Developing a Framework for Risk-Responsive Building Codes of Office Buildings: A Healthy Building Perspective

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Abstract

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The COVID-19 pandemic has reshaped our understanding of office buildings' designs and operations, particularly in response to airborne transmission risks and occupants' health. While building codes are intended to ensure safety, protect occupants' health, and minimize risks, they lack adequate responsiveness to airborne transmission risks, including COVID-19. Additionally, there is a dearth of studies on the ability of building codes to mitigate airborne transmission. In response, this dissertation introduces a novel Risk-Responsive Framework (RRF) to evaluate and enhance building codes' risk responsiveness, with a specific focus on providing healthier office environments. The specific objectives of this research are to: (1) identify the key factors that determine building codes' risk responsiveness to mitigate airborne transmission, including COVID-19; (2) develop a framework to assess the risk responsiveness of current building codes; (3) apply this framework to U.S. case studies to determine their effectiveness; and (4) provide recommendations to improve building codes in preparation for future public health crises. A mixed-methods approach was employed, combining qualitative and quantitative data through content analysis, expert interviews, and the Delphi method. A multi-criteria analysis method of simple additive weighting was used to weigh and rank the final factors that determine a building code's risk responsiveness. This comprehensive approach led to the identification of four criteria and eleven key factors influencing building codes' risk responsiveness. These criteria include prevention effectiveness, associated energy costs, and ease of monitoring, reporting, implementation, and enforcement, while key factors such as increased ventilation rates, higher air filtration, space design, clean air delivery rates, and bringing in outdoor air were identified. These factors were used to construct RRF, which aims to evaluate building codes' effectiveness in mitigating airborne transmission risks. RRF was applied to 30 U.S. cities and 30 states to assess their current responsiveness to airborne transmission risks. The findings revealed that most existing building codes are not sufficiently responsive to these risks. Only a few states and cities scored relatively higher due to the inclusion of relevant health-focused factors, such as higher air filtration, in their building codes. This underscores the significant need for integrating health considerations into building codes to enhance their responsiveness to airborne transmission risks. This research provides significant insights by identifying gaps in current building codes and proposing the novel RRF to enhance their responsiveness to airborne transmission risks. It also highlights the importance of integrating health-focused requirements into building codes to ensure safer and healthier office environments in the post-pandemic era. Finally, this research offers recommendations to improve building codes' risk responsiveness to future airborne disease outbreaks.

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ACRONYMS

AHU : Air Handling Unit

AIA : the American Institute of Architects

ASHRAE : the American Society of Heating, Refrigerating and Air Condition Engineers

ASTM : American Society for Testing and Materials

BEAM Plus : Building Environmental Assessment Method Plus

BREEAM : Building Research Establishment Environmental Assessment Methodology

CBRE : Coldwell Banker Richard Ellis

COVID-19 : Coronavirus disease

CO_2 : Carbon dioxide

CDC : Centers for Disease Control and Prevention

DGNB : Deutsche Gesellschaft für Nachhaltiges Bauen (the German Sustainable Building Council)

GBCI : Green Business Certification Inc

HEPA : High Efficiency Particulate Air

JLL : Jones Lang La Salle Inc

HQE : Haute Qualité Environnementale/High Environmental Quality (the French Green Building Certification System

HVAC : Heating, Ventilation, and Air Conditioning

IAQ : Indoor air quality

IBC : International Building Code

IMC : International Mechanical Code

LEED : Leadership in Energy and Environmental Design

MCA : Multi-Criteria Analysis

MCDA : Multi-Criteria Decision Analysis

MCDM : Multi-Criteria Decision Making

MERV : Minimum Efficiency Reported Value

NFPA : the National Fire Protection Association

REHVA : the Representatives of European Heating and Ventilation Associations

RH : Relative Humidity

RRF : Risk-Responsive Framework

SARS-CoV-2 : Severe acute respiratory syndrome coronavirus 2

SAW : Simple Additive Weighting

SHASE : the Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan

UNDRR : United Nations Office for Disaster Risk Reduction

U.S. : United States of America

UV : Ultraviolet

UW : University of Washington

UVGI : Upper-room Ultraviolet Germicidal Irradiation

VOC : Volatile organic compounds

WHO : the World Health Organization

WSDOH : Washington State Department of Health

WSM : Weighted Sum Method

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DEDICATION

In loving memory of my mom

Chapter 1. INTRODUCTION

Chapter 1 aims to present the research background, research aims, objectives, questions, and significance of the study in the context of building codes and mitigation for the future pandemic. It will conclude with a dissertation outline that contains brief information about each chapter.

1.1 RESEARCH BACKGROUND

As a black swan event, the recent COVID-19 global pandemic has changed the perspective on the design and operation of office buildings regarding occupants' health and safety. These identified changes are primarily focused on minimizing airborne transmission risk in office and workspace settings during the recent pandemic and post-pandemic situations. In other words, office buildings are expected to be more adaptive and adjust, redefining the future of workplaces in the new normal (Gujral et al., 2020) to minimize such health and safety risks.

Consequently, office buildings must comply adequately with health requirements recommended by engineering and health experts for re-occupation and mitigation of airborne transmission, including COVID-19. Initial findings from the resources listed below have identified the following factors that are important for the reoccupation of buildings such as (1) space management, (2) ventilation rates, (3) air filtration, (4) temperature and relative humidity (RH) setting, (5) air disinfection, (6) monitoring indoor air quality (IAQ), (7) operation compliance with standards and guidelines, and (8) disinfection and cleaning management:

- World Health Organization/WHO (WHO, 2020a, 2020b)
- Centers for Disease Control and Prevention/CDC (CDC, 2020c, 2020a, 2020b, 2021a)
- American Society of Heating, Refrigerating and Air-Conditioning Engineers/ASHRAE (ASHRAE, 2021b),

- American Institute of Architects/AIA (AIA, 2020b, 2020a), and
- Building Owners and Managers Association/BOMA (Areno, 2020) and
- journal publications from Morawska et al. (2020), Dietz et al. (2020), Xu et al. (2020), and Sloan Brittany et al. (2020)

Even though the global pandemic has changed to an endemic, the risks remain. Therefore, these factors were considered essential in future office-building practices in mitigating airborne transmission, including COVID-19.

In addition, the literature indicates that building codes aim to address society's essential concerns, including public health and safety, environmental protection, cost efficiency, and investment policy. In large part, building codes establish building quality, safety, and energy performance for years to come because the initial design and construction decisions determine operational and maintenance costs for the life of the building (Vaughan & Turner, 2013).

Historically, building codes in the U.S. have been evolving to minimize the risks from both natural hazards and man-made disasters, including earthquakes, fire, wind, and floods. Those hazards have led to various improvements to mandate safer practices and reduce losses (Burby & May, 1999; Cote & Grant, 2008; Rossberg & Leon, 2013). However, building codes in the US have historically been limited to addressing historical hazards, rather than emerging ones (Eisenberg, 2020), indicating a lack of responsiveness to future risks.

To that point, building codes are essential in ensuring safer building practices by helping understand the risks to the occupants and gradually acknowledging the risks for improvements. However, there is a notable lack of discussions and research on how building codes could respond and become more adaptable to this challenging environment, where health and safety are crucial issues in mitigating airborne transmission diseases, including COVID-19. In response, the overarching aim of this research is to investigate how building codes could be more risk-responsive to airborne transmission and, with the remaining risk, mitigate similar public health crises in the future.

1.2 PROBLEM STATEMENT

The discussions on the role of building codes in airborne transmission are limited, even in previous similar events such as SARS (2003). In response to those events, some studies have identified changes and modifications in healthcare facilities (Loutfy et al., 2004) and high-rise residential buildings (Yu et al., 2004). Recent studies have suggested the opportunity to improve building regulations, codes, and standards to mitigate the COVID-19 pandemic (Awada et al., 2021; D. Eisenberg, 2020; Megahed & Ghoneim, 2021) ensuring occupant's health and preparing for the future pandemic. However, there are still few publications on how building codes can better respond to the pandemic and post-pandemic.

The literature indicated that buildings are critical for infectious disease transmission, including COVID-19. Lessons learned from previous outbreaks of airborne diseases, e.g., SARS in Canada (2003) and Hong Kong (2003), have resulted in some recommendations focused on design and engineering strategies for healthcare facilities (Loutfy et al., 2004; Naylor et al., 2004; Ng, 2020) and multi-story residential buildings in response to future risks (Azuma et al., 2020). Even so, there are no or very limited discussions on incorporating these previous experiences into building codes to ensure better preparation in the future.

The enormous scale of the previous COVID-19 pandemic has also prompted many recommendations on space design, engineering, and operations. As more buildings resume operations and occupants return to workplaces in the post-pandemic working environment, changes and improvements in how buildings operate safely are required. Unfortunately, with the building codes mainly focusing on design requirements and the limited scale of building construction, it raises another concern about the performance of buildings during the operation phase.

The latest evolution of building codes in the U.S. has resulted in one unified model, the International Building Code (IBC) model. This model combines specific concerns based on the risks of natural hazards while making the codes more efficient and driving smooth adoption among the state and local governments (Rossberg & Leon, 2013). The current IBC model includes more detailed and specific categories to accommodate building types (e.g., non-residential and residential, or for existing codes), mechanical systems (e.g., plumbing, sewage, or fuel gas code), safety (e.g., fire code), and specific topics such as energy conservation code, performance code, or property maintenance (IBC, 2021).

The codes have also been expanded and diversified into more detail due to increasing challenges and risks, with a three-year cycle of updates. This cycle is designed to make the code's content more responsive, enabling them to better anticipate unforeseeable risks (Rossberg & Leon, 2013). However, recognizing that the U.S. building codes were have been insufficient in addressing existing and emerging risks, it is imperative to assess the current code's effectiveness against airborne transmission, including COVID-19.

The latest discussions suggested the importance of recognizing a healthy building perspective as a point of departure in preventing the transmission of airborne diseases. The healthy buildings perspective emerged from practices that promotes fulfillment of indoor air quality contribution to human health and productivity and avoiding diseases (Allen & Macomber, 2020; Altomonte et al., 2020; Cedeño-Laurent et al., 2018; Loftness et al., 2007), as well as its occupant's physical, mental, and social well-being. Thus, these practices were related to the COVID-19 pandemic, where buildings should play a critical role in minimizing indoor transmission risks (Awada et al., 2021).

Recognizing that some of the healthy building elements relevant to COVID-19 mitigation, such as increased ventilation rates or higher air filtration to support good indoor air quality (Allen & Macomber, 2020), can make future office buildings healthier and safer, this is an opportunity to include these elements in building codes as minimum requirements. By doing so, future office building codes will have a great combination to drive healthier practices and, at the same time, prepare for future airborne diseases.

In summary, while building codes in general aim to provide safety, protect health, and minimize any risk to the occupants, the current codes appear to lack responsiveness to the emerging and remaining risks of airborne transmission, including COVID-19. As office buildings re-opened and occupants entered the post-pandemic era with increased understanding and demand for a safer and healthier working environment, it is imperative for building codes to not only mitigate the current and remaining risks but also prepare for future pandemic events of a similar nature.

1.3 RESEARCH AIMS AND RESEARCH OBJECTIVES

Given the lack of research on building codes' risk responsiveness in mitigating airborne transmission, this research aims to develop a framework to assess the current status of existing building codes for office buildings and investigate how the codes could be more responsive to the risks of airborne transmission, including COVID-19.

In that regard, the research objectives include:

- To identify factors that determine building code risk-responsiveness to mitigate airborne transmission, including COVID-19
- To develop a framework to assess the risk responsiveness of existing building codes

- To apply the risk-responsive framework to the U.S. case studies and determine the risk-responsiveness levels of existing codes
- To provide recommendations to improve risk-responsiveness in preparation for future public health crises.

1.4 RESEARCH QUESTIONS

To achieve the objectives, the research questions were formulated as one primary research question and four sub-research questions. The primary research question is, "How can building codes be more responsive in mitigating future airborne transmission risks, including COVID-19?" In support of that, the sub-research questions are:

1) What are the factors that determine the building code's risk-responsiveness?
2) How do we assess or evaluate the current risk-responsiveness levels of building codes?
3) What is the status of the U.S. building codes in terms of risk-responsiveness levels?
4) What recommendations can be provided to prepare for similar airborne disease crises in the future?

1.5 SIGNIFICANCE OF THE RESEARCH

This research aims to investigate how to improve the risk-responsiveness level of office building codes for post-pandemic situations by learning from the current situation. The literature review on the impacts of COVID-19, office building codes, and healthy building perspectives confirmed the importance of making changes to building design and operation requirements to mitigate current and future airborne diseases such as COVID-19.

This research argues that those changes in future office building codes can be effectively implemented only by identifying the gaps between current codes and the expected future codes regarding risk-responsiveness and airborne transmission risk. However, there is a dearth of studies specifically investigating how the existing building codes should be improved in preparation for future pandemics. This research aims to contribute to the body of knowledge by developing a novel framework to assess the risk-responsiveness level of current building codes and make recommendations for improving it in response to the identified knowledge gap.

The results of this research will increase awareness and attention to the lack of safer and healthier building design and operation practices. It will also shed light on how research in these interdisciplinary fields can improve code performance to provide safer and healthier building practices in the future.

1.6 DISSERTATION OUTLINE

Chapter Two: Literature Review: I will present a summary of the literature review, starting with the impact of COVID-19 on office buildings, the relationship between building codes and the COVID-19 pandemic, healthy building perspectives, and health issues in building rating tools. The literature review will also cover measures to reduce airborne transmission risks. Finally, I will discuss the multi-criteria analysis (MCA) as a tool for weighting and ranking in decision-making processes for determining the risk-responsiveness factors.

Chapter Three: Research Methodology: In this chapter, I will discuss the employed research methodology in detail. I will begin with the background of using a mixed-method approach, combining qualitative and quantitative methods to gain a comprehensive understanding of the factors that determine building codes' risk-responsiveness. Following this, I will present the research framework and its phases, including content analysis, expert interviews, the Delphi method, and the use of Multi-Criteria Analysis (MCA), particularly the Simple Additive Weighting/Weighted Sum Method (SAW/WSM). The discussion of the research methodology also includes a step-by-step explanation, the goals and output of each phase, and the data collection methods used.

Chapter Four – Results: In this chapter, I will present the results of the data collection, including content analysis, expert interviews, and the Delphi method. This chapter will cover the development and the finalization of risk-responsiveness factors, including weighting and ranking procedures. Then, I will also discuss the application of these factors to RRF by examining building codes from U.S. case studies and displaying the risk-responsiveness levels of sampled states' and cities' building codes. Finally, this chapter includes a discussion on three related topics to future building codes in mitigating airborne transmission: a) maintaining building design and operation; b) higher requirements for emergency situations; and c) the best paths to compliance for future building codes.

Chapter Five – Discussions. In this chapter, I will present an analysis of the research findings and explore their significance in response to the research questions. I will then discuss each research finding based on four research questions and compare them with the literature review. The comparison will underline the similarities and contrasts, or additional insights, identified during data collection and analysis.

Chapter Six – Conclusions: In this chapter, I will conclude the research by summarizing the key findings concerning the research objectives and questions. This chapter will also include the contribution to the body of knowledge, research limitations, and future research opportunities that can offer more in-depth and further discussion related to building codes in mitigating airborne transmission in the future.

Chapter 2. LITERATURE REVIEW

As introduced in Chapter 1, this research investigates how building codes can be more responsive in mitigating future airborne transmission risks, including COVID-19, in office buildings. To build a solid foundation for this investigation, this chapter presents a summary of the literature review on key topics. It aims to review and synthesize knowledge about building codes, the concept of healthy buildings, health issues in building rating tools, measures for airborne transmission risk reduction found in related industries, and academic literature. This chapter also discusses the risk-responsive criteria and the use of multi-criteria analysis (MCA) for this research. Figure 2.1 illustrates the process followed in this literature review.

Figure 2.1. Guide for Literature Review Process

2.1 IMPACT OF THE COVID-19 PANDEMIC ON OFFICE BUILDINGS

The COVID-19 pandemic significantly impacted the office building sector due to health concerns about indoor risk infection (Berry, 2020; CBRE US, 2020; JLL, 2020). Studies (Ijaz et al., 2020; Vuorinen et al., 2020; Xu et al., 2020) and guidelines from WHO (2021), CDC (2020f), and Taylor (2020) have identified COVID-19’s three modes of transmission:

1) Direct contact (e.g., handshake) or indirect contact transmission (e.g., via contaminated surfaces, handhelds, etc.)
2) Droplet transmission via respiratory droplet
3) Droplet nuclei or airborne or aerosol transmission

Airborne or aerosol transmission has been identified as the possibly dominant transmission mechanism (Evans, 2020; Morawska et al., 2020; Vuorinen et al., 2020) through discrete events (e.g., coughing or sneezing) or continuous activity such as breathing and talking (Evans, 2020). The limited knowledge of transmission in a building setting has driven efforts to curb the increasing infection rates, which have made office building managers halt or limit their operation for the sake of the occupants' safety and health.

A large number of research studies and published guidelines investigated the unknowns of COVID-19 (DeGraw, 2021) and recommended three broad strategies: space management, engineering, and building operations.

First, studies by Dietz et al. (2020) and Xu et al. (2020) underscored how space management can reduce the risks of transmissions by allowing one person to sit at every other desk and setting the maximum number of people in an area. Similar strategies from AIA (AIA, 2020a, 2020b) and CDC (2021) focused on desk reorientation, additional barriers between desks, and the use of partitions, combined with a 6-foot (1.8-meter) safe distance in large common areas such as auditoriums, dining rooms, conference rooms, and assembly areas.

Second, engineering strategies refer to operating a building's HVAC systems to reduce COVID-19 transmission risks through dilution and filtration in building settings. Dilution aims to add more fresh air and maintain high air quality through filtration. The recent literature and guidelines have identified the prioritization of fresh air in buildings, including avoiding recirculated air, as the first strategy. Other non-HVAC strategies include prioritizing natural ventilation, including using operable windows in working areas (Dietz et al., 2020; Morawska et al., 2020; Sloan Brittain et al., 2020; Xu et al., 2020).

These findings emphasized optimizing the inflow of outdoor air to supply fresh air before adjusting the building's HVAC system. Increasing the ventilation rate (Atkinson et al., 2009; Megahed & Ghoneim, 2021; Morawska et al., 2020; Sha et al., 2021; Sloan Brittain et al., 2020) and air exchange rate (Evans, 2020) through HVAC systems are more effective in minimizing the transmission risk.

Improving a building's filtration level seems effective in filtering out smaller virus particles (Nediari et al., 2021; Sha et al., 2021; Xu et al., 2020) by using portable high-efficiency particulate air (HEPA) filters for individual rooms (Morawska et al., 2020; Sloan Brittain et al., 2020; Xu et al., 2020). Other findings in the literature identified the importance of air filtration system maintenance for filtration performance (Morawska et al., 2020; Xu et al., 2020). Flushing a building with fresh outdoor air before and after occupancy hours is also recommended (AIA, 2020a; ASHRAE, 2021c; CDC, 2020e). The use of UV devices, either in the mechanical ventilation lines or during vacant hours, provides more protection from infection risk (AIA, 2020b; CDC, 2020d).

Lastly, several studies emphasized that monitoring buildings' indoor air quality reduces transmission risks during operating hours (AIA, 2020a; ASHRAE, 2021c; Dietz et al., 2020; Morawska et al., 2020; Sloan Brittain et al., 2020; Xu et al., 2020). Since COVID-19 airborne transmission is difficult to detect, monitoring relative humidity (RH), temperature, and particularly CO2 levels provides an indicator of indoor air quality (Allen & Macomber, 2020) and acts as a proxy to estimate the infection risk spread of COVID-19 in buildings (Peng & Jimenez, 2021).

In terms of design, future office buildings will be subjected to several changes in layout and design solutions, working spaces, shared facilities, density, and building heights (Megahed & Ghoneim, 2020; Nediari et al., 2021). For example, Awada et al. (2021) suggested advanced

HVAC design and operations practices, humidity control and spatial configuration, and human interactions. Awada et al.'s (2021) article also suggested conducting flushing two hours before and after building occupancy hours, maintaining RH at 40%–60%, increasing ventilation rates by eight liters per second per person, or two times more than the ASHRAE standards. In addition, the article also identified increasing air filtration levels by using HEPA filters and reducing the current density and spatial configuration as proper measures to minimize transmission risks (Awada et al., 2021).

In conclusion, the COVID-19 pandemic significantly impacted the office building sector, leading to operational changes and a focus on mitigating airborne transmission risks. Research recommended strategies in space management, engineering (including HVAC optimization and air quality monitoring), and building operations. Based on these findings, future office buildings would require improvements emphasizing advanced HVAC practices and spatial configuration adjustments to minimize transmission risks.

2.2 BUILDING CODES IN THE U.S.

Building codes address society's essential concerns, including public health and safety, environmental protection, cost efficiency, and investment policy. In large part, building codes establish building quality, safety, and energy performance for years to come because the initial design and construction decisions determine operational and maintenance costs for the life of the building (Vaughan & Turner, 2013). In the U.S., building codes are essential in mitigating the risks from natural hazards and man-made catastrophes such as fires, earthquakes, and hurricanes (Burby & May, 1999; Cote & Grant, 2008; Rossberg & Leon, 2013). In this regard, building codes minimize casualties and economic losses by mandating minimum requirements for buildings (Baum, 2005; Cheng, 2013; Cote & Grant, 2008; Fakunle et al., 2020; Vaughan & Turner, 2013).

In the aftermath of many hazards and catastrophes, building codes have been gradually revised and improved, thus becoming more risk-responsive to anticipate future threats.

Building codes, standards, and rating tools are the primary references in building design and construction practices. These codes define the minimum requirements for design and construction to protect health and safety. They also attempt to balance optimum safety and economic feasibility, and they are bound to specific jurisdiction areas (Cote & Grant, 2008). Project stakeholders such as contractors and building owners establish their own requirements in compliance with the minimum code requirements.

Building standards are voluntary-based specific requirements or guidelines developed by consensus (Listokin & Hattis, 2005) from the private sector, such as professional engineering societies, building material trade associations, federal agencies, and testing agencies. In general, standards define an expected quality and often establish performance and safety criteria (Roos, 2009) and more detailed elaboration references to meet the building codes (NFPA, 2022).

Standards become mandatory when adopted in the building codes (Cote & Grant, 2008). For example, the 2018 Washington State Building Code and Energy Code used NFPA, ASTM, or ASHRAE standards as references. In the NFPA definition (Jones, 2019), a code is a set of rules people must follow, while standards are essential for meeting the code.

In contrary, a building rating tool, or certification, is a tool to assess a building's compliance with specific standards (GBCI, 2022), such as energy efficiency standards, water consumption standards, or the design of high-performance green buildings. It benchmarks buildings based on those standards or requirements and awards certain levels of certification based on their compliance level.

The latest evolution of building codes in the U.S. has resulted in one unified model: the International Building Code (IBC) model. This model combines specific concerns based on the risks of natural hazards while making the codes more efficient and driving smooth adoption among the state and local governments (Rossberg & Leon, 2013). The current IBC model includes more detailed and specific categories to accommodate building types (e.g., non-residential and residential, or for existing codes), mechanical systems (e.g., plumbing, sewage, or fuel gas code), safety (e.g., fire code), and specific topics such as energy conservation code, performance code, or property maintenance (IBC, 2021). Over time, these codes have been expanded and diversified due to increasing challenges and risks. Moreover, the three-year cycle of updates improves the responsiveness of the IBC code's contents in anticipating unforeseeable risks (Rossberg & Leon, 2013).

There are three paths to compliance with codes associated with building performance:

1) Prescriptive or compliance code
2) Performance-based or outcome-based code
3) Combined code or hybrid code

Recently, performance-based codes have emerged as future practices (Babrauskas, 2000; Eisenberg, 2016), although prescriptive codes have been the most accepted path. Unlike a prescriptive code that specifies materials, details, components, and methods, a performance-based code outlines how to meet the objectives and allows some flexibility for building designers to comply (Cote & Grant, 2008). Table 2.1 provides more details about the comparison between these three codes.

Table 2.1. Comparison of Prescriptive, Performance-based and Combined Codes

Prescriptive	Performance-based (Outcome-based)	Combined (Hybrid)
• The most generally accepted type • Specifies materials, details, components, and methods • Relatively easy to implement and easy to verify	• Emerged recently • Outlines how to meet the objectives and allows flexibility for building designers to comply • Encourages innovative solutions to pursue a higher performance level • Used for energy efficiency and responsiveness to earthquakes, fires, and climate change • Challenges in the scale of the project, additional costs, verification method, and the capacity of the building inspectors	• Combines prescriptive minimum requirements and higher performance requirements • Aims to find a balance between the freedom to choose solutions and products with the more accepted method for verification

A performance-based code encourages innovative solutions to pursue a higher performance level (Rossberg & Leon, 2013) in specific requirements. For example, energy efficiency and responsiveness to earthquakes, fires, and climate changes are some of the performance-based requirements in the performance-based building codes (Babrauskas, 2000; Burby & May, 1999; Cote & Grant, 2008; Eisenberg, 2016; Rossberg & Leon, 2013). However, several challenges are associated with a performance-based code, such as the scale of the project, additional costs (Babrauskas, 2000), verification methods, and the capacity of the building inspectors (Foliente, 2000). These examples can make their implementation challenging in achieving health, safety, and environmental goals (Coglianese et al., 2002).

The third type is a mix of prescriptive and performance codes, so-called “combined” or “hybrid codes.” A hybrid code aims to combine prescriptive minimum requirements and higher performance-based requirements. Building designers, clients, and owners have viewed hybrid codes as a solution for addressing the challenges associated with the performance codes (Foliente, 2000). In that regard, Foliente (2000) argued that a hybrid code aims to find a balance between the freedom to choose solutions and products and the more accepted method for verification. Foliente (2000) also provides an example of a mix between performance and prescriptive, with detailed dimensions of particular building materials and the minimum resistance to hold the required force.

A study by Wang (2014) identified the roles of hybrid building codes in disaster-prone areas that enhance residents' protection. The term hybrid code has been discussed in urban planning, combining conventional zoning codes with specific requirements in form-based code, such as setbacks, materials, bulks, and architectural features (Rangwala, 2009). Combining a conventional zoning code and a detailed form-based code suggests an option to achieve the expected objective and overcome identified challenges in one code.

