DIOXIDE LEVELS AS A PROXY FOR AIR QUALITY

Install CO_2 monitoring and sensors which can provide data that act as a proxy measurement for air quality. These sensors can be linked to ventilation control systems in smart buildings (see Section 5.2.6) to adjust ventilation demand accordingly, and to address areas of poor ventilation. Alternatively, monitoring can alert building operators of areas which consistently perform poorly, to inform more wholesale adjustments to ventilation system settings.[{6}]

Note there are certain scenarios where this will not be an effective measure:

- Where air filtration is in use, CO_2 will not act as a useful metric, as although the filters may be reducing pathogens in recirculated air, CO_2 levels will remain high, rendering the CO_2 measurement a poor proxy for air quality of other metrics.
- Where CO_2 is produced as part of an industrial process.[{4}]
- Large open spaces where the overall number of occupants changes over a short period time, such as train concourses, and warehouses where air mixing is reduced.[68,{3}]

This section references research using data from the USA, Singapore, the UK and Europe

NON-TYPOLOGY SPECIFIC CASE STUDY

USE OF CARBON DIOXIDE MEASUREMENTS TO ASSESS VENTILATION IN AN ACUTE CARE HOSPITAL[70]

Name: Cleveland VA Medical Center

Client: -

Location: Ohio, US

An assessment was undertaken of CO_2 levels at various clinical and non-clinical locations including the lobby, cafeteria, inpatient rooms and bathrooms in patient care areas within Cleveland VA Medical Center in Cleveland Ohio. The hospital engineering department maintains ventilation requirements throughout the facility in accordance with ASHRAE recommendations - a minimum of 2 air changes of outdoor air per hour are maintained in clinical areas.

Using an IAQ-MAX COW Monitor and Data Logger (CO_2Meter, Inc), carbon dioxide levels were continuously monitored and recorded every minute over 12 hours from 7 AM to 5 PM in the main lobby, cafeteria, physical therapy, and emergency department. The peak number of people present in these locations during monitoring was recorded.

The results showed that CO_2 levels remained consistently below 800ppm in most areas, even those which had high occupancy such as the main lobby and cafeteria. However, in some other areas, such as the small conference room and offices, the high CO_2 readings indicated that the ventilation may be suboptimal when overcrowded, or when doors were kept closed. The study notes, however, in its conclusion that, "additional studies are needed to determine if interventions to improve ventilation based on carbon dioxide monitoring are effective in reducing transmission of SARS-CoV-2 and other respiratory viruses.

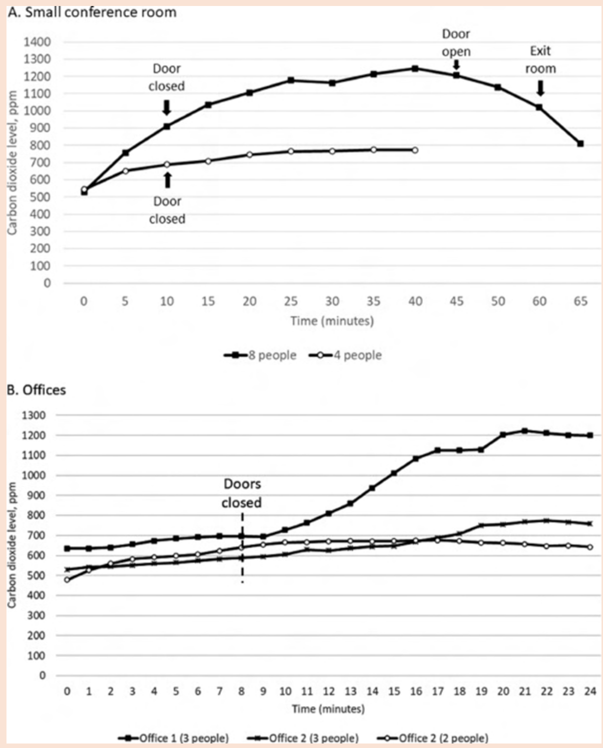


Figure 7: CO_2 levell monitoring for small conference rooms (above) and offices (below)[70]

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.2.4

Improved indoor air quality (IAQ) - Humidity control

Humidity control has a bearing on infectious disease transmission and mould growth. However, there is a balance between too moist and too dry air; higher relative humidity has been shown to affect droplet size and lifetime for SARS-CoV-2 and other viruses[71] and air with a higher moisture content encourages mould growth which can then exacerbate asthma and trigger allergies[72]. Conversely, dry air leads to irritable nasal passages which increases the amount of aerosol propagation due to increased sneezing and coughing of occupants[71]. Studies undertaken on the survival of SARS-CoV-1 particles have shown that relative humidity (RH) over 40% is detrimental to the survival of the virus, but greater than 80% may promote mould growth[73].

The IWBI recommends always maintaining relative humidity between 40% and 60% by increasing or decreasing moisture in the air. This aims to limit the growth of pathogens and maintain relative humidity levels that are conducive to human health and well-being. The recommendation also points to a number of supporting standards including: ASHRAE's Guidance for Building Operations During the COVID-19 Pandemic, the ByggaF's Industry Standard Method for Moisture Safety of the Construction Process, the EPA's Moisture Control Guidance for Building Design, Construction and Maintenance, and the WHO's Guidelines for Indoor Air Quality[40].

Additionally, after a prolonged shutdown and before occupants return, the US CDC recommends that buildings should be assessed for mould and excess moisture which may have built up during the building closure[74]. Also within the US, the National Institute for Occupational Safety and Health (NIOSH) recommends the use of the New York City Department of Health and Mental Hygiene's "Guidelines on Assessment and Remediation of Fungi in Indoor Environments" to do a visual and odour assessment for the presence of mould[75].

POTENTIAL MEASURES - HUMIDITY CONTROL

Short-term	Medium-term	Long-term
• Where humidity controls exist in existing systems, set these to maintain RH between 40% and 60%.[40] • Conduct regular inspections and perform preventive maintenance to safeguard against mould growth, especially after periods of inoccupation.[40,74] • Evaluate whether unusual water consumption patterns may be caused by preventable leaks, and address any such issues.[40] • After a period of inoccupation, facility maintenance to undertake purging or "flush-out" of the HVAC system of at least 48 -72 hours.[74]	• Install additional HVAC infrastructure to provide humidity control kit; any retrofits to integrate these into existing systems.[71] • Implement condensation management procedures in existing buildings.[76]	• If renovating or constructing a building or space, design it to be inhospitable to mould, microbes and pests with proper design of curtain wall, water piping assemblies and ventilation systems, and selection of appropriate materials for areas where condensation is likely.[40]

This section references research using data from the USA, Egypt and global data published by the IWBI task force on COVID-19.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.3

Material and surface characteristics

Environmental contamination of the built environment has been shown to be caused through contact by infected persons, or settling of aerosolised viral particles on surfaces. For example, a study in South Korea of patients infected with MERS-CoV demonstrated that almost every touchable surface in their wards had been contaminated[77]. This included surfaces which were not readily accessible by the infected persons, indicating spread onto these surfaces by other parties such as the healthcare workers and visitors. Similar results were demonstrated in a study in Canada of healthcare facilities housing SARS-1 patients, showing positive samples obtained from a refrigerator handle in a nurses' medication station and a television remote control in a patient room[78]. While the risk is higher in healthcare settings, this transmission can also be present in other infrastructure types, particularly high-touch surfaces such as door handles and lift buttons[79].

In order to mitigate against surface transmission of pathogens, appropriate material selection, surface characteristics and treatments can impact the length of time microbes survive. Research has shown that:

- Particles can settle on surfaces from a couple of hours up to 5 days depending on the material selected.[73]
- Survival of pathogens lasts longest on plastic surfaces (15.9 hours) and shortest on copper (3.4 hours).[73]
- Different types of pathogens may be found to adhere to surfaces depending on the function space (i.e., a sink countertop, or an elevator button) and this together with its purpose may impact the selection of the material.[80]

Some pathogens are better suited for surface transmission than others[79]. For COVID-19 specifically, there has been research which highlights the variation in transmission via surfaces, some of which show that this is a less common transmission pathway.[81,82] However, studies are being undertaken to evaluate the relative effectiveness of different pathways and have shown that it can be transmitted via surfaces, albeit less effectively[83]. Additionally, other infections such as methicillin-resistant Staphylococcus aureus, respiratory syncytial virus and norovirus do often transmit via fomites[81], and therefore this should be considered important in infrastructure design.

Measures to reduce transmission of infections via surface contact are recommended by international bodies including both the IWBI[40] and the WHO[84], plus regional guidelines such as Australia's Victoria Department of Health's "Infection control - standard and transmission-based precautions"[85]. Regarding anti-microbial surfaces, the International Organization for Standardization (ISO) reviewed their standard "ISO 22196:2011: Measurement of antibacterial activity on plastics and other non-porous surfaces" in 2021 to confirm that it remained current in light of the COVID-19 pandemic[86], with the USA's Environmental Protection Agency issuing similar guidelines[87].

POTENTIAL MEASURES - MATERIAL AND SURFACE CHARACTERISTICS

Short-term

- Reduce contact points by keeping doorways clear, propping open doors etc.[(2),(3)] However America's National Fire Prevention Agency issued a warning that this should not be done for fire doors as this then increases the risk of fire spread.[88]
- Increase cleaning regimes in high occupancy spaces and for high-touch surfaces that require frequent disinfection e.g. counters/tables in kitchen spaces, food contact surfaces, conference rooms, reception areas; manual opening mechanisms (knobs/ handles) on bathroom and entrance doors, closets, cabinets/drawers; and smaller items such as remote controls and serving utensils.[40]
- Provide hands-free hand sanitiser dispensers at high-contact locations.[40,70,(6),(4)] Place hand sanitiser dispensers directly in the line of vision rather than adjacent to the doorway to encourage use.[40]
- Verify the effectiveness of microbial disinfection through a test such as Adenosine triphosphate (ATP) swabbing.[40]

Medium-term

- Replace high-contact surfaces such as handles and rails in hallways, stairs and lifts with ones using antimicrobial materials. Similarly, replace buttons and switches with hands-free equipment as part of an interior re-fit.[40,(2),(3),(5)]
- Install contactless access technology such as automatically opening doors and gates for entryways including the introduction of digital technologies such as facial recognition and voice control.[(5)]

Long-term

- Design systems to including booking and payment options by apps on personal devices (e.g. for meeting rooms, activities and classing, check-out for shopping).[40,(5),(6)]

This section references research from South Korea, Australia, Canada, USA and Hong Kong and research published by the IWBI global task force on COVID-19.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.4

Alteration of spatial configuration - Spatial configuration, occupancy density and schedules

Spatial configuration of buildings can encourage or discourage social interactions. Visual transparency and open plan concepts are now key aspects valued in design for public and private spaces. Open plan concepts intentionally direct occupants to nodes for "chance encounters" and encourage degrees of connectivity[73]. However, these spaces may inadvertently enhance opportunities for transmission of viruses, both through direct contact and aerosols.

It is necessary to consider where the high risk hotspots lie within each building and also who is to be protected through implementing mitigation measures. In commercial offices, employers are investigating necessary mitigation measures in conference rooms as they present the highest risk of infection transmission due to the interaction of employees with visitors, recognising that employers cannot control the vaccination status of individuals or PPE protocols of external firms. In education environments it is important to protect the faculty of staff as they are in a higher risk category if they contract an infectious disease than their students.

Occupancy density and schedules are influenced by building type and programme; indoor activity and movement patterns influence the transmission of human-associated microorganisms[73].

- Higher occupant density and increased indoor activity level typically increase social interaction and connectivity[89].
- Occupancy schedules affect connectivity e.g. times people enter and exit buildings, how often they leave the leave the building and the timespan they are absent. For example, schools and libraries have long occupancy schedules and high turnover of individuals through spaces in a day[90].

Factors such as age of the occupants, day of the week and multi-function use of buildings are other factors that influence occupation schedules and decreasing density may not feasible (or economically viable) in some infrastructure typologies.

Infrastructure is able to encourage **physical distancing** measures whilst still achieving purpose of function. Spaces can be fully functional but designed with flexibility in mind to achieve the principle of social distancing by providing wider spaces and encourage distance among users, however within a set space constraint, this will limit the overall capacity of the infrastructure.

POTENTIAL MEASURES - SPATIAL CONFIGURATION

Short-term

- Develop a decision-making process to consider whether to implement social-distancing measures, to what extent to limit occupant density, and for how long to implement the measures.[(6)] These could include temporary suspension of shared spaces (such as meeting rooms or cafeterias) or equipment (such as workstations or technology)[40]
- Change or stagger operational activities which create pinch points (i.e. lots of people going from a large space and then all filtering through a narrow hallway to enter or exit).[40,(5),(6)]

Medium-term

- Review level of connectivity of common room and door configurations of existing building layouts (i.e. the number of rooms you need to walk through to access facilities such as the washing or kitchen facilities) and where possible, adjust internal configurations to reduce these.
- Repurpose unused spaces (rooftops, alleys etc) for outdoor seating, exercise and meeting.[40]

Long-term

- Evaluate conflicting demands in a building between large open plan spaces that improve the occupants' experience of a building, against the subdivision of larger spaces to reduce opportunities for transmission. This can be done through the use of computational fluid dynamics (CFD) modelling to consider appropriate layouts or potential measures such as partition heights in the design of new buildings.[(6),(7)]

This section references research using data published by the IWBI global task force on COVID-19.

POTENTIAL MEASURES - OCCUPANCY DENSITY AND SCHEDULES

Short-term

- Introduce methods that can be employed to reduce occupancy density, such as traffic control, with one-way systems and restrictions of entry and exits.[40,(1),(4),(6)]
- Change or stagger operational activities which create large crowds or queues.[(4),(6)]
- Provide signage which indicates the maximum occupancy of any space to building users.[40]

Medium-term

- Use smart buildings technology and AI to track, minimise and predict occupancy density around a building or asset (i.e. a specific day that is anticipated to have increased demand for public transport such as a public holiday or large sports event, and thus an increased frequency of services is supplied).[(6)]

Long-term

- Design in flexibility within floorplates for times when decreased occupancy density and schedules are required, particularly in high traffic areas such as lift lobbies and entranceways which typically have large numbers of users at a particular moment.[90,50,92]
- Place stairways in a salient location and make them inviting and aesthetically pleasing to encourage stair use, and discourage use of lift which limits the ability to physically distance.[93]

This section references research using data from USA, West Africa, South Africa, Singapore and Indonesia.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.5

Reducing water borne infection transmission

Water system stagnation becomes a concern in buildings that have had an unoccupied / partially occupied phase (either due to lockdowns or inherent periodic use patterns, such as in universities).[94]

In addition to disruption in occupancy of buildings, there are numerous case studies and research papers indicating the prevalence of Legionella Disease as a result of water stagnation.[95,96,97]

Exposure to a range of contaminants in water can result in negative health impacts, including the spread of infectious disease. Water is typically treated with chlorine to keep it free of pathogens. However, if left stagnant after a period of vacancy, chlorine is likely to lose its disinfection power, creating opportunity for pathogens to contaminate the water.[94]

Specifically, Legionella bacteria can grow and spread in the water system which has been well documented, and many countries already have legislation or building regulations in place to control Legionella bacteria in water systems, which should be adhered to where:[94]

- water is stored or re-circulated in the system;[98]
- the water temperature in all or some parts of the system may be between 29-42 °C[94], or 20-45 °C[98]
- there are deposits that support bacterial growth, including Legionella, such as rust, sludge, scale, organic matter and biofilms;[98]
- it is possible for water droplets to be produced and, if so, whether they can be dispersed.[98]

In addition to the spread of pathogens through stagnant water, consideration should also be made to the transmission of infections through the water system. As mentioned previously, Hong Kong has updated its building regulations for plumbing to include specific features, such as the “W-trap,” after this was shown to be a primary transmission route in a superspreading event of SARS-CoV-1.

Initial guidance in early 2020 from the WHO indicated this may also be a SARS-CoV-2 transmission route. However, while there is much evidence of virus RNA being detectable in wastewater, and the potential for this to track infection levels, evidence on the transmission potential of this route is still emerging[99]. Additional research has shown this transmission route is potentially not limited to respiratory infections - a study of a hospital complex in 2014 showed results following PCR testing of different areas of the drainage system which indicated similar transmission routes of Norovirus in their wastewater systems[100] and another, undertaken in Hong Kong, showed that airborne pathogens can be emitted during toilet flushing[101].

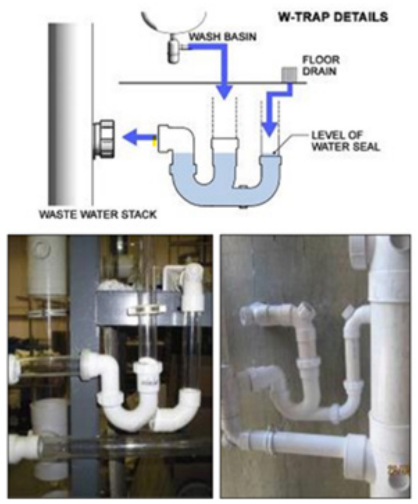


Figure 8: W-Traps in use in Hong Kong

POTENTIAL MEASURES - REDUCING WATER BORNE INFECTION TRANSMISSION

Short-term (operational changes)	Medium-term	Long-term
• Carry out water testing to ensure safe water for consumption in the building when reoccupation occurs[98] • Undertake a risk assessment for Legionella in line with relevant regulation (in the UK this is published by the HSE, but similar guidelines exist in many countries globally as noted previously)[98] • Update and verify existing water management plans. Incorporate flushing schedules to maintenance programmes that acknowledge occupancy disruptions.[94] • Flush all u-bends with water regularly, paying particular attention to those which are less frequently used, such as floor drains or in sinks and showers after periods of non-use.[102] • Use signage to encourage users to close the toilet lid before flushing.	• Implement ongoing water testing regimes to track infections in wastewater outfalls.[94] • Review the safe operation and control measures for the design and operation of any evaporative cools systems, hot and cold water systems or any other systems which may produce aerosols, thus posing a foreseeable risk of exposure to Legionella. The HSE guidance provides a non-exhaustive list of these for the UK context.[103] • Review drainage design to identify if there is a risk of U-traps being frequently dried, for example in floor drains and replace with W-traps or similar. Where this not possible, connect grey and black water outfalls to separate stacks to avoid cross contamination.	• Design in flushing valves that work on the controls circuit to remove any potential human error, with manual / personnel responsible for flushing.[94]

This section references research using data from Hong Kong China, Italy, UK, Spain and the USA.