2.3 HEALTHY BUILDING PERSPECTIVE RELATED TO THE RISKS OF AIRBORNE TRANSMISSION, INCLUDING COVID-19

Recent studies have highlighted the emergence of the healthy buildings concept and its defining characteristics (Awada et al., 2021). The term "healthy building" applies to the following:

- A building practice focused on the fulfillment of indoor environmental quality to contribute to health, productivity, and quality of life (Loftness et al., 2007).
- A building practice focused on human health, satisfaction, and productivity (Cedeño-Laurent et al., 2018).
- A building preventing discomfort and dissatisfaction and avoiding diseases and ill-health (Altomonte et al., 2020).

- Building practices improving human health and performance and increasing economic value through productivity (Allen & Macomber, 2020).
- A building, including all systems, that promotes and sustains the health of its occupants as a state of complete physical, mental, and social well-being (Awada et al., 2021). This building concept pertains to the COVID-19 pandemic, where buildings can help minimize indoor transmission risk.

These studies define "healthy buildings" as prioritizing indoor environmental quality for occupants' wellness, including health, productivity, and satisfaction. These buildings are pivotal in preventing diseases and discomfort, enhancing economic value, and minimizing indoor transmission risks, especially in the context of the COVID-19 pandemic.

Loftness et al. (2007) also discussed a broad and comprehensive perspective on healthy buildings based on the following perspectives:

- Sustainable development focuses on design and land use. Sustainable design recognizes the importance of improving health, productivity, and quality of life. This recognition translates into a high-performance building design that delivers health benefits through high-quality air, thermal control, light, ergonomics, privacy, interaction, and access to the natural environment.
- The role of occupants within buildings impacts their indoor air quality daily. This role covers how the occupants behave and respond within the buildings, such as personal cleaning habits and behaviors, selections of consumer products and furnishings, and decisions on appliance varieties.
- The recent development of building products and materials, relevant certification systems, and labeling procedures indicate trends toward addressing current health problems. For

example, control measures to ensure low-emitting consumer products and building materials that reduce material susceptibility and establish performance requirements in compliance with the building codes, such as consumer-oriented product labeling and support to professionals and consumers, such as training and disseminating information.

As for the sustainable development in building design, Loftness et al. (2007) emphasized the components of high-performance designs that protect human health:

- Sustainable, healthy air aims to improve the quality and quantity of outside air by maximizing natural ventilation, mixed-mode ventilation, and HVAC strategies, including filtration.
- Sustainable thermal control aims to separate ventilation air from thermal conditioning, dynamic thermal zone, individual thermal control, etc.
- Sustainable light aims to provide daylight without glare, high-quality lighting fixtures, separation of task and ambient light, etc.
- Workplace ergonomics and environmental quality improve the well-being of occupants through optimal lighting, temperature, placement of furniture, and healthy indoor materials.
- Access to the natural environment aims for daylight without glare and access to natural ventilation.
- Land use and transportation improve mixed-use communities by improving mobility and transportation.

In another recent study, Allen et al. (2016) published nine foundations of healthy buildings as the nine cores of healthy indoor environments, each affecting human health and contributing to productivity and learning. Figure 2.2 illustrates these nine foundations of healthy buildings in more detail. A summary of each foundation is as follows:

1) *Ventilation* focuses on supplying high-quality indoor air by meeting or exceeding outdoor ventilation rates, improving air filtration and operation, and better maintenance.
2) *Air quality* focuses on limiting the volatile organic compound (VOC) emissions to the occupants by selecting low-chemical office supplies, furnishings, and materials, maintaining humidity levels, air quality testing, and responding to occupants' concerns.
3) *Thermal health* focuses on the provision and consistency of temperature and humidity settings.
4) *Water quality* focuses on meeting the U.S. National Drinking Standards at point-of-use, testing regularly, and installing water purification systems to remove contaminants, control microbes, and prevent water stagnation in pipes.
5) *Dusts and pests* focus on minimizing dust and dirt accumulation and pest problems, providing integrated pest management, and avoiding pesticides.
6) *Lighting and views* focus on the provision of comfortable lighting and access views to the exterior, avoiding glare and incorporating nature indoors.
7) *Noise* focuses on the protection from outdoor noise and control of indoor noises.
8) *Moisture* focuses on the prevention of moisture or mold.
9) *Safety and security* focus on providing safety from fire, security in building areas, and communication plans with the occupants.

Figure 2.2. Healthy Building Foundations (Figure 6.1 in Allen and Macomber, 2020)

Cedeño-Laurent et al. (2018) followed the nine foundations of healthy buildings in a study investigating the potential of green building practices transforming into public health tools and their role in a healthier built environment. Allen and Macomber (2020) focused more on the economic impact of healthy buildings achieved from increased occupant productivity and performance by increasing the ventilation rates in indoor space settings.

Awada et al. (2021) compared the previous concept of the healthy building before COVID-19, which is more focused on sick buildings and sick-building syndrome (SBS), and proposed that healthy buildings include all systems that promote and sustain the health of occupants as a state of complete physical, mental, and social well-being in the time of COVID-19.

In conclusion, there is emerging knowledge on what a healthy building is and what constitutes a building being "healthy." While Loftness et al. (2007) mentioned one comprehensive system of healthy buildings, including design, occupants' role, material control, and verification, McArthur and Powell (2020) and Awada et al. (2021) included social well-being and psychological well-being. The nine foundations presented by Allen (2016) and supported by Cedeño-Laurent et al. (2018) focused more on the key determinants of health in the buildings in relationship to occupant's health and productivity.

2.4 HEALTH ISSUES IN BUILDING RATING TOOLS

Efforts to improve building practices have resulted in the development of building rating tools to achieve sustainable building practices (McArthur & Powell, 2020a). These rating tools have only recently started addressing the issue of healthy buildings. In their study, McArthur and Powell (2020) investigated the relationship between health and wellness and incorporated them into sustainable building rating tools such as BEAM Plus, Building Research Establishment Environmental Assessment Methodology (BREAAM), the German Sustainable Building Council (DGNB), Green Globes, Green Mark, Green Star, High Quality for Environment (HQE), and Leadership in Energy and Environmental Design (LEED). This study emphasized that sustainable building rating tools address indoor quality issues and ventilation, including higher ventilation rates, which affect occupants' health. It also identified eight themes related to health and productivity in commercial buildings:

1) Indoor air quality
2) Thermal comfort
3) Visual comfort
4) Acoustic comfort

5) Ergonomics and movement
6) Safe water supplies and diet
7) Psychological well-being
8) Social well-being

The real estate sector has increased its focus on health and wellness, and interest in building rating tools such as WELL and Fitwel has increased (McArthur & Powell, 2020a). Among the eight critical themes above, indoor air quality was the most widely addressed and continuously discussed. WELL and Fitwel, established in 2013 and 2016, respectively, focus more on strategies related to occupants' health, such as ventilation, air filtration, temperature, and relative humidity.

Sustainable building rating tools, such as LEED, gradually incorporated health requirements. In LEED V4, there are some requirements to obtain more credits when ventilation rates and air filtration are higher than standard or building codes. Recently, Fitwel and WELL responded to the COVID-19 pandemic by acknowledging increased ventilation rates above ASHRAE standards and higher air filtration levels than building codes require.

In conclusion, sustainable building rating tools have integrated health and wellness criteria along with sustainable measures that intersect with health and productivity factors in relation to indoor air quality and thermal comfort. Healthy building rating tools like WELL and Fitwel prioritize occupants' health and emphasize ventilation and air filtration. Recent adjustments in response to COVID-19 included increased ventilation rates and higher air filtration levels, underscoring a growing focus on indoor air quality.

2.5 CONTROL MEASURES IN REDUCING AIRBORNE TRANSMISSION RISKS

In terms of the office setting, many organizations offer standards for environmental indoor control systems, such the Federation of European Heating, Ventilating, and Air Conditioning (REHVA);

the Japanese Society of Heating, Air Conditioning, and Sanitary Engineers (SHASE); and ASHRAE. These organizations have addressed the potential indoor transmission and recommended ventilation control measures (Morawska et al., 2020). An overall reduction of airborne infection risks for the current buildings' operations is described as follows per Morawska et al. (2020):

- A combination of ventilation and an adequate filtration system can achieve effective ventilation to remove exhaled virus-laden air and lower its overall concentration.
- Increase ventilation rates by system modification for mechanically ventilated buildings with the involvement of HVAC engineers to reduce transmission risk, including modifying factors relevant to indoor air, such as temperature, relative humidity, airflow distribution, and direction.
- Avoid air circulation to minimize transporting contaminants, including viruses, and distribute them inside buildings.
- Air cleaning and disinfection may be beneficial when improving ventilation is difficult. Ultraviolet (UV)-based cleaning and disinfection, such as UV-germicidal irradiation (UVGI), may offer a solution for this situation or a portable, smaller air filter for smaller rooms.
- Minimize the number of people within the same environment to lower the concentration of airborne virus-carrying particles.

A study by Awada et al. (2021) emphasized that no single strategy can eliminate the transmission of COVID-19 in a typical indoor environment. Awada et al. (2021) suggested on the primary research on engineering controls, such as HVAC design and operations, humidity controls, and non-engineering controls, such as spatial configurations and human-building interactions, to address future pandemics.

Megahed and Gnoheim (2021) also argued that building practices should address SARS-CoV-2 and air pollution in design and operation strategies. They emphasized on the importance of engineering as an essential part of overall building hazard controls by redesigning or modifying the building systems and engineering strategies. This argument highlighted the need to address COVID-19 and other risks, such as air pollution, at the same time and implement multi-strategies in building operations.

In summary, Table 2.2 outlines the strategies for a recent pandemic of COVID-19 and future pandemics and their impact on buildings.

Table 2.2. Strategies for the COVID-19 and Future Pandemic

COVID-19 Pandemic (Morawska et al., 2020)	Future Pandemic (Awada et al., 2021)
• Multi-strategies in building operation • Focus on better ventilation, better air filtration, maintaining temperature and RH, airflow, and direction, and portable air cleaning for buildings with a poorer ventilation system • Paired with limiting the number of people in the same environment	• Multi-strategies in building operation • Addresses air pollution and COVID-19 at the same time • Redesign and modification of the building systems and engineering strategies • Focus on the layout design, adequate ventilation, air filtration, and temperature control

To sum up, the key strategies from engineering and construction controls target to improve IAQ and protect occupants from airborne transmission risk by:

- Adequate ventilation, including ventilation rates and air filtration.
- Indoor air quality, including air recirculation, air cleaning and disinfecting, and HVAC system operations.
- Thermal health, including temperature and humidity.

- Spatial configuration and human-building interactions to complement the engineering control strategies.

2.5.1 Adequate Ventilation, including Ventilation Rates and Air Filtration

The main objective of an adequate ventilation strategy in reducing the risks of airborne transmission is to decrease the number of viral particles in indoor settings by increasing the outdoor air as much as possible (WSDOH, 2020). There are some strategies for a building with an HVAC system to reduce the risks of COVID-19 transmission (WSDOH, 2020). For example, the general considerations are upgrading the existing filters to MERV 13, cleaning and inspecting the HVAC system, reducing air recirculation and maximizing outside air, maintaining the humidity level of 40%–60%, and maintaining local exhaust in the restroom above the code minimum. For buildings with an existing HVAC system, the consideration focuses more on optimizing HVAC adjustments to allow outside air as much as possible and reduce air recirculation. In addition, any changes in HVAC systems must be consulted with an HVAC specialist.

Studies have also recognized ventilation as a way to reduce airborne transmission and, at the same time, IAQ issues. This premise is based on the central principle that ventilation is the key to removing contaminated indoor air with clean outdoor air (Morawska et al., 2020) by dilution (Megahed & Ghoneim, 2021). Ventilation influences indoor air quality in buildings; which makes meeting sufficient outdoor air and an effective airflow pattern important (Awada et al., 2021). In addition, appropriate ventilation distribution ensures adequate dilution (Morawska et al., 2020).

The existing literature has shown a link between ventilation and control of airflow direction within the building and the spread of infectious diseases (Megahed & Ghoneim, 2021). Since ventilation influences other factors, any interventions or improvements in existing ventilation systems should involve HVAC engineers to comply with updates from official ventilation guidance (e.g., ASHRAE) (Megahed & Ghoneim, 2021).

Increasing ventilation rates are critical to infection risk (Awada et al., 2021). One preliminary study from Yuguo Li quoted in Awada et al., (2021) suggests that better ventilation rates and avoiding crowded areas may help reduce the risk. Li recommends 8–10 L/s per person for ventilation rates, which will result in reasonable rates to minimize COVID-19 transmission. However, due to unknown uncertainties, the exact ventilation rates that would reduce the transmission of an airborne virus, such as SARS-CoV-2, are not provided and need more research (Awada et al., 2021; Taylor, 2020).

Furthermore, some considerations for modifying a building's HVAC system to provide more ventilation rates, such as its relationship with temperature, RH, airflow distribution, and direction, need to involve HVAC engineers (Morawska et al., 2020). Increased ventilation rates are one of the most discussed topics for addressing COVID-19 in an indoor setting; however, the exact ventilation rate is mainly unknown in almost any application of the pandemic (Taylor, 2020). Disease transmission was not a consideration during the development of ASHRAE Standard 62.1 Ventilation and Acceptable Indoor Air Quality, even in the healthcare setting (Taylor, 2020). This argument for increased ventilation rates is also consistent with Awada et al. (2021), who stated that higher ventilation rates may help reduce risks.

For naturally ventilated buildings, the outdoor airflow rate used to increase the ventilation rate depends on specific local conditions (opening sizes, relative position, climate, and weather conditions). It should be estimated case by case, ranging from 2 to 50 ACH. Some naturally ventilated public buildings in a cold climate require additional heating to maintain thermal comfort (Morawska et al., 2020).

Since the exact ventilation rates are largely unknown (Allen & Macomber, 2020; Awada et al., 2021; Taylor, 2020), measuring ventilation performance to maintain indoor air quality could use the level of CO_2 indoors as a proxy. Office buildings in the U.S. have two common problems: low ventilation rates and a high concentration of CO_2 (Allen & Macomber, 2020) with more than 1,500 ppm. Allen and Macomber (2020) recommend that besides increasing ventilation rates to 30 cfm/person or 14.16 L/s per person and choosing adequate air filters, buildings need to monitor ventilation performance through real-time monitoring of CO_2.

The measurement provides a sense of indoor quality, which impacts the occupant's health (Allen et al., 2016). For example, the level of outdoor CO_2 is 420 ppm, typical indoors ~1000 ppm, and in schools ~1500 ppm. Studies suggest that CO_2 impacts cognitive performance at 600 ppm (Scully et al., 2019). These findings emphasize that CO_2 in particular rooms or indoor settings can be used to detect whether more ventilation and air changes are necessary (Allen & Macomber, 2020).

Peng & Jimenez (2021) argue that measuring CO_2 allows for estimating the COVID-19 infection risk. This study also suggests that in any environment where the level of CO_2 doubles, the risks of transmission roughly double. This finding strengthens the use of measuring CO_2 levels as a proxy to detect COVID-19 transmission in buildings.

Air filtration is needed to prevent pollutant outdoor air from entering the building from outside (Megahed & Ghoneim, 2021). In the COVID-19 pandemic, effective air filtration eliminated smaller particles, including viruses. A HEPA filter claims to eliminate over 99.97% of airborne particles down to 0.03μm (Awada et al., 2021). However, considering the size of SARS-CoV-2 is smaller, it raises questions about the extent to which the filter can catch the virus. Some questions also arise on how engineers can bring air to meet the thermal comfort zone when the outdoors is polluted (Megahed & Ghoneim, 2021). Smaller rooms can use a portable HEPA filter for buildings with challenges to improve the ventilation system (Awada et al., 2021).

Another suggestion is to upgrade the air filter to a minimum MERV-13 and flush the building before and after the occupation hours. Optimizing natural ventilation by opening windows and reducing occupancy is most favorable for buildings without an HVAC system. WSDOH (2020) suggests additional portable air filtration for critical rooms with poor ventilation and isolated areas, performing air changes five to six changes per hour, and the use of a HEPA filter as an additional recommendation. These considerations indicate the variety of building strategies for COVID-19 risk reduction.

The building space layout and partitioning rooms can be barriers to adequate ventilation, but secondary measures can overcome this. Unlike hospitals, public buildings tend to have lower ventilation rates caused by limiting airflow and energy savings considerations (Morawska et al., 2020). A gap in the body of knowledge underlines that there is no clear guidance on where sufficient ventilation is available for patient management.

2.5.2 Indoor Air Quality, including Air Recirculation, Air Cleaning and Disinfecting, and HVAC System Operations

Air recirculation is a measure to save energy in buildings (Morawska et al., 2020). However, studies show a higher risk associated with recirculated air and COVID-19 infection rates; therefore, it is not recommended (Megahed & Ghoneim, 2021). Treatment and careful handling of air recirculation must be performed when applicable (Megahed & Ghoneim, 2021) because it can transport airborne contaminants, including viruses, from one space to another (Morawska et al., 2020).

In the building HVAC system, particulate filters and disinfection equipment can reduce the risks. Still, the HVAC system must be purposely designed to control the risks and need regular maintenance and service to maintain their effectiveness. Morawska et al. (2020) do not recommend using air recirculation for buildings with centralized AHU to serve multiple levels and zones, and systems should be operated in 100% outdoor air whenever possible. Suppose that it is not possible to use 100% outdoor air. Morawska et al. (2020) recommend combining outdoor air levels and installing UVGI filters to remove the contaminated air from the circulated air to reduce the transmission risk.

ASHRAE (2021a) recommends reducing the recirculation air and increasing the percentage of outside air fraction according to the system capacity for buildings with a recirculation system. Considering seasonality, this increase might require a supplement and increased energy usage (ASHRAE, 2021a). As an alternative, using high levels of filtration, such as MERV 14 to MERV 16, combined with recirculation, is comparable with the increasing outside air.

Air cleaning and disinfecting with UV technologies have been identified as approaches when it is challenging to improve ventilation (Morawska et al., 2020). The air cleaning and disinfection cover UV germicidal irradiation (UVGI) and UV-C light. Studies have suggested a cautious approach when using UVGI due to the irradiation, thus limiting its use for human health due to associated risks to the eyes and skin (Megahed & Ghoneim, 2021).

UVGI equipment is practical in building settings, either installed in upper-room air or through in-duct irradiation. Upper-room UVG is a good option for crowded, poorly ventilated environments where the ability to improve ventilation is limited. At the same time, UVG within the air conditioning and in the duct may also be practical for disinfection in cases where there is no way to stop the air recirculation of ventilation flows.

Morawska et al., (2020) also estimates that the UVGI may reduce infection risks by double compared with increasing ventilation rates. One gap in this system is that it has a few benefits against person-to-person infection when installed in a once-through system that does not circulate the air into spaces (Morawska et al., 2020).

The use of new technology, far UV-C, shows a more effective result in inactivating viruses and bacteria, including in heavy traffic and high-risk public spaces, to inactivate SARS Cov-2 and other viruses and bacteria (Megahed & Ghoneim, 2021). Far UV-C can also cause damage to the eyes and skin, even if it is less than UVGI. Morawska et al. (2020) identified a lack of a thorough study of UV-C safety and economy as the gap. Because of the safety concerns, Morawska et al. (2020) recommend using this technology where nobody is present during the disinfection to avoid adverse health effects. Overall, UV-based technologies require considerable attention to the necessary precautions, and maintenance options and control strategies must be provided (Morawska et al., 2020).

In smaller rooms, portable consumer air-cleaning devices may be beneficial (Morawska et al., 2020). Portable HEPA air filtration supplements poorly ventilated rooms and should be maximized in space for two hours before and after occupancy (WSDOH, 2020). WSDOH recommends not using personal air purifiers and periodically replacing the HEPA filters.

Proper operation of the HVAC system includes not turning off the system even when indoor spaces are vacant and running the system two hours before and after occupant hours to clean up lingering viruses in the building (Faulkner et al., 2021). When the building is vacant, the HVAC system needs to maintain a lower speed for effective circulation to remove the virus from the building with limited energy (Awada et al., 2021).

2.5.3 Temperature and Relative Humidity (RH)

A relative humidity (RH) setting of less than 40% is associated with higher survival and increased infectivity for influenza and other viruses (Awada et al., 2021). This is because droplets become nuclei at a low RH level and remain in the air for a longer period of time. Professional organizations, such as ASHRAE, recommend an indoor RH ranging from 40% to 60%, which can help reduce the COVID-19 infection risk. The Society of Heating, Air-Conditioning and Sanitary Engineering of Japan (SHASE) recommends an indoor RH between 40% and 70% with a temperature between 17°C and 28°C (63°F and 82°F) (Awada et al., 2021).

2.5.4 Spatial Configurations and Human-Building Interactions

Studies have identified that current design practices encourage social interaction through their design, and some building types have a higher density for more interactions, e.g., schools, increasing the probability of interacting and the chance of virus transmission (Awada et al., 2021). The reason is that the current buildings' designs do not accommodate six to ten feet (1.8 to 3.0 meters) of recommended safe distance between occupants, e.g., corridors, elevators, stairwells, or cubicles. Occupants interact with their buildings more frequently, e.g., through touch screens, increasing the risks of deposited virus particles, which can survive on the surfaces for a few hours to five days (Awada et al., 2021).

However, while there is more evidence of the transmission of SARS-CoV-2 through droplets, more research is required to understand other modes of transmission, such as via surfaces, the prevention incorporated into the building design and operation, and how long prevention measures will be implemented (Awada et al., 2021). Furthermore, to complement the engineering controls to reduce the risk of transmission, Morawska et al. (2020) suggest minimizing the number of people in the same environment, even though there is no specific value for the number of people who could share the same space during pandemics as the identified gap.

To sum up, these discussions underscored the significance of ventilation in mitigating COVID-19 transmission risks, focusing on strategies for HVAC-equipped buildings and the challenges public spaces pose. The discussions emphasized the link between ventilation, indoor air quality, and the need for interventions guided by HVAC engineers. Air filtration, CO2 monitoring, and temperature control were also explored, as were air recirculation risks and the role of air cleaning technologies. Lastly, spatial configurations influencing human-building interactions and virus transmission were considered.

From a healthy building perspective, studies shared that some of the healthy building foundations were similar to the strategies for mitigating airborne transmission, which are: a) ventilation, including air filtration; b) air quality, including air quality monitoring for pollutants; and c) thermal health, including temperature and humidity control. Acknowledging the strength of these foundations in building codes would be considered an excellent opportunity to address future pandemics.

2.6 RISK-RESPONSIVENESS AND RISK-RESPONSIVE FRAMEWORK

The Centers for Disease Control and Prevention (CDC) (2022) defined six factors that influence the risk of COVID-19 transmission based on higher, moderate, or lower risks: 1) duration of exposure, 2) coughing or heavy breathing, 3) symptomatic condition of the infected person, 4) mask quality, 5) ventilation and filtration, and 6) distance from the infected person. Due to the nature of office working environments, this discussion focuses on the risk factors of ventilation and filtration and the distance from the infected person.

Regarding ventilation and filtration, the CDC underscored that using more outdoor air can decrease the risk of transmission. A well-ventilated indoor space is categorized as a moderate risk, and poorly ventilated indoors are at a higher risk for COVID-19 transmission. The CDC also recognized that being closer to someone infected with COVID-19 increases the risk of transmission. Crowded settings can raise the likelihood of being close to someone with COVID-19. In this situation, a distant distance is categorized as a lower risk. In contrast, a moderate distance is considered a moderate risk, and very close to touching distance is regarded as a higher risk. These crowded and very close distances were considered possibilities in office working environments.

The term “responsiveness” (noun) refers to the quality of having a reaction to something or someone, especially a quick or positive reaction (Cambridge Dictionary, 2024), where the origin of the word “response” according to the United Nations Office for Disaster Risk Reduction/ UNDRR (2007) means “actions taken directly before, during, or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety, and meet the basic subsistence needs of the people affected.” Several studies on COVID-19 discuss the term “responsiveness” as a response to adapt to any emerging future scenario (Itma & Monna, 2022), particularly in disease threats such as pandemics (Neogi & Preetha, 2020) to overcome the current vulnerability to mitigate unexpected and unprecedented challenges (Łukasik & Porębska, 2022).

Based on these studies, I proposed the term “risk-responsiveness” as a means of responding quickly to airborne transmission, including COVID-19 risks in office building environments in the future.

Then, I also proposed the term “risk responsive framework,” or RRF, as a structure or an approach built by using the finalized risk-responsiveness factors. The use of RRF is to evaluate the current responsiveness levels of building codes based on their ability to mitigate airborne transmission, including COVID-19, in the future. This research aims to identify the factors determining the building code's risk-responsiveness of airborne transmission, including COVID-19, and use the factors in RRF to perform code examinations to understand the risk-responsiveness levels for mitigating future risks.

2.7 MULTI-CRITERIA ANALYSIS (MCA) AND DELPHI METHOD

Considering the inherent complexity of building codes and health requirements, the relationship between each requirement must be taken into account, specifically to determine whether each requirement has a similar or different weight and rank to determine a priority scale.

To understand each factor's weight in a group of requirements, multi-criteria analysis (MCA), also known as multi-criteria decision making (MCDM) or multi-criteria decision analysis (MCDM/MCDA) (Kurka & Blackwood, 2013), can support the multi-criteria decision-making process. MCA can be defined as a formal, structured approach for individuals or groups to determine overall preference among alternative options by considering multiple criteria and indicators (Kurka & Blackwood, 2013). MCA is used to solve complex problems by identifying a single most preferred option, ranking alternative options, and determining acceptable options. The literature shows that MCA is a preferred tool to support decision-making given that numerous and sometimes conflicting evaluations caused by rapid technological and economic growth have resulted in complex decision-making problems (Toloie-Eshlaghy & Homayonfar, 2011).

The broad use of MCA in various fields, such as transportation and logistics, business and financial management, management, and strategic planning, project management and evaluation, and environment management (Toloie-Eshlaghy & Homayonfar, 2011), has been more recently highlighted in the sustainable engineering field, which considers more environmentally focused solutions in the construction of facilities (Stojčić et al., 2019). The literature suggested the broad use of MCA in building-related fields for assessment of overall building performance (Alizadeh et al., 2018; Balcomb & Curtner, 2000; D'Cruz & Radford, 1987; Harirchian et al., 2020; Soebarto & Williamson, 2001), integrated green technologies (Si et al., 2016) and specific building components and technologies, such as wall cladding (Friedrich & Luible, 2016) and wall insulation (Ruzgys et al., 2014).