NON-TYPOLOGY SPECIFIC CASE STUDY

REDUCING WATER BORNE INFECTION TRANSMISSION: A LONDON HOSPITAL

Name: Legionella Control Using a Copper and Silver Ionisation System in a UK Hospital

Client: -

Location: UK

Overview

A copper and silver ionisation system was installed in a UK hospital to address positive detection of Legionella.

Legionella can be particularly dangerous in hospitals due to the presence of patients with compromised immune systems. The Legionella genus can survive in wide ranging temperatures but thrives between 20 to 45 degrees Celsius. For this reason, temperature regimes have been seen as sufficient to control the culture production of L. pneumophila. However, the risk remains – the study found that even in hot water supplies in the hospital ranging from 52 to 59.4 degrees Celsius (within the temperature recommendations for prevention), six out of seven supplies tested positive for Legionella detection.

This study implemented five copper and silver ionisation systems, in conjunction with temperature control, to suppress the ability of L. pneumophila to produce cultures. The system is comprised of two electrodes, one of 99.99% copper and the other 99.99% silver. The water flows through a turbine flow sensor, which sends a signal to a control unit, and passes through a low current between the two electrodes, causing the release of copper and silver ions into the water.

Copper and silver ionisation systems have been implemented and analysed for their success in suppressing Legionella in the USA. However this study presents a UK hospital's specific case.

Samples were taken prior to installation from 140 outlets identified as potentially at risk of Legionella, such as blended outlets, those with attached rubber-lined hoses, and low use outlets. 20 out of the 140 outlets had positive counts. After one year, Legionella counts decreased, and after two years, counts were only detected in 3 outlets. Between the second and final year of the study, no Legionella was detected in any of the outlets.

Key Infection Resilience Measures

- Temperature control alone is not sufficient – This study evidenced that temperature control alone is not sufficient to limit the ability of *L. pneumophila* to produce cultures. Instead, a combined approach (temperature regime and the copper and silver ionisation system) was shown to be optimal as an infection resilience measure.
- Installation upstream of water tanks – The study shows the importance of installing the ionisation system upstream of the water storage tanks to encourage an adequate build up of copper and silver in the tanks, so that good levels were available for distribution to outlets.
- Flow regulating valves – Flow regulating valves were shown to be an important infection resilience measure as they ensured optimum activation of the copper and silver ionisation systems.
- Automatic adjustment – In order to ensure that the necessary levels of copper and silver were released, the ionisation system was designed and fitted with automatic adjustment mechanisms to cater for variable flow rates and water qualities.
- Remote interrogation – Copper and silver levels, electric current settings, and flow rates were all able to be interrogated remotely.
- Prevention of scale – Preventing scale formation on the electrodes was important to ensure that the release of copper and silver ions was not obstructed in hard water. This was prevented through the use of copper and silver electrodes instead of copper-silver alloys.
- Controlled release – The use of copper and silver electrodes instead of copper-silver alloys also allowed for the controlled release of copper and silver ions by being able to increase or reduce the electrical current output of each separately.
- Automatic polarity regulation – The polarity of the electrodes is designed to automatically switch between anode and cathode, meaning that ions that may have attached to the surface of the cathode are released when the polarity was switched.
- Regular maintenance – The ionisation system must also be checked and maintained regularly – in this study the condition of the system was checked and maintenance work was carried out once a month – to ensure consistent optimum operation.

NON-TYPOLOGY SPECIFIC KEY FINDINGS 5.2.6

Use of smart technology

Smart buildings and effective use of control systems can enhance infection protection in buildings.

- Air quality sensors can provide information on CO_2 levels and measure levels of pollutants such as volatile organic compounds (VOCs) or fine particulate matter (PM2.5/PM/10) which provides information on how effectively the ventilation systems are working at that time.[104]
- Systems are also able to monitor other health metrics such thermal comfort levels and body temperature of occupants and visitors.[104]

Taking a data-driven approach where results from building sensors are used by AI-based platforms, which also draw on historical data, can provide insights into the most effective mitigation measures and allow real-time corrective action to be made, or even predict when health thresholds may be surpassed to implement measures pre-emptively.[104]

POTENTIAL MEASURES - SMART TECHNOLOGY

Short-term (operational changes)	Medium-term	Long-term
Integrate any existing sensors into a monitoring dashboard and develop action thresholds to instigate feedback to systems such as ventilation or entry control.[(5),(6)]	Install new sensors which monitor air quality and other metrics such as body temperature of occupants.[(6)]	Incorporate learnings from the AI assessments of effectiveness of mitigation measures and feed into design of new builds or large retrofits.[(7)]

This section references research using data from Hong Kong

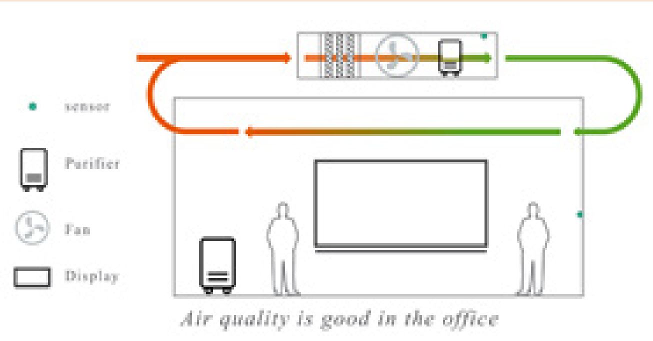
NON-TYPOLOGY SPECIFIC CASE STUDY

NEURON HEALTH[59]

Name: Harbour East
Client: -
Location: Hong Kong, China

Overview

Harbour East is a commercial building in Hong Kong which piloted an AI and analytics platform for smart buildings called Neuron Health. This is a cloud-based management platform which provides a detailed real-time picture of how a building or facility is operating, and what kind of experience its occupants are having. This is achieved through a network of installed sensors within the building which captures a number of air quality metrics on a continuous basis.



Key Infection Resilience Measures

- Operation insights include optimising the disinfection system and HVAC systems and the importance of striking a balance among air quality, human health and comfort and energy consumption. The implementation process is shown in Figure 9:
- The introduction of the platform aimed to enhance the indoor air quality through a data-driven approach. The combination of sensors, data, and AI enables facilities managers to control the settings for the buildings HVAC systems based on more information than provided by analogue surveys or reports, in order to improve the condition of the environment of the building.
- In addition, the platform can automatically turn on the air purification system when the air quality reaches a certain trigger level.
- **This reduced "high risk hours" by 33%.**

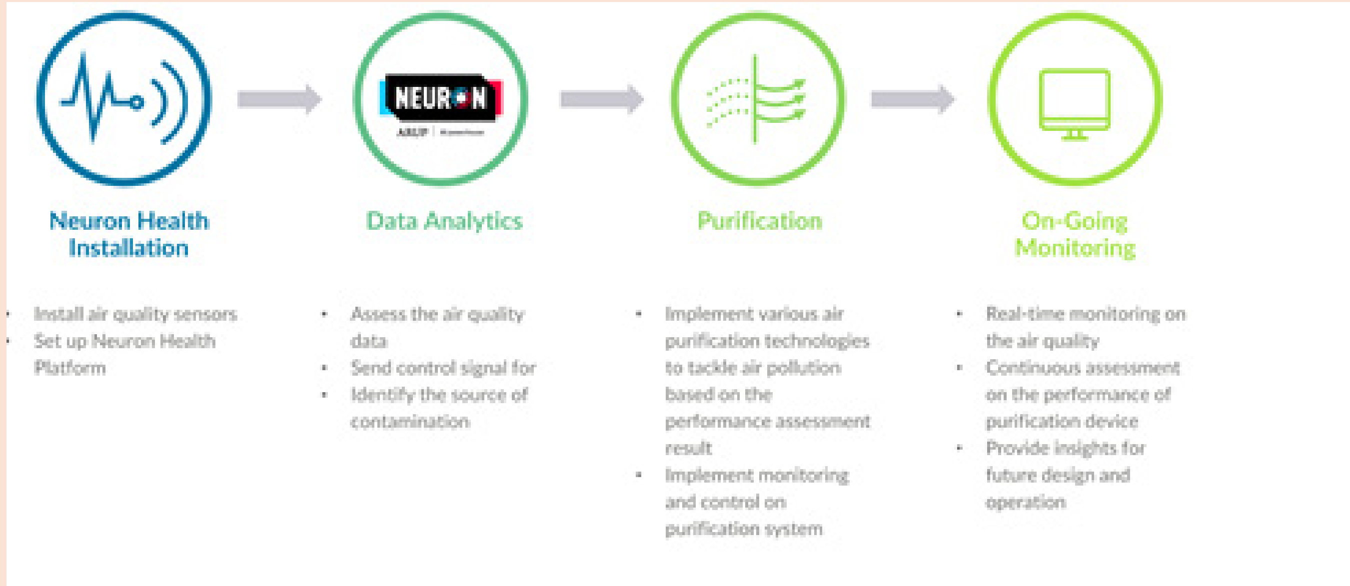


Figure 9: Neuron recirculation data cycle (above), Neuron health implementation process (below)

5.3 Commercial Buildings

5.3.1 SUMMARY

There is extensive literature and good awareness of infection resilience within the commercial sector, particularly following on from the outbreak of the COVID-19 pandemic as commercial building owners and tenants have had to consider the best methods to encourage employees, shoppers, diners, gym-goers and members of the public into these spaces, post-lockdown. The commercial sector has been heavily impacted, for example in June 2020 in New Zealand, sales for food and beverage services fell 40% in the quarter, which was the largest drop of any industry in the country[105]. This has forced the sector to put health at the forefront its agenda as its economic prosperity depends on people to continue using commercial buildings. However, initial findings suggest that this has led to higher rental value. A study of ten cities within the United States showed that effective rents of buildings which have a health standard certification (in this case WELL or Fitwel), increased by 4.4% to 7.7% in comparison to other nearby non-certified buildings[92].

Infrastructure Type In this Section:

Commercial (Class E)

Specific Use Classes:

- E(a) Display or retail sale of goods, other than hot food
- E(b) Sale of food and drink for consumption
- E(c) Provision of financial, professional, or other services
- E(d) Indoor sport, recreation or fitness
- E(e) Provision of medical or health services - not attached to consultant or practitioner
- E(f) Creche, day nursery or day centre
- E(g) Office, research and development, industrial processes

COMMERCIAL BUILDINGS 5.3.2

Retail Experience

Key elements of shaping the retail experience to have health and infectious disease resilience at its focus include:

- Supermarkets and pharmacies will form part of the critical infrastructure that will remain open during infection peaks, and their design will need to account for these scenarios[12].
- Confidence will need to be built, of both consumers and the retail workforce, that the spaces are safe to use, including visual aids (e.g. provision of hand sanitiser within eyeline, signage and barriers) and operational aids (e.g. improved air ventilation)[106].

POTENTIAL MEASURES - RETAIL

Short-term	Medium-term	Long-term
• Implement rigorous operational policies aimed at improving cleaning practices, reducing respiratory-particle exposure and surface contact.[107] • Provide hands-free hand sanitiser dispensers within eyeline on entry.[106] • Develop emergency preparedness and management procedures for future infectious disease peaks.[108] • Introduce signage to control movement, such as one-way systems, and social distancing markers for queues.	• Develop improved air ventilation and air quality strategies and policies. These may require upgrades to HVAC systems to achieve minimum ventilation rates.[58] • Install capacity monitors with external signage (e.g. traffic light system for entry).[7]	• Design spaces to account for larger areas required for social distancing in queueing, browsing and reduced capacities. • Increase the queueing spaces, or provide covered outdoor queuing spaces for overflow during reduced capacity periods due to future infection peaks. This applies particularly to supermarkets.

This section references research using data from Hong Kong, Romania, American Standards, Chinese Standards, WHO, UK standards and European standards.

COMMERCIAL BUILDINGS 5.3.3

Office Spaces

Office spaces can be adapted to react to different and flexible ways of working in a post-pandemic and pandemic-resilient future environment. For example:

- The acceleration of digital transformation increases the number of platforms that make up what we can consider to be the 'workspace', or the space where we perform our work.[7]
- Future hybrid working styles will include a mix of office, home-office and informal working spaces such as cafes and public libraries.[109]

POTENTIAL MEASURES - OFFICES

Short-term (operational changes)

- If desks are shared, implement strict cleaning regimes between occupants. In addition, provide cleaning supplies for occupants to wipe down surfaces in common spaces, such as kitchen handles and supplies.[6]
- Make circulation zones one way to reduce congestion. Similarly, provide signage in meeting rooms and informal meeting spaces to indicate maximum meeting numbers.[1]
- Implement mask-wearing in enclosed spaces such as lifts.[6]
- Reduce capacities in meeting rooms, and restrict use of meeting rooms without windows.[6]

Medium-term

- Consider use of movable furniture in communal zones so that people can spread out, and add acoustic treatments so that they can hear each other well without sitting closely.[6]
- Repurpose surplus space for co-working hubs to manage fluctuations in vacancy rates.[1,6]

Long-term

- Design office space to allow for flexibility of use and function, considering the range of purposes that the office will be used for in the future. Collaborative working arrangements to include breakout spaces, larger meeting rooms, open booths, and "pods", with focus rooms for individual concentration.[6] Consider implications for flexibility of use and space on ventilation requirements.

This section references research using data from the Americas, Australasia, East Asia, Europe, UK, India and the Middle East.

COMMERCIAL BUILDINGS 5.3.4

Food Retail and the Hospitality Industry

Spatial strategies for food retail and the hospitality industry and its impact on how people eat and occupy spaces are required given that restaurants are a critical part of the public sphere. This includes:

- Spatial guides and cues to optimise operations that keep people safe.[110]
- Understanding that the 2m rule is not a solution inside many restaurants, thus reducing the number of diners by 50-70% depending on the space.[110]
- Recognising that social distancing will continue as an important consideration in the immediate, medium, and long-term for both sit-down meals, queueing and takeaways.[110]
- Considerating the design requirements for delivery services such as a designated delivery doorway, back-of-house delivery activity rooms, loading and unloading zones.[110]

POTENTIAL MEASURES - FOOD AND HOSPITALITY

Short-term (operational changes)

- Expand into the outdoor street and reclaim the restaurant's role in the public realm.[110]

Medium-term

- Evaluate new food safety and sanitation protocols to react to new spatial challenges for social distancing.[110]
- Examine the spaces of restaurants with flexible and creative reconfigurations in mind, considering tables, bar seating, booths and use of barriers.[110]

Long-term

- Consider the use of open-plan kitchens that make the act of safe and clean food handling visible to both the restaurant employees and diners, thus promoting continuing good practice.[110]
- Incorporate exchange zones for delivery control, customer hand-off, don and doff procedures, ventilated storage and cooking.[110]

This section references research using data from the USA.

COMMERCIAL BUILDINGS 5.3.5

Gyms and indoor sports facilities

Gyms and indoor sports facilities will need to adapt their physical spaces and operational structure acknowledging that exercise activities generate more aerosols[111]. This creates scheduling implications for sports facilities when trying to reduce the chances of transmission, which include limiting class and activity capacities, traffic of people into and out of facilities and movement during activity.

Transmission of respiratory infections had not been a primary concern in gyms prior to the COVID-19 pandemic. However specific guidance on this has now been published by owners and operators for example, the UN Department of Operational Support issued guidance for use of gyms within UN premises[112]. Some government agencies have also issued guidance, such as the Netherland's NOC*NSF's "Protocol for Responsible Physical Exercise", which is part of new regulations in response to COVID-19. While much of the guidance is behavioural, some has relevance to building infrastructure.

POTENTIAL MEASURES - GYMS AND INDOOR SPORTS FACILITIES

Short-term	Medium-term	Long-term
• Increase hygiene regimes, cleaning in between occupants and restrict equipment sharing; introduce clear social distancing guidelines and limited access to classes and facilities. Increase spacing of equipment and participants in classes.[113]	• Switch mouth-to-tap water fountains for models which allow users to fill up personal water bottles or disposable cups.[112]	• Increase sizes of changing room facilities, doorways, hallways, entry and exit strategies (those that have just finished exercising and are generating more aerosols, hence minimise their contact with those entering the sports facility). • Include outdoor exercise spaces such as outdoor studio spaces and weights.

This section references research using data from the UN, Netherlands, Saudi Arabia.

COMMERCIAL BUILDINGS 5.3.6

Creche and Nursery Day Care

There are a number of considerations for buildings providing creche and nursery day care services, recognising that temporary and permanent closure of childcare settings has had an impact on social, emotional and behavioural development during the COVID-19 pandemic.[114] These include:

- Access to outdoor spaces is important for physical activity and mental health.[114]
- Restricting touch points is not typically a viable mitigation measure due to the difficulty of preventing infants and toddlers from putting items and their fingers in their mouths. Instead, the focus should be on measures which reduce the likelihood of transmission between carers, to help ensure continuity of business and minimise large outbreaks.

POTENTIAL MEASURES - CRECHE AND NURSERY DAY CARE

Short-term	Medium-term	Long-term
• Introduce shift patterns and reduced hours of care to allow for "bubbles" of children to continue to attend nursery services in low class sizes.	• Establish procedures for when staff or children become unwell, and train staff and teachers to conduct risk assessments and take appropriate action to provide support when needed.	• Provide outdoor spaces and designing the built environment for learning.

This section references research using data from the UK.

COMMERCIAL BUILDINGS - CASE STUDY

FISHER BROTHERS RETURN TO WORKPLACE[58]

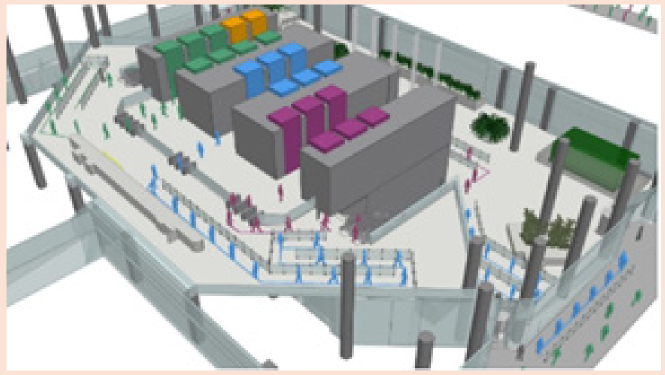
Name: Fisher Brothers Return to Workplace Study
Client: Fisher Brothers
Location: New York, US

Overview

Arup developed a wayfinding plan that guides users through new lobby operations and layouts that prioritise public health and physical distance for workers returning to the office.

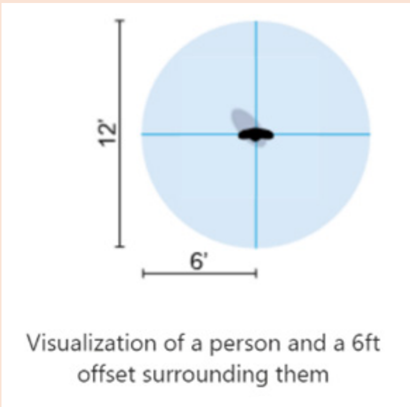
The lobby operation plans needed to consider the impacts of social distancing in lobby areas and elevators, as well as new protocols such as temperature checks. Working with the client, scenario testing was done to understand lobby operations with different building populations, operational set ups or assumed processing times.

Implementation plan in action within the MassMotion model built for the project



Key Infection Resilience Measures

- Elevator cabs in the Fisher Brother lobbies allow for an offset of 6ft between each person if they were to stand in each corner of the cab. The consensus was that four people in the elevator cab could be tolerated if masks were enforced. (Figure 10, left)
- Intuitive wayfinding was facilitated by developing a signage and placement strategy so that employees are provided with the information they need. A full design intent package was provided so that the client could directly engage a manufacturer to ensure high-quality results. (Figure 10, right)
- Pedestrian flow layouts informed recommendations provided to the client on a seamless return-to-work experience which incorporated separate inbound and outbound flows, routes for people with reduced mobility needs, wayfinding plans, and staffing requirements, as well as flexible queuing options to accommodate different building occupancy rates. The wayfinding plans include:
  - Passenger limits in elevators
  - Accessible routes for wheelchair users
  - New health protocols such as thermal scanning upon entry
- These changes improved visitor processing, minimising crowding at major choke points near doors, elevators, and reception, and promoting a safe physical environment for employees and visitors.



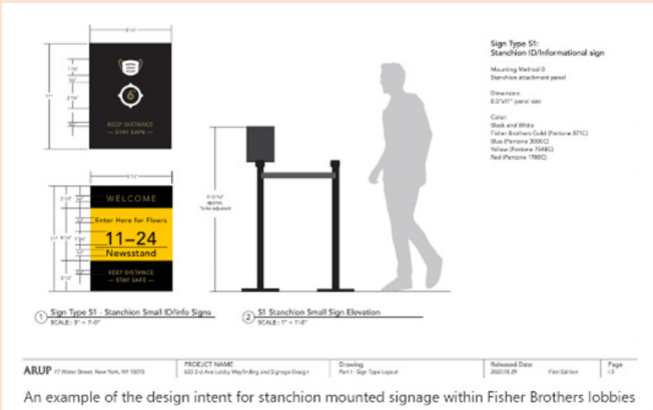


Figure 10: 6ft surrounding each person in lift cart (left), signage and placement strategy in office (right) , pedestrian flow through office (above)

COMMERCIAL BUILDINGS - CASE STUDY

80 CHARLOTTE STREET, ARUP[60]

Name: 80 Charlotte Street
Client: Arup
Location: London, UK

Overview

The London office leader worked alongside the design team and FM to best understand what measures could be implemented to create the safest office space possible.

The fitout of adaptation of the occupied space in 80 Charlotte Street was based on learnings taken from the management of Arup's previous office in London, focusing on measures that made a real impact to the safety and comfort of employees in their workplace post COVID-19.

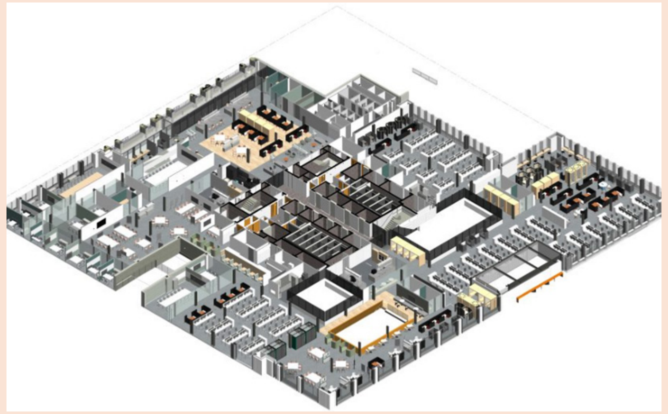


Figure 11: 80 Charlotte Street floorplate

Key Infection Resilience Measures

Measures that were introduced to improve the safety of the workspace and make employees feel more comfortable about coming into work include:

- "SMART" enabled building strategy including air quality monitors, desk booking systems and sound and temperature sensors.
- Body temperature scanners on entry into the building which has been seen to be successful. Feedback from building operators is that this has mainly acted as a deterrent for those who are feeling unwell from coming into the office, as opposed to revealing if someone has contracted COVID-19.
- Anti-microbial surface pads for doorways.
- Introduction of apps to order food and drink from the café and to book desks and meeting rooms in the office.
- QR codes to order food and drink and scan coffees at the coffee points on each floor to enable a touch free experience.
- Fitout adjustment based on experience post COVID-19, i.e. consideration of increased hallway width, reduction of capacity in meeting rooms and spaces and more single-occupant 'booths' for increased number of video calls
- Digital hybrid-office meeting rooms that allow for video conferencing and in person functioning
- Increased frequency and requirements of cleaning protocols that have continued beyond initial COVID-19 outbreak. Even now, when it is understood that it is less transmissible by surfaces, this has strengthened employee's confidence that the office is a safe environment to work in.

5.4 Industrial Buildings

5.4.1 SUMMARY

There is limited literature on the topic of infection resilience in the industrial sector. Consultations with key stakeholders in the sector confirmed that the topic of infection resilience in industrial buildings has not been widely considered thus far, and that that the efficiency of the manufacturing or industrial process eclipses all other aspects of the building's design[(4)].

Unlike the other building typologies, the arrangement and operation of industrial buildings are entirely dependent on the individual industrial business model, hence there is limited scope for using "off-the-shelf" solutions[115]. Each individual industrial process has a strict set of requirements that define the specific arrangement and operation of the building, hence off-the-shelf solutions do not tend to be appropriate.

Data centres and highly mechanised industrial units, due to their purpose, are often sparsely populated and well-ventilated spaces that do not lend themselves to be high risk for the transmission of infection diseases. This section therefore has focused on the types of industrial buildings that do present characteristics of higher risk, due to the density of people present or the specific function of the space.

Infrastructure Type:

- Industrial (Class B)

Specific Use Classes:

- B2 General industrial
- B8 Storage or distribution

INDUSTRIAL BUILDINGS 5.4.2

Optimised Building Design and Operation

There are several key aspects of the operation of industrial buildings which impact the likelihood of infection transmission in these spaces including:

- Occupancy density in production halls.[(4)]
- Peak worker periods (for loading times or shift cross-over).[(4)]
- Efficiency of production and storage typically drives building design decisions, with cost margins, leaving little room to change designs for other reasons.[(4)]
- In some cases, high air quality requirements for non-infection reasons, such as in data centre environments.[(4)]
- Exposure of employees to external workforces through delivery and goods drops.[116]

POTENTIAL MEASURES - HUMIDITY CONTROL

Short-term (operational changes)	Medium-term	Long-term
• Stagger shifts with a small down-time to avoid overlap in shifts, thus reducing the risk of infection spreading across large sections of the workforce. Allow administrative staff to work remotely and reduce non-essential warehouse visits.[(4)] • Introduce temperature checking on entry.[(4)]	Provide larger waiting spaces for drivers during loading/unloading to provide safe distances between employees, delivery drivers and external workforces.[(4)]	• Rearrange spaces including processing and manufacturing halls to allow for social distancing whilst operating at full capacity.[(4)]

This section references research using data from the USA.

INDUSTRIAL BUILDINGS 5.4.3

Increased Automation in Industrial Units

Increasing automation improves resilience and diversification in the industrial market. Businesses should consider the opportunity to automate processes in warehouse and industrial units to further reduce occupancy, increase supply chain transparency and predictability, and increase flexibility to repurpose production, thus allowing for efficient workspace reconfiguration and staff tracking[117].

Increasing automation addresses the following challenges in the sector:

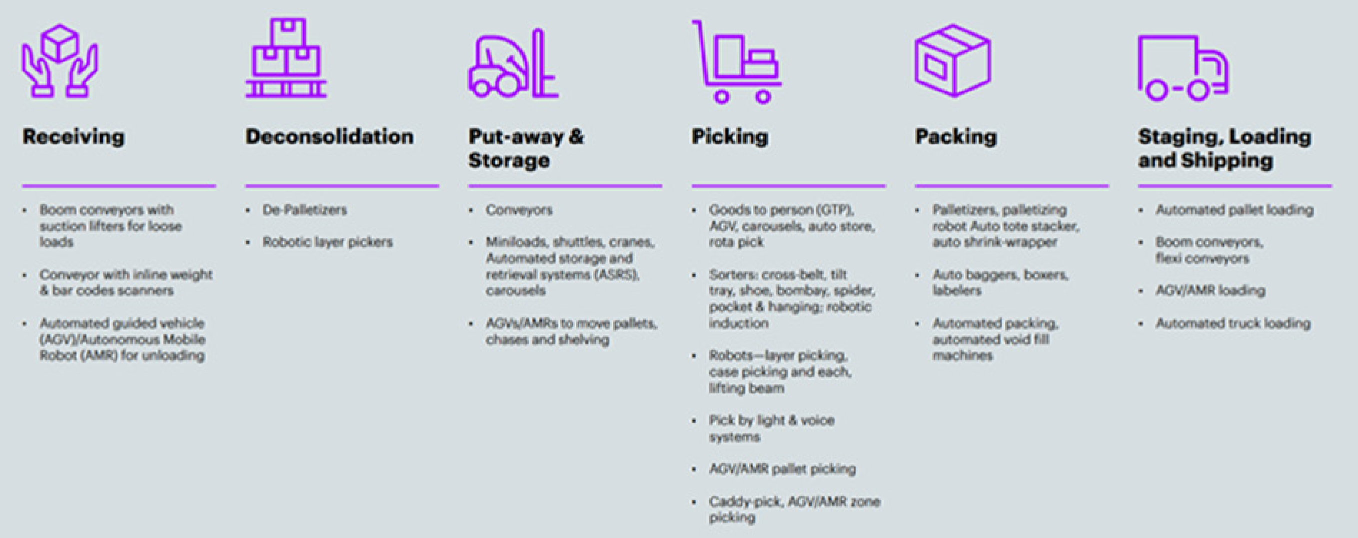
- Addressing new and changed business requirements is one of the top three drivers for automation and robotics in warehouses.[118]
- Labour challenge is a dominant theme emerging from interviews with warehousing and logistics senior executives who have greater concerns regarding health and social distancing due to COVID-19.[118]
- Warehouse automation is expected to attract 15% more investment in the next five years than previously predicted.[119]

POTENTIAL MEASURES - AUTOMATION IN INDUSTRIAL UNITS

Short-term	Medium-term	Long-term
• Improve low-scale operations of conventional picking with process improvements [118]	• Introduce mechanised solutions such as conveyor/pick modules and layer picking [118]	• Introduce semi-automated and fully-automated robotic systems to meet consistent and reliable demand requirements, for example, automated warehouse picking robots which are used at Ocado Customer Fulfilment Centres (CFCs)[120]. Other examples include sorting systems, pallet cranes, robotic product-handling, shuttle systems, fully-autonomous robots and drone-based surveying systems.[118] • Design building floorplates for these loading scenarios if using heavy robots on a large scale in multi-floor buildings. [118]

This section references research using data from Germany, Singapore, Japan, South Korea and China

Figure 12: Various warehouse functions can be automated either partially or fully[118]



INDUSTRIAL BUILDINGS 5.4.4

Meat Processing Plants (MPPs)

One specific function of industrial spaces is meat processing plants (MPPs), where evidence has shown a particularly high incidence of COVID-19 outbreaks which have occurred in a confined working area over long periods of time[121]. In Victoria, Australia, a spate of 14 outbreaks of COVID-19 were found to have originated in MPPs, accounting for 5.6% of all cases in the state[122], while the government of New South Wales subsequently issued guidance for abattoirs and the meat processing industry[123]. Physical distancing guidance appears to vary slightly by location, for example the Australian guidelines recommend a separation distance of 1.5m, while and Irish guidelines recommend 2m.

Analysis of infection outbreaks in MPPs show that the facilities' environmental conditions such as low temperature, low air exchange rates, and constant air recirculation, together with relatively close distance between workers and demanding physical work, promote efficient aerosol transmission, and these may all have contributed to a relatively higher transmission risk in these contexts[121].

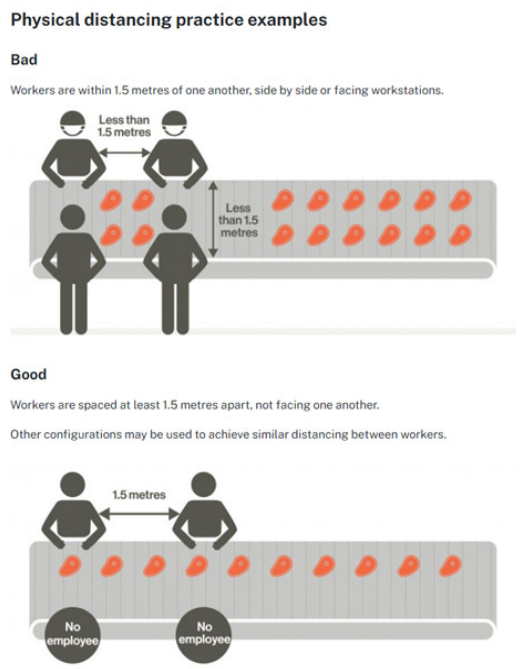


Figure 13: Guidance on Physical Distancing in MPP in New South Wales

POTENTIAL MEASURES - MEAT PROCESSING PLANTS

Short-term	Medium-term	Long-term
• Increase air temperature and ventilation rates in high-risk locations such as boning halls and other environments where aerosol build-up is likely. • Clean boot and washrooms (including hoses) after each major break[123] • Reconfigure delivery protocol to ensure delivery drivers and hauliers do not mix with plant staff.[124]	• Upgrade spacing in packing areas. For example, where belts are narrower than 2m wide, adjust packaging set up so that face-to-face working is avoided.[124] • Set up electronic delivery paperwork systems which do not require wet signatures from delivery drivers.[123]	• Improve ventilation systems to allow for more control, in order to adjust air temperature rates and temperatures more reactively to infection threats. • Optimise airflow management and install filtering devices.

This section references research using data from Australia, Ireland, USA and Canada.

INDUSTRIAL BUILDINGS 5.4.5

Food Storage and Distribution Units

Grocery distribution centres operations are amongst the most labour intensive of any industry. High cubic volumes of merchandise are shipped to retail stores with frequent deliveries to ensure product freshness[125].

The COVID-19 pandemic resulted in an increased impact on demand in the cold storage market (refrigerated storage spaces) due to an consumers panic buying food products in the short-term and an overall increase in online food retail[126].

POTENTIAL MEASURES - FOOD STORAGE AND DISTRIBUTION		
Short-term	**Medium-term**	**Long-term**
• Develop and reconfigure alternative paths and methods for drivers and delivery drops to be done in ways that minimise physical interaction, through electronic or outside systems.	• Extend of processing lines to provide spacing between workers.	• Design ability to be able to increase storage facilities and capabilities whilst ensuring that this does not require an increase in personnel.[116]

This section references research using data from the USA and UK.

INDUSTRIAL BUILDINGS - CASE STUDY

LOADING BAYS IN INDUSTRIAL UNIT

Name: Loading bays - Unnamed Confidential Project
Client: Prologis
Location: Northern Europe

Overview

Prologis manage of a number of industrial unit assets in Northern Europe and this case study focuses on a particular industrial unit and the measures implemented following the outbreak of COVID-19.