A key to the MCA process is assigning weighting and ranking criteria (Odu, 2019). This procedure is categorized in two ways: 1) direct weighting methods, such as assigning scales, ranking weight, or point allocation procedures, and 2) indirect approaches, such as weight derived from theories and mathematical methods. In particular, Odu (2019) notes that assigning ordinary ranks to the different criteria under consideration for decision-makers is preferable to assigning a relative numerical weight.

Weights assigned to criteria in multi-criteria evaluation can have qualitative and quantitative data to achieve more accurate decision-making, yet need to anticipate the influence of the decision-maker's preferences. To prevent any potentially biased preference, assigning a numerical scale to transform qualitative data into quantitative data is preferable, for example, a 1 to 9 scale where 1 = equal importance and 9 = extreme importance (Odu, 2019; Saaty, 1977).

Weight classifications can be grouped into three categories: subjective, objective, and integrated or combined weighted methods (Ginevičius & Podvezko, 2005; Odu, 2019). Subjective weight determination is based on expert opinion, whose function is to get subjective judgments. It is normal to present decision-makers with a set of questions in the process. The main disadvantage of this method lies in its time-consuming nature, especially when there is no agreement between decision-makers involved in the problem under consideration. In addition, the subjectivity of human judgment can result in certain levels of inaccuracy even with the most careful measurement (Olson, 2006).

The most commonly used subjective weighted methods are a) the point allocation method, b) the direct rating method, c) the ranking method, d) pairwise comparisons (AHP), e) the rating method, f) the swing method, g) the Delphi method, h) the nominal group technique, and i) the Simple Multi-Attribute Ranking Technique (SMART) (Odu, 2019). One particular method, Simple Additive Weighting (SAW) or Weighted Sum Method (WSM), is one of the simplest MCA methods and requires minimal explanation (Kaliszewski & Podkopaev, 2016). Some advantages of SAW include providing faster and more reliable results, which can be useful for policymakers in understand and addressing problems that are complex and unstructured (Nurmalini & Rahim, 2017).

Sustainable or health-focused building rating tools such as LEED, Fitwell, or BREEAM (McArthur & Powell, 2020b) often use the subjective point method for weighted decision-making. This method involves obtaining points based on the list of performance criteria in several categories. Each category has a different weight, as proven by the maximum number of points collected. For example, energy efficiency and indoor air quality mostly have more significant weight than other criteria.

The Delphi method has emerged as another preferred method in the MCA research (Odu, 2019). It is a method for structuring group communication to effectively allow individuals to deal with a complex problem (Linstone & Turoff, 2002). It aims to reach a consensus among a group of experts (Chan et al., 2001). The process is iterative through rounds of feedback comprising experts' opinions and judgments on a particular subject (Hallowell & Gambatese, 2010). Usually conducted through questionnaires, the interaction is managed anonymously (Martino, 1983;

Robinson, 1991; Sourani & Sohail, 2015). The Delphi method depends on the collective knowledge and experience of selected experts in each given area (Ameyaw et al., 2016), with two distinctive strengths:

a) Compared to interviews, the Delphi method is a more reliable and efficient alternative for solving cases with high uncertainties (Chan et al., 2001; Sourani & Sohail, 2015).
b) Compared to questionnaires, the Delphi method offers better interaction with respondents and could potentially explain complex problems (MacCarthy & Atthirawong, 2003; Mullen, 2003).

The selection of panelists, number of expert panelists, number of rounds, and anonymous feedback process are the key determinants of the Delphi method (Ameyaw et al., 2016).

The Delphi method is open to modification to adjust to the type of research. For quantitative research, the Delphi method is combined with statistical analysis methods, such as fuzzy sets, the analytical hierarchy process (AHP), or the analytical network process (ANP) (Ameyaw et al., 2016). These Delphi modifications were common in construction engineering and management research. For example, combining the Delphi method with interview techniques, such as participatory action research (PAR), during the data collection for qualitative research. This combination is to understand the changing perceptions of managing the health system (Fletcher & Marchildon, 2014). This combination can also increase the applicability of the Delphi method in various fields.

To sum up, MCA is a suitable method to solve complex problems involving individuals or groups to determine the overall preference among options with identified criteria and indicators. MCA has proven its flexibility in light of its broad adoption and application in various fields. Weighting and ranking in MCA transform the data collected for more straightforward analysis;

however, this process can be time-consuming in its attempt to reach a consensus. Therefore, the Delphi method can shorten the process by providing more specific key determinants, making it more reliable.

Chapter 3. RESEARCH METHODOLOGY

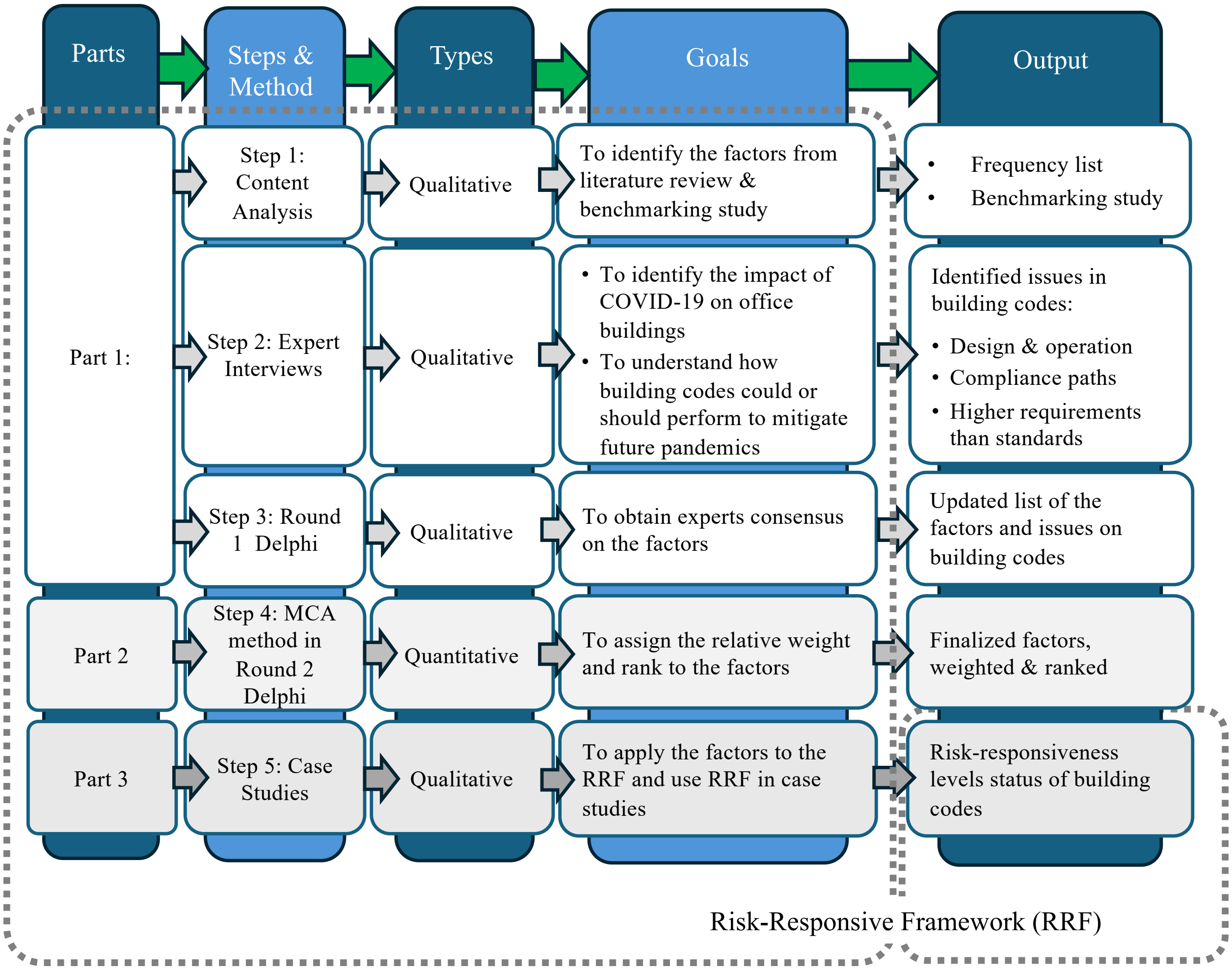
In Chapter 2, I explored the literature on building codes in the U.S. and their role in preventing airborne transmission, including during COVID-19. I also reviewed the development of healthy building perspectives, building rating tools, control measures to reduce airborne transmission risks, risk-responsive criteria, Risk-Responsive Framework (RRF), and the use of multi-criteria analysis for this research. Next, Chapter 3 presents the research methodology employed for this research. It starts with explaining the use of mixed qualitative and quantitative approaches, methods, goals, and output from each part of the research methodology. The qualitative approach covers content analysis, expert interviews, the round 1 Delphi method, and the U.S. case studies. The quantitative approach covers the round 2 Delphi method, where I used SAW/WSM to weigh and rank the risk-responsiveness factors.

3.1 RESEARCH METHODOLOGY

This research employs a mixed qualitative and quantitative approach. The goal of this mixed approach is to obtain a better understanding of the factors that determine building codes' risk-responsiveness in mitigating airborne disease transmission, including COVID-19, in office buildings. Figure 3.1 on the next page illustrates the research framework for this study, including the sequences, techniques used, goals, and output.

Part 1 entails using qualitative approaches in content analysis (Step 1), expert interviews (Step 2), and Delphi Round 1 data collection (Step 3). Part 1 is designed to identify determining factors that have the potential to mitigate airborne disease transmission, including COVID-19, based on various sources and reach experts' consensus. Part 1 responds to the first research question, "What are the factors that determine the building code's risk-responsiveness?"

Part 2 involves a quantitative approach to assign the relative weighting and ranking of the factors from Delphi Round 1. Part 2 seeks to finalize the factors to construct RRF and responds to the second research question, “How are the current risk-responsiveness levels of building codes evaluated?”



Parts	Steps & Method	Types	Goals	Output
Part 1:	Step 1: Content Analysis	Qualitative	To identify the factors from literature review & benchmarking study	• Frequency list • Benchmarking study
	Step 2: Expert Interviews	Qualitative	• To identify the impact of COVID-19 on office buildings • To understand how building codes could or should perform to mitigate future pandemics	Identified issues in building codes: • Design & operation • Compliance paths • Higher requirements than standards
	Step 3: Round 1 Delphi	Qualitative	To obtain experts consensus on the factors	Updated list of the factors and issues on building codes
Part 2	Step 4: MCA method in Round 2 Delphi	Quantitative	To assign the relative weight and rank to the factors	Finalized factors, weighted & ranked
Part 3	Step 5: Case Studies	Qualitative	To apply the factors to the RRF and use RRF in case studies	Risk-responsiveness levels status of building codes

Figure 3.1. Research Framework and Sequences

Finally, Part 3 uses a qualitative approach for case studies. Part 3 tests and validates the factors included in RRF by applying them to U.S. case studies. The result of Part 3 is the status of risk-responsiveness levels in U.S. building codes, which responds to the third research question, “What is the status of U.S. building codes in terms of risk-responsiveness levels?” From these results, a conclusion is developed that responds to the final research question, “What recommendations can be provided to prepare for similar airborne disease crises in the future?”

3.1.1 Step 1: Content Analysis

This research utilizes a content analysis method on the literature review. Content analysis has been broadly accepted as a technique for making inferences by objectively and systematically identifying specified characteristics of messages and allowing inferences to be made, which can then be corroborated using other methods of data collection (Stemler, 2001). Content analysis is preferable due to the absence of techniques to infer from symbolic data that would be either too costly, no longer possible, or too obtrusive (Krippendorff, 2004). Since the literature review in this research intends to make inferences on factors that have the potential to mitigate airborne transmission in office buildings, the content analysis method was selected. Moreover, this method is known for its high flexibility in determining whether it can be either empirically or theoretically driven (Stemler, 2015).

To be more specific, the goal of content analysis in this study is to investigate factors contributing to the risk of airborne transmission diseases, including COVID-19. I performed content analysis on the literature published from 2020 to 2022, spanning from the early COVID-19 pandemic to the development of this research. I utilized a summative content analysis to generate keywords to contextualize and compare across the literature. These keywords were used to determine the publications or literature for review.

For example, the search strategy used “COVID-19” and “office building” as search keywords. The searches were conducted on several databases, such as EBSCO, PubMed Central, ProQuest, and Google Scholar. Based on this search, I compiled a frequency table of identified factors relevant to mitigating airborne transmission in office buildings. The results of the content analysis were developed and formulated for expert interviews. Chapter 4 will present the frequency table as part of the results.

In addition, I performed a benchmarking study between the identified factors vs. building rating tools in the U.S. The benchmarking study aims to provide a more comprehensive understanding of healthy building requirements responding to airborne transmission in the voluntary building rating tools. This study includes the sustainable building rating tool LEED v4, two human-health and well-being rating tools, WELL and Fitwel, and the emerging indoor air quality rating tool RESET. Then, I compared the benchmarking study results to the expert interview results and used them to develop questionnaires for the Delphi method.

3.1.2 Step 2: Expert Interviews

The expert interviews method in this research was used to gather information from experts in building design and engineering on the COVID-19 impact on office buildings. A semi-structured expert interview method was selected considering several advantages (Merriam & Tisdell, 2016) as follows:

- Questions are more flexibly worded, or interviews can be a mix of more and less structured questions; usually, specific information is desired from all participants.
- Guided by a list of questions to be explored, a determined wording or order of questions is not required.
- Allows the researcher to respond to a situation at hand during the emerging worldview of participants and to new ideas of the topic.

Figure 3.2 describes the expert interviews procedure used in this research. In the development phase, I developed the interview questions based on findings from the literature review. Then I established a set of interview protocols as a guideline during the process. As for the expert pool, I compiled a dataset of various group stakeholders, including government agencies (state and city levels), building code developers such as the International Code Council (ICC), building professionals and engineers related to HVAC design, experts from architectural firms, representatives from ASHRAE, experts from mechanical engineering firms, and professors involved in research related to airborne transmission. Additionally, I sought advice and recommendations from these experts on other potential experts who might be interested in participating in this research.

During the request participation phase, I sent an email to experts on the expert pool asking for participation in interviews, and I sent a second email as a reminder after one week. Once I received their confirmation, I sent the interview questions.

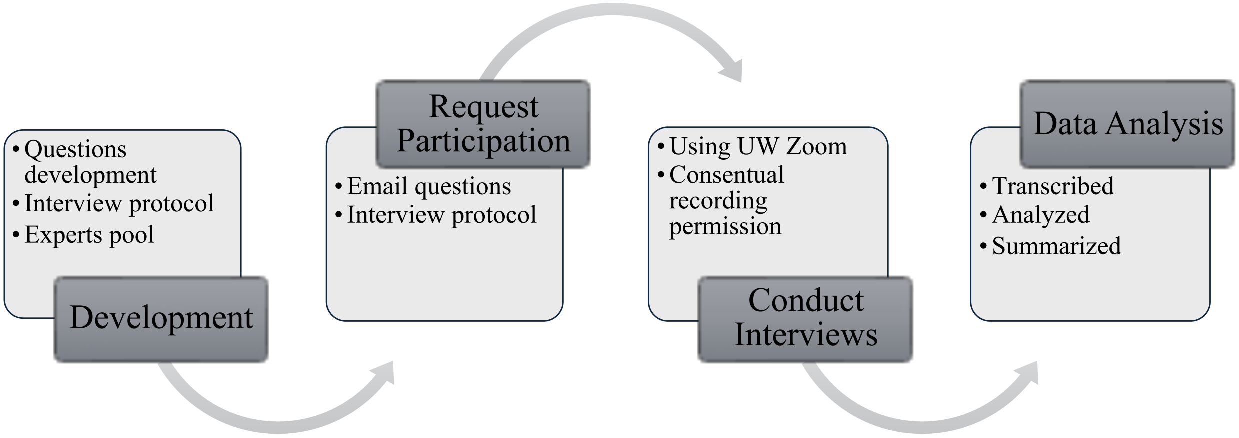


Figure 3.2. Expert Interviews Procedure

The expert interviews were conducted synchronously (real-time) through a computer-mediated communication platform, Zoom, connected through the University of Washington account (UW). The reasons for using UW Zoom are as follows:

- Secure connection, confidentiality, and alignment with the institution’s policy conduct.
- Availability of audio and video recording features and transcript-ready option.

I used the University of Washington (UW) Zoom platform to overcome several challenges primarily during the pandemic, such as working-from-home situations and geographical reasons. In addition, recorded interviews enabled me to explore or review nonverbal cues later during data analysis. For interview smoothness, I developed probes to guide the interview process.

Selected experts were invited to provide their perspectives and insights on COVID-19 and office buildings. The selection has several key factors:

- Proven knowledge and experience, e.g., expertise in building code development and adoption process, expertise in building engineering specifically related to HVAC and health requirements for office building design and operations, member of esteemed professional associations, or involved in research related to airborne transmission risks and indoor air quality in buildings.
- Resides in U.S. jurisdiction.
- Willingness to participate.
- Sufficient time to participate.
- Practical communication skills.

The questions covered the following points in the interviews:

a) The current impact of COVID-19 on office building design and operation.
b) How building codes could and should prevent airborne transmission in the future.
c) Current building codes are primarily intended for building design while building performance during operation is also essential.
d) Type of building code's compliance path: prescriptive, performance-based, and hybrid codes in the context of anticipating future health crises.

e) Several healthy building requirements mitigate airborne transmission, such as higher ventilation rates, higher air filtration levels, and maintaining indoor air quality.
f) Improvements or updates in building codes to respond to the COVID-19 transmission risks.
g) Opinions on the factors identified from content analysis.

I used the paid online transcription software Happyscribe, which ensures information confidentiality. Then, I downloaded, transcribed, and summarized the audio and video files of the interviews. These questions are attached in Appendix A.

To sum up, the expert interview method presents some advantages by (1) enhancing the conception of building codes' role during the COVID-19 pandemic, (2) receiving experts' responses on the challenges of building code implementation in responding to airborne transmission, including COVID-19, and (3) recognizing several areas for improvement for the next Delphi method for data collection.

3.1.3 Step 3&4: Delphi Data Collection Method

The Delphi method in these steps is to structure expert group communications to allow each expert to deal with the problem (Linstone & Turoff, 2002) and reach a consensus among them (Chan et al., 2001). In addition, the Delphi method has the ability to modify changes to the type of research common in the construction engineering and management research field (Ameyaw et al., 2016).

I intended to invite the experts to at least two Delphi method rounds to obtain consensus on the factors determining risk-responsiveness and the additional questions related to building codes. I used SurveyMonkey's online questionnaire platform because of it can collect and store data and features in creating a survey, including templates and question banks.

Then, I utilized the SAW/WSM method to assign weighting and ranking of factors from the previous Delphi method. The SAW/WSM method aimed to understand the complexity and relationship between each factor, which must be considered. This method is one of the simplest MCA methods. It is known for its flexibility when combined with other methods in the MCA analyses (Toloie-Eshlaghy & Homayonfar, 2011). The SAW/WSM is also known as the most widely applied approach (Mela et al., 2012; Odu, 2019).

The following section explains the Delphi method Round 1 and Round 2 data collection plans in more detail.

3.1.3.1 Delphi Round 1: Factor Agreement

The goal of Round 1 Delphi is to reach an agreement on the identified factors from content analysis, and building codes-related questions obtained from the expert interviews. The questionnaires were developed, tested, and revised prior to online distribution. I used SurveyMonkey, an online survey platform, to manage the online questionnaire and received the responses from the experts. Additionally, SurveyMonkey helped survey participants overcome geographical challenges. Each participant received an invitation email with a link to the questionnaire page. Figure 3.3 depicts the Round 1 analysis procedure and explains results retrieval, agreement analysis, and use of the results for developing the next round of Delphi method data collection.

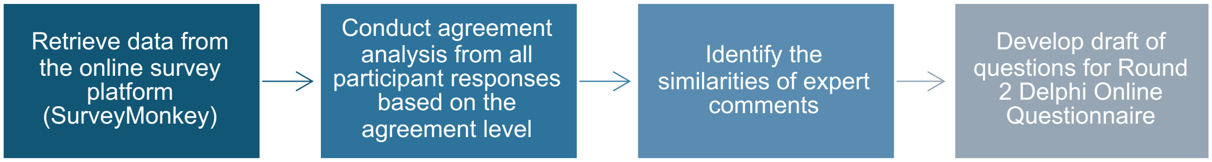


Figure 3.3. Analysis Procedure for Delphi Round 1 Result

3.1.3.2 Delphi Round 2: Weighting and Ranking Using SAW/WSM

The goal of Round 2 Delphi is to assign weightings and rankings to the agreed-upon factors from Round 1. In this process, I used Microsoft Excel spreadsheets to calculate the weighting and ranking of expert responses using the SAW method. Figure 3.4 describes the Round 2 analysis procedure.

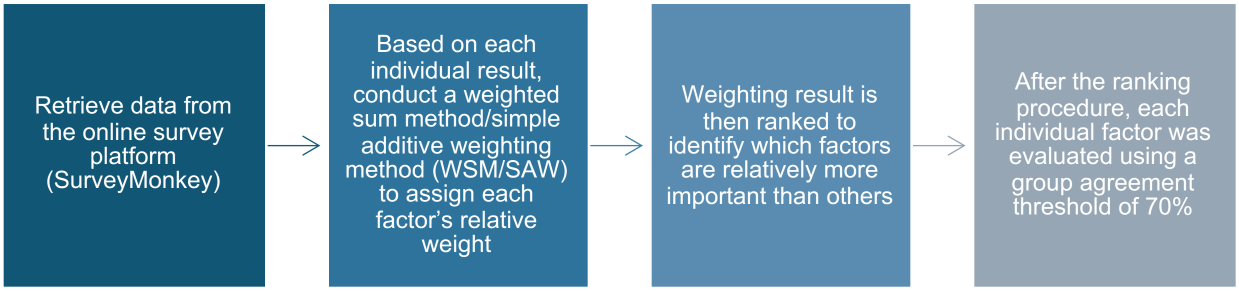


Figure 3.4. Analysis Procedure for Delphi Round 2 Result

3.1.3.3 *Weighting and Ranking Procedure*

The goal of the weighting and ranking using the SAW method is to establish individually relative weights of importance and then continue to assess the agreement level of responses. The procedure for SAW follows the equation below:

$$Ai = \sum_{j=1}^{m} wj \; (x_{ij})_{normal}$$ Equation 3.1

Where Ai is the ranking of i^{th} alternative, x_{ij} is the normalized values of a_{ij}, and wj is the weight of j_{th} criterion (Vafaei et al., 2022). In this method, each alternative or "criteria" is assessed with regard to every attribute. Then, each expert response is calculated using SAW, which is normalized in the decision matrix. Using a simple statistic (median value), group consensus is obtained. The final results were the identified factors to mitigate airborne transmission, including COVID-19, in office buildings, ranked from the highest to the lowest.

3.1.4 Step 5: The U.S. Case Studies

The agreed-upon factors from the Delphi Method data collection were used in examining the risk-responsiveness levels of building codes in the sampled states and cities. I used a collective case study by taking samples from 30 states and 30 cities in the U.S. The collective case studies, which include multiple case studies, sought to gain in-depth insights into the research topic (Creswell, 2007; Kekeya, 2021), focusing on both within and across cases (Kekeya, 2021). This approach is suitable for understanding how the current building codes compare with factors that promote requirements to mitigate airborne transmission.

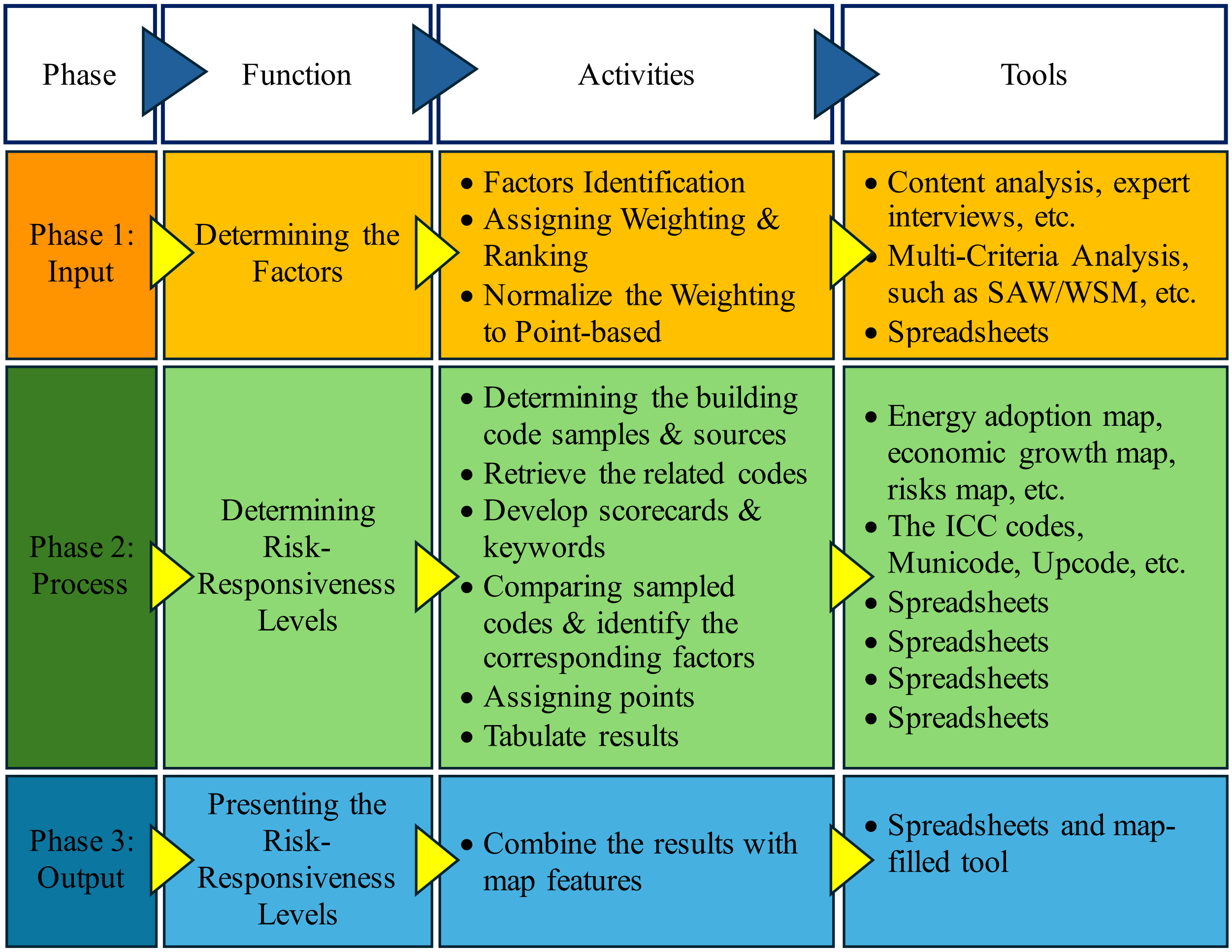
The sampled states were based on the state-level energy code adoption status, while the sampled cities were chosen based on the criterion of being the largest city within each state. The U.S. Department of Energy (DOE) performs the energy code adoption status and tracking analysis (DOE, 2024), from which I derived the status data. The energy code adoption status was selected as a proxy for the anticipated response to future risks in building practices, representing more advanced building code practices. I chose this approach because it is anticipated that airborne transmission risks, such as COVID-19, will necessitate more advanced building code practices.

I gathered building code data from various sources, such as from the International Code Council (ICC) database, which provided additional information on the year of adoption status and a variety of codes, such as mechanical codes.

The examination of the building codes uses the comparison between factors and the codes to assign points and obtain the risk-responsiveness levels. The results of the code examination in the sampled states and cities will determine the types of strategies expected or recommended to improve risk-responsiveness levels.

3.2 RISK-RESPONSIVE FRAMEWORK (RRF)

Figure 3.1 shows RRF activities within the dashed-line boundary. I used RRF as a structure or approach to guide the overall process of code examination. RRF consists of three phases: 1) Phase 1: determining the factors, 2) Phase 2: determining the risk-responsive levels, and 3) Phase 3 presenting the results. Figure 3.5 lists RRF phases, activities, and tools involved.



Phase	Function	Activities	Tools
Phase 1: Input	Determining the Factors	• Factors Identification • Assigning Weighting & Ranking • Normalize the Weighting to Point-based	• Content analysis, expert interviews, etc. • Multi-Criteria Analysis, such as SAW/WSM, etc. • Spreadsheets
Phase 2: Process	Determining Risk-Responsiveness Levels	• Determining the building code samples & sources • Retrieve the related codes • Develop scorecards & keywords • Comparing sampled codes & identify the corresponding factors • Assigning points • Tabulate results	• Energy adoption map, economic growth map, risks map, etc. • The ICC codes, Municode, Upcode, etc. • Spreadsheets • Spreadsheets • Spreadsheets • Spreadsheets
Phase 3: Output	Presenting the Risk-Responsiveness Levels	• Combine the results with map features	• Spreadsheets and map-filled tool

Figure 3.5. RRF Phases and Tools

RRF lists more details on activities and the tools required to perform the function in each phase. The tools described here were identified and used during this research development; therefore; they could be adjusted or expanded in different research or case studies as needed.

In relation to the research methodology, RRF has some similarities. Figure 3.6. illustrates the overlapped RRF activities in Part 1, Part 2, and Part 3 of the research methodology.

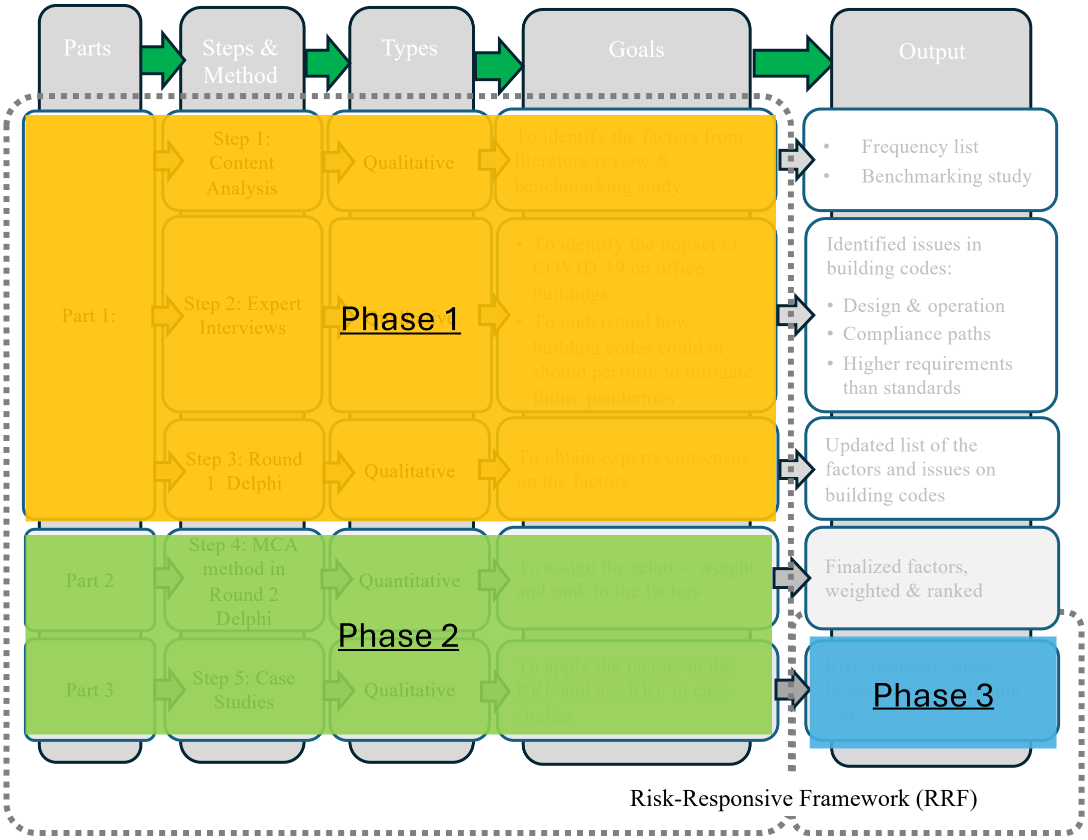


Figure 3.6. The Overlap Between RRF and Research Methodology

This figure explains the boundaries between RRF and the research methodology. In this figure, Phase 1 RRF determining the factor included Part 1 and Part 2 of the research methodology, which covers factors identification until assigning weighting and ranking of identified factors. Phase 2 RRF, essential in determining risk-responsive levels, included code examinations from determining reliable sources, developing scorecards, performing code examinations, and tabulating the final results of examination building codes. In the last phase, Phase 3, RRF covered the presentation of results by suggesting the use of a map-filled tool to obtain a greater understanding.

Chapter 4. RESULTS

Having established a robust research methodology through the use of mixed qualitative and quantitative approaches, including content analysis, expert interviews, and the Delphi method in Chapter 3, I will now present the research results. The Chapter 4 presents the results of the data collection and analysis. The data collection was performed based on a mixed qualitative and quantitative method involving content analysis, the Delphi method, and case studies. This chapter aims for the following:

1) Identify the determining factors in mitigating airborne transmission risks, including COVID-19, from the data collection methods (content analysis, expert interviews, and Delphi online questionnaires, as presented in Chapter 3) and present the final weighted and ranked factors.
2) Apply these factors to RRF and validate these factors by U.S. case studies.
3) Analyze experts' opinions about future building codes.

To follow these three intentions, the discussions were divided into three main parts. Figure 4.1 illustrates the data collection timeline from May 2022 to September 2023.

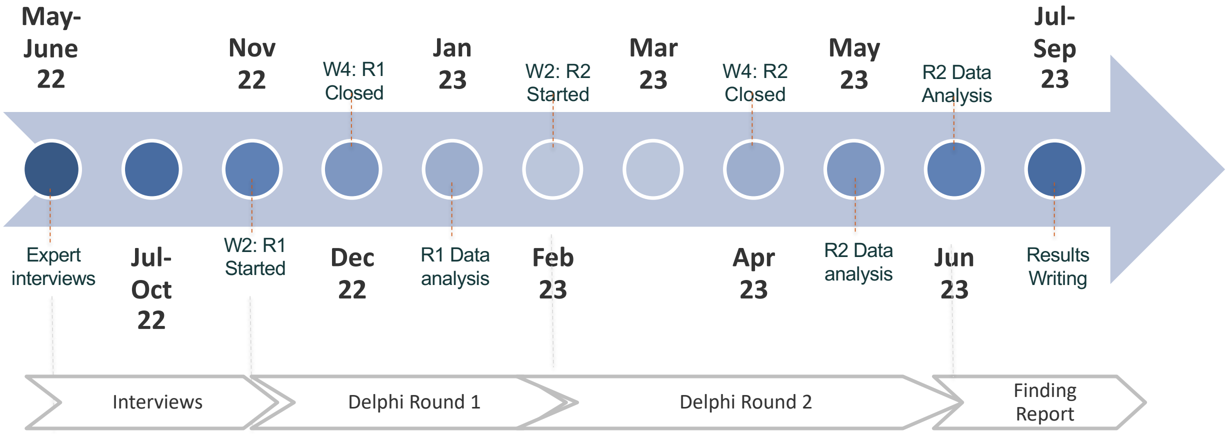


Figure 4.1. Data Collection Timeline

4.1 IDENTIFYING FACTORS

The identification of factors required a series of data collection methods involving content analysis, expert interviews, and two rounds of the Delphi method. The discussions of each of these method is presented in the following sections.

4.1.1 Content Analysis

Using “COVID-19” and “office buildings” as keywords, I performed a summative content analysis relevant to mitigating airborne transmission, including COVID-19, that added to the body of knowledge. From a total of 28 guidelines and 11 journal papers, it finally resulted in 16 guidelines by professional associations and 6 journal papers that were published from 2020 to 2022, The guidelines included in this content analysis are from the following professional associations:

- American Institute of Architects (AIA)

- American Society of Heating, Refrigerant, and Air-Conditioning Engineering (ASHRAE)
- Building Owners and Managers Association (BOMA)
- Occupational Safety and Health Administration (OSHA)
- International Facility Management Association (IFMA)
- Health organizations such as the World Health Organization (WHO)
- Centers for Disease Control and Prevention (CDC)
- National Institute for Occupational Safety and Health (NIOSH)

I grouped the results into several codes for categorization. The codes were developed to guide the content analysis process and to categorize the results based on the corresponding factors. Table 4.1 below lists the codes used for content analysis.

Table 4.1. Codes for Content Analysis

Code	Corresponding Factors
SPCE	Space management
ADIS	Air disinfection
AFIL	Air filtration
MIAQ	Monitoring indoor air quality
OPCOM	Building operation compliance
TRH	Temperature and relative humidity (RH)
VENT	Ventilation
CLM	Cleaning and disinfecting management
OCC	Occupants' tracing management

Tables 4.2 through 4.8 list the reviewed guidelines and journals in more detail in the following pages. Table 4.2 present content analysis result that categorized in "space management" factor, which aimed to maintain a safe distance and avoid infection risk between occupants in office settings. There were 33 results identified, ranging from limiting the number of occupants in the

working area, setting a safe distance in crowded spaces, modifying seating layout and workspace, separating exit and entrance routes, and providing physical barriers to maintain a safe distance and direct contact.

Table 4.3 present results on “air disinfection” factor. It aimed to disinfect the air in high-risk indoor settings, such as crowded spaces where maintaining physical distance is difficult. Air disinfection uses UV technology, including supplemental UV germicidal irradiation for mechanical paths or an upper room for high-risk indoor settings or crowded spaces. A UV light is considered effective but has safety concerns for human health. There were 13 results identified, ranging from UV technology, including supplemental UV germicidal irradiation for mechanical paths or an upper room for high-risk indoor settings or crowded spaces.

Table 4.4 presents the results of “air filtration” factor. It aimed to capture small particles and viruses, including COVID-19, to prevent the spread of COVID-19. 20 results were identified, covering the use of higher air filtration levels, such as at least MERV-13, or the use of a HEPA portable air filter.

Table 4.5 presents the results of “monitoring IAQ” factor, which aimed to detect the potential crowd in specific spaces, a proxy for the need for more outdoor air. 7 results were identified. These results range from monitoring of RH temperature and CO2 levels for occupancy and activity with a suggested indoor limit of 450 ppm instead of 100 ppm based on the pandemic guidelines. Table 4.5 also presents the results of “building operation compliance” factor. 5 results were identified, including performing systems equipment commissioning to check issues, building systems, and operation protocols for safer operation in compliance with engineering guidelines, such as ASHRAE standards.

Table 4.2. Reviewed Guidelines and Journals on Space Management

Factors	Code	Contents	Guidelines							Journals				Guidelines										Journals		Frequency
			AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Brittain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
SPACE MANAGEMENT	SPCE	Physical barrier between desks (i.e.: cobbles, shelves, etc.)	1	1												1										3
	SPCE	One person in every other sitting desk									1	1														2
	SPCE	Physical barriers in personal workspace (i.e.: partitions/plexiglass)	1	1																						2
	SPCE	Temporary partitions/tall booths in dining area	1	1																						2
	SPCE	Temporary, movable partitions to subdivide large working spaces (i.e.: auditorium)	1	1																						2
	SPCE	Limiting the occupant density										1							1							2
	SPCE	6-feet distances in dining room/break room	1													1										2
	SPCE	6-feet distances of plumbing fixtures in restrooms	1																					1		2
	SPCE	Reduce the amount of equipment	1																							1
	SPCE	Limiting capacity at the same time at the same area								1																1
	SPCE	Re-orienting the working desks facing one direction	1																							1
	SPCE	Interior expansion for queuing	1																							1
	SPCE	Aerosolized particles are possible to transmit beyond six feet									1															1
	SPCE	Short range pathogen is about 1.5 m/5 feet										1														1
	SPCE	Installing physical barriers, such as clear plastic and sneeze guards						1																		1
	SPCE	Decrease density as part of social distancing plan							1																	1
	SPCE	Stay 6-feet minimum with others who don't live in the same space																					1			1
	SPCE	Spatial connectivity configuration corresponds to the microbial spread									1															1
	SPCE	Exit and entrance separation of the building	1	1			1																			3
	SPCE	Limited number of people in the elevator at one time	1	1			1																			3
		TOTAL																								**33**

Table 4.3. Reviewed Guidelines and Journals on Air Disinfection

			Guidelines							Journals				Guidelines										Journals		Frequency
Factors	Code	Contents	AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Brittain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
AIR DISINFECTION	ADIS	Installing UV germicidal irradiation in mechanical ventilation	1	1						1	1	1														5
	ADIS	Installing UV C during non-occupant hour	1	1							1															3
	ADIS	Consider installing UG germicidal irradiation for mechanical ventilation paths or in upper room to indirectly treat air	1																							1
	ADIS	The use of UVGI as a supplemental treatment in poor room ventilation															1									1
	ADIS	The use of UVGI is considered for high-risk indoor setting such as crowded spaces, spaces when people must take off masks areas where it is difficult to keep 6 feet distance															1									1
	ADIS	The use of UVGI to disinfect indoor air																						1		1
	ADIS	The use of UV light in reducing virus is 90% effective, but has safety concerns to human's health									1															1
		TOTAL																								**13**

Table 4.4. Reviewed Guidelines and Journals on Air Filtration

			Guidelines							Journals				Guidelines										Journals		Frequency
Factors	Code	Contents	AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Britttain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
AIR FILTRATION	AFIL	Confirming the ventilation (minimum outdoor air) and filtration (MERV 13 or better) for re-opening																								0
	AFIL	Using portable HEPA filter	1	1						1		1	1													5
	AFIL	Improvement air filtration level (MERV 16 for recirculated air ducts, MERV 13/14 for filtering airborne viruses)	1	1	1							1														4
	AFIL	Daily cleaning and maintenance of air filtration	1	1						1		1														4
	AFIL	MERV 13 has the potential to remove the virus since it is likely aerosolized									1															1
	AFIL	Use combination of air filter and cleaners at least MERV 13, or better levels of performance for air recirculated by HVAC system																			1					1
	AFIL	Increase level of air filtration in AHU, to the extent the systems and fans can overcome the additional pressure	1																							1
	AFIL	MERV 13 is a good balance between indoor air quality and operational cost for medium sized office building																							1	1
	AFIL	Improve the mechanical air filter as high as possible as recommended by ASHRAE tables															1									1
	AFIL	The use of HEPA filter and portable HEPA cleaners to enhance air cleaning in a higher risk area															1									1
	AFIL	The use of HEPA filter or portable air cleaners to eliminate 99.7% of smaller airborne particles																						1		1
		TOTAL																								**20**

Table 4.5. Reviewed Guidelines and Journals on Monitoring IAQ and Building Operation Compliance

			Guidelines							Journals				Guidelines										Journals		Frequency
Factors	Code	Contents	AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Brittain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
MONITORING IAQ	MIAQ	Monitor relative humidity, temperature and CO2 level (RH: 40-60%)	1	1						1	1	1	1													6
	MIAQ	Monitoring CO2 as proxy to indicate number of occupants, activity, and the need of outdoor air. The appropriate limit for indoor CO2 suggested is 450 ppm, lower than non-pandemic guideline 1000 ppm																1								1
		TOTAL																								**7**
BUILDING OPERATION COMPLIANCE	OPCOM	Maintain building operation refer to ASHRAE standards																						1		1
	OPCOM	Perform system commissioning for the equipment, systems, and protocols to check possible issues on re-opening buildings to comply with ASHRAE standards																		1						1
	OPCOM	Run the building HVAC system at the maximum airflow for 2 hours prior and after building occupation time													1											1
	OPCOM	Proper operation of HVAC, e.g., running the system 2 hour prior and after operation																						1		1
	OPCOM	Running the system before and after occupancy hour, to achieve 3 ACH of outdoor air, or equivalent including effect of outdoor air, particulate filtration, and air cleaners																		1						1
		TOTAL																								**5**

Table 4.6. Reviewed Guidelines and Journals on Ventilation

			Guidelines							Journals				Guidelines										Journals		Frequency
Factors	Code	Contents	AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Britttain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
VENTILATION	VENT	Increase outdoor air ventilation to reduce the recirculation air	1	1	1					1	1	1	1													7
	VENT	Ventilation system for acceptable indoor air quality	1	1						1	1	1														5
	VENT	Increase ventilation rates and air changes	1	1							1	1														4
	VENT	Provision of operable windows and natural ventilation	1	1						1			1													4
	VENT	Utilize operable windows for natural ventilation	1	1		1																1				4
	VENT	Fresh air optimization as much as possible			1							1								1						3
	VENT	Prioritizing fresh air than recycled air, with adjustment in HVAC system	1	1																						2
	VENT	Increase ventilation rates in the work environment						1																1		2
	VENT	Higher outdoor air fraction and higher air exchange rates to dilute indoor contaminants	1																							1
	VENT	Increase ventilation rates and fresh air intakes if outdoor air quality and thermal conditions are acceptable	1																							1
	VENT	Increase ventilation rates when needed								1																1
	VENT	Preliminary study supports the increase rate to 8-10 l/s per person is sufficient ventilation in minimizing COVID-19 transmission												1												1
	VENT	Increase airflow							1																	1
	VENT	Natural ventilation for infection control (Natural)				1																				1
	VENT	Limiting number of occupants per HVAC zone	1	1																						2
	VENT	Avoid the room fans to blow directly to occupants	1	1																						2
	VENT	Vent toilets separately	1	1																						2
	VENT	Prepare HVAC mitigation strategies			1																					1
	VENT	Encouraging the natural ventilation to dilute the air when no mechanical ventilation is available	1																							1
	VENT	Prioritize the use of meeting rooms that have access to operable windows (windows)	1																							1
	VENT	Conducting pre- and post-occupancy flushing strategy			1																					1
	VENT	Flush the building two hours before and after office hour	1	1																						2
		TOTAL																								**49**

Table 4.7. Reviewed Guidelines and Journals on Temperature and RH

Factors	Code	Contents	Guidelines							Journals				Guidelines										Journals		Frequency
			AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Britttain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
TEMPERATURE AND RELATIVE HUMIDITY (RH)	TRH	Maintain the low relative humidity to lower virus survivability	1																							1
	TRH	Maintain and monitor relative humidity preferable in range 40-60%	1																							1
	TRH	Maintain low relative humidity in range 40%-60% according to ASHRAE and temperature between 17-18 C and RG 40%-70%																						1		1
	TRH	The virus survival rate when RH is in range of 40%-60% and should not be taken as the only measure in reducing the risk															1									1
	TRH	RH above 40% is detrimental in survival of many viruses and maintain the range 40%-60% may limit the spread and survival of SARS COV-2									1															1
	TRH	Early study suggests that air quality index, PM2.5, NO2 and temperatures are variables contribute in COVID-19 transmission												1												1
	TRH	Monitor RH preferably 40-60%, temperature and CO_2 levels regularly to identify and resolve issues quickly	1																							1
		TOTAL																								**7**

Table 4.8. Reviewed Guidelines and Journals on Disinfection Management Factors

			Guidelines							Journals				Guidelines										Journals		Frequency
Factors	Code	Contents	AIA, 2020	CDC, 2020	ASHRAE, 2020	WHO, 2020	BOMA, 2020	OSHA, 2020	IFMA, 2020	(Morawska et al., 2020),	(Dietz et al., 2020)	(Xu, Lo, Yu and Cao, 2020)	Britttain, Wood, and Kumar, 2020)	Li, 2020	CDC, 2021	OSHA, 2021	CDC, 2021	NCCEH, 2021	IFMA	ASHRAE, 2021	ASHRAEb, 2021	NIOSH, 2022	BOMA, 2022	Awada et al, 2021	Faulkner, 2021	
TEMPERATURE AND RELATIVE HUMIDITY (RH)	TRH	Maintain the low relative humidity to lower virus survivability	1																							1
	TRH	Maintain and monitor relative humidity preferable in range 40-60%	1																							1
	TRH	Maintain low relative humidity in range 40%-60% according to ASHRAE and temperature between 17-18 C and RG 40%-70%																						1		1
	TRH	The virus survival rate when RH is in range of 40%-60% and should not be taken as the only measure in reducing the risk															1									1
	TRH	RH above 40% is detrimental in survival of many viruses and maintain the range 40%-60% may limit the spread and survival of SARS COV-2									1															1
	TRH	Early study suggests that air quality index, PM2.5, NO2 and temperatures are variables contribute in COVID-19 transmission												1												1
	TRH	Monitor RH preferably 40-60%, temperature and CO_2 levels regularly to identify and resolve issues quickly	1																							1
		TOTAL																								**7**
OCCUPANTS TRACING MANAGEMENT	OCC	Requirement for the occupants to participate in tracing protocol as part of public health surveillance to minimize the airborne transmission risks by identifying the potential source and reducing the transmission impact to other office occupants.	1	1																						2
		TOTAL																								**2**

Table 4.6 presents the results from “ventilation” factor. It aimed to reduce the transmission of COVID-19 using various strategies for optimizing indoor air quality by focusing on building ventilation. 49 results were identified, including increasing outdoor air ventilation, increasing or adjusting ventilation rates and air changes, meeting acceptable indoor air quality, prioritizing fresh air over recycled air, adjusting HVAC system, diluting indoor contaminants with higher outdoor air fraction and exchange rates, etc.

Table 4.7 presents the results from Temperature and RH. It aimed to maintain RH between 40% to 60% is recommended to limit virus survivability, especially for SARS-CoV-2. 7 results were identified, including a regular monitoring of RH, the temperature at 17-18°C and CO2 levels, Lastly, Table 4.8 covers “cleaning and disinfection management” and “occupants tracing management.” The former factor aimed to minimize the risk of infection through surface cleanings of frequently touched surfaces during building operations. 16 results were identified, including implementing cleaning and disinfection protocols for high-touch surfaces like elevators and handrails and developing comprehensive cleaning and disinfection procedures for restrooms, hand sanitizer stations, etc. Two results were identified from the latter factor with the goal of reducing the spread of airborne transmission. These results aimed to identify potential sources and spread patterns that could affect other office occupants.

The content analysis led to the identification of the nine factors as most relevant to mitigating COVID-19 in office buildings. Based on the findings in Table 4.2 through Table 4.8, describes the identified factors that served as the basis for an interview questionnaire used during the next step of data collection, which is the expert interviews. Table 4.9 on the next page summarizes the description of the identified factors and the frequency of each factor from content analysis.

Table 4.9. Factors Description and Frequency

Factors	Description	Frequency (n)
Space management	Space management aims to maintain a safe distance and avoid infection risk between occupants in office settings. The strategies include limiting the number of occupants in the working area, setting a safe distance in crowded spaces, modifying seating layout and workspace, separating exit and entrance routes, and providing physical barriers to maintain a safe distance and direct contact.	33
Ventilation	Ventilation aims to reduce the transmission of COVID-19 using various strategies for optimizing indoor air quality by focusing on building ventilation. These ventilation strategies include engineering strategies such as increasing outdoor air ventilation, increasing or adjusting ventilation rates and air changes, meeting acceptable indoor air quality, prioritizing fresh air over recycled air, adjusting HVAC system, diluting indoor contaminants with higher outdoor air fraction and exchange rates, conducting pre- and post-occupancy flushing two hours prior and after office hours, recommending ventilation rates per person and additional building-related rates, and developing HVAC mitigation strategies. Non-engineering strategies include encouraging more natural ventilation, optimizing operable windows in crowded spaces such as meeting rooms, and limiting the number of occupants per HVAC zone.	49
Air filtration	Air filtration aims to capture small particles and viruses, including COVID-19, to prevent the spread of COVID-19. To achieve this goal, air filtration levels should be improved by at least MERV-13 or higher to remove aerosolized viruses and improve filtration. The use of MERV-13 level air filters is believed to meet the balance of IAQ with operation costs for medium-sized office buildings. For high-risk areas, HEPA portable air filters and cleaners could be used.	20
Temperature and relative humidity (RH)	Maintaining RH between 40% to 60% is recommended to limit virus survivability, especially for SARS-CoV-2. Regular monitoring of RH, the temperature at 17-18°C and CO_2 levels are advised as a proxy to identify the potential risk of transmission.	7
Monitoring indoor air quality (IAQ)	Monitoring indoor air quality aims to detect the potential crowd in specific spaces, a proxy for the need for more outdoor air. This includes regular monitoring of RH temperature and CO_2 levels for occupancy and activity with a suggested indoor limit of 450 ppm instead of 100 ppm based on the pandemic guidelines.	7
Air disinfection	Air disinfection aims to disinfect the air in high-risk indoor settings, such as crowded spaces where maintaining physical distance is difficult. Air disinfection uses UV technology, including supplemental UV germicidal irradiation for mechanical paths or an upper room for high-risk indoor settings or crowded spaces. A UV light is considered effective but has safety concerns for human health.	13
Building operation compliance	Building operation compliance aims to operate office buildings to reduce the risk of infection, particularly before re-opening. The strategies include performing systems equipment commissioning to check issues, building systems, and operation protocols for safer operation in compliance with engineering guidelines, such as ASHRAE standards.	5
Cleaning and disinfection management	Cleaning and disinfection management aims to minimize the risk of infection through surface cleanings of frequently touched surfaces during building operations. The strategies include implementing cleaning and disinfection protocols for high-touch surfaces like elevators and handrails and developing comprehensive cleaning and disinfection procedures for restrooms, hand sanitizer stations, and washing facilities.	16
Occupants' tracing management	Tracing management aims to require tracing protocol to the occupants to minimize the airborne transmission risks by identifying the potential source and reducing the transmission spread to other office occupants. This also as part of public health surveillance.	2

In addition to the content analysis based on the guidelines and journals, I conducted another content analysis to benchmark building rating tools relevant to airborne transmission strategies, including COVID-19. I sampled the market-leading LEED V4, WELL V2, Fitwell VRM building rating tools, and RESET, an emerging real-time monitoring building rating tool. Building rating tools have been developed for sustainable building practices (McArthur & Powell, 2020a). Building rating tools have recently started addressing the issue of healthy buildings.