In normal operating times, the warehouse would rely on external workforces to help with loading and unloading of stock to optimise the overall operation of the unit.

Key Infection Resilience Measures

The following measures were taken to minimise large outbreaks from occurring and to ensure that the warehouse could continue to operate:

- External workforces were not allowed to mix and assist permanent employees with loading and unloading of items to minimise the risk of transmission of COVID-19 between the groups which could have resulted in a large outbreak leading to closure of industrial unit.
- Measures were made to limit exposure of internal staff through grouping systems to reduce chances of transmission, despite this resulting in a reduction of efficiency and an overall increase in the total production line time. `

Decisions were made by the client to minimise the disruption to the overall production line, even if that meant that measures led to slight inefficiencies.

INDUSTRIAL BUILDINGS - CASE STUDY

UNNAMED DATA CENTRE

Name: Unnamed Data Centre
Client: Confidential
Location: Benelux Region Central Europe

Overview

The project site is a large-scale data centre campus complete with four existing data centres on the campus, 4 operational buildings completed and 1 building in construction.

COVID-19 transmission mitigation measures are instructed by head office in the US for existing buildings (including the 1 in project handover phase). For the fifth building, the construction phase data centre, COVID-19 mitigation measures were managed by the General Contractor with input from the client. These policies are to ensure operation and to protect staff from the COVID-19 virus. Responsibility for the incorporation of infection resilience mitigation measures lay with individuals, data centre employees and construction site management.

Management attitudes on the client slide (four operational data centres) was for strict adherence to all mitigation measures. For the construction site, first-hand account detailed the local authorities twice reviewing COVID-19 mitigation policies as breaches of these measures were reported. The resulting action of this was the local authorities shutting down the construction site until COVID-19 transmission mitigation measures were addressed. There was a low compliance and enforcement from individuals and management.

In the operational data centre buildings, the considerations for COVID-19 mitigation measures were centred around maintaining operation, i.e. ensuring critical system workers did not catch or transmit COVID-19 at work. In particular, the operations and facility management (Ops & FM) team for the data centre are a lean team and are an example of critical operations employees.

For the construction site, the consideration for COVID-19 was to mitigate cost and schedule implications from worker illness relating to COVID-19.

Key Infection Resilience Measures

Measure	Perceived Success of Measure
Social distancing • 2m social distancing is mandated • One-way systems were used	The 4 data centre operational buildings are sparsely occupied, thus social distancing was an easy and effective measure to incorporate. For the construction site, one-way systems were used throughout the site to encourage the spacing of workers. In addition, technology such as Google Glasses was used to reduce the amount of specialised inspection staff onsite at any one time. The use of this technology meant that remote inspections could take place.
Increased cleaning & designated cleaning teams Cleaning staff were managed such that there are two dedicated cleaning teams: • 1 for Ops & FM areas • 1 for construction crew areas	The success of increased cleaning can be measured under two criteria: • **Felt confidence in space safety:** The designated cleaning crews provided a sense of safety for staff that cross contamination between construction crew and data centre Ops & FM crew was being managed. • **COVID-19 case reduction:** COVID-19 case reduction data is not available at present.
Mask Wearing At the outset of the pandemic, data centre workers were instructed by the head office to wear masks at all times on site. Construction workers, as above, were required to wear masks. However, they were offered either mask and goggle PPE or a full face shield (due to visibility issues resulting from the mask and goggle wearing).	Adherence for FM & Ops crew was high to mask wearing, and strict enforcement was in place. In addition, adherence for construction crew was high due to client representatives enforcing mask wearing. Although enforcement was high, it was understood that it in certain instances it was challenging for workers to wear masks. For example, during hot summer conditions lone workers were not reprimanded for poor mask etiquette.
7 Day Purge of Spaces Spaces occupied by construction crew were left unoccupied by all people on site, to ensure the safety of the Ops & FM team.	This measure did not create a sense of safety among staff in both the construction and data centre operations. It was seen as being overly restrictive.
Increased Ventilation In both construction office settings, natural ventilation was encouraged, and windows were to remain open with increased space heating to mitigate the effects of decreased thermal comfort. For data centre operations there were no operable windows so no increased natural ventilation was introduced. Doors were not propped open for security risk reasons.	The effectiveness of constantly opened windows had mixed success. Occupants closed windows when spaces became too cold. This mitigated the success of the measure. This measure was seen as a short-term solution. Medium to long-term ventilation mitigation measures were not considered because of cost. Windows were closed when the noise level from the adjacent construction site impacted the workers in the office.

INDUSTRIAL BUILDINGS - CASE STUDY

PRECIOUS METAL REFINERY

Name: Precious Metal Refinery
Client: Confidential
Location: United Kingdom

Overview

The project site is a precious metal refinery with a large site footprint and 300–400 workers on site during full operation hours. The site remained fully operational during the entirety of the COVID-19 pandemic.

The shite contained multiple processes that include “clean rooms” and “dirty rooms” with large amounts of dust particulates. These rooms have high rates of ventilation to protect occupants, and to remove harmful particles from the air. Other processes relate to the specific procedures of treating previous metals in their native state. These include:

- Crushing spaces
- Sampling and analysis
- Offices spaces for administration works
- Canteens & worker welfare facilities

Workers in these spaces wore full PPE that was cleaned on site every night and new PPE is available for staff working in these areas.

Measures were chosen to ensure no shutdowns were seen for production. The measures were specifically chosen to ensure operation, with the by-product or outcome of protecting the health of workers.

Overall, management personnel incorporated these measures and required strict tolerances for adherence as shutdowns and delays in production would have been hugely costly for the client.

Key Infection Resilience Measures

Measure	Perceived Success of Measure
Social Bubbling Controlling the contacts of those working on site was used to reduce the amount of close contacts thus reducing transmission of COVID-19.	Bubbling was effective on site as the specialised process and worker density meant that numerous close contacts were minimised.
Mask Wearing / PPE	The use of PPE as a COVID-19 mitigation measure was successful because PPE was already in place to protect workers from inhalation of precious metal particles.
Canteen Management Canteens made all food-stuff free, to reduce the congregation of workers at their locker spaces. In addition, it aimed to reduce the risk of bringing in further contaminants.	This was a successful measure that did in fact encourage workers to eat at the canteen. This reduced congregation of workers at lockers.
Shift Management Shifts were managed to avoid the cross contamination of workers. Shift workers were unable to extend their shifts and work overtime.	Management implemented this measure effectively. It reduced close contacts of shift workers and made it easier to manage their access to welfare facilities as they left work.
Ventilation No guidance was provided on natural ventilation measures. However, air filters were installed in December 2021 and windows remained closed on the whole.	It was felt by staff that air filtration measures were incorporated too late into the pandemic.
One-Way Systems & Social Distancing In order to gain access to and exit from, the site, workers were required to pass through metal detectors. A one-way system was implemented to control the flow of people, and markers were drawn to indicate the 2m rule.	The management and implementation of the one way system was effective. Workers adhered to the one way and social distancing even during adverse weather conditions.

5.5 Community Buildings

5.5.1 SUMMARY

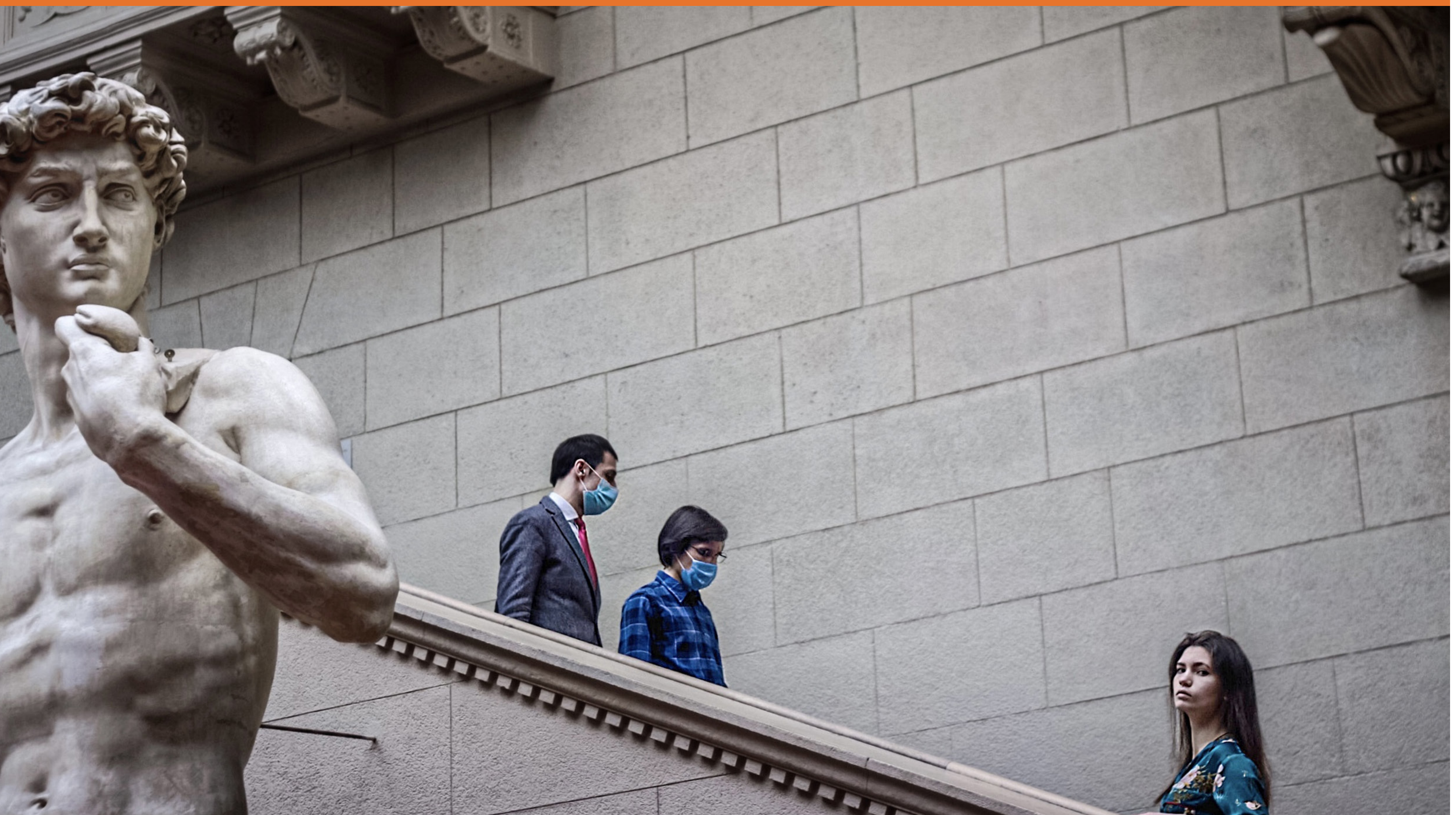
There is considerable awareness of infection resilience in the community sector with the literature predominantly covering mitigation measures for schools and education institution environments. The COVID-19 pandemic disrupted education provision at an unprecedented scale through extended school closures and abrupt changes to normal school operations. At the height of the pandemic, over 82% of total enrolled learners globally were impacted, and 151 countries imposed country-wide closures of schools[127]. The Responses to Educational Disruption Survey (REDS) international report by UNESCO included a study of the systematic and comparative picture at secondary education level in 11 countries spanning Africa, Asia, the Arab states, Europe and Latin America. It highlighted that more effort is needed to prepare schools and students for future disruptions, and uncovered a need for further research on identifying and developing tailored measures to aid them during disruptions[128]. Furthermore, as highlighted in the case studies in this section, governments globally have focused on operational guidance over building mitigation measures.

Infrastructure Type In this Section:

Local Community (Class F)

Specific Use Classes:

- F1 Learning and non-residential institutions including
  a. Provision of education
  b. Display of works of art
  c. Museums
  d. Public libraries or public reading rooms
  e. Public halls or exhibition halls
  f. Public worship or religious instruction
  g. Law courts
- F2 Local community



COMMUNITY BUILDINGS 5.5.2

Educational Institutions

Reshaping the building requirements for educational institutions including schools, higher education campuses and public libraries has a number of facets:

- Loss of instructional time delivered in a school setting during infection peaks requires hybrid working facilities in the classroom and for students at home.[129]
- Class sizes are a critical parameter for the opening of schools, with the current use of "bubbles" being one such tactic, and the operational implications of these cluster systems.[129]

In New South Wales, Australia an advice note was prepared to provide School Infrastructure NSW (SINSW) with a roadmap outlining a range of measures that need to be considered in preparing both primary and secondary schools for reopening in October 2021 after the initial phase of lockdown post COVID-19. The assessment was based on a typical 65m² classroom, with 26 people, and single sided natural ventilation (windows on one side) as the worst-case scenario, and focused on advice on air quality, in particular naturally ventilated classrooms. The study found that the recommended ventilations from WHO could be achieved in classrooms with conventional opening windows that are sized to the Building Code in Australia, along with mitigation measures to address smoke (wildfire) or excessive heat outside. It was advised that where natural ventilation cannot be provided, and if the department wishes to use the classroom, then mechanical ventilation systems should be installed. This could be via duct systems, wall mounted fans or pedestal fans placed adjacent to natural ventilation openings[130].

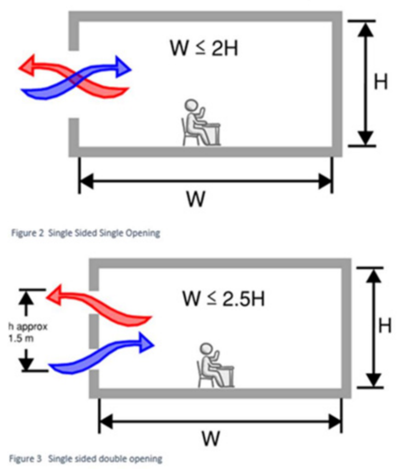
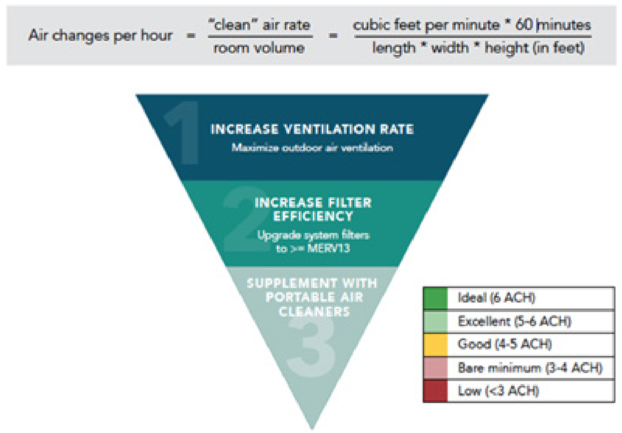


Figure 14: Single sided single and double opening air flow diagrams (above) from the SINSW Classroom Guidance Note



The Harvard T.H. Chan School of Public Health has launched a new programme, called Schools for Health, co-directed by Drs. Joseph Allen and Richard Siegrist, that emphasises higher expectations around health protection, promotion, and equity for a "health-first" era. They have produced a guidance document for K-12 schools in the US, "Risk Reduction Strategies for Reopening Schools[131]" detailing measures to be taken to safely reopen schools during the COVID-19 pandemic. The recommended measures are shown in Table 5.

Other examples from around the globe show similar trends in recommendations, with the provincial government of Ontario requiring children and staff to remaining separated in cohorts of ten. Similarly, schools in Denmark operate in "protective bubbles", with students being sectioned off into small groups of twelve students. In Japan, rather than bubbles in the schools, students attend school on alternate days to limit mixing, and enable social distancing.[132]

MEASURES RECOMMENDED FOR K-12 SCHOOLS IN US IN SCHOOLS FOR HEALTH GUIDANCE

Increase outdoor air ventilation
- Bring in more fresh outdoor air

Filter indoor air
- Increase the level of the air filter to MERV 13 or higher on recirculated air
- Inspect filters to make sure they are installed and fit correctly
- Check that sufficient airflow can be maintained across the filter
- Maintain and change filters based on manufacturer's recommendation

Supplement with portable air cleaners
- Supplement ventilation and filtration with air cleaning devices
- Select portable air cleaners with HEPA filters
- Size devices carefully based on the size of the room

Consider advanced air quality techniques
- Verify ventilation and filtration performance
- Attempt to maintain indoor relative humidity between 40-60%
- Consider advanced air cleaning with ultraviolet germicidal irradiation (UGVI)

Use plexiglass as physical barrier
- Install plexiglass shielding in select areas with fixed interactions (e.g., reception desk, cafeteria checkout)
- Check the air mixing and interzonal air flows in indoor environments to ensure the plexiglass does not alter ventilation in some areas

Install no-contact infrastructure
- Adjust existing infrastructure to make it touchless
- Install touchless technology for dispensers of hand soap, hand sanitiser, and paper towels

Keep surfaces clean
- Adjust existing infrastructure to make it touchless
- Install touchless technology for dispensers of hand soap, hand sanitiser, and paper towels

Focus on bathroom hygiene
- Keep bathroom doors and windows closed and run any exhaust fans at all times
- Install lids on all toilet seats, if possible, and keep the lids closed during flushing
- Stagger bathroom use

Table 5: Single sided single and double opening air flow diagrams (above) from the SINSW Classroom Guidance Note

POTENTIAL MEASURES - EDUCATIONAL INSTITUTIONS

Short-term

- Stagger arrival classes, breaks and attendance to reduce mixing between year groups; introduce one-way systems, "bubbles" and the use of masks within the classroom.[(2)]
- Improve layout to provide a suitable radius around all occupiable seats so students and teachers can effectively socially distance in the classroom.[133]
- Designate space for sanitising and hand washing areas throughout, particularly at entry points into building and classrooms.[133]

Medium-term

- Develop "door-free" buildings and facilities with shared "learning streets" that are wider and provide better air flow instead of corridors.[(2)]
- Introduce CO_2 monitors and improvements to air ventilation systems.[131]
- Train teachers and staff to establish procedures for when staff or students become unwell, conduct risk assessments and take appropriate action to support them when needed.[131]
- Provide covered outdoor areas so that break times are not limited to being indoors if it is raining.[(2)]

Long-term

- Increase the space allocated for recreation, exercise spaces and outdoor learning provisions.[133,(2)]
- Provide learning spaces that are designed for hybrid digital and in person learning when some students are isolating, and others are in the classroom with digital enabled spaces that allow students in both formats to learn effectively.[(2)]
- Consider building layout to avoid "dead end" circulation spaces and increase the flexibility and adaptability of spaces to accommodate for multiple functions[91].