The real estate industry has increased its focus on health and wellness, and interest in certification programs such as WELL and Fitwel has increased (McArthur & Powell, 2020a). WELL and Fitwel, established in 2013 and 2016, respectively, focus more on strategies related to occupants' health, such as ventilation, air filtration, temperature, and relative humidity. Sustainable building rating tools, such as LEED, gradually accommodate health requirements. For example, LEED V4 includes some requirements to obtain more credits when ventilation rates and air filtration are higher than standard or building codes. Recently, Fitwel and WELL have responded to the COVID-19 pandemic by acknowledging increased ventilation rates above ASHRAE standards and higher air filtration levels than codes require. Table 4.10 lists the benchmarking of building rating tools with the factors.

Table 4.10. Benchmarking Factors with Building Rating Tools

Factors	Building Rating Tools			
	LEED V4	WELL V2	Fitwel VRM	RESET
Space management	N/A	N/A	N/A	N/A
Ventilation rates	15% or 30% higher than standard	30% or 60% higher than standard	30% higher, or outdoor air rate, or CDC recommendation	N/A
Air filtration	At least MERV-13	At least MERV-13	MERV-8 in normal situations, or at least MERV-13 in emergency	N/A
Temperature and relative humidity (RH)	Maintain range 60ºF-80ºF with max. RH 60%	At least 59ºF and RH under 60%	RH 30%-60%	Monitor only; there is no requirement to meet a specific threshold
Monitoring IAQ	Maintain minimal outdoor rate based on standards	Provision of records on air filtration/sanitization maintenance, as per the manufacturer's recommendations	Monitoring and testing policy and protocols and improvement protocols	At least three months of real-time continuous measurement, reported and analyzed with specific protocols
Air disinfection	N/A	Optional integration of UV germicidal irradiation (UVGI) device or photocatalytic oxidation for spaces with more than 10 occupants	Upper Room UVGI light or UV-C light; both based on standards	N/A
Building operation compliance	N/A	N/A	N/A	N/A
Cleaning and disinfection management	N/A	Cleaning surfaces and contact management	Cleaning policy during operation and management	N/A
Occupants' tracing management	N/A	N/A	N/A	N/A

The benchmarking study concluded that several similarities and contrasts exist between the reviewed building rating tools and factors relevant to mitigating airborne transmission, including COVID-19. There are some similarities and differences among rating tools as follows:

- None of these rating tools have space management requirements.
- LEED, WELL, and Fitwel have two higher requirements than the standards: a) ventilation rates and b) air filtration levels, and they require a specific range of indoor temperature and relative humidity.
- Regarding IAQ monitoring, RESET requires at least three months of real-time continuous measurement, reporting, and analysis with specific protocols to better understand the IAQ in monitored spaces.
- LEED requires a room to maintain a minimal outdoor rate based on standards.
- WELL requires maintenance documentation of air filtration, and Fitwel requires monitoring testing policies and improvement protocols.
- Only WELL and Fitwel acknowledge air disinfection using UV devices based on the standards and require cleaning management.
- None of the reviewed building rating tools require building operation compliance or the occupant tracing management.

In conclusion, this benchmarking study provides insights into mitigating airborne transmission, including COVID-19. First, higher-than-standard requirements were identified in ventilation rates, ranging between 15% and 60%, or the same as the outdoor rate, or based on CDC recommendations. It is similar to the air filtration factor, where at least MERV-13, instead of MERV-8, is used. Second, Fitwel employs a flexible approach for air filtration levels, where a MERV-8 could be used in normal situations and at least a MERV-13 during emergencies. These findings have shown that different approaches, such as higher-than-standard requirements and flexibility, can mitigate the risk of airborne transmission in future building codes.

4.1.2 Expert Interviews

Expert interviews are to gather experts' perspectives on the impact of the recent COVID-19 pandemic on office buildings. For these interviews, I developed a set of questions to cover various aspects, including (1) the impact of the COVID-19 pandemic on office building design and operation, (2) the role of building codes in responding to current and future pandemics, (3) the type of compliance paths, and (4) the description of factors. I contacted the experts to obtain their participation agreement and sent the questions for their review before conducting the interviews. Table 4.11 details the questions for experts.

Table 4.11. Questions for Expert Interviews

Key Points	Questions
Impact of COVID-19 on office building design and operation	Q1. How does the current COVID-19 pandemic affect office buildings in office design and operation?
Building code's role in responding to current and future pandemic	Q2. How do you see the current building code requirements for office buildings playing a role in responding to current and future pandemics? In what ways could and should building codes prevent airborne disease transmissions such as COVID-19 or SARS?
Building code content	Q3. What is your opinion on current building codes that focus primarily on a building's design? Do you think that codes should include the operation side? Or both?
Type of building code that is responsive to pandemic	Q4. What is your opinion on the current "prescriptive" code's ability to respond to this pandemic? And how does it compare with other code types, such as "performance-based" and "hybrid" codes, specifically in preparing for ongoing and future health crises?
Multiple healthy building requirements in responding to the codes	Q5. In the recent healthy buildings literature, some healthy building foundations are associated with multiple strategies for mitigating the airborne transmission of COVID-19, such as higher ventilation rates, higher air filtration levels, and maintaining indoor air quality. How do you see these requirements in current building codes?
Improved/added code requirements to be more responsive	Q6. Are there any requirements in the current building codes that should be added or improved to be more responsive to the infection risks of COVID-19 or future airborne diseases?
Comments on the identified factors	Q7. Please refer to the table in Attachment I on the next page in response to this question. Based on your experience prior to and during the COVID-19 pandemic, what do you see as the significance of the factors listed in Table 1 in influencing future building codes for office buildings and office spaces? Are the identified factors sufficient to determine appropriate requirements for office buildings and spaces as reflected in building codes to prepare for a future pandemic, or are there others?

I conducted expert interviews from May to June 2022. In total, I sent 12 invitations through emails and telephone calls. Six experts were willing to participate, with four experts participating through online interviews and two experts through phone calls. I used UW's Zoom platform and cellular phone connection for the interviews. I conducted six semi-structured phone interviews, about 1,5 hours long for each participant. Based on the interview results, I continued with data analysis from July to October 2022. Table 4.12 lists the interview participation.

Table 4.12. Experts Interview List

Institution	Participants
HVAC designer and contractor	1
Local building code developers/agencies	2
Professional association	2
Non-governmental organization (NGO)	1
Total	**6**

I downloaded the video and text data retrieved from the Zoom platform through the UW account, and transcribed it using Happyscribe, an online audio and video transcriber. After analyzing and comparing the text and video data, I summarized the results based on the questions. Figure 4.2 shows my sequence for interviewing these experts from Q1 to Q7.

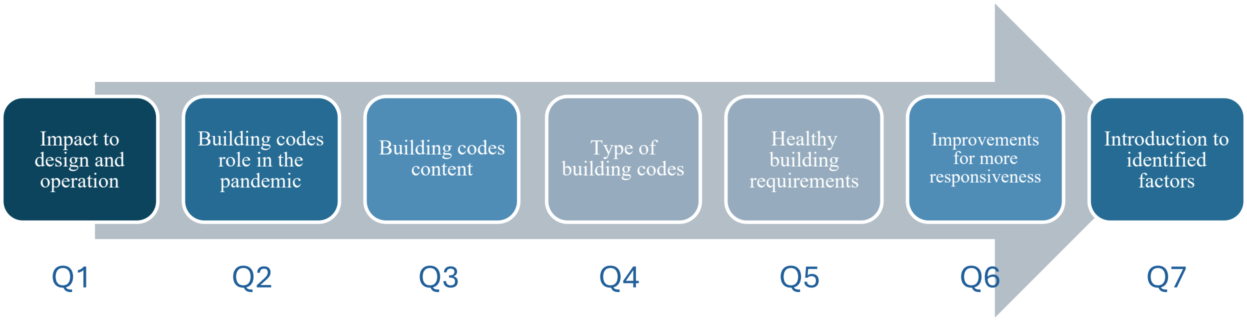


Figure 4.2. Sequence for Interviewing the Experts

The findings for Q1 indicated a unanimous agreement among all experts that the COVID-19 pandemic has significantly impacted the design and operation of office buildings. The shift from office-centric to remote and flexible work arrangements has contributed to a decrease in the current popularity of open-space designs. Moreover, the pandemic has heightened the awareness of IAQ issues in office settings, particularly ventilation. This situation has increased demand for IAQ strategies in future office buildings and posed challenges for existing buildings. One expert emphasized the importance of ensuring ventilation effectiveness in all required areas as stipulated in the ASHRAE standards.

The findings from Q2 underscored the significance of perceived risk or risk tolerance as a crucial consideration before implementing any changes in building codes. One expert provided an example from another disaster: wildfires in Washington State a few years ago. This example highlights that the simultaneous occurrences of disasters, such as wildfires, alongside the COVID-19 pandemic, may prompt the adoption of more advanced air filtration measures. Two experts underlined that political dynamics influence the code change process and may not always result in actual code adoption; an option is “non-code adoption,” which means building codes do not necessarily include the additional or suggested updated requirements.

The Q3 findings highlighted a divergence of opinions regarding design and operation requirements in building codes. While experts recognized the challenges of maintaining design requirements during building operations, they acknowledged the potential benefits of incorporating operational requirements. However, four of six experts agreed that implementing operational requirements in building codes would be very challenging. As a result, design and construction requirements still constitute the most optimal scope for building codes.

The Q4 findings indicated a prevailing preference for a prescriptive compliance path for building codes, often referred to as “prescriptive codes” for future health crises. Costs, technical challenges, resource availability, different perspectives of building designers, and the stance of local jurisdictions are the attributes of prescriptive code preference. Despite the potential impact of performance-based or hybrid codes in pursuing building performance and mitigating the risk of transmission, five out of six experts favored a prescriptive code approach over performance-based or hybrid codes for their perceived practicality in addressing challenges associated with future health crises.

The Q5 findings highlighted specifically healthy building requirements, such as air filtration and indoor air quality. These requirements, associated with strategies to mitigate airborne transmission such as COVID-19, are anticipated to undergo changes or adjustments. Four out of six experts agreed that some code changes were expected, with three out of six experts agreed that the focus on changes is particularly on mechanical code. This indicated the necessity for code adaptations to address airborne transmission in office building settings. Additionally, one expert stressed the importance of the inclusion of the dual modes of operation, in building codes, which allows the use of higher air filtration levels during emergency mode and respond to the energy costs.

The Q6 findings recommended additions and improvements in building codes to enhance responsiveness to the transmission risk of COVID-19. Five out of six experts agreed that air filtration should be a requirement, as it addresses not only to COVID-19 but also other disaster such as wildfires. One expert expressed that improvements should prioritize requirements that are quantifiable and can address enforcement issues, suggesting the following factors: air filtration level, ventilation rates, and monitoring IAQ.

Two experts agreed that monitoring IAQ system would need improvement, and one expert emphasized the importance of outdoor air to complement monitoring indoor air quality. One expert underlined the code’s flexibility to adjust their operations by switching to higher air filtration during disasters, such as COVID-19 and wildfires.

Upon the introduction of the identified factors from the content analysis in Q7 to the experts, four out of six experts indicated that they were well-acquainted with various factors, including ventilation, IAQ, air filtration, temperature, and RH, as evident from discussions during interviews. Most experts expressed concerns about the practical implementation of these factors in building codes, emphasizing enforcement as a primary challenge. This enforcement issue resonates with the prevailing preference for prescriptive codes over performance-based or hybrid codes, driven by considerations of costs and ease of implementation from both building designers' and local jurisdictions' perspectives. In addition, one expert underscored the significance of real-time monitoring of IAQ by linking sensors to inform the nearest suspected COVID-19 person to obtain proof of cross-infection between rooms.

In conclusion, the findings from Q1 to Q7 shed light on the multifaceted impact of the COVID-19 pandemic on office buildings. Here are the key takeaways from the interviews:

1) All experts agreed that the COVID-19 pandemic has impacted office buildings in both design and operation. As a result, several factors were discussed, such as ventilation, IAQ, air filtration, and monitoring systems for IAQ, which emerged as strategies to mitigate the risk of transmission in office buildings. The experts expected changes and adjustments in building codes based on these factors to mitigate the risk of airborne transmission, including COVID-19.
2) Other aspects emerged during a discussion in terms of building codes. First, "non-code adoption" could be one option in accommodating requirement changes to make building codes more responsive to the risk of transmission. Second, the potential benefits of including both design and operation requirements in building codes address the challenges during building operations. Third, there is a preference for prescriptive codes over performance-based or hybrid codes due to their perceived practicality during future health crises. Lastly, the suggestion of a dual mode of operation—emergency and non-

emergency—emerged as a potential solution to respond not only to the risk of transmission but also to other disasters such as wildfires.

The expert interviews provided valuable insights for developing the questionnaire used in the Delphi method to collect data on factors relevant to mitigating the risk of transmission in office buildings. Factors such as ventilation, monitoring IAQ, and air filtration were compiled and developed into questions as key considerations for mitigating airborne transmission in office buildings.

Subsequently, the questionnaire used in the Delphi method encompassed questions related to the scope of building codes pertaining to design and operation requirements. It also explored various compliance paths, such as prescriptive, performance-based, and hybrid building codes. In addition, it also sought experts' agreement and opinions on improvements or additional requirements to respond to the transmission risk.

4.1.3 Delphi Method Data Collection

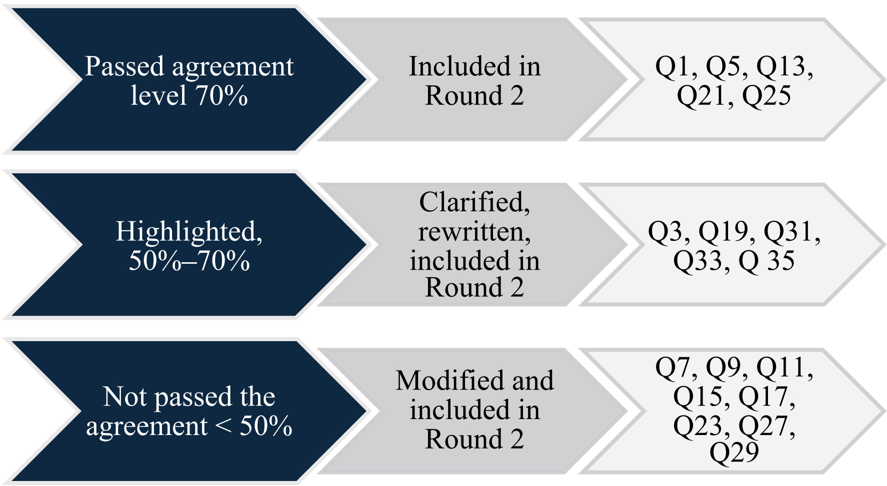
4.1.3.1 Delphi Round 1

In Delphi Round 1, I sent 18 invitations to industry experts, 14 of which completed responses (Response rate = 78%). Using SurveyMonkey, I retrieved the responses for further data analysis. Table 4.13 contains the list of completed responses.

Table 4.13. Delphi Round 1 Participants

Institution	Participants
HVAC designer and contractor	5
Local building code developers/agencies	2
Professional association	3
Academicians, researchers	2
NGO	1
Building designer	1
Total	**14**

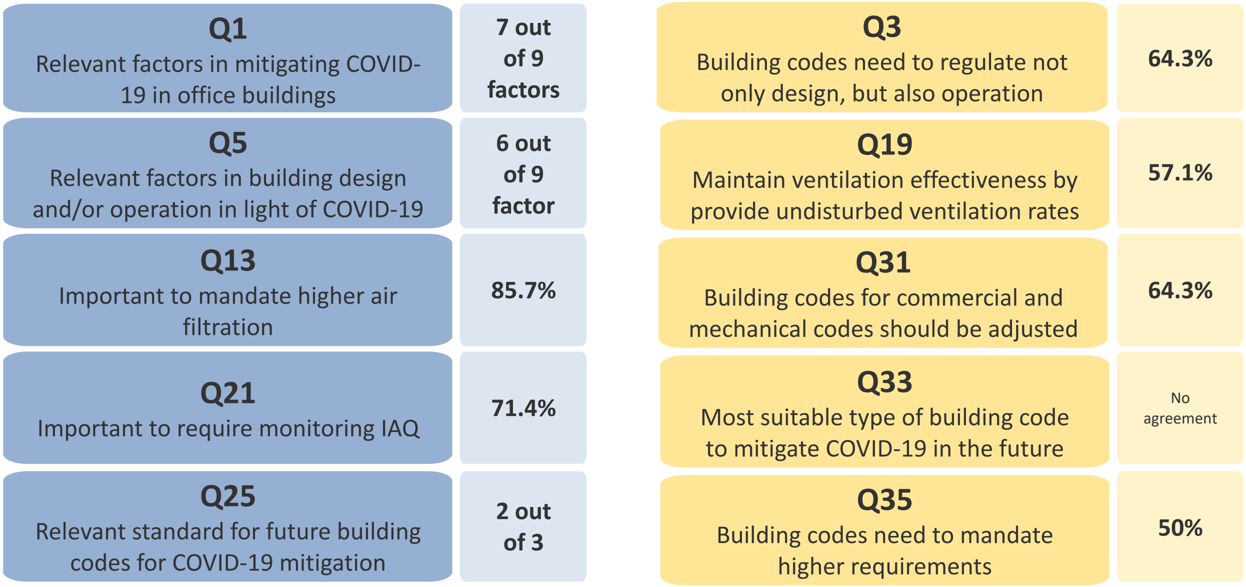
There were 30 questions in the online questionnaires. Fifteen odd-numbered questions (Q1, Q3, Q5 to Q15) were mandatory. They employed a 5-point Likert scale (Strongly Disagree, Disagree, Neither Agree nor Disagree, Agree, and Strongly Agree), while the 15 even-numbered questions (Q2, Q4, Q6 to Q30) were voluntary and asked for comments or feedback on the corresponding odd-numbered questions, if any. The agreement levels are the sum of the Agree and Strongly Agree scores. In this round, I used a minimum of 70% agreement levels. The entire questions for Round 1 can be found in Appendix B. Figure 4.3 depicts the questions that passed and did not pass the minimum agreement level.



Passed agreement level 70%	Included in Round 2	Q1, Q5, Q13, Q21, Q25
Highlighted, 50%–70%	Clarified, rewritten, included in Round 2	Q3, Q19, Q31, Q33, Q 35
Not passed the agreement < 50%	Modified and included in Round 2	Q7, Q9, Q11, Q15, Q17, Q23, Q27, Q29

Figure 4.3. Round 1 Delphi Result Map

I carried forwarded the questions with experts' agreement of more than 70% to Round 2. For questions that received experts' agreement between 50% and 70%, these were clarified, analyzed, and included in Round 2 due to their importance. I modified the questions that received less than 50% agreement and included them in Round 2 due to their significance in determining the factors. Figure 4.4 shows the agreement distribution from the Round 1 questions with the answers.



Q1 Relevant factors in mitigating COVID-19 in office buildings	7 out of 9 factors	**Q3** Building codes need to regulate not only design, but also operation	64.3%
Q5 Relevant factors in building design and/or operation in light of COVID-19	6 out of 9 factor	**Q19** Maintain ventilation effectiveness by provide undisturbed ventilation rates	57.1%
Q13 Important to mandate higher air filtration	85.7%	**Q31** Building codes for commercial and mechanical codes should be adjusted	64.3%
Q21 Important to require monitoring IAQ	71.4%	**Q33** Most suitable type of building code to mitigate COVID-19 in the future	No agreement
Q25 Relevant standard for future building codes for COVID-19 mitigation	2 out of 3	**Q35** Building codes need to mandate higher requirements	50%

Figure 4.4. Round 1 Agreement Distribution

The following paragraphs discuss the questions and experts' responses that reached a consensus or agreement in detail. This discussion includes questions Q1, Q5, Q13, Q21, and Q25.

Figure 4.4 responds to the Q1 question: Please indicate your opinion by selecting whether or not these factors *are relevant or not relevant to mitigate COVID-19 in office buildings* (n=14). In Q1, the experts agreed that 7 out of 9 factors are relevant to mitigating COVID-19 in office buildings. Table 4.14 lists these factors and the agreement levels.

Table 4.14. Q1 Responses

Factors	Agreement Levels	Passed/Not Passed
Space management	89%	Passed
Ventilation	100%	Passed
Air filtration	100%	Passed
Temperature and relative humidity	56%	Not Passed
Air disinfection	89%	Passed
Monitoring indoor air quality	78%	Passed
Compliance with operation standards	100%	Passed
Cleaning and disinfection management	56%	Not Passed
Occupants' tracing management	89%	Passed

Then, from Q5: *Please indicate your opinion on the factors most relevant to building design and/or building operation in light of COVID-19* (n=14), the results showed that experts agreed that 6 factors were relevant in office building design and operation. Table 4.15 lists these factors and the agreement levels.

Table 4.15. Q5 Responses

Factors	Agreement Levels	Passed/Not Passed
Space management	83.7%	Passed
Ventilation	96.4%	Passed
Air filtration	96.4%	Passed
Temperature and RH	55.6%	Not Passed
Air disinfection	80.2%	Passed
Monitoring indoor air quality	74.6%	Passed
Compliance with operation standards	75.0%	Passed
Cleaning and disinfection management	49.2%	Not Passed
Occupants’ tracing management	51.6%	Not Passed

On Q13: *It is important to mandate a higher air filtration level (e.g., changing the existing filter level to at least MERV 13 or HEPA filter and a portable HEPA filter for higher-risk spaces) in future building codes* (n=14), experts reached a consensus with 85.7% agreement. One expert noted that this requirement had been enacted in the California Mechanical Code, requiring a higher MERV-13 for better IAQ than other states codes.

Some experts suggested that better air filtration is required, even if there are no airborne infectious diseases, since other threats, such as fine particulate matter (PM) exposure indoors and outdoors, are some of the most preventable severe health risks.

On Q21: *It is important to require monitoring indoor air quality (e.g., monitoring indoor levels of CO, CO2, PM 2.5, PM 10, etc.) in future building codes* (n=14), the experts’ agreement level was 71.43%, which requires monitoring IAQ.

On Q25, the experts reached a consensus of 79% each on two ASHRAE guidelines and standards for building operations in the future:

1) ASHRAE standard 180-2018 for Inspection and Maintenance of Commercial Building HVAC Systems

2) ASHRAE's Core Recommendation for Reducing Airborne Infectious Aerosol Exposure (October 19, 2021).

In 2023, ASHRAE (2023) issued a new standard related to infectious aerosols, Standard 241 Control of Infectious Aerosols, regarding mitigating airborne transmission, including COVID-19. This latest standard shows the seriousness of updating the standard for building code references on airborne transmission. Figure 4.5 depicts the agreement distribution for this question.

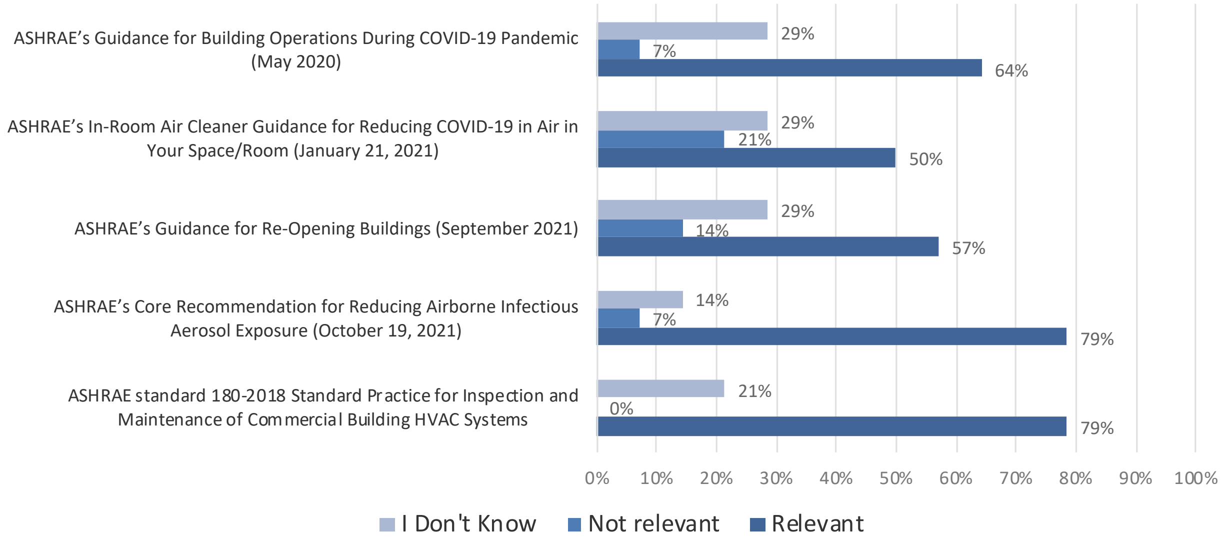


Figure 4.5. Round 1 Delphi Result Map

The following discussions describe the results from questions with agreement levels between 50% and 70%. These cover Q3, Q19, Q31, Q33, and Q35. For Q3: *Building codes need to regulate not only design requirements but also operational requirements* (n=14), the experts responded that building codes need to regulate not only design requirements but also operational requirements (64.29%).