This section references research using data from, Australia, UK, Denmark, Singapore, Netherlands and USA

COMMUNITY BUILDINGS 5.5.3

Museums

A shift in the arrangement of museums is necessary to promote safe and comfortable exhibition spaces. Key elements include:

- A clear benefit must be presented to attendees regarding what will be gained in person against what could be experienced online.
- Precaution and emergency methods must enable museums to remain economically viable.
- The air quality management within museums (humidity and temperature) is often highly controlled to protect the displayed items. Ths will likely override any priorities on infection resilience.

POTENTIAL MEASURES - MUSEUMS

Short-term	Medium-term	Long-term
• Introduce precautionary and preparation methods for the future with temperature screening, hand sanitisers, regulation of one-way flows, enforcing distancing and avoiding big groups.[134]	• Shift patterns of staff, extending opening hours to attendees to reduce capacity in exhibitions paired against revenue implications.[135]	• Develop infrastructure to support digital and hybrid online exhibitions.[135]

This section references research using data from a global survey with respondents from Europe, North America, LAC, Arab countries, Africa, Asia, and the Pacific.

COMMUNITY BUILDINGS 5.5.4

Place and Community Spaces

Place and community spaces play a large role for many individuals, which may include places of worship and local community centres. Considerations include:

- Spaces support a sense of community aimed at increasing social interaction whilst providing a safe environment for all.
- These can be important pieces of infrastructure for many who rely on these spaces as a lifeline or support for religious, mental, and physical health reasons.
- Visual connection is as important as physical connection based upon the recommendations of the HAPPI report and allows users to feel connected even when they cannot interact physically. It is important to be mindful of designing in connection for more vulnerable residents.
- Many places of worship are in very old buildings with limited capacity to retrofit or start again for future design practices.

POTENTIAL MEASURES - COMMUNITY SPACES

Short-term	Medium-term	Long-term
• Stagger opening times and increase the number of services to maintain services through infection peaks.[136]	• Promote flexible units and shared assets.[136]	• Expand community spaces into the outdoors, via promoting gardening and biodiversity clubs to encourage individuals to come together in outdoor environments.[136]

This section references research using data including case studies from Denmark, Netherlands, Germany, Switzerland, Sweden and the UK.

COMMUNITY BUILDINGS - CASE STUDY

VENTILATION AS AN INFECTION RESILIENCE MEASURE IN EDUCATIONAL SPACES – SOUTHWESTERN EUROPE[137]

Name: Ventilation as an Infection Resilience Measure in Educational Spaces – Southwestern Europe

Client: -

Location: Portugal and Spain

Overview

A study was conducted on infection resilience through varying ventilation configurations in educational spaces in Portugal and Spain. The Azurem Campus (Guimaraes, Portugal) and the Fuentenueva Campus (Granada, Spain) were chosen to be a representative sample of teaching spaces in university buildings.

In a post-pandemic world, greater attention is being given to infection resilient building design and, specifically, the need for good indoor air quality in public buildings – particularly those in which occupants spend a long time indoors, such as educational buildings. Inadequate ventilation in these spaces can lead to an increased risk of the spread of airborne viruses, such as COVID-19. During the pandemic, many educational buildings in Europe were closed to reduce the risk of infection. Since reopening, mitigation measures in infection risk have been implemented through better building and spatial management – such as addressing ventilation rates.

Natural ventilation is the predominant ventilation strategy in educational buildings in Europe. However, the study also considers the merit of mechanical ventilation systems. Ventilation rate was studied in various configurations (all windows, one door, two doors, closed spaces) using the CO_2 tracer gas decay method. The probability of infection risk was calculated using the Wells-Riley equation. The study was conducted between March and July 2021. Measures were taken after 2 hour durations, as this is the average time spent in the lecture spaces at both universities.

Key Infection Resilience Measures

Natural ventilation measures – The study found that natural ventilation measures were the most effective ventilation strategy for infection resilience, in comparison with mechanical ventilation systems.

Cross-natural ventilation configuration – The most effective ventilation configuration for infection control is cross-natural ventilation (i.e., multiple windows and doors open on different sides of the room). This configuration was found to be more effective than single-ventilation configurations (such as a single door open).

Improved mechanical ventilation systems – Recommendations were made for adjustments to the ventilation rates of mechanical ventilation systems when indoor educational spaces are retrofitted for improved infection control.

Installation of CO_2 sensors – CO_2 concentration was found to be an indicator of effective ventilation. The use of automatic sensors can be effective in addressing infection resilience in indoor environments – when alerted to inadequate ventilation rates, action can be taken immediately (such as opening windows or doors). A monitoring system is especially relevant in spaces which rely on natural or hybrid ventilation systems, in which the ventilation control requires manual action from occupants (i.e., opening windows or doors), as opposed to being mechanically ventilated.

Recognising exacerbating/interrelated factors in infection risk in indoor educational spaces – It is important to recognise that the correlation between ventilation rate and risk of infection is closely linked to many interacting factors within the indoor educational space. For example, the study found that human factors such as high voice volume, physical activity, lack of well-fitting masks, occupancy numbers, lack of social distancing, and exposure time can all exacerbate the risk of infection. Furthermore, pre-established physical environment factors should also be recognised such as the size of the original room design. Ventilation measures need to be considered in conjunction with these other factors.

Importance of protocols and legislation – The study emphasises the importance of clear protocols, standards and legislation on ventilation rates to ensure infection control in indoor spaces. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and the American Society of Heating, Ventilating, and Air-Conditioning Engineers (ASHRAE) published recommended ventilation control measures after recognising the potential for indoor airborne hazards. The World Health Organisation also recommended stated measures for infection control, including effective ventilation by frequently opening windows and doors. The clarity provided by protocols and legislation is important to ensure infection control through implemented ventilation configurations.

COMMUNITY BUILDINGS - CASE STUDY

COMMUNITY BUILDINGS CASE STUDY: EDUCATIONAL BUILDING IN INDONESIA

Name: Institut Teknologi Sumatera (ITERA)[138]

Client: -

Location: South Lampung, Indonesia

Overview

Research was undertaken to evaluate the impact of adapting to the COVID-19 Pandemic on a lecture building of an educational facility in Indonesia.

The proposed design was evaluated for thermal comfort, which is important for the leaning outcomes of the facility, and prevention of disease transmission, and a new floor layout proposed.

Key Infection Resilience Measures

The layout was configured to include an additional corridor on the outside face of the façade with the highest heat gain. This enabled a new one way system to be implemented to reduce social interactions in corridors and simultaneously reduce classroom temperatures.

This study notes that the redesign has sacrificed daylight in a number of classrooms for better circulation and thermal comfort. Further research would be required over a longer period to understand any additional implications of this change on learning outcomes.

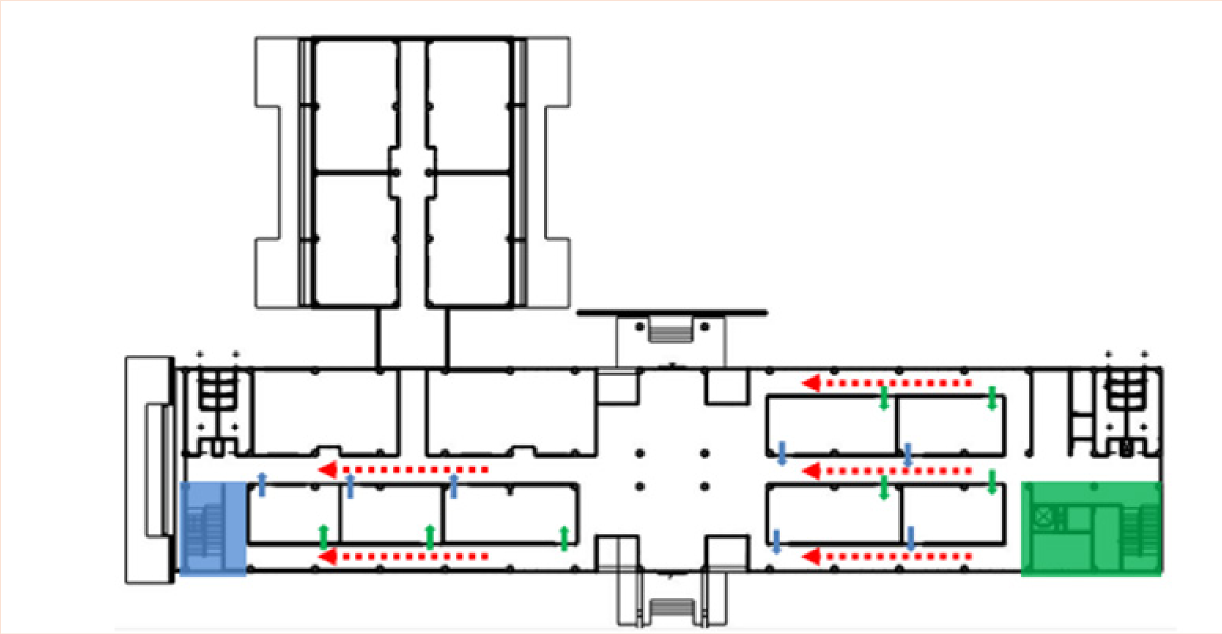


Figure 15: One-way system configuration for layout of educational facility[138]

5.6 Residential Buildings

5.6.1 SUMMARY

The literature review revealed that there has been adequate thinking around the idea of infection resilience in residential spaces, particularly in hotels, hostels, and privately and publicly managed high-rise residential blocks where there is a building operator or owner who is responsible for providing a service to the tenant or guest. There is less supporting literature for specific mitigation measures for single dwelling houses or houses in multiple occupation, and published guidance for infection resilience tends to look at mitigation measures on an urban design and planning scale rather than an individual building scale.

Humans become solely reliant on their homes when isolating with an infectious disease, and this forces the home to take on an increase in the number of functions it is meant to fulfil, including functioning as a workspace, for recreation and for exercise.

The requirement for adaptability in residential spaces is crucial so that mitigating measures can react to emerging infectious disease threats and provide the necessary functions to its inhabitants at short notice and for prolonged periods of time if necessary.

Infrastructure Type In this Section:

Residential (Class C)

Specific Use Classes:

- C1 Hotels
- C1 Hotels
- C2 Residential institutions
- C2A Secure residential institution
- C3 Dwelling houses
- C4 Houses in multiple occupation

RESIDENTIAL BUILDINGS 5.6.2

Infection Prevention and Control Measures in Hospitals

Learnings for infection prevention and control can be taken from best design practice for hospitals and translated into measures which are applicable in the wider built environment. It should be acknowledged that some of the measures implemented in hospitals are very costly and/or energy intensive and may only be applicable in environments where it is known that infected persons are contained.

Lessons learnt in hospital buildings:

- Hospital buildings must be designed to balance and maintain code required air changes in terms of both total air and ventilation air changes.[2]
- Hospitals have facilities staff who are aware of the filter loading and responsible for maintaining and monitoring filters in the building.[2]
- Hospitals track temperature and humidity in sensitive rooms due to licensing requirements.[2]

POTENTIAL MEASURES THAT COULD BE APPROPRIATE IN OTHER HEALTHCARE BUILDINGS INCLUDE:

- Positive pressurisation and how this impacts on other pressurised spaces in other building types such as stairways[20]
- Implications from red/green infection zones for quarantine spaces within other building types[139]
- Use of UV sterilisation of equipment and surfaces[20]
- Use of building details which are easy to clean such as curved floor to wall interfaces instead of traditional skirting boards, which reduces crevices and corners which can harbour pathogens.[140]

RESIDENTIAL BUILDINGS 5.6.3

Increase of Space Functions

In a pandemic situation, a house must adapt so that it can facilitate all activities that were previously carried out outside of the home, with these spaces taking on an increase of functions.[141]

- Previously houses were largely used a place to rest, but now they serve as our offices, play spaces, schooling spaces, place for sports and quarantine.[141]
- Trend and preferences for open-plan living may override an infection resilience perspective for where more separated living would limit transmission of aerosols (for infection) and sound (for working).[141]

POTENTIAL MEASURES - INCREASE OF FUNCTIONS

Short-term	Medium-term	Long-term
• Set up temporary workspaces such as fold away desks and collapsible dining tables.[2]	• Add of partitions in rooms to compartmentalise the home for different space functions.[141]	• Widen doorways and corridors to enable physical distancing.[141] • Set new home quality standards that have outdoor design priorities, and multipurpose rooms that can adjust to the required function.[141]

This section references research using data from Japan, the UK, the USA, Italy and Indonesia.

RESIDENTIAL BUILDINGS 5.6.4

Isolation Spaces

Residential buildings must also adapt into isolation spaces during lockdowns, or act as quarantine for infected people.

- To reduce transmission of diseases between household members, good ventilation and air circulation are key throughout residential buildings.[141]
- Use of natural light and materials, outside access and good sanitation are key to occupants who may need to isolate in rooms separate to the rest of their household.[141]

POTENTIAL MEASURES - ISOLATION SPACES

Short-term	Medium-term	Long-term
• Replace home materials and furniture with hygienic and anti-bacterial materials that can be easily cleaned (i.e. carpets, rugs, fabric sofas).[141]	• Install hands-free door openings.[141]	• Widen doorways and corridors to enable physical distancing between occupants.[141] • Incorporate an isolation room that must be facilitated with in-room bathrooms and has access to the outdoors to get access to sunlight.[141] • Introduce a requirement for a sanitation room where one can clean themselves before entering the home, a temporary stop before goods from online food and grocery apps are brought into the house to prevent infection.[141]

This section references research using data from the USA, Italy and Indonesia.

RESIDENTIAL BUILDINGS 5.6.5

High-Rise Blocks

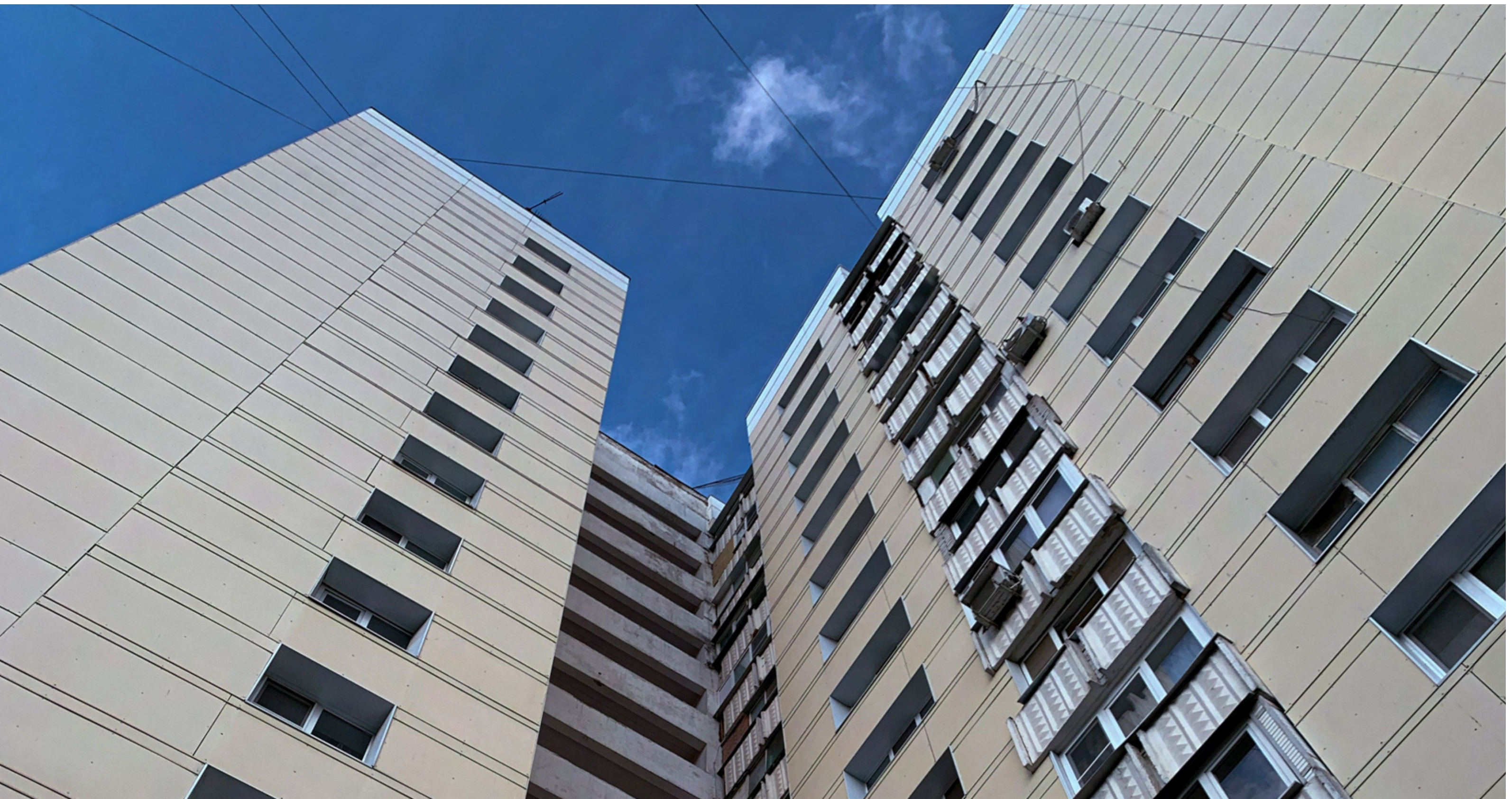
High-rise blocks provide an environment for epidemic transmission as they have shared entrances, indoor areas, hallways stairs and elevators as opposed to low-rise buildings which have separated ground floor access and an outside pedestrian walkway.[90]

- Urban residents spend a larger portion of their time indoors and thus their health is directly impacted by the space they inhabit[90]
- This is often linked to lack of outdoor access during periods of quarantine[90]

POTENTIAL MEASURES - HIGH-RISE BLOCKS

Short-term	Medium-term	Long-term
• Increase frequency and strategy of cleaning and sanitising routes with high-traffic and high-touch points.[90]	• Consider methods to retrofit existing high-rise blocks that may alter behaviours and reduce chance of transmission in shared spaces, with hands-free doors, contactless lift buttons and data information available to residents for infection in the building.	• Consider provision of multiple flights of stairs and more lifts to allow for deep cleaning of shared spaces (which can alternatively be deep cleaned whilst the other is in use) and one-way systems to increase overall operational flexibility, thus reducing the number of interactions between residents.

This section references research using data from USA, West Africa, South Africa and Singapore.



RESIDENTIAL BUILDINGS 5.6.6

Inequality Between Neighbourhoods and Homes

There is an inequality between neighbourhoods and homes as not all individuals have the same opportunity to isolate from others, socially distance, have access to green spaces within walking distance, access to natural materials, and access to outside space within their home[142]. Access to safe, flexible and adequate green space for all becomes more than a 'nice to have' in the context of a pandemic situation.

POTENTIAL MEASURES - INEQUALITY BETWEEN HOMES

Short-term (operational changes)	Medium-term	Long-term
• Review and introduce temporary measures if tenants or occupants of buildings do not have the ability to isolate from others (i.e. social housing tenants put up in additional housing if there is not space for them to effectively self-isolate or socially distance).	• Retrofit existing residential developments of homes to consider increase of green space, wider corridors, and doorways, increasing size of apartments or homes where appropriate and separation of families or households.	• Implement plans and standards that define a minimum requirement for space, access to outdoor space and daylight for all residential buildings.

This section references research using data from the UK.

RESIDENTIAL BUILDINGS - CASE STUDY

DESIGNING SENIOR HOUSING FOR SAFE INTERACTION[143]

Name: Designing Senior Housing for Safe Interaction

Client: -

Location: Eastern United States

Overview

A study produced by MASS Design Group endeavoured to determine best practice in designing senior housing for safe interaction, and discouraging social isolation. Early on in the COVID-19 pandemic, it became clear that the virus was disproportionately affecting older adults. Statistics show that 38% of deaths in the US are from people living in nursing homes or assisted living centres.

The case study selected a multi-family affordable housing project for older adults to apply guidelines for infection control. The study assumes that some basic services are provided to residents, but most care is delivered through health aides or other vendors. There is a breakdown of each zone from the public to private spectrum and identification of specific applications of each of the principles.

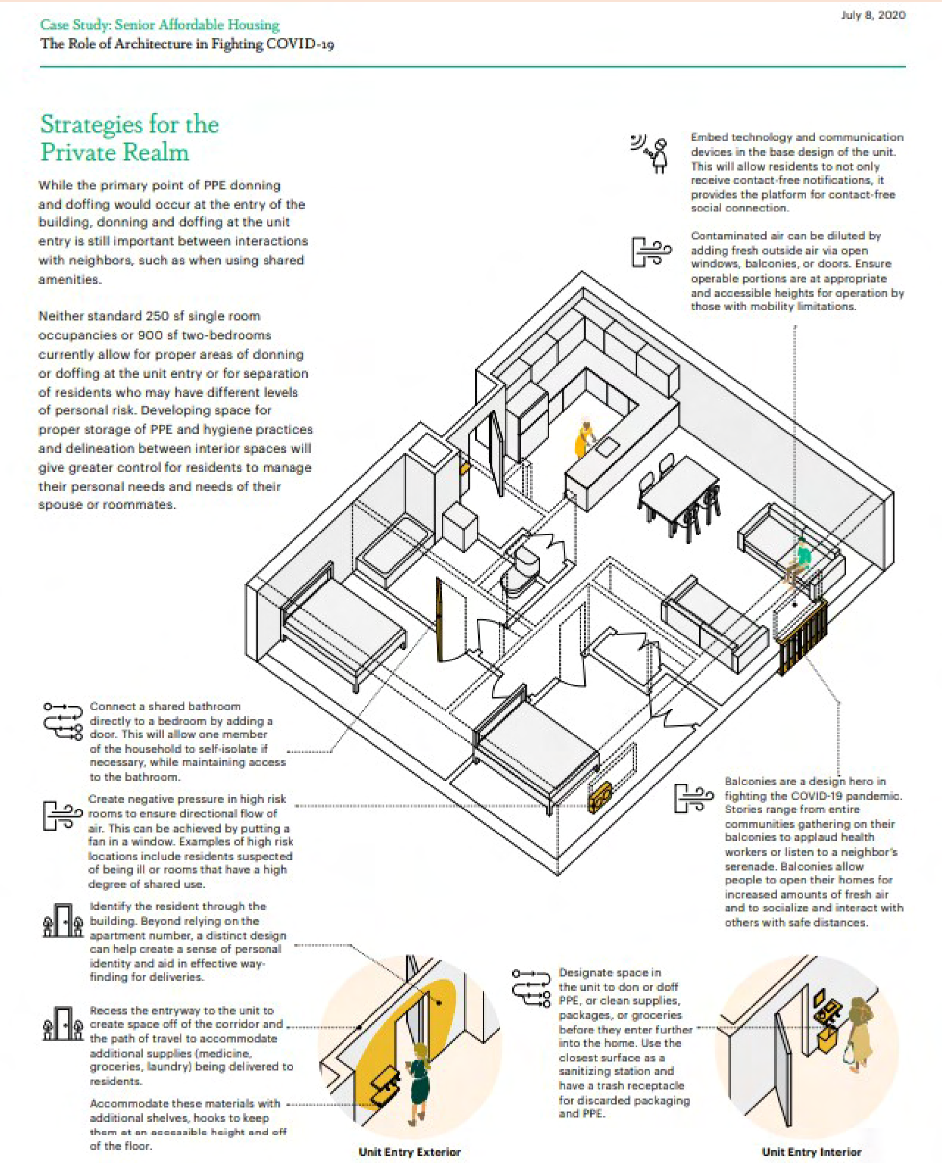


Figure 16: Case study strategies for the private realm of a residential home [143]

Key Infection Resilience Measures

Focusing on strategies for the Semi-Public Realm:

- Reduce or eliminate use of buttons such as through “destination dispatching” for elevator functions, where a key card or fob indicate destination.
- Create buffer zones where people may be queuing for shared bathrooms, mailboxes or elevators, to allow for distancing.
- Adapt space where possible to accommodate additional services and provide basic amenities such as small grocer or health screening stations within the building.

Focusing on strategies for the Semi-Private Realm (based on the example of a floor with a corridor in the middle of the floor plan, with flat units coming off both sides):

- Provide access to the outdoors on each floor to help residents access nature, fresh air and sunlight without having to take the elevator or stairs.
- Claim additional outdoor space as necessary design space. Opportunities for exercise are especially important, as residents have limited time outside. Walking loops make it easy for residents to use without getting lost or ending up too far from their units.
- Use furniture that can be appropriately spaced for social distancing, with upholstery that is easily sanitised.
- Insert common spaces at each floor to allow people to gather and participate in community programming (shared kitchen, living, laundry) which can help reduce social isolation, while still reducing degree of exposure and allowing for easy contact tracing where necessary.
- Widen hallways where possible to increase circulation space to operate as interior public realm (i.e. hallways, corridors and lifts).
- If the hallway is less than 2m wide, introduce pause points so residents can have room to safely pass one another in long corridors or circulatory paths.
- Bring amenities closer to residential units to allow residents to stay closer to home. This also reduces the risk of lengthy queues where residents may need to stand for periods of time.

Focusing on strategies for the Private Realm:

- Embed technology and communication devices in the base design of the unit to allow residents to not only receive contact-free notifications, but provides the platform for contact-free social connection.
- Provide openable windows, balconies or doors for fresh outside air. Ensure operable portions are at appropriate and accessible heights for operation by those with mobility limitations.
- Provide balconies to allow people to open their homes for increased amounts of fresh air and to socialise and interact with others at a safe distance.
- Connect a shared bathroom directly to a bedroom by adding a door from the bedroom to allow one member of the household to self-isolate, if necessary, while maintaining access to the bathroom.
- Design unit entry interior and exterior to accommodate extra space off the corridor or in the unit, for additional supplies (medicine, groceries, laundry) being delivered to residents, and to clean packages, groceries and don or doff PPE with the provision of additional shelves or hooks to keep items at an accessible height and off of the floor.

5.7 Transport

5.7.1 SUMMARY

Transport presents some unique challenges when it comes to planning for infection resilience. Much of the infrastructure and operations are seen as critical to the functioning of towns and cities, which means they need to remain operational throughout heightened periods of infection to provide transportation to key workers such as medical staff.

The inherent nature of public transport means that it is designed to carry a large volume of people, resulting in greater opportunities for the spread of infection at key points throughout the journey, whether it is dwelling on concourses or in waiting areas, funnelling through gate lines or security checks, or travelling within high-capacity vehicles. Furthermore, staff are critical to maintaining the operation of transport infrastructure and measures preventing the spread of infection between passengers and staff are important to ensure operational continuity.

While the role of transport in spreading infection is well documented, the research paints a much more mixed picture of infection transmission in transport systems themselves. A 2016 study noted that, at the time, the overall scientific literature on airborne infection transmission in various transport hubs and means was "limited"[144]. A recent collation of evidence by the UK SAGE Environmental and Modelling Group during the COVID-19 pandemic, however, notes that there "there is a good body of evidence to associate public transport with transmission of respiratory infections from a mixture of epidemiological studies and modelling studies[145]." This suggests that over the past 5 years, research and studies on the topic have become more widespread. However, the translation of this research into regulation around the world has been mixed. Prior to COVID-19, European guidelines determined air quality by CO_2 levels only, and did not refer specifically to bacteria counts, viruses or fungi. However, in Asia the picture is different. Since 2014, indoor air quality guidelines for public transport have been enforced in Korea, which includes thresholds for total airborne bacteria[146]. Guidance had also been produced prior to COVID-19 in Singapore, Taiwan and Hong Kong, the latter leading to air quality on transportation being monitored[147].

At multi-modal transport interchanges, collaboration between different modal operators is critical to ensuring consistency of message to the passenger, and that processes for infection mitigation are aligned.[148]

While many transport structures, such as railway stations and bus stops, can be well ventilated and often open to air, enclosed buildings, the vehicles themselves, and subsurface transport, do require special consideration.

Infrastructure Type In this Section:

Transport & Transport Related Development

Specific Use Classes:

- 8 (A) Railway or light railway
- 8 (B to C) Dock, pier, harbour, water transport, canal, inland navigation undertakings
- 8 (F to N) Development surrounding airport
- 9 (A to E) Roads, Highways, Toll roads, Tramway and road transport undertakings

TRANSPORT 5.7.2

Critical Infrastructure

Public transport is a key part of critical infrastructure, ensuring that critical activities can continue in a pandemic, such as transporting people to hospitals, work, and delivery systems.

- Specific guidance is required for terminal and public transport carts that specify minimum guidance for safe spaces, including social distancing requirements.
- Recommendations include shifting modes towards walking and cycling, or encouraging remote working, in order to reduce demand on public transport.[149]
- Different strategies and requirements are needed for keeping operational staff and passengers safe.[150]

POTENTIAL MEASURES - TRANSPORT CRITICAL INFRASTRUCTURE

Short-term	Medium-term	Long-term
• Introduce contactless temperature screening, obstacles to maintain social distance, and temporary barriers which restrict the usage of seats to alternate places (checkerboard). Reduce contact transmission through the provision of free hand sanitiser, regular clearing of buttons, help points and machines, automatically opening doors and gate lines, and encouraging contactless payment.[151] • Use middle-door boarding on buses and other carts to keep drivers safe during the pandemic.[151] • Increase cleaning of shared mobility forms such as hire bikes, e-scooters and car club vehicles, and encourage better hygiene behaviour from users. • Use existing systems to increase rates of airflow including running existing HVAC at higher rates of flow and opening windows (especially on rolling stock and vehicles).[152]	• Close roads to allow for improved pedestrian and bicycle infrastructure, and create emergency cycle lanes for key workers to travel safely to work.[153] • Designate 'slow streets' to provide more outdoor space for communities.[153] • Install protective screens to limit particulate transfer between passengers and operational staff, or between operational staff members.[152] • Introduce outdoor waiting areas to encourage fresh air dwelling with a potential reduction in interior seating.	• Incorporate large waiting areas in future public transport terminals. • Provide more spacious vehicles and longer trains to allow for greater flexibility. • Use materials with antibacterial and antiviral properties in the most highly trafficked areas or at key touchpoints such as buttons, steering wheels and handlebars.[108]

This section references research using data from the UK, Belgium, USA and New Zealand.

TRANSPORT 5.7.3

Information Management Systems

Improve information management systems are needed to improve transit accessibility for all citizens and to decrease traffic congestion.

POTENTIAL MEASURES - INFORMATION MANAGEMENT SYSTEMS

Short-term

- Adapt operational strategies in stations to include socially distanced queuing/seating, phased train boarding and alighting, one-way systems, use of traffic lights/'Emergency Do Not Enter' signage to stop people from entering areas liable to congestion, and regular cleaning of public areas and train interiors.[154]

Medium-term

- Provide greater levels of information on journey planning apps, such as levels of crowding in buildings and vehicles, allowing users to plan their journey based on exposure risk.[148]

Long-term

- Utilise live crowdflow modelling to identify which stations may be experiencing crowding above a safe, social distance threshold, linking to dynamic wayfinding and journey planning.[155]
- Incorporate Mobility as a Service allowing people to seamlessly plan their door-to-door journeys in line with their specific user needs, taking into account a range of preferences including exposure risk.[156]
- Adopt new technology to allow for gateless revenue protection and travel validation, as well as more detailed journey information allowing for reduced or off premises dwelling.[155]
- Use automation, smart technology, and robots to reduce contact between operational staff and passengers.[157]

This section references research using data from Singapore, Nigeria, Brazil, Colombia, the UK, Europe and Hong Kong.

TRANSPORT 5.7.4

Legislation, Guidance and Standards

Continuous review of legislation, guidance and standards is required, considering the following:

- Risk to operations.
- Temporary infrastructure and alterations to existing infrastructure.
- Permanent changes to existing and new infrastructure.
- Clarification to determine the effectiveness of mandating certain behaviour e.g. mask wearing and breaching of social distancing rules.

POTENTIAL MEASURES - LEGISLATION, GUIDANCE AND STANDARDS

Short-term

- Mandate mask wearing as a condition of carriage, giving operators powers of enforcement.[154]
- Ensure industry-wide collaboration for consistency of approach.[152]

Medium-term

- Reconsider conditions of franchises and third-party tenants.[158]

Long-term

- Review existing legislation (e.g. H&S at Work Act) and how this may need to be adapted to protect employees and members of the public.
- Encourage infrastructure Owners and Managers (Network Rail) to update design and operational guidance.[152]

This section references research using data from Hong Kong, the UK and Japan.

TRANSPORT 5.7.5

Emergency Measures and Zones

Emergency measures and zones may be required where people can temporarily isolate in and be separated from the rest of the population.

- It is important to consider these spaces for cruises, and long-haul travel where the R rate may be significantly higher than in normal community settings.

POTENTIAL MEASURES - HUMIDITY CONTROL

Short-term (operational changes)	Medium-term	Long-term
• Repurpose existing spaces, on a temporary basis, as a 'sanitorium' where necessary (on cruise ships or long haul transport vessels).[108] • Restrict use of transport for critical journeys only.[154]	• Consider how existing public transport systems can be refitted to accommodate emergency zoning through the use of further partitions and compartmentalisation.[108]	• Design future public transport carts and vessels to consider emergency and isolation spacing and how this may impact passenger capacity and spacing (e.g. if someone on board a cruise ship contracts an infection, where are they quarantined and are there systems in place to be able to distance many people if the infection has already spread to some passengers?).[108]

This section references research using data from China and the UK.

TRANSPORT - CASE STUDY

LYNETTEHOLMEN METRO PEDESTRIAN PLANNING[159]

Name: Lynetteholmen Metro Pedestrian Planning
Client: Copenhagen Metro
Location: Copenhagen, Denmark

Overview

The study examined the impact social distancing has on the station and train capacity in the Copenhagen Metro, and assessed the impact of proposed intervention solutions intended to mitigate the effects of social distancing on capacity.