On Q19: *In future building codes, it is important to require the maintenance of ventilation effectiveness by supplying the ventilation rates without any disturbance for occupied spaces during* *office operation* (n=14), the experts emphasized that maintaining ventilation effectiveness by supplying undisturbed ventilation rates during office operation is important (57.14%).

On Q31, the experts expressed that mechanical and building codes should address adjustments or improvements relevant to mitigating airborne transmission, including COVID-19 (64.29%).

On Q33: *Please indicate your opinion on which type of code is most suitable for the following factors for mitigating COVID-19 in office buildings* (n=14), the experts were not in favor of the most suitable type of building code for the identified factors. Only ventilation rates received 64% of the agreement for the hybrid code type. Figure 4.6 below provides the details of this result.

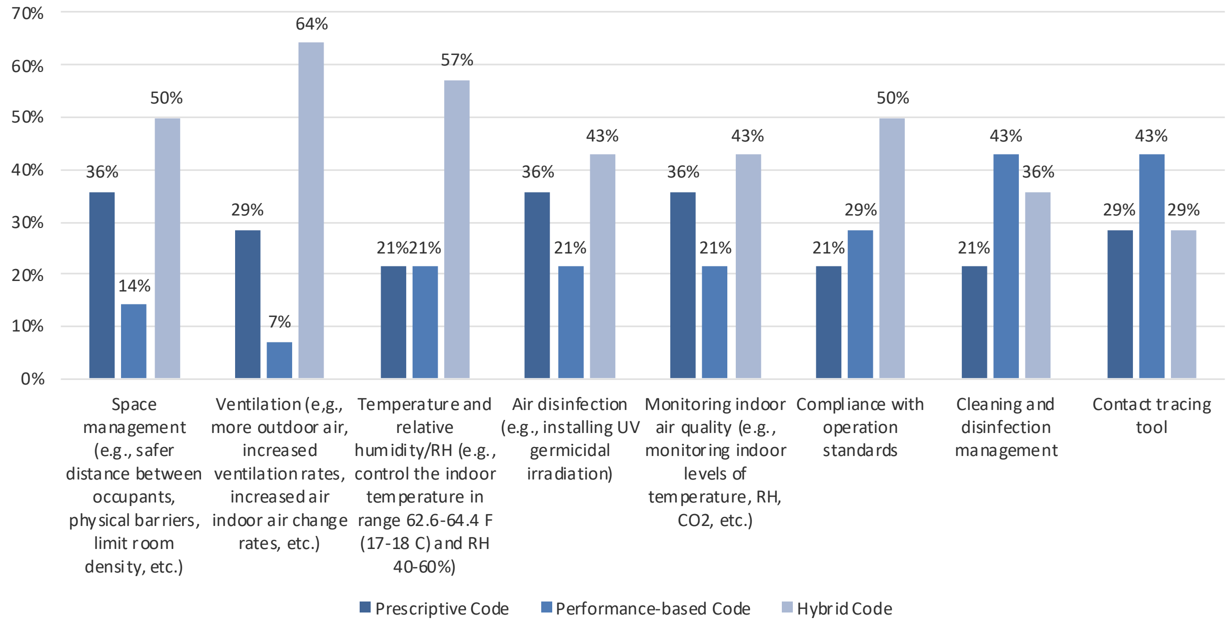


Figure 4.6. Round 1 Delphi Result Map

Lastly, on Q35, a half of the experts (n=7) agreed that building codes need to mandate higher requirements (e.g., via increased ventilation rates, higher air filtration levels, more frequent air changes, etc.) during emergencies and hazardous situations.

Next, the following paragraphs discuss the results from questions where no agreements were reached. These cover Q7, Q9, Q11, Q13, Q15, Q17, Q25, Q27 and Q29. These questions asked experts to indicate agreement to include the factors in future building codes. The questions were designed to expand the Q1 and Q5 questions in more detail. Table 4.16 lists the results of these questions.

Table 4.16. Results on the Inclusion of Factors into Building Codes

Questions and Factors	Agreement Levels for the inclusion to building code	Passed/Not Passed
Q7. Space management	21.43%	Not Passed
Q9. Higher ventilation rates	35.71%	Not Passed
Q11. Increased ACH	42.86%	Not Passed
Q13. Higher air filtration level	85.71%	Passed
Q15. Maintain T and RH	42.86%	Not Passed
Q17. Air disinfection	14.29%	Not Passed
Q19. Maintain ventilation effectiveness	57.14%	Not Passed
Q21. Monitoring IAQ	71.43%	Passed
Q25. Compliance with operation standards	79%	Passed
Q27. Cleaning and disinfection management	28.57%	Not Passed
Q29. Occupants’ tracing management	42.86%	Not Passed

These results showed that, in general, experts did not agree on the inclusion of these factors in building codes except for higher air filtration, monitoring IAQ, and compliance with operation standards. Align with these results, experts identified several concerns regarding the inclusion of these factors in future building codes. Table 4.17 describes expert comments on factors listed in Table 4.16.

Table 4.17. Summary of Experts' Comment on Non-Agreed Factors

Factors	Comments
Q7. Space management	• The enforcement mechanism is unavailable • Under the pandemic mode, this is agreed • It makes sense more in guidelines, not in regulation • Might have impacts on tenants, landlords and real estate
Q9. Higher ventilation rates	• Energy costs concern • Technical difficulties, there is a need to correlate with energy/carbon balance, and not all places have adequate outdoor air • Higher ventilation rates are not necessarily safer
Q11. Increased ACH	• Energy costs concern • Under the pandemic mode, this is agreed
Q15. Maintain T and RH	• It has not been proven to mitigate COVID-19 transmission. • Additional impacts, such as molds and fungus • Under the pandemic mode, this is agreed
Q17. Air disinfection	• Less effective and costly than standard air filter • Limited by application, it applies to high-density vulnerable populations such as K0-12 schools. • Health concerns on skin and eyes
Q19. Maintain ventilation effectiveness	• The system needs to be operated and maintained as intended to avoid failure • Maintain outdoor air as stated in standard under all load conditions
Q27. Cleaning and disinfection management	• No enforcement mechanism is available • Ineffective for COVID-19 and common cold
Q29. Occupants' tracing management	• No enforcement mechanism is available • Should not be in the code, even if it is effective

Compared with the results of Q1, where experts agreed that 7 out of 9 of the factors were relevant to mitigate COVID-19 in office buildings, and results of Q5, where experts agreed that 6 out of 9 were relevant in office building design and operation, the expert responses in Table 4.15 and 4.16 show disagreement on the inclusion of the factors except for higher air filtration, monitoring IAQ, and compliance with the operation standards. This finding indicates several challenges for these factors to become part of building codes in responding to similar disasters in the future.

The experts also actively discussed the factors outlined in the Round 1 questionnaire. One expert recommended designing spaces with low-speed air diffusers (30 fps or less) and low on-the-wall returns to facilitate air movement, thereby minimizing the airborne pathogen's presence. Bringing in equivalent or more outdoor air (OA) emerged as a concern twelve times, with considerations for cost consequences, while clean air delivery rates (CADR) were mentioned twice. The experts also mentioned effective systems of operation and monitoring two times, aiming to ensure the optimal performance of building systems during operation. Given the repeated emphasis on these opinions, I included these four additional factors in the Round 2 Delphi questions:

1) Space design
2) Bringing more outdoor air
3) Clean air delivery rates (CADR)
4) Effective system of operation and monitoring

In conclusion, this Round 1 has led to several agreements, additional insights, and modifications of the questions to be used for Round 2 of the Delphi data collection. Listed below are the classifications of the Round 2 questions:

1) Questions that reached consensus or agreement levels of at least 70%. These questions were relevant factors in light of COVID-19 in building design and operation, which covered:
    - Space management
    - Ventilation

- Air filtration
- Air disinfection
- Monitoring IAQ
- Compliance with operation standards

2) Questions that reached agreement levels of 50%–70% were then analyzed, clarified, and rewritten for Round 2. These questions were about the following topics:
    - Design and operation inclusion in building codes
    - Ventilation effectiveness
    - Scope of building codes subject to be adjusted for mitigating the airborne transmission (building code and mechanical code)
    - Compliance paths that are suitable for mitigating airborne transmission, including COVID-19, in the future
    - Higher requirements inclusion in building codes

The experts made additional suggestions on these four factors, which included in Round 2:

1) Space design
2) Bringing more outdoor air
3) Clean air delivery rates
4) Effective system of operation and maintenance (O&M)

3) The questions that obtained 50% or less agreement were modified and included due to their importance in determining the factors. For instance, the "ventilation" factor was broken down into more detail as "increased air change rates" and "increased ventilation rates." The "air filtration" factor was clarified to "higher air filtration." The total number of factors for Round 2 increased to 11, as listed in Table 4.18.

Table 4.18. List of Updated Factors for Delphi Round 2

Factors	Summary
Higher air filtration	Using a higher air filtration, e.g., MERV 14, with a focus more on the filtration of recirculated air
Bringing outdoor air	Bringing an equivalent outdoor air or, if required, more outdoor air during building operation
An effective system of operation and monitoring	Performing tests and demonstrating an effective system operation and monitoring for a safer building operation
Clean air delivery rates	Requiring a particular rate for air cleaners, which measure the amount of clean air in a fixed amount of time, to indicate the effectiveness in removing small airborne particles
Space design	Minimizing the movement of the pathogen in a space setting, e.g., by installing a low-speed air diffuser at 30 fps or less or installing low wall or floor return
Space management	Limiting the number of occupants in a space, e.g., by setting a maximum occupancy in occupied spaces or space distancing for relatively denser spaces, such as in workstations or call centers
Monitoring indoor air quality	Monitoring levels of indoor contaminants, primarily CO_2, to indicate how well the indoor ventilation in space, and other pollutants, e.g., CO, PM 2.5, VOCs
Air disinfection	Using air disinfection technology, e.g., upper room ultraviolet germicidal irradiation (UVGI), which is preferable for high-risk indoor settings and crowded spaces, spaces with insufficient or no mechanical HVAC systems, or spaces with inadequate natural ventilation
Increased air change rates	Using higher air change rates, e.g., higher than typical 2 to 3 per hour for office spaces, to minimize the risk of infection
Increased ventilation rates	Using higher ventilation rates, e.g., higher than typical 20 cfm/person for office spaces, to minimize the risk of infection
Compliance with operation standards and guidelines	Operating buildings in accordance with specific guides to minimize the risk of infection, e.g., ASHRAE Core Recommendations for Reducing Airborne Infectious Aerosol Exposure (October 2021) and ASHRAE Building Readiness (May 2022) or the updated version

Further analysis of experts' comments helped identify several concerns about implementing these factors and whether they should be included in building codes. These concerns included the factors' effectiveness in preventing the risk of transmission, the potential additional costs of having more energy and costs for installation and maintenance, and the ease of enforcement due to required monitoring, measurement, and reporting. Table 4.19 lists the frequency of the experts' concerns.

Table 4.19. Frequency Table of Experts' Comments

Concerns	Frequency (n)
Prevention effectiveness in risk caused by airborne transmission	13
Cost concerns, including energy cost and installation cost	18
Ease of enforcement, including monitoring, measurement, and reporting	11
Ease of implementation, including maintenance and operation	4
Others	2

Based on these findings, I addressed these four primary concerns and developed them as "criteria" to assess each factor's relative weight of importance. Table 4.20 lists the developed criteria for Round 2 of the Delphi data collection.

Table 4.20. Criteria for Evaluating Factors

Criteria	Description
Prevention effectiveness	The factor's implementation can effectively eliminate or reduce the risks of airborne transmission in office buildings
Associated energy costs	The factor adds cost for energy consumption due to significant energy use
Ease of monitoring and reporting	The factor makes it easy to implement a monitoring system to report the results of the intervention for decision-making processes
Ease of implementation and enforcement	The factor's ease of implementation includes installation, operation, maintenance, and enforcement

To sum up, the findings from Round 1 were used in developing the questions for Round 2 data collection. For this purpose, the questions for Round 2 used eleven factors from Round 1 to get experts' confirmation. In addition, four criteria were used as a relative weight for the factors. These questions were then finalized into a questionnaire, tested prior to the distribution, and distributed to the experts for the second round of Delphi data collection.

4.1.3.1 Delphi Round 2

In Delphi Round 2, I sent invitations to the 14 experts who participated in Round 1, resulting in nine completed responses for four questions (Response rate = 64%) and eight (n=8) completed responses for one question (Response rate = 57%). The completed nine responses are the questions on relative weight, assessment of factors, operation, higher requirements for building codes, and the paths of compliance. One question that received eight (n=8) completed responses is the question on maintaining building design and operation requirements. Table 4.21 lists the completed responses.

Table 4.21. List of Completed Responses

Institution	Participants
HVAC designer and contractor	2
Local building code developers/agencies	1
Professional association	1
Academicians, researchers	4
Building designer	1
Total	**9**

The questions for Round 2 were developed based on the Round 1 results. Round 2 questionnaire consisted of:

- Criteria for identified factors, where I used a Simple Additive Weighting (SAW)/ Weighted Sum Method (WSM)
- Assessment of factors
- Question on maintaining design and operation
- Question on higher requirements for emergency situation and modes of operation
- Question on paths of compliance or building code types.

There are a total of five questions, and the full question list can be found in Appendix C. SAW/WSM, as one of the widely-used multicriteria analysis (MCA) methods, was employed to provide a relative weighting of concerns or “criteria or alternatives” to the available factors or “options.” The online questionnaire asked each expert to provide responses in accordance with the sequence in Figure 4.7.

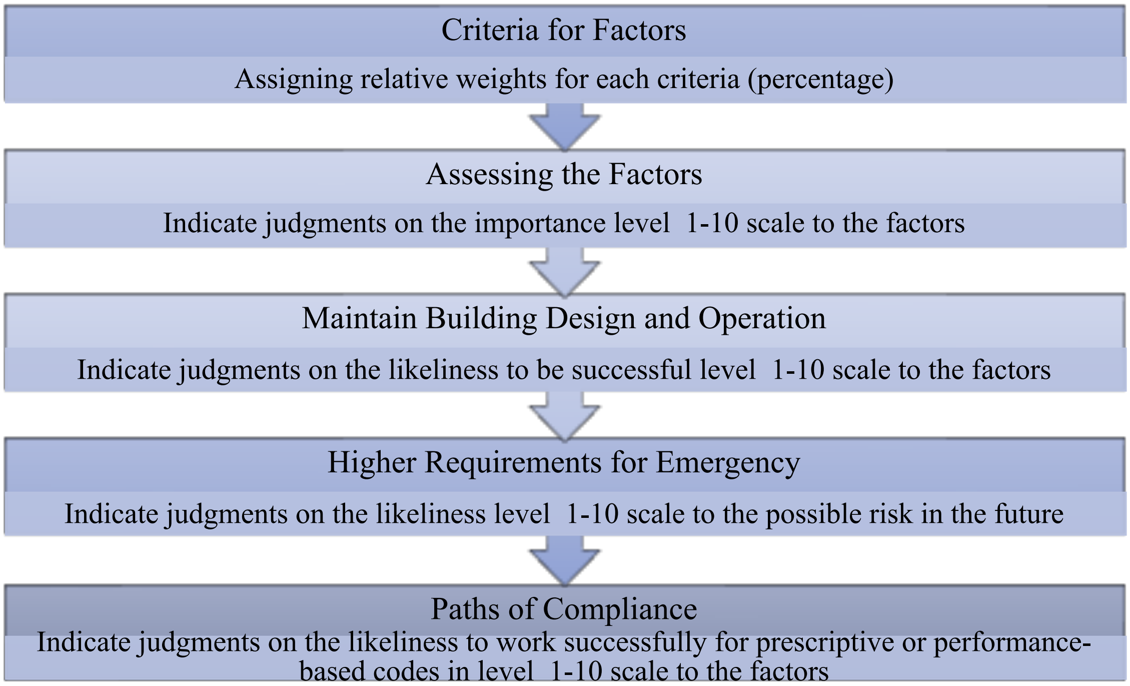


Figure 4.7. Sequence of Round 2 Questionnaire

Experts entered their responses with a designated number required for each question. For Q1 on relative weight, experts were asked to distribute 100 points among four criteria based on their relative importance. A higher number represented a relatively higher importance level, while a lower number represents a relatively lower importance level. For Q2 on assessing the factors, experts were asked to indicate their judgments on the updated list of factors by entering a number from 1 to 10, where 0 = “Not at all important” and 10 = “Extremely important.”

I downloaded the results of Q1 and Q2 from SurveyMonkey and then tabulated them in Microsoft Excel spreadsheets. I calculated each expert response using the SAW/WSM formula to obtain each expert's A matrix value. Figure 4.8 explains the keymap on how to read the SAW/WSM results, and Figures 4.9 and 4.10 show the A matrix values from the SAW/WSM calculations.

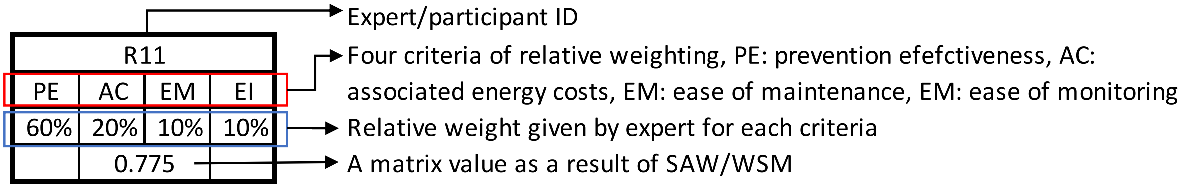


Figure 4.8. Keymap for Reading the SAW/WSM Results

Factors	Relative Weight and SAW/WSM Results																			
Higher air filtration	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	5%	30%	25%	30%	10%	35%
		0.775				0.787				0.771				0.717				0.685		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.700				0.889				0.810				0.715						
Bringing OA	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
		0.763				0.876				0.775				0.555				0.635		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.350				0.714				0.900				0.850						
Effective system of O&M	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
		0.608				0.787				0.658				0.235				0.589		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.150				0.769				0.515				0.535						
Clean air delivery rates	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
		0.668				0.876				0.627				0.717				0.359		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.750				0.744				0.665				0.345						
Space design	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
		0.330				0.886				0.708				0.412				0.492		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.750				0.950				0.840				0.415						
Space management	R11				R10				R09				R08				R07			
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
	60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
		0.380				0.711				0.688				0.300				0.627		
	R06				R05				R04				R03							
	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI				
	25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%				
		0.600				0.508				0.595				0.335						

Figure 4.9. SAW/WSM Results (1)

Monitoring IAQ

R11				R10				R09				R08				R07			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
	0.608				0.911				0.481				0.390				0.665		

R06				R05				R04				R03			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%
	0.150				0.750				0.780				0.605		

Air disinfection

R11				R10				R09				R08				R07			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
	0.583				0.768				0.494				0.278				0.672		

R06				R05				R04				R03			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%
	0.150				0.900				0.675				0.135		

Increased ACH

R11				R10				R09				R08				R07			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
	0.800				0.876				0.781				0.555				0.690		

R06				R05				R04				R03			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%
	0.300				0.639				0.685				0.505		

Increased ventilation rates

R11				R10				R09				R08				R07			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
	0.775				0.876				0.781				0.555				0.620		

R06				R05				R04				R03			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%
	0.300				0.694				0.810				0.850		

Compliance with operation standard

R11				R10				R09				R08				R07			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
60%	20%	10%	10%	40%	10%	20%	30%	60%	20%	5%	15%	40%	25%	0%	30%	25%	30%	10%	35%
	0.475				0.876				0.763				0.000				0.561		

R06				R05				R04				R03			
PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI	PE	AC	EM	EI
25%	25%	25%	25%	50%	0%	25%	25%	60%	10%	5%	25%	40%	15%	25%	20%
	0.350				0.825				0.835				0.535		

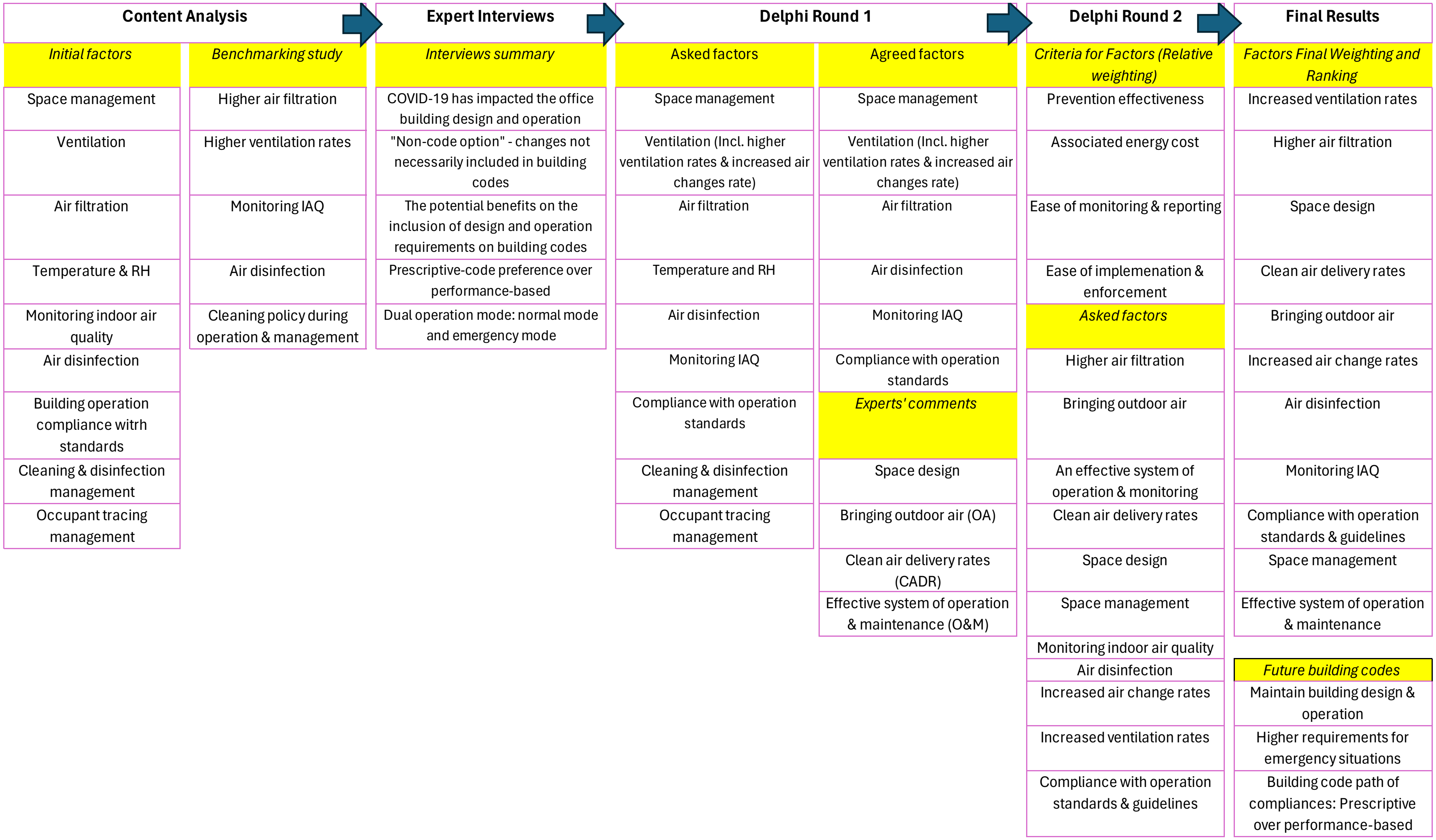
Figure 4.10. SAW/WSM Results (2)

Then, I calculated the median values of all A matrices from experts' responses for each factor. For the Delphi method, the median value is better used as a statistical representative of the group answer (Dalkey, 1969). Finally, I ranked all median values from highest to lowest. Table 4.22 details the result of the SAW/WSM method for Delphi data collection in Round 2, including the median values and rank for each factor and the agreement level threshold of 70%, similar to Round 1.

Table 4.22. Final Factor Median Values and Ranking

Factor name	Factor #	Factor Rank	Median Values	Agreement Level 70%
Increased ventilation rates	10	1	78%	Passed
Higher air filtration	1	2	75%	Passed
Space design	5	2	75%	Passed
Clean air delivery rates	4	4	72%	Passed
Bringing OA	2	5	71%	Passed
Increased ACH	9	6	69%	No
Air disinfection	8	7	67%	No
Monitoring IAQ	7	8	67%	No
Compliance with operation standards and guidelines	11	9	65%	No
Space management	6	10	60%	No
Effective system of OM	3	11	59%	No

Five factors were identified above the 70% agreement threshold, ranging from 71% to 78%. The next four factors ranged from 69% to 65%. The last two factors were closely aligned, with agreement scores of 60% and 59%, respectively. Given the relatively close distribution of values, all 11 factors were included to construct RRF. Figure 4.11 summarizes the factor development from content analysis, expert interviews, and Delphi data collection.



Content Analysis

Initial factors
- Space management
- Ventilation
- Air filtration
- Temperature & RH
- Monitoring indoor air quality
- Air disinfection
- Building operation compliance witrh standards
- Cleaning & disinfection management
- Occupant tracing management

Benchmarking study
- Higher air filtration
- Higher ventilation rates
- Monitoring IAQ
- Air disinfection
- Cleaning policy during operation & management

Expert Interviews

Interviews summary
- COVID-19 has impacted the office building design and operation
- "Non-code option" - changes not necessarily included in building codes
- The potential benefits on the inclusion of design and operation requirements on building codes
- Prescriptive-code preference over performance-based
- Dual operation mode: normal mode and emergency mode

Delphi Round 1

Asked factors
- Space management
- Ventilation (Incl. higher ventilation rates & increased air changes rate)
- Air filtration
- Temperature and RH
- Air disinfection
- Monitoring IAQ
- Compliance with operation standards
- Cleaning & disinfection management
- Occupant tracing management

Agreed factors
- Space management
- Ventilation (Incl. higher ventilation rates & increased air changes rate)
- Air filtration
- Air disinfection
- Monitoring IAQ
- Compliance with operation standards

Experts' comments
- Space design
- Bringing outdoor air (OA)
- Clean air delivery rates (CADR)
- Effective system of operation & maintenance (O&M)

Delphi Round 2

Criteria for Factors (Relative weighting)
- Prevention effectiveness
- Associated energy cost
- Ease of monitoring & reporting
- Ease of implementation & enforcement

Asked factors
- Higher air filtration
- Bringing outdoor air
- An effective system of operation & monitoring
- Clean air delivery rates
- Space design
- Space management
- Monitoring indoor air quality
- Air disinfection
- Increased air change rates
- Increased ventilation rates
- Compliance with operation standards & guidelines

Final Results

Factors Final Weighting and Ranking
- Increased ventilation rates
- Higher air filtration
- Space design
- Clean air delivery rates
- Bringing outdoor air
- Increased air change rates
- Air disinfection
- Monitoring IAQ
- Compliance with operation standards & guidelines
- Space management
- Effective system of operation & maintenance

Future building codes
- Maintain building design & operation
- Higher requirements for emergency situations
- Building code path of compliances: Prescriptive over performance-based

Figure 4.11. Factors Development Chart

4.2 APPLYING FACTORS TO THE U.S. CASE STUDIES

4.2.1 Applying Factors to RRF

As a result of the data analysis from Delphi Round 2, each factor's rank has been determined by assigning relative weight to each factor based on its median value. Table 4.22 above describes the results of final relative weighting, median values, and rank for all factors. As their median values ranged from 78 to 59, I used all factors to construct RRF. Then, I converted the final median values to the 100-point scale to improve their usability, which can further support the code examination later. To make the examination smoother, I developed a set of scorecards with keywords as references to guide the code examination process, as shown in Table 4.23 below.