By using passenger simulation software (MassMotion), the team directed the client to assess various scenarios to compare situations, to present a broad range of possibilities using an automated simulation workplan. The results indicated the critical area of the station tends to be the platform area, particularly when considering the time spent in proximity (1m or less) to another passenger.

Key Infection Resilience Measures

The study highlighted the following list of measures that were communicated to the client based on the findings of pinch points and high traffic areas from the passenger simulation throughout the Copenhagen station:

- Increasing train frequency
- Increasing door time operation
- One-way doors on the trains (i.e. having defined 'boarding' doors and 'alighting' doors)
- Use of increased train carriage capacity (from three carriages to four carriages)
- Implementing defined waiting areas on the platform
- Using bi-directional escalator pairs (two escalators side by side that can be reversed in direction as necessary as is already used at numerous metro stations)
- A revised station layout, with a central intermediate landing and escalators down each side (similar to Gammel Strang station on Cityringen)
- A revised station layout with escalators at the platform ends

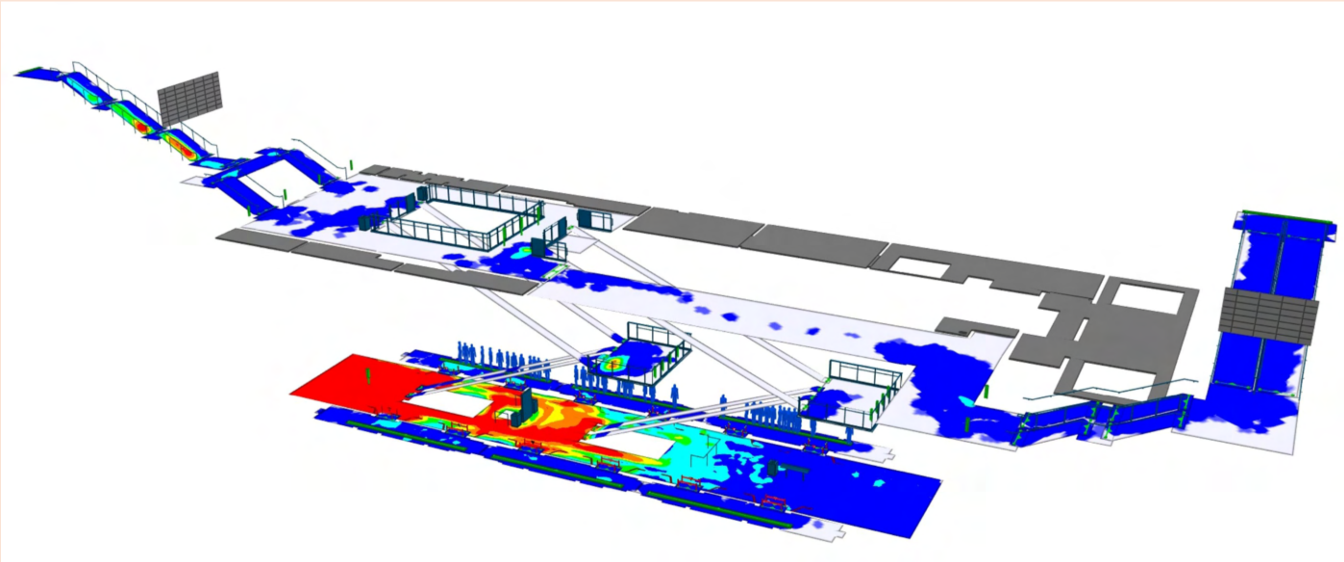


Figure 16: Pedestrian flow modelling of Lynetteholmen Metro in Copenhagen showing highly trafficked areas in red and low-trafficked areas in blue[159]

TRANSPORT - CASE STUDY

COVID-19 PUBLIC TRANSPORT MEASURES IN EAST ASIA[160]

Name: COVID-19 Public Transport Measures in East Asia
Client: -
Location: East Asia

Overview

Arup Hong Kong have been undertaking research to document a series of public transport measures that have been implemented for both operational interventions and design of facilities for a number of case studies across the region of East Asia.

Figure 17: Temperature scanning at Metro stations (above), mitigating measures for COVID-19 on public transport in East Asia locations (below)

Key Infection Resilience Measures

Operation Measures (see Figure 17)

Design of Facilities:

- Utilising new coating material technology for rolling stock services
- Use of self-cleaning technologies
  - Sterilising the escalator handrail with UV technology (Hong Kong MTR)
  - Sterilising empty carriages with UV light when trains turn around at the end of the line (New York Subway)
  - Use of mobile autonomous UV scanners that can kill the virus on surfaces and in the air (St. Pancras Station, London)
- Contactless 'wave' buttons on lifts using infrared technology (Hong Kong MTR)
- Advanced bus shelters with temperature-checking doors, ultraviolet disinfection lamps and air-conditioning systems to improve quality of air change rate (Seoul)
- Retrofitting window vents to provide improved air ventilation systems on buses (Hong Kong MTB)

Cities	Tokyo	Hong Kong	Singapore	Taipei	Shanghai	Beijing	Guangzhou
Operator/ Measure	JR-East	MTR	LTA	Metro	Metro	Bus	BRT
Requiring face masks	✓	✓	✓	✓	✓	✓	✓
Body Temperature, health code					✓		✓
Limiting ridership					✓	✓	
Adjust the service schedule	✓				✓		✓
Social distancing measures	✓			✓ (~ 3 ft)			
Modified or reduced fares to reduce touch points				✓			
Closing non-essential amenities				✓			
Frequent and more stringent cleaning protocols	✓	✓		✓		✓	✓

TRANSPORT - CASE STUDY

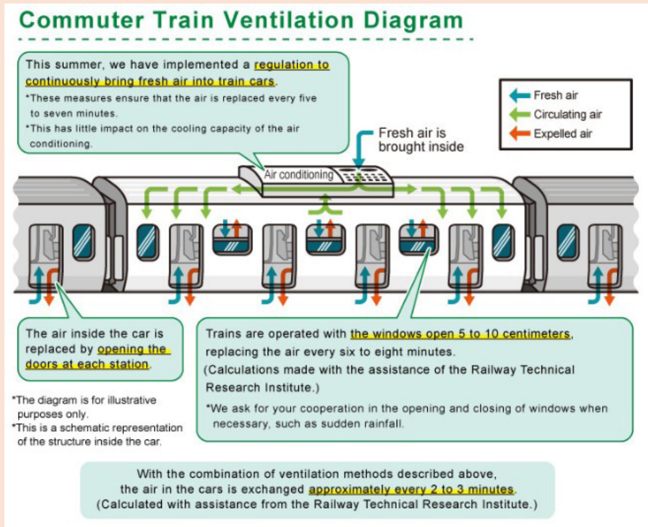
ALTERATION MEASURES FOR TRAIN CARS[161]

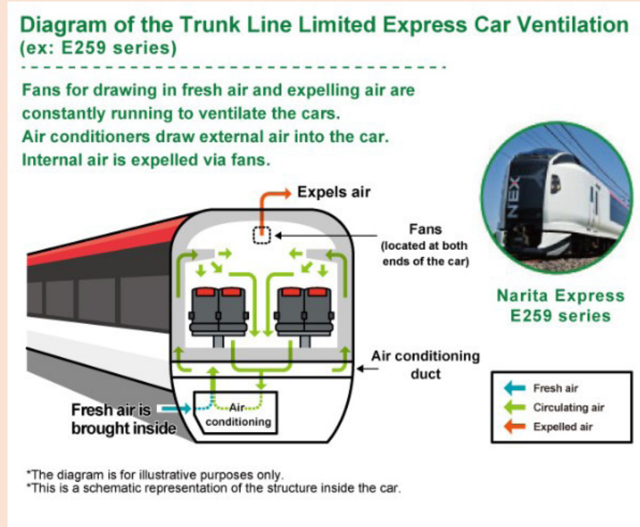
Name: Alteration Measures for Train Cars
Client: East Japan Railway Company
Location: Japan

Overview

JR East Group have implemented the following measures. These are based on government recommendations, such as the "Guideline for Railway Operators to Prevent the Spread of COVID-19" (Japanese only). Ventilation strategies for different rolling stock typologies were devised as shown in the following diagrams:

A 2021 study has evaluated the effectiveness of the improved ventilation measures for the Commuter Train (lefthand image), but data on the effectiveness of the other train types does not appear to be available at the time of writing. This study concluded that by implementing the measure, of opening the windows and turning on the AC ceiling units, the infection risk in the train may be reduced by 91-94%. The study notes that additional comparative research into filtration and other ventilation methods would be warranted.





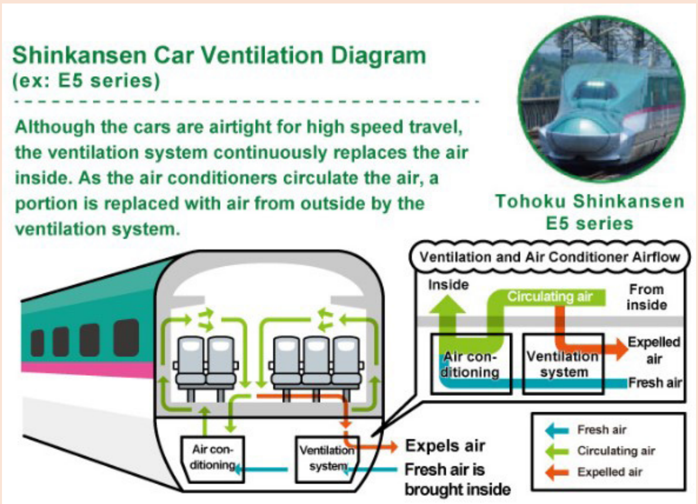


Figure 18: Alteration measures for train cars with ventilation diagrams

6. IMPLEMENTATION EXAMPLES

The following scenarios have been prepared to show how the combination of the principles and the interventions described in Section 5 might be employed, in order to demonstrate how the decision making regarding interventions to support infection resilience are influenced by the context.

They have been chosen to reflect a range of environments and contexts, each with different constraints, in order to illustrate how infection resilient design could be integrated, taking the approaches of “As low as Reasonably Practicable”, “Planning for Adaption” and “Integration within Broader Design Decision-Making.”

In order to explain the connection between context and intervention, each example focuses on only one infection threat. However, it is appreciated that in reality implementers may need to respond to more than one threat simultaneously, which may change the choice of interventions.

Example 1: SARS in a School

DESCRIPTION OF THE EXAMPLE AND KEY CONTEXTUAL ISSUES:

A large secondary school is planning improvements to their school and, as they are in a country with a previous outbreak of SARS, they would like to consider infection resilience within their refurbishment. The school is situated in a hot climate, affected by rising temperatures, and is located in a city-centre location. Some of the key issues which will influence their decision making are:

- The school is run by the local authority which allocates only a small amount for annual maintenance costs.
- Safeguarding has been an important factor for the Parent Teacher Association who have been lobbying for measures which improve security as well
- The school has an existing HVAC system which is only 5 years old, installed to comply with strict new regulations on energy usage which came into force at that time.

TRANSMISSION MECHANISMS

SARS is an airborne virus and can spread through small droplets of saliva in a similar way to the cold and influenza, and it can also be spread indirectly via surfaces that have been touched by someone who is infected with the virus[163]. Aerosol infection can lead to a higher viral load in the body, and therefore increasing air quality and rates of ventilation are crucial for preventing transmission[164]. SARS survives longest on plastic surfaces, in environments of 40% relative humidity and conversely SARS aerosol survival is at its lowest at 65% relative humidity[165]. There is evidence of SARS transmission from a study in Hong Kong that found SARS was caused by the dried-up bathroom floor drain, and stack effect of air movement into other bathrooms of the upper floors[166].

PRIORITISED BUILDING INTERVENTIONS WHICH RESPOND TO THESE TRANSMISSIONS WITH CONSIDERATION FOR THE SCHOOL CONTEXT, MIGHT INCLUDE:

- Install a filtration system within the existing HVAC system, selecting a system which has low disposables (filter medium) replacement costs, noting these two aspects may mean that a lower filtration standard is achieved than MERV 13.
- Install a humidity control system to maintain the RH between 40-80%, aiming for 65%.
- Install W-traps to reduce the need for maintenance to keep floor drains sealed by flushing with water regularly.
- Install handwashing facilities throughout the building (to include at entrances to classrooms).
- Do not include contact free door operation or operable windows within the upgrades to minimise risk to security.
- Design and run training for FM staff on use and maintenance requirements of the new elements of the system. Additionally, run awareness raising sessions with staff and the student body to further share design intent in terms of infection resilience.

Example 2: Norovirus in a Restaurant

DESCRIPTION OF THE EXAMPLE AND KEY CONTEXTUAL ISSUES:

A restaurant is fitting out a new location with a kitchen and seating area. They want to incorporate best practice for food and hygiene standards into the design as another site experienced an outbreak of Norovirus the previous year. Some of the key issues which will influence their decision making are:

- Currently there is only one entrance to the site and there is only one plumbing connection into the building.
- There is an increased demand on the kitchen to provide takeaway services for customers with a high turnover of delivery drivers.
- The restaurant no longer employs dedicated cleaning staff, but passes the responsibility for hygienic facilities to the restaurant staff.

TRANSMISSION MECHANISMS

Norovirus is the most common foodborne illness globally[167] and can be spread from person to person by consuming contaminated food or water. It can also be spread indirectly via surfaces that have been touched by someone who is infected with the virus, or through faecal-oral transmission. In addition, it can be spread through contaminated water, which can subsequently contaminate food during preparation[168]. In buildings, it is commonly spread through touching contaminated surfaces or objects, otherwise known as fomites. Studies using a tracer virus similar to norovirus have shown that contamination of just 1-2 commonly touched surfaces led to 40-60% of surfaces within the test areas becoming contaminated within 4 hours[169]. In the intervention phase of the study, cleaning personnel and employees were provided with QUATS (quaternary ammonium compounds) disinfectant wipes and instructed on proper use (use of at least once daily). The number of fomites on which the virus was detected was reduced by 80% or more, and the concentration of the virus reduced by 99% or more.

PRIORITISED BUILDING INTERVENTIONS WHICH RESPOND TO THESE TRANSMISSIONS WITH CONSIDERATION FOR THE RESTAURANT CONTEXT, MIGHT INCLUDE:

- Review restaurant layout to remove as much cross over between food preparation routes and customers, including creating new building egress points. Include a delivery services zone that may include a separate doorway or back entrance, with specific loading and unloading zones to reduce surface contacts between staff, customers and delivery.
- Install new plumbing to allow the layout to be planned so that the route to the bathrooms (for both staff and customers) does not intersect with food delivery or preparation and confirm that the incoming water supply is suitable for food preparation.
- Install more handwashing stations or facilities throughout the restaurant, specifically more handwashing stations in prominent locations in the kitchen space to promote regular handwashing.
- Create cleaning stations with designated rubber gloves and cleaning products which are registered "Antimicrobial Products Effective Against Norovirus"[170] for the staff who are rostered to maintain the facilities. Provide appropriate training on faecal-oral transmission routes and overall use of correct cleaning products.
- Put in place a cleaning regime for all surfaces with disinfecting wipes containing quaternary ammonium compounds (QUATS) that includes visible rotas displaying the frequency of cleaning to customers.
- Change common fomite locations (doorhandles, light switches, buttons and countertops) for installations with antimicrobial materials such as copper.
- Design the kitchen layout with specific preparation zones that separate uncooked and cooked foods including fruits and vegetables, shellfish and meat.

Example 3: COVID-19 in Transport Rolling Stock

DESCRIPTION OF THE EXAMPLE AND KEY CONTEXTUAL ISSUES:

A train operator for a rail service that runs into a large city in a temperate climate with low pollution levels is considering how they can upgrade their train carriages over a medium to long-term period to reduce the chance of transmission of COVID-19 and influenza between passengers on board their service. Some of the key issues which will influence their decision making include:

- There is low feasibility of social distancing between passengers at peak periods.
- The service will need to remain operational during peak seasons or epidemiological waves, so the consideration of the safety of passengers and train operator staff is essential.
- The existing ventilation system consists of no openable windows, and a mechanical ventilation system that recirculates air in the carriage.
- The rolling stock is of variable ages, with assets coming out of service and replaced on an ongoing basis rather than in large overhauls.

TRANSMISSION MECHANISMS

COVID-19 is a respiratory illness that can spread from an infected person's mouth or nose to another individual, through particles produced when the infected person coughs, sneezes, speaks and breathes. These particles range from larger respiratory droplets to smaller aerosols. In a train carriage, methods of transmission would include airborne transmission throughout the cart and droplet transmission between passengers in close proximity. Strong evidence was found for transmission of COVID-19 in domestic passengers from Wuhan travelling by train[171]. A 2021 study in Japan evaluated that by opening windows and turning on the air conditioning ceiling units, the infection risk in the train may be reduced by 91-94%[172].

PRIORITISED BUILDING INTERVENTIONS WHICH RESPOND TO THESE TRANSMISSIONS WITH CONSIDERATION FOR THE TRAIN CARRIAGE CONTEXT, MIGHT INCLUDE:

For retrofit of existing carriages

- As there is minimal pollution risk and generally clement weather, retrofit windows on all trains to allow them to be operable, to improve natural ventilation. At the same time, maintain rail safety standards by including cross bars to prevent accidents[173].
- Adjust existing mechanical system to maximise air change rates and provide training for operators on the approach and relation to infection control.
- Install contactless 'wave' buttons for operation of carriage doors.
- Develop smart technology to provide information on the levels of crowding on the service and communicate this to users via an information management system. This should provide capability for phased train boarding, one-way, and traffic light systems to indicate busyness of each carriage.
- Fit out with antibacterial surfaces and materials with antiviral properties for the key touchpoints including buttons, grab handles, and steering wheels on all trains

For new carriages

- When the rolling stock is next replaced, introduce more spacious train carts. Similarly, when stations are being upgraded, introduce longer platforms to allow longer trains to increase capacity.
- Install flexible seat fixtures and arrangements in the carriage, e.g. an arrangement of 4 chairs facing each other can be switched to 4 chairs all facing in the same direction if required in future peaks. Colour coding of chairs could also be used so that during infection peaks passengers are asked to only use a specified colour to implement social distancing.