Table 4.23. Scorecards and Keywords for Code Examination

Factors	Summary	Keywords
Increased ventilation rates	This point is intended to encourage the use of higher ventilation rates as stated in the ASHRAE 62.1: Table 6.1 Minimum Ventilation Rates in Breathing Zone (for office buildings).	Ventilation, ventilation rates, outdoor rates
Higher air filtration	This point is intended to measure the use of higher air filtration, e.g., MERV 13 or MERV 14, with a focus more on the filtration of recirculated air.	Air filtration, MERV
Space design	This point is intended to minimize the movement of the pathogen in a space setting, e.g., by installing a low-speed air diffuser at 30 fps or less or installing low wall or floor return.	Pathogen, space setting
Clean air delivery rates	This point is intended to encourage the use of a particular rate for air cleaners, which measure the amount of clean air in a fixed amount of time, to indicate the effectiveness in removing small airborne particles.	Clean air delivery rates
Bringing outdoor air	This point is intended to encourage to bring an equivalent outdoor air or, if required, more outdoor air during building operation.	Outdoor air, outdoor rates
Increased air change rates	This point is intended to encourage the use of a higher air change rates, e.g., higher than typical two to three per hour for office spaces, to minimize the risk of infection.	Air change rates, outdoor air
Air disinfection	This point is intended to encourage the use of air disinfection technology, e.g., upper room ultraviolet germicidal irradiation (UVGI), which is preferable for high-risk indoor settings and crowded spaces, spaces with insufficient or no mechanical HVAC systems, or spaces with inadequate natural ventilation.	Air disinfection
Monitoring indoor air quality	This point is intended to encourage to provide a monitoring system for levels of indoor contaminants, primarily CO_2, to indicate how well the indoor ventilation in space, and other pollutants, e.g., CO, PM 2.5, VOCs.	Monitoring, indoor contaminants
Compliance with operation standard and guidelines	This point is intended to encourage the building operation in accordance with specific guides to minimize the risk of infection, e.g., ASHRAE Core Recommendations for Reducing Airborne Infectious Aerosol Exposure (October 2021) and ASHRAE Building Readiness (May 2022) or the updated version.	Testing, operation
Space management	This point is intended to limit the number of occupants in a space, e.g., by setting a maximum occupancy in occupied spaces or space distancing for relatively denser spaces, such as in workstations or call centers.	Density, function, person/CFM
Effective system of operation and monitoring	This point is intended to encourage building operation to perform tests and demonstrate an effective system operation and monitoring for a safer building operation.	Testing, operation, monitoring

4.2.2 Applying RRF to the U.S. Case Studies

This section discusses the application of RRF to U.S. case studies. Based on the state-level energy code adoption status, I employed a dataset of 30 states and 30 cities across the U.S. for code examination based on the U.S. Department of Energy (DOE) Status of State Energy Code Adoption (U.S. Department of Energy, 2023) for commercial buildings.

The dataset of building codes selected for the case studies was a combined collection of the following sources:

- The International Code Council (ICC): a global source of model codes, standards, and building safety solutions.
- UpCode: a search platform for the U.S. construction and building codes, including databases for adopted codes by Authority Having Jurisdictions (AHJs).
- Municipal Code Corporation (Municode): a codifier of legal documents for local governments in the U.S.

The selected U.S. states were categorized into seven groups (Groups 1 through 7) based on the energy-code adoption statuses of the ASHRAE Standard 90.1 Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings in their building codes (Standard 90.1). Group 1 represents states that adopted the latest 2019 version of Standard 90.1, and Groups 2, 3, 4, and 5 represent the states with older adoption versions between 2016 and 2007. Finally, Group 7 means that no statewide energy code was adopted. Figure 4.14 shows a color-coded U.S. states in terms of states' categorizations.

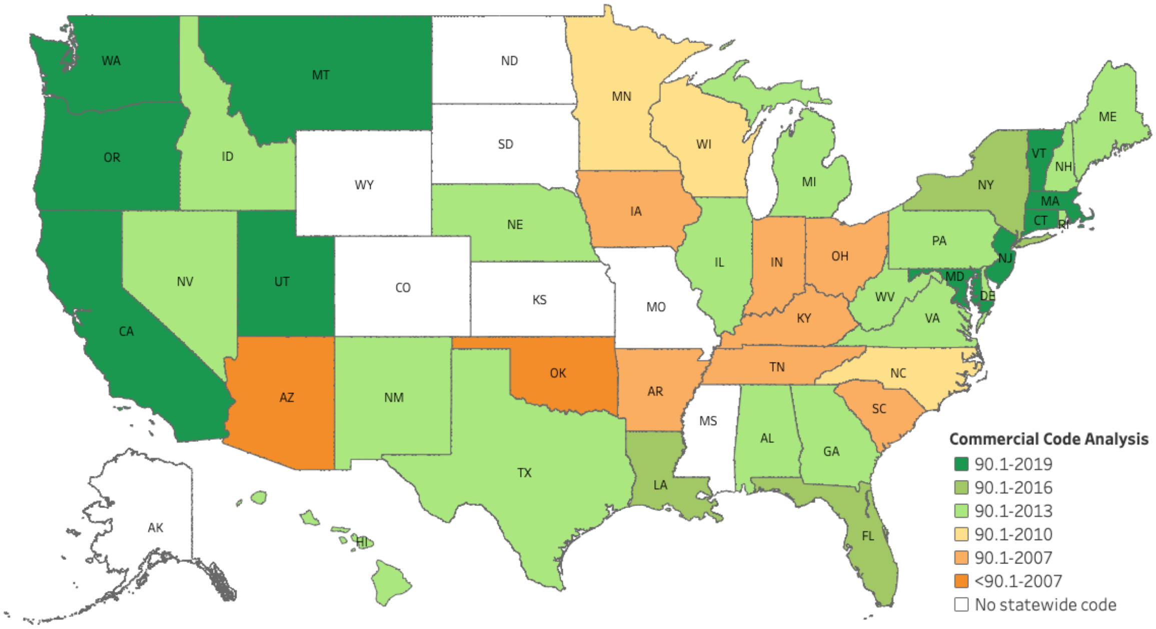


Figure 4.12. Status of Energy Code Adoption for Commercial Buildings in the U.S. (DOE, 2024)

The following Table 4.24 lists the sampled states and cities for code examination.

Table 4.24. Sampled States and Cities for Code Examination

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7
90.1-2019	90.1-2016	90-1-2013	90.1-2010	90.1-2007	<90.1-2007	No statewide energy code
Washington *(Seattle)*	New York *(New York City)*	Idaho (*Boise*)	Minnesota (*Minneapolis*)	Indiana (*Indianapolis*)	Arizona (*Phoenix*)	Missouri *(Kansas City)*
Oregon *(Portland)*	Louisiana *(New Orleans)*	Nevada *(Las Vegas)*	Wisconsin *(Milwaukee)*	Ohio (*Columbus)*	Oklahoma *(Oklahoma City)*	Wyoming *(Cheyenne)*
California *(Los Angeles)*		Texas *(Houston)*	North Carolina **(***Charlotte)*	Arkansas *(Little Rock*)		Kansas *(Wichita-Sedgwick)*
Massachusetts *(Boston)*		Florida *(Jacksonville)*		South Carolina *(Charleston)*		Mississippi *(Jackson)*
New Jersey *(Newark)*		Pennsylvania *(Philadelphia)*		Kentucky *(Louisville)*		South Dakota *(Sioux Falls)*
Maryland *(Baltimore)*		Virginia *(Virginia Beach)*				North Dakota *(Fargo)*

The largest populated city in each of the selected states was selected and then examined by using the same RRF to obtain a broader understanding of building codes' risk responsiveness levels both statewide and citywide.

The code examinations were conducted per RRF using keywords for each factor. The examinations were focused on determining factors in mechanical codes since these codes are the most relevant. During the examinations, a spreadsheet containing the list of selected states and cities was developed and compared to other codes under review. Points were assigned to codes that correspond to the factors listed in RRF, with half of the possible maximum points awarded for factors in the codes that are in accordance with the standards.

For instance, ventilation rates in office buildings were based on ASHRAE 62.1 Ventilation and Acceptable Indoor Air Quality from Table 6-1 Minimum Ventilation Rates, and the typical value is 20 cfm/person (Allen & Macomber, 2020). It must be noted that experts have a variety of opinions on these higher ventilation rates than the typical values mentioned above (Allen & Macomber, 2020; Awada et al., 2021), and the exact values are still undecided. However, the discussions favored higher rates than the ASHRAE standard 62.1 (Allen & Macomber, 2020; Atkinson et al., 2009; Awada et al., 2021; Megahed & Ghoneim, 2021; Morawska et al., 2020; Sha et al., 2021; Sloan Brittain et al., 2020), as discussed earlier in Chapter 2 Literature Review.

The ventilation rates examined in the codes are referred to the ASHRAE Standard 62.1 Table 6-1. Since the examined code has the component of the identified factor but not in the same value, half of the possible maximum points (5 out of 10) are then awarded. Another example is "higher air filtration" factor, where a minimum MERV of 13 is stated. From code examinations, air filtration requirements were less than MERV 13. Therefore, half of the maximum points (5 out of 10) were assigned.

Table 4.25 shows the factors and corresponding sections in the examined building codes. I conducted the examination strategy by following a list of the factors corresponding to the sections in building codes. Then, the sections were reviewed in accordance with the factors. Points were awarded when the factors were identified in the corresponding sections.

Table 4.25. Factors in Examined Building Codes

Factors	Location in Code
Increased ventilation rates	Section 403 Mechanical Ventilation, Table 403.3.1.1 Outdoor Airflow Rate
Higher air filtration	Section 605 Air Filters
Space design	N/A
Clean air delivery rates	N/A
Bringing OA	Refer to Section 403 Mechanical Ventilation, Table 403.3.1.1 Outdoor Airflow Rate
Increased ACH	Refer to Section 403 Mechanical Ventilation, Table 403.3.1.1 Outdoor Airflow Rate
Air disinfection	N/A
Monitoring IAQ	N/A Only refer to smoke detectors
Compliance with operation standards and guidelines	N/A
Space management	The density refers to Refer to Section 403 Mechanical Ventilation, Table 403.3.1.1 Outdoor Airflow Rate
Effective system of O&M	N/A

I conducted the code examination by seeking the factors in the building codes, reviewing them, and assigning points. Table 4.26 lists the code examination example for a state or a city.

Table 4.26. State and City Code Examination Example

Factor Name	Possible Points (rounded)	Points Given	Section
Increased ventilation rates	10	5	Section 403 Mechanical Ventilation, Table 403.3.1.1 Outdoor Airflow Rate
Higher air filtration	10	0	Section 605 Air Filters
Space design	10	0	N/A
Clean air delivery rates	9	0	N/A. Notes. This measure is combined with portable HEPA air filter.
Bringing OA	9	5	N/A. The Outdoor Air has been determined according to Table 403.3.1.1 Minimum Ventilation Rates
Increased ACH	9	5	Section 401.2 Ventilation Required. Mechanical ventilation refers to Section 403
Air disinfection	9	0	N/A
Monitoring IAQ	9	0	Section 907.3.1 Smoke Detectors. Only for smoke detector installation for fire alarm system, and not specific to indoor contaminants.
Compliance with operation standard and guidelines	9	0	N/A. These operation procedure are relatively new.
Space management	8	4	The density refers to 403.1.1 Outdoor Airflow Rate.
Effective system of O&M	8	0	N/A
SCORE	100.0	18	

In alignment with this example, I performed a code examination on the rest of the states' and cities' datasets. Table 4.27 summarizes the results of the code examinations for the dataset of 30 states and 30 cities. The city names were intentionally written in italics to differentiate them from the state names.

Table 4.27. Results of Code Examination from Sampled States and Cities

State	**Points**	**City**	**Points**	**State**	**Points**	***City***	**Points**
Washington	32	*Seattle*	31	New Jersey	18	*Newark*	18
New York	18	*New York City*	23	Maryland	18	*Baltimore*	18
Idaho	18	*Boise*	18	Florida	18	*Jacksonville*	18
Minnesota	18	*Minneapolis*	18	Pennsylvania	18	*Philadelphia*	18
Indiana	18	*Indianapolis*	18	Virginia	18	*Virginia Beach*	18
Arizona	18	*Phoenix*	18	Wisconsin	23	*Milwaukee*	18
Missouri	18	*Kansas City*	18	North Carolina	18	*Charlotte*	18
Oregon	18	*Portland*	18	Arkansas	18	*Little Rock*	18
Louisiana	18	*New Orleans*	18	South Carolina	18	*Charleston*	18
Nevada	28	*Las Vegas*	18	Kentucky	18	*Louisville*	18
Ohio	18	*Columbus*	18	Oklahoma	18	*Oklahoma City*	18
California	28	*Los Angeles*	28	Wyoming	18	*Cheyenne*	18
Massachusetts	18	*Boston*	18	Mississippi	18	*Jackson*	18
Texas	18	*Houston*	28	South Dakota	18	*Sioux Falls*	18
Kansas	18	*Wichita-Sedgwick*	18	North Dakota	18	*Fargo*	18

From the code examinations, the following four factors were identified:

1) Ventilation rates
2) Outdoor air
3) Air change rates, and
4) Space management

Ventilation rates, outdoor air, and space management factors were examined in the mechanical ventilation section of the codes, which refer to the Table of Minimum Ventilation Rates of ASHRAE 62.1 Ventilation and Acceptable Indoor Air Quality Standard. The air filtration factor was examined in the air filter section of the codes. These factors were present in the examined codes; however, others were not identified. The states and cities received points for these factors. For those states and cities, 18 points were given based on the half-maximum points rule. Table 4.26 shows that 26 out of 30 state codes (87%) and 26 out of 30 city codes (87%) received 18 total points.

Four states, Washington, California, Nevada, and Wisconsin, received higher scores from all other sampled states, with Washington having the highest score at 32, California and Nevada sharing the same 28 scores, and Wisconsin at 23.

In particular, the two factors, “higher air filtration” and “effective system of operation and maintenance,” enabled the Washington Mechanical Code, which was adopted from the 2018 International Mechanical Code (IMC), to receive the highest score. The former factor identified from an advanced air filtration in Section 605.5 Smoke Filtration requires an air filtration system with a minimum efficiency of MERV 13. The latter factor was identified from testing and commissioning for natural and mechanical ventilation in Section 401.7, where testing, commissioning, and documentation are required in accordance with the Energy Conservation Code.

Both California and Nevada have similar air filtration requirements. In Nevada, a minimum MERV of 13 is required for mechanically ventilated buildings under Appendix E Sustainable Practice, Section 603 Pollutant Control, whereas in California, a MERV of 13 or higher is required under Section 402.1.2 Filters.

The “increased air changes” factor was identified from Wisconsin Mechanical Code Amendment Section 2, where an air change rate of six per hour must be provided in each space.

This amendment stated a higher air change rate than the typical two or three air change rates for office buildings.

In summary, the Washington Mechanical Code stands out for its exemplary performance in two crucial factors: "higher air filtration" and "effective systems of operation and maintenance. California and Nevada Mechanical Codes exhibit a comparable air filtration factor, whereas the Wisconsin Mechanical Code addresses "the increased air changes." In short, these observations underscore the significance of higher air-quality requirements across different regions.

Based on Table 4.27, Figure 4.13 presents a color-coded U.S. map with the state-level building codes' risk-responsiveness levels based on the study findings. The darker color indicates that the state building codes adopted are more responsive to the risk of transmission as they have relatively higher points than those in lighter colors. The gray ones represent states that were not taken as samples. Most leading states are located on the West Coast, specifically Washington, California, and Nevada. One of the other high-score states is Wisconsin, which is in the upper Midwest.

The model codes and adoption years of these four states are as follows:

1) Washington (IMC 2021 with amendments)
2) Nevada (UMC 2018)
3) California (IMC 2021 with amendments)
4) Wisconsin (IMC 2015 with amendments)

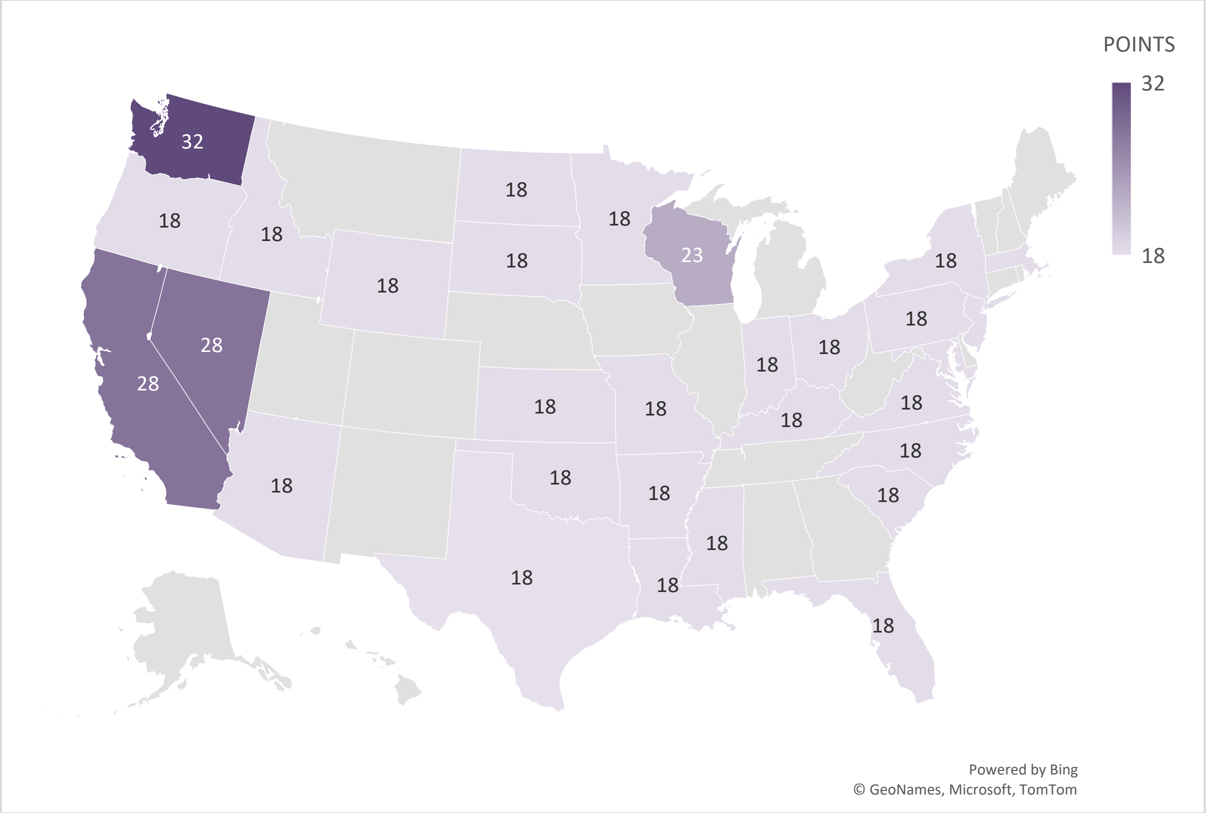


Figure 4.13. The State's Risk-Responsive Levels Map

Comparing these four states with other states that received lower scores shows that the model codes and adoption years do not always correlate with higher risk responsiveness. Some state building codes that received lower scores adopted the latest 2021 model codes; however, they did not include the advanced requirements or factors to mitigate airborne transmission, such as higher air filtration. This case also occurred in the city codes.

Based on the examination, the building codes of states and cities currently include requirements for ventilation rates, air filtration, outdoor air, air change rates, and space management. On the contrary, the six other factors—space design, clean air delivery rates, air disinfection, monitoring of indoor air quality, compliance with operation standards, and an effective system of operation and maintenance—are currently not included.

Higher air filtration requirements of minimum MERV 13 were common in the high-score states and cities. Higher air filtration requirements were identified in the Washington (32), California (28), and Nevada (28) codes. Table 4.28 provides more details on these states' points.

Table 4.28. Detail in Points Between High-Scoring States and Others

Factors	Washington	California	Nevada	Wisconsin	Others
Increased ventilation rates	5	5	5	5	5
Higher air filtration	10	10	10	0	0
Space design	0	0	0	0	0
Clean air delivery rates	0	0	0	0	0
Bringing OA	5	5	5	5	5
Increased ACH	5	5	5	5	5
Air disinfection	0	0	0	0	0
Monitoring IAQ	0	0	0	0	0
Compliance with operation standards guidelines	0	0	0	0	0
Space management	4	4	4	4	4
Effective system of O&M	4	0	0	0	0
Score	32	28	28	23	18

The Washington code also requires testing and commissioning for mechanical and natural ventilation. Additionally, I identified higher air filtration requirements in the codes of the three highest-scoring cities: Seattle, Los Angeles, and Houston. Figure 4.14 summarizes the code comparison between the high-scoring states and those with lower scores.

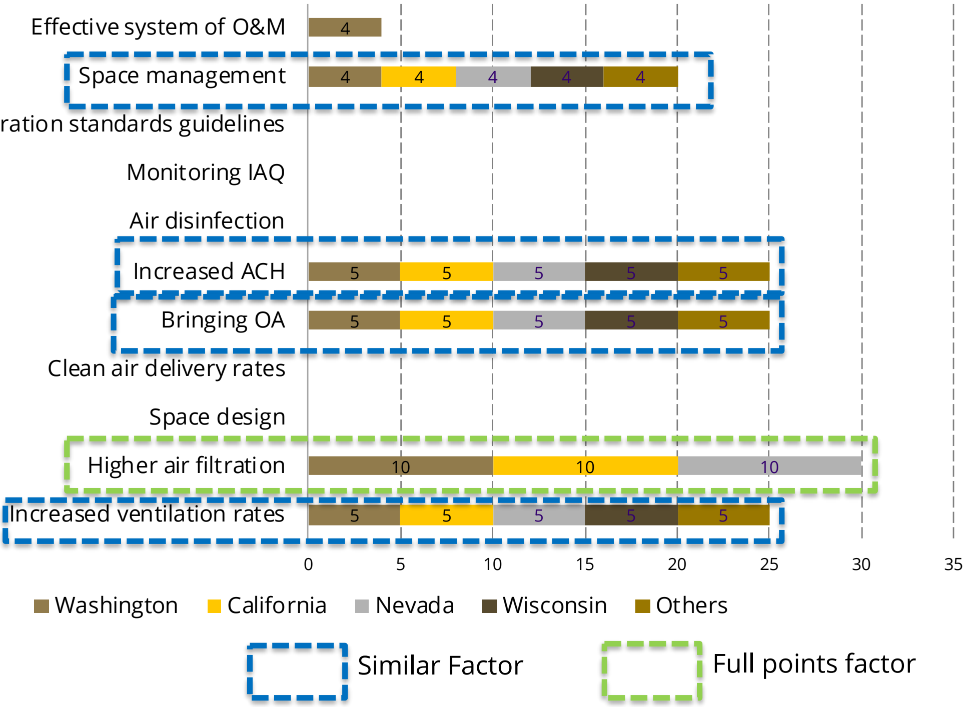


Figure 4.14. Comparison Between High-Scoring States and Others

Similarly, Figure 4.15 describes the code comparison between the high-scoring cities and those with low scores. Five factors were identified in Seattle, Los Angeles, Houston, and New York City: increased ventilation rates, increased air filtration, outdoor air, air change rates, and space management based on the ASRHAE 62.1 standard. Los Angeles and Houston had higher air filtration requirements, which required MERV 13 at a minimum. The Seattle code requires advanced testing and commissioning for natural and mechanical ventilation.

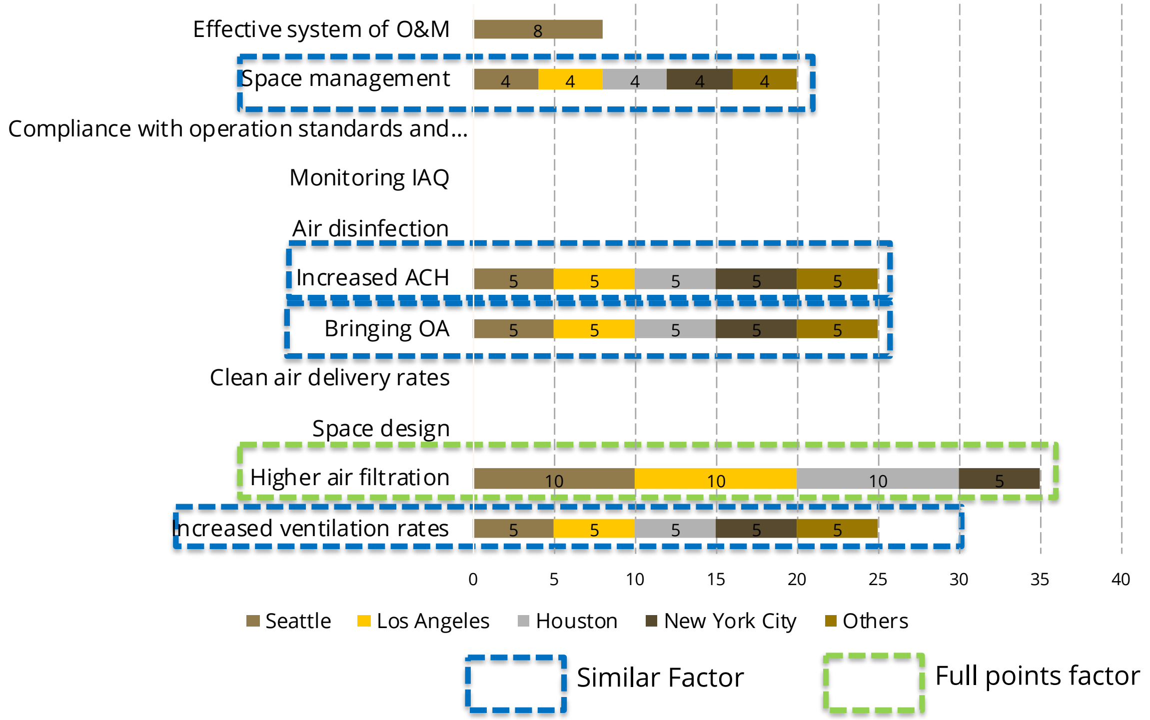


Figure 4.15. Comparison Between High-Scoring Cities and Others

Among the sampled cities, Seattle, New York City, Los Angeles, and Houston have higher scores than others. Seattle scored 36, New York City 28, and both Los Angeles and Houston 23. Seattle and New York City adopted IMC 2018 with amendments, and Los Angeles adopted the California Mechanical Code (CMC) 2022, which adopted the Universal Mechanical Code (UMC) 2021. Houston adopted an earlier version of UMC in 2015. Table 4.29 provides more details of points on these cities compared to others.

Table 4.29. Detail in Points Between High-Scoring Cities and Others

Factors	Seattle	Los Angeles	Houston	New York City	Others
Increased ventilation rates	5	5	5	5	5
Higher air filtration	10	10	10	5	0
Space design	0	0	0	0	0
Clean air delivery rates	0	0	0	0	0
Bringing OA	5	5	5	5	5
Increased ACH	5	5	5	5	5
Air disinfection	0	0	0	0	0
Monitoring IAQ	0	0	0	0	0
Compliance with operation standards and guidelines	0	0	0	0	0
Space management	4	4	4	4	4
Effective system of O&M	8	0	0	0	0
Score	36	28	28	23	18

These four cities have similar requirements regarding ventilation rates, air filtration, outdoor air, air change rates, and space management per the ASHRAE 62.1 standard. In the Seattle code, additional points were given because engineering calculations for natural and mechanical ventilation also require testing and commissioning, as shown in Section 401. In addition, a higher air filtration requirement, requiring a minimum MERV of 13 in Section 605.5 Smoke Filtration, is also present. Los Angeles, Houston, and Seattle shared the higher air filtration factor, which requires air filtration of at least MERV 13. New York City has the lowest air filtration factor among these four cities.

These observations show that these cities share similar air filtration factors but differ in the levels of points, with Seattle standing out for additional points on testing and commissioning and higher air filtration factors.

4.3 MOVING FORWARD TO FUTURE BUILDING CODES

4.3.1 Maintaining Building Design and Operation

Previously, in Round 1, I asked experts their opinions on whether indoor airborne transmissions can be mitigated by regulating building design and operational requirements. This question resulted in experts expressing challenges in maintaining design requirements during building operations. The following are three key summaries of the experts' responses.

1) The building design and operation phases are essential for minimizing airborne disease transmission risks. However, current building codes are primarily for building design and construction.
2) A building's operational performance needs to be enforced to ensure it performs as intended. For this reason, dedicated enforcement, inspection, and reporting systems, combined with local penalties, will be required to achieve operation performance during the operation phase.
3) Buildings' owners and operators have limited knowledge about maintaining design requirements, particularly after buildings are completed. This situation makes it difficult to maintain building performance as intended after completion.

Based on the Round 1 results above, experts were asked in Question 3 of Round 2 about their opinion of the factors that could be successful in mitigating the risk of transmission in three scenarios:

1) The availability of building codes that cover design and operation requirements
2) The availability of enforcement systems
3) The availability of knowledge improvements.

Experts (n=8) indicated their judgments on the likelihood of contributing to successful design and operation requirements implementation by entering a number between 0 and 10, where 0 = "Not at all likely to be successful" and 10 = "Most likely to be successful." Table 4.30 depicts the median values and rank of experts' opinions.

Table 4.30. The Likeliness of a Successful Implementation of Building Design and Operation Requirements (n=8)

Factors	Median Value Availability Design and Operation Codes	Rank	Median Value Availability of Enforcement System	Rank	Median Value Knowledge Improvements for Owners and Operators	Rank
Higher air filtration	7	4	7	1	6	3
Bringing OA	8.5	2	5.5	3	6	3
Effective system of O&M	6	7	4	8	5	6
Clean air delivery rates	4.5	9	4.5	5	4.5	10
Space design	4	10	4.5	5	5	6
Space management	4	10	4.5	5	5.5	5
Monitoring IAQ	6.5	5	5.5	3	7	1
Air disinfection	5	8	2	11	4	11
Increased ACH	7.5	3	3.5	10	5	6
Increased ventilation rates	9.5	1	6	2	6.5	2

Figure 4.16 provides a detailed depiction of the median values of factors side-by-side in accordance with the tree scenario above for each factor.

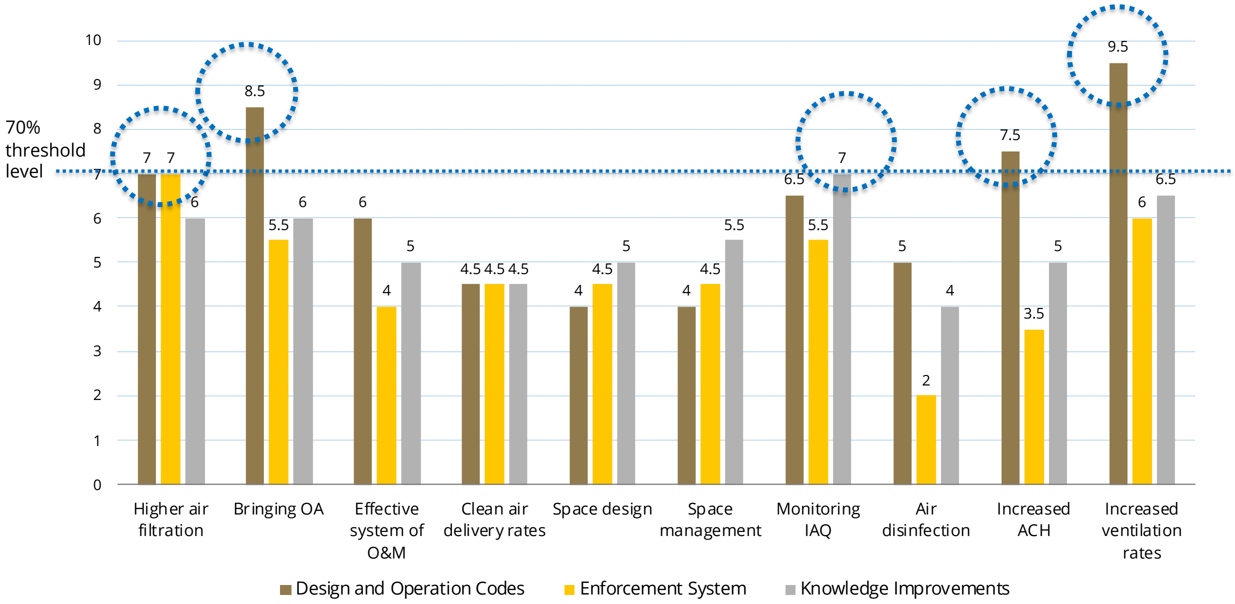


Figure 4.16. Factors' Median Values of Agreement Side-by-Side with Three Scenarios on Maintaining Design and Operation

Regarding the first scenario on whether the availability of design and operation codes is likely to contribute to a successful design and operation in mitigating the risk, all experts reached a consensus on four factors out of 11. The following are the agreed-upon factors ranked from highest to lowest median values:

- Increased ventilation rates
- Bringing outdoor air
- Increased air change rates
- Higher air filtration

In terms of the second scenario on whether the availability of enforcement systems, e.g., inspection, reporting, and penalties provided by the local government, is likely to contribute to a successful design and operation in mitigating the risk, all experts (n=8) again reached a consensus for one out of 11 factors—air filtration.

Regarding the third scenario, whether knowledge improvement for building owners and building operators will likely contribute to successfully implementing design and operation requirements, the experts unanimously agreed that indoor air-quality monitoring was the most crucial factor. This finding could be interpreted as that by providing more knowledge on the topic of indoor air quality monitoring to the building owners and operators, will contribute to a successful building performance during operation

Furthermore, the information in the monitoring IAQ system could be a proxy to identify potential problems in buildings related to indoor air. This information could lead to a mutual understanding of how a building should be improved between operators and owners.

In conclusion, examining the three scenarios addressing the risk of transmission in building design and operation yielded notable insights. The experts identified and reached a consensus on four pivotal factors:

1) Increased ventilation rates
2) Bringing outdoor air
3) Increased air change rates
4) Higher air filtration in the context of design and operation codes

The consensus in the second scenario emphasized the significance of the air filtration factor within local government enforcement systems. In the third scenario, unanimous agreement among experts underscored the critical role of knowledge improvement, particularly around monitoring IAQ, in highlighting its potential to enhance collaboration between building owners and operators. This holistic understanding points toward comprehensive strategies for effective risk mitigation and improved building performance.

4.3.2 Higher Requirements for Emergency Situations

In Round 1, all experts (n=14) were asked their judgments on whether or not building codes need to mandate higher requirements—such as increased ventilation rates, higher air filtration, more frequent air changes, etc.—during emergencies and hazardous situations. The result shows that 50% of the experts agreed, 36% were neither in agreement nor disagreeing, and 14% disagreed. The following is a summary of the experts' responses:

1) In addition to the normal operating mode, buildings should have an emergency mode. In the event of an emergency, higher requirements are acceptable.
2) Building codes generally do not include higher requirements than standards unless there is a risk present, and it occurs frequently.
3) There may not be a need for code changes, depending on the risks or hazards, even if the risks or hazards are present. Energy efficiency and cost considerations must be considered when making code changes.

Following these results, in Question 4 of Round 2, I asked all experts for their opinion on the likeliness of a) continuing the risk of airborne transmission, b) whether building codes should address the risk, c) whether higher requirements in codes would be necessary, and d) whether building codes should allow normal and emergency modes of operation.

All experts (n=9) indicated their judgments on the risk-responsive factors corresponding to the questions by entering a number between 0 and 10, where 0 = "Not at all likely to be successful" and 10 = "Most likely to be successful." Table 4.31 shows the result in median values.

Table 4.31. The Likeliness of Continuing Risk and Building Codes to Address the Risk and Higher Requirements Needed (n=9)

Questions	Median Value	Pass or No Agreement Level (70%)
Do you think that the airborne transmission risk such as COVID-19 in office buildings will continue?	10	Passed
Do you think that building codes should address the risk?	10	Passed
Do you think that having higher or more stringent requirements in building codes would be able to adequately anticipate risks in the future?	8	Passed
In your opinion, would having a normal mode of operation and an emergency mode of operation be able to mitigate the risk of infection?	7	Passed

All experts unanimously agreed that the risk of airborne transmission, including COVID-19, will persist in office buildings. This consensus mirrors the federal government’s announcement on May 11, 2023, concluding the COVID-19 Public Health Emergency (PHE) Declaration and marking the shift from pandemic to endemic after three years (CDC, 2023). The announcement emphasized that the risks still persist. Despite this transition, the enduring risk underscores the continuous nature of transmission. Furthermore, the observed year-round prevalence of COVID-19, independent of the specific season (Zarefsky, 2022), emphasizes the consistent risk throughout the year.

As a follow-up to the previous question, the experts were asked about the best method to accommodate higher or more stringent emergency requirements. Figure 4.14 describes the agreement distribution.

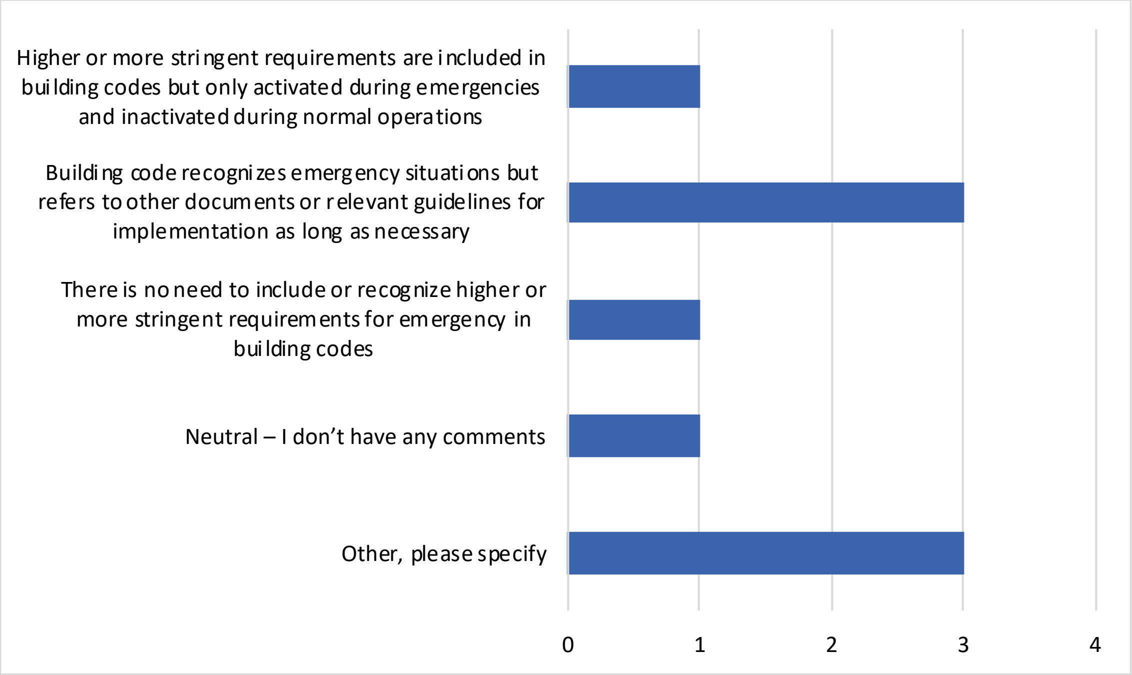


Figure 4.17. Agreement Distribution on the Best Way to Accommodate a More Stringent Requirement for Emergencies (n=9)

The response to this question revealed a divided opinion among the experts, with no consensus reached. Some experts expressed that it is unnecessary to incorporate provisions for emergency situations directly into building codes, suggesting that these scenarios should be addressed in separate documents or guidelines. On the contrary, one expert recommended including higher requirements in the code specifically for emergencies, with the provision to deactivate them during non-emergency periods.

Three other experts provided "Other, please specify" responses, offering nuanced perspectives on the need for constant protection codes, the recognition of different hazards, and calling for more performance-based options in building codes. One expert emphasized the importance of nimble codes that adapt to emerging issues such as COVID-19 and wildfire smoke, advocating for creative solutions and performance-based options with proper training and documentation. The following are their comments:

“But to get at this question, I don’t think there is a need for emergency protocol as long as buildings/indoor air ventilation is kept to a high standard all the time. Between COVID-19, wildfire smoke, and just general particulate/VOCs in office buildings, I think it would always be under ‘emergency’ protocol. How about we just protect people all the time?”

“I agree with the first option, but multiple emergencies may require different things. If there is COVID and wildfire smoke, blindly introducing more outdoor air is not a good solution. These are two known hazards. Ten years ago, we wouldn't even have thought about these things as issues. The code needs to be nimble, which it is far from.”

“Building codes should be moving to more performance-based options, as I indicated in the last question. Give a design team a target IAQ standard that includes an eCADR, and let them creatively solve the problem. The solution must require the design team to provide the code officials and owners with the necessary training and documentation to enforce and operate the building as designed.”

In conclusion, the experts unanimously acknowledged the persistent risk of airborne transmission, including COVID-19, in office buildings, aligning with the federal government’s recognition of the shift of COVID-19 from pandemic to endemic. The divergent opinions on emergency provisions in building codes emphasize the nuanced approach needed, ranging from advocating separate guidelines to endorsing performance-based options. These insights underscore the ongoing challenge of balancing safety measures and adaptability within building codes.

4.3.3 The Best of Compliance Path for the Factors in Future Building Codes

In Round 1, all experts were asked for their opinion on which type of code would best implement the factors. In response to the experts’ comments, the associated question was revised to include two types of compliance codes: prescriptive and performance-based. As a result, in

Round 2, I asked experts for their opinion (n=9) on the best path of compliance for these factors in mitigating airborne transmission for office buildings. They were asked to indicate their judgments on the risk-responsive factors corresponding to the questions by entering a number from 0 to 10, where 0 = "Not working at all" and 10 = "Working successfully." Table 4.32 and Table 4.33 depict the agreement distribution on the best compliance path for each factor for prescriptive and performance-based paths.

Table 4.32. Agreement Distribution on Prescriptive Path for Factors in Building Code (n=9)

Factors	Prescriptive path (Median Values)	Factor Rank	Pass the Agreement Level 70%
Higher air filtration	7	1	Yes
Bringing OA	7	1	Yes
Increased ACH	7	1	Yes
Increased ventilation rates	7	1	Yes
Compliance with operation standards and guidelines	6	5	No
Clean air delivery rates	5	6	No
Space design	5	6	No
Monitoring IAQ	5	6	No
Effective system of O&M	4	9	No
Air disinfection	4	9	No
Space management	1	11	No

The experts reached a consensus that four out of 11 factors would perform better under the prescriptive compliance path of building codes. These factors are:

1) Higher air filtration
2) More outdoor air
3) Increased in air change rates and
4) An increased ventilation rate

Conversely, in a performance-based compliance path, the experts agreed on five out of 11 factors that outperformed others. These factors are:

1) Clean air delivery rates
2) Increased ventilation rates
3) Bringing more outdoor air
4) Effective operation and maintenance and
5) Increased air change rates

These findings suggest a collective expert perspective favoring clean air delivery rates and increased ventilation rates in performance-based path building codes over the other three factors.

Table 4.33. Agreement Distribution on Performance-Based Path for Factors in Building Codes (n=9)

Factors	Performance Path (Median Values)	Factor Rank	Pass the Agreement Level 70%
Clean air delivery rates	8	1	Yes
Increased ventilation rates	8	1	Yes
Bringing OA	7	3	Yes
Effective system of O&M	7	3	Yes
Increased ACH	7	3	Yes
Higher air filtration	5	6	No
Monitoring IAQ	5	6	No
Air disinfection	5	6	No
Compliance with operation standards and guidelines	5	6	No
Space design	3	10	No
Space management	3	10	No

Both Tables 4.32 and 4.33 indicate that the experts shared an agreement on three factors that bringing outdoor air, increasing ventilation rates, and increasing air changes per hour will perform the best, either on a prescriptive or performance basis. Regardless of the compliance path, it can be concluded that the experts were in favor of these three factors.

Based on the comparison of median values, I concluded that performance-based paths are slightly more favorable than prescriptive paths. It is evident that both prescriptive and performance-based compliance paths are expected to have a comparable impact on implementing risk-responsive building codes. Two factors in the performance-based path of compliance—1) clean air delivery rates and 2) increased ventilation rates—received slightly higher median values than other factors and might provide added benefits in the context of performance-based building codes.

Chapter 5. DISCUSSIONS

Having meticulously analyzed data collected through the mixed-method approach, including content analysis, expert interviews, and two rounds of the Delphi method, I will continue to Chapter 5. This chapter aims to analyze the research findings and explore their significance and implications in response to the research questions. Each research finding from Chapter 4 will be discussed based on the four main research questions and compared with the literature review. This comparison will underline the similarities, contrasts, and additional insights identified during data collection and analyses.

5.1 RESEARCH FINDINGS

5.1.1 What Factors Determine Building Codes' Risk-Responsiveness to Airborne Transmission, Including COVID-19?

This research extensively investigated the factors that determine the building code's risk responsiveness to mitigate airborne transmission, including COVID-19, through content analysis, expert interviews, and two rounds of the Delphi method. From the initial nine factors, six factors during Delphi Round 1 and Round 2 resulted in 11 final factors. This research identified two key findings during the analysis: 1) criteria to evaluate factors; and 2) weighted and ranked final factors. The following discussions will focus on these two key findings.

5.1.1.1 Criteria in Evaluating Factors

During the Delphi method process, this research identified four criteria on factors' importance used to assess factors' relative weight of importance. These criteria are listed in Table 5.1 below:

Table 5.1. Criteria for Evaluating Factors (Modified from Table 4.20)

Criteria	Description	Frequency (n)
Prevention effectiveness	The factor’s implementation can effectively eliminate or reduce the risks of airborne transmission in office buildings	13
Associated energy costs	The factor adds cost for energy consumption due to significant energy use	18
Ease of monitoring and reporting	The factor makes it easy to implement a monitoring system to report the results of the intervention for decision-making processes	11
Ease of implementation and enforcement	The factor’s ease of implementation includes installation, operation, maintenance, and enforcement	4

These four criteria emerged from several experts’ concerns about the factors that should be included in building codes. Prevention effectiveness is the biggest concern, followed by associated energy costs, ease of monitoring and reporting, and ease of implementation and enforcement, which are the least concerns.

Compared with the Chapter 2 Literature Review, this finding shared some similarities with the discussion on building codes in the U.S. and their relationship with the COVID-19 pandemic. By definition, the criteria for evaluating factors support the objective of building codes, which are essential in mitigating risks from natural and man-made (Burby & May 1999; Cote & Grant, 2008; Rossberg & Leon, 2013) and minimizing casualties and economic losses by mandating the building’s minimum requirements (Baum, 2005; Cheng, 2013; Cote & Grant, 2008; Fakunle et al., 2020; Vaughan & Turner, 2013). Mitigating risks and minimizing economic losses were two aspects that aligned with prevention effectiveness and costs.

Prevention effectiveness became a first concern due to the objective of building codes in mitigating risks: to ensure that any strategies, changes, improvements, or modifications in building codes will contribute to lowering airborne transmission, including COVID-19. Those changes or modifications were perceived to have a strong basis or were proven to reduce the risk of airborne transmission. On the other hand, cost emerged as the second most significant concern as the growing body of knowledge on HVAC strategies to combat COVID-19 has led to additional energy costs required in building operations. The literature review did not address the other two criteria: ease of monitoring and ease of implementation in the context of building codes. It is assumed that those two criteria were closely related to building operations, while current building codes focus primarily on building design and construction phases, not the operations.

The evaluating criteria could be used as precautionary measures to ensure that any changes, modifications, or improvements to future building codes comply with their objective: to provide occupants with health and safety by gradually improving based on previous risks.

5.1.1.2 Final Weighted and Ranked Factors

This research has identified important factors in determining the building codes' risk responsiveness. Table 5.2 lists the final factors, all of which are weighted and ranked.

Table 5.2. Final Weighted and Ranked Factors

Factors	Factor Rank	Median Values	Conversion to 100 scale points
Increased ventilation rates	1	78%	10.32
Higher air filtration	2	75%	9.90
Space design	2	75%	9.90
Clean air delivery rates	4	72%	9.46
Bringing OA	5	71%	9.43
Increased ACH	6	69%	9.05
Air disinfection	7	67%	8.88
Monitoring IAQ	8	67%	8.78
Compliance with operation standards and guidelines	9	65%	8.58
Space management	10	60%	7.92
Effective system of O&M	11	59%	7.78

This research found five factors meet the minimum agreement levels based on the four criteria. These include:

1) Increased ventilation rates
2) Higher air filtration rates
3) Space design
4) Clean air delivery rates (CADR)
5) Bringing outdoor air

The importance of these factors for mitigating airborne transmission, including COVID-19, in office building settings was consistent with the literature review. The literature recognized that increased ventilation rates are critical in reducing infection risk (Awada et al., 2021). Increased ventilation rates are one of the most discussed topics for addressing COVID-19 in an indoor setting, even though the exact rates are unknown (Allen & Macomber, 2020; Awada et al., 2021; Taylor, 2020). Determining these rates needs more research (Awada et al., 2021; Taylor, 2020). At the same time, modifying a building's ventilation rates requires engineers' involvement.

The findings on higher air filtration are consistent with the literature review. In general, a higher MERV 13 filter is at least required, along with an additional strategy such as flushing the building before and after the occupation hours (WSDOH, 2020). Another strategy involves utilizing a MERV 14 to MERV 16 air filter combined with air recirculation comparable to an increase in outdoor air (ASHRAE, 2021a).

Research findings on space design are consistent with the literature review, although not as specific. The literature review underlines changes in future office building designs, including layouts and design solutions for working spaces (Megahed & Ghoneim, 2020; Nediari et al., 2021).

It should be noted that the current development of space design factor is closely linked to HVAC strategies for reducing transmission risks.

The research findings identified the Clean Air Delivery Rates (CADR) as one of the factors; however, the literature review has yet to acknowledge CADR. The discussion on the importance of CADR was identified during Delphi Round 1, where two experts addressed CADR as a potential strategy for mitigating the risk of transmission. In Round 2, CADR emerged as one of the final factors in determining building codes' risk responsiveness.

The literature review and research findings acknowledged the importance of bringing in outdoor air. Initially, outdoor air was part of the ventilation factor (Morawska et al., 2020) in Round 1 of the Delphi Method, but it was separated for more clarification. The literature review underlines the role of outdoor air in reducing the transmission risk of viral particles in an indoor setting (WSDOH, 2020) by dilution (Megahed & Ghoneim, 2021) and being a part of indoor air quality and airflow patterns in buildings (Awada et al., 2021).

The following paragraphs discuss the factors that did not reach the agreement levels based on the four previous criteria. These include:

1) increased ACH
2) air disinfection
3) monitoring IAQ
4) compliance with operational standards and guidelines
5) space management
6) effective system of operation and monitoring (O&M)

The importance of increased ACH in mitigating airborne transmission is consistent with the research findings, which obtained slightly less than the minimum agreement level (69%). Initially, this research recognized that increased ACH as a part of the ventilation factor or as part of a combination with increased ventilation rates (AIA, 2020b; CDC, 2020e; Dietz et al., 2020; Xu et al., 2020) is essential to mitigating airborne risks. For example, the Wisconsin Mechanical Code has an increased ACH factor and requires at least a six-air change rate to be provided in each space. This rate is higher than the typical two- or three-air exchange rates for office buildings. While the experts underscored the importance of an increased ACH factor, there is a slight difference in their agreement levels.

Research findings acknowledged air disinfection and monitoring IAQ as two factors that received less than agreement levels (67%). Even