Example 4: COVID-19 in a Meat Processing Plant (MPP)

DESCRIPTION OF THE EXAMPLE AND KEY CONTEXTUAL ISSUES:

The owner of several meat processing plants (MPPs) wishes to strengthen the resilience of the plants to protect their staff and ensure consistent production efficiency after they had experienced a particularly high incidence of COVID-19 outbreaks. Due to the economic impact of these outbreaks on the overall output of the MPPs, the owner wishes to implement these measures as soon as possible whilst reducing the impact on day-to-day operations. Some of the key issues which will influence their decision making are:

- The temperature and relative humidity of the MPPs must remain within the acceptable controlled environment for meat processing conditions.
- The number of staff and spatial configuration of the plant cannot be changed as this would disrupt the process line.
- The equipment in half of the MPPs has just been replaced, so the owner does not wish to change this, but the other half require a full equipment upgrade with opportunity to optimise for infection resilience.
- The plants cannot afford to be completely shut down at any point during the renovations, but they all have available space within the existing floor plate.

TRANSMISSION MECHANISMS

COVID-19 is a respiratory illness that can spread from an infected person's mouth or nose in small liquid particles when they cough, sneeze, speak, or breathe. These particles range from larger respiratory droplets to smaller aerosols. Workers in the meat and poultry industry are not exposed to COVID-19 through the meat products they handle. However, there is the potential for an increased risk of exposure to COVID-19 due to tasks that normally require close interaction between workers, such as processing lines and the rapid nature of the work[174]. The main transmission modes will include airborne transmission from recirculation in the mechanical ventilation system, and droplet transmission between workers in close proximity for prolonged periods of time[175].

PRIORITISED BUILDING INTERVENTIONS WHICH RESPOND TO THESE TRANSMISSION MECHANISMS IN THE MPP CONTEXT, MIGHT INCLUDE:

- Adjust the air temperature and humidity levels within the allowable controlled range in high-risk locations such as boning halls where aerosols build-up is likely due to chilled air being continuously circulated, while optimising for infection resilience (i.e. as high as possible without comprising food safety).
- For plants that have not yet been upgraded, amend specification of the replacement packing belts with belts that are wider than 1.5m to aid social distancing. For plants that have already had the equipment upgrade, adjust packaging set up so that face-to-face working is avoided by offsetting packing stations.
- Install filtration within the existing HVAC system, retrofitting them one hall at a time. Where possible, at the same time adjust the ducting to reduce recirculation between adjacent rooms.
- Install more handwashing stations or facilities in boot and washrooms, specifically more handwashing stations in prominent locations to promote regular handwashing. Provide training in infection prevention for both factory staff and the FM team .
- Build a lobby area by the delivery entrance to allow drivers to wait without interacting with plant staff and designate specific loading and unloading zones to reduce contact between delivery drivers, visitors and plant staff.

Example 5: Legionella in an Office Building

DESCRIPTION OF THE EXAMPLE AND KEY CONTEXTUAL ISSUES:

A large-size commercial business is wanting to move into a bigger office to accommodate an increase in staff numbers, and so is moving into a new building that is currently at the fit-out stage, so that they have control over the design. Some of the key issues which will influence their decision making are:

- The building is in a new development site, so there is scope to impact the energy and water strategy for the building.
- There are expected periods of inoccupancy as they will be the sole occupier of the building, and in the case of any future infection peaks, work-from-home mandates would be introduced.
- The move will require increasing the number of FM staff considerably, and therefore a simple maintenance system is desired for training of new FM staff, and retaining of existing staff.

TRANSMISSION MECHANISMS

Legionnaires' disease is a constant endemic threat in the built environment, caused by exposure to a bacterium that is found in water and soil. The most common form of transmission of Legionella is inhalation of contaminated aerosols which contain the the bacteria produced in conjunction with water sprays, jets or mists[176]. Less commonly, transmission can be through aspiration of drinking water containing Legionella[177]. These transmission mechanisms can be mitigated by regular maintenance, cleaning and disinfection of water and air conditioning systems to minimise the growth of the Legionella bacterium.

PRIORITISED BUILDING INTERVENTIONS WHICH RESPOND TO THESE TRANSMISSIONS MECHANISMS IN THE OFFICE CONTEXT, MIGHT INCLUDE:

- Install automatic flushing valves within the new plumbing system that can be flushed through the central building's control circuit to remove any requirement for manual flushing by FM staff.
- Establish a water testing regime, to be carried out at regular intervals, alongside protocols for additional testing in the building prior to reoccupation following a period of closure or in the event of any equipment failure or downtime. Provide appropriate training to FM staff on the protocols.
- Update the fit-out specification to include toilet lids which are click closed to flush, to reduce the risk of contaminated airborne particles being released.
- Define safe operation and control measures for evaporative cool systems, hot and cold-water systems to include temperature control, flow regulating valves and regular maintenance programmes. Provide training for FM staff on undertaking regular risk assessments and monitoring control points.

7. INTERACTIONS WITH OTHER AGENDAS AND PRIORITIES

This research has focussed on the interventions which can be put in place to reduce the risk of infection transmission. However, through this research programme it has become evident that there are specific priority topics that may be in tension with infection resilience mitigation measures. These topics are detailed in the following sections and should be considered by decision makers in any wider application of infection resilience.

7.1 SUSTAINABILITY

A large focus in infection resilience is around indoor air quality, and in many cases, this results in an increase in demand for mechanical ventilation systems to achieve higher air change rates (refer to Section 5.2.2). This increased demand on the system inevitably translates to higher energy consumption, and hence conflict with commitments to carbon reduction. It has been noted in some research that use of filtration may help to mitigate the increased energy demand for large increases in fresh air intake but the appropriateness of this is determined by the exact system in place. The increased demand can also be mitigated by heat recovery, which is the process of collecting and re-using heat that would otherwise be lost. Similar to the use of filtration, the suitability of heat recovery will be dependent on the type of ventilation and heating system in place.

However a recent study[6] looking at COVID-19 mitigation measures specifically showed that, of the long term mitigation measures, many were compatible with improved sustainability outcomes, and potentially a renewed focus on the quality of infrastructure would equally benefit the goals of minimising infection transmission and improving sustainability.

In the transport sector, during the COVID-19 pandemic, there has been a shift in favour of personal vehicle transport for risk reduction measures. For example, a study in Germany from the German Aerospace Centre found that respondents expressed unease about public transport, rail, air travel and car sharing, and that owning a vehicle was regarded as a feel-good factor[178]. During the transport workshop the topic was discussed that the presence of the pandemic also factored into some individuals' decision to buy a car despite living in a city[(3)]. This pattern shift in a pandemic scenario has significant environmental impacts and inversely impacts the UK's Decarbonising Transport campaign towards a low carbon world[149].

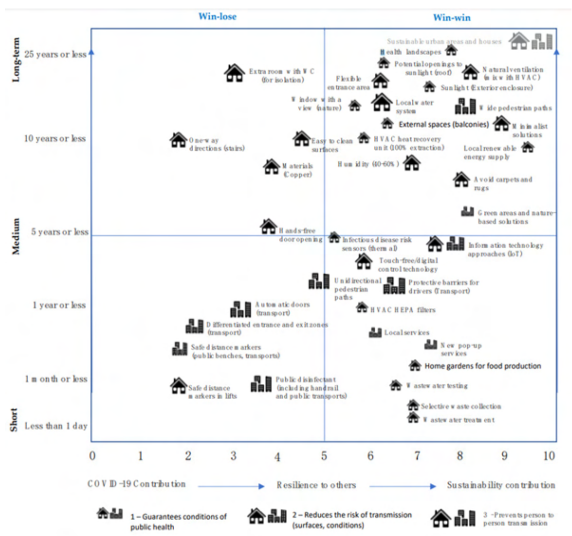


Figure 19: COVID-19 risk reduction measures in urban areas and buildings[6]

Additionally, in lockdown, isolation, and hybrid working scenarios, there is a less efficient use of workspaces, with people using home offices that need to be heated in addition to commercial office spaces, which results in an overall increase of energy use[179].

When considering the appropriate infection mitigation measures for a building, decision makers should consider energy use and transport choice behaviours as detailed above.

7.2 OUTDOOR AIR QUALITY

Section 5.2.2 describes the opportunity to use natural ventilation to increase ventilation in indoor spaces. In some cases, the impact of bringing more outdoor air in for ventilation may worsen indoor air quality or have other undesirable consequences. For example, this may apply in urban areas which have high pollution, where there are frequent wildfires, dust storms or in environments with mosquitos.

The location of the building with regard to outside air quality and other potential environmental threats to health should be considered when defining the ventilation system of an indoor space.

7.3 PRIVACY AND SECURITY

Some countries have used big data technology and artifical intelligence (AI) to predict usage and potential outbreaks through the use of personal devices. For example, in China during the COVID-19 pandemic they tracked location and travel data from personal devices, medical and health data and government data[180]. Whilst this may effectively help to prevent and control future outbreaks, the use of AI may be seen to infringe on personal privacy in certain settings and countries. Countries such as the USA and the UK already have regulatory controls in place to prevent the use of this type of data by the government, notably the HIPAA and GDPR laws respectively.

Furthermore, the application of contactless door functions and increasing operable windows may compromise security requirements in certain settings such as schools and prisons[(2)].

Building owners and operators should consider the implications on privacy of big data technology and the necessity to maintain certain security measures in such building environments.

7.4 OCCUPATIONAL DENSITIES

The mitigation measures for infectious diseases may go against the trend to pack more people into spaces (i.e. office and commercial spaces have become denser over the last 10 years or so). Desks have become smaller and more densely packed, so workers sit closer together, which is in conflict with expert advice for social distancing. Desk sharing results in many different workers using the same facilities which leads to more frequent and intense cleaning routines to sanitise workstations before a new user takes over. The trend for desk-sharing may be reviewed or reversed if there are future demands to reduce occupational density or specific concerns about contact contamination routes[181].

7.5 FACILITIES MANAGEMENT SKILLS GAP

FM services control the environment of buildings, most commonly found in commercial and managed residential buildings. Prevention and mitigation measures can be adopted by FM teams to optimise the full suite of operational and maintenance functions of a building to effectively reduce the risk of transmission of infectious diseases in buildings. Examples of this will include the management of HVAC systems, water systems, cleaning and maintenance protocols.

There is a need to provide information on building systems to FM staff on how the systems work to reduce transmission risk to ensure they are operated as designed and intended[(6)]. Without this training, the full potential of the building's operational and maintenance functions cannot be maximised to reduce the infection risk.

7.6 REDUCTIONS IN SOCIAL INTERACTION

Section 5.2.4 describes how the spatial configuration of buildings can encourage or discourage social interactions. Typically it has been desirable to increase social interactions within the built environment. For example, in commercial buildings there are open plan concepts and stairways that intentionally direct occupants to nodes of chance encounters. This design aspect is in conflict with the public health measures of reducing interactions that have been introduced worldwide during the COVID-19 pandemic. Similarly, in residential buildings such as high-rise blocks, residents may be encouraged not to use public and shared facilities to reduce the chances of transmission of infections. The MASS Design Group case study in Section 5.6.7 acknowledges that the presence of outdoor balconies can provide the opportunity for safe social interactions between residents even in a lockdown scenario.

The risks of infection transmission in each building context will need to be weighed against the benefit of increased social interactions of the individuals within it.

7.7 ACCESSIBILITY

Infection resilience mitigation measures may lead to certain shifts in areas of building design, such as centring stairs on a floor plan and hiding lifts at the back of a building to encourage active movement and discourage people being confined in a lift cab. Pushing for more active modes of travel may provide poorer experiences for those with reduced mobility as they will not experience the same welcome entrance as those who are non-disabled, or may lead to larger wait times for lifts.

Designers and building operators should consider the experience of all members including accessibility and inclusivity factors when including mitigation measures for infection resilience in their building.

7.8 SOCIAL INEQUITY

As stated in Section 5.6.5, there is an inequality between neighbourhoods and homes, linked to opportunity for individuals to effectively isolate from others, socially distance and have access to green spaces within walking distance and access to outside space within their home varies considerably.

Using COVID-19 in the USA as a case study, those living in poorer neighbourhoods were likely to suffer from infectious diseases more acutely than those in wealthier neighbourhoods due to factors such as worse baseline health, more crowded housing, limitations on people from distancing from each other, and a short supply of parks and open greenspace. The general pattern of COVID-19 across neighbourhoods was a stark reminder of persistent inequities in the built environment, requiring wide-ranging political, economic, and social solutions. Importantly, high-risk neighbourhoods were more likely to be home to frontline workers - delivery drivers, supermarket workers, nursing home aides and public transport operators[182].

Design practitioners should ensure that all members of society are provided with the opportunity to safely minimise the chance of contracting infectious diseases, and given the ability to self-isolate in habitable conditions, to ensure equality across the built environment.

Appendix A: Literature Review Framework

Research Questions	1. To develop an understanding of how widespread the idea of making an environment, such as a building or transport system, less susceptible to disease transmission is internationally; how that is conceptualised and articulated and what it is considered to entail. 2. To understand what methods exist to create infection resilient buildings and transport systems internationally. 3. To identify what constitutes best practice in infection resilient environments from an international perspective. 4. To outline emerging challenges and opportunities with significant potential impact on creating infection resilient environments	
Infrastructure Typology	Use Class	Industrial (Class B) Residential (Class C) Commercial (Class E) Local Community (Class F) Transport (Part 8A - 9E)
	Specific Building Type (if applicable)	See Annex A Building Classes tab for full breakdown of subclasses.
	Space Function	i.e. Hallways, Sanitation Facilities, Open-plan office space, Meeting rooms, etc.
Specific Information	Transmission Methodology	Direct contact transmission Surface (fomite) transmission Airborne (aerosol) transmission Oral (ingestion) transmission. Note if observed in documentation: • Vector-borne transmission • Zoonosis • Environmental transmission
	Mitigating Measure or Design Approaches Described	
	Project Life-Cycle Stage	Governance Design Construction Operation & Use Retrofit Management
	Negative Externalities	
	Case Studies	Add any relevant projects referenced in the document
	Stakeholders	Add any specific stakeholders referenced in the document

Appendix B: Literature Review Document List

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WORKSHOP REFERENCES:

{1} Miro Board for Commercial Workshop

{2} Miro Board for Residential & Community Workshop

{3} Miro Board for Transport Workshop

{4} Miro Board for Industrial Workshop

{5} Miro Board for Asia Workshop

{6} Key Informant Interview – Tim Chapman Arup

{7} Key Informant Interview – Mass Motion Lachlan Miles Arup

{8} Key Informant Interview, Alexander Alexiou, Foresight Arup

{9} Key Informant Interview – Perkins Will

Appendix C: Stakeholder Consultation Summary

STAKEHOLDER GROUP	ORGANISATIONS	CONSULTEE NAME	CONSULTATION DATE/TIME
Industrial Buildings Workshop	Prologis	Arthur van Kooij	Tuesday 15th February 2022 15:30-17:00 GMT
	Arup	James Chimeura	
		Felix Bianeyin	
		Ryan Dunne	
		Rob Lunn	
		Jennifer Dimambro	
		Matthew Evans	
Community & Residential Buildings Workshop	Affordable Housing Institute	David Smith	Thursday 3rd February 2022 15:30-17:00 GMT
	Affordable Housing Institute	Davina Wood	
	Newstory Charity	Victor Mendoza	
	WELL Institute	Angela Spangler	
	Arup	Alexej Goehring	
	MOE Artelia Group	Kasper Bach Johannsen	
Transport Workshop	Metropolitan Airports Commission	Dawn Errede	Thursday 10th February 2022 15:30-17:00 GMT
	Arup	Dan Evenson	
		Giles Pettit	
		James Alton	
		Trent Lethco	
		Neerav Kapila	
		Richard Matthews	
	EBRD	Harry Karandeinos	

STAKEHOLDER GROUP	ORGANISATIONS	CONSULTEE NAME	CONSULTATION DATE/TIME
Commercial Buildings Workshop	CUF Infante Santo	Maria Neto	Wednesday 02nd February 2022 16:00-17:30 GMT
	Arup, Senior Engineer San Francisco	Joseph Hewlings	
	Arup	Ann Dalzell	
		Andrew Jones (P)	
Asia Workshop	Arup	Tony Lam	Wednesday 16th February 2022 08:30-10:00 GMT
		Felix Chan	
		Natalie Leung	
		Polly Tsang	
		Pui-Fung Ko	
		Makito Shirahige	
		Trudy Taftiana	
Key Informant Interview - Arup London Office Leader	Arup	Tim Chapman	Thursday 27th January 2022 13:00-14:00 GMT
Key Informant Interview - MassMotion Modelling Expert	Arup	Lachlan Miles	Thursday 27th January 2022 13:00-14:00 GMT
Key Informant Interview - Foresight Team	Arup	Alexander Alexiou	Friday 28th January 2022 15:30-16:30 GMT
Key Informant Interview	Perkins Will	Erika Eitland	Friday 18th February 2022 13.00-14.00 GMT

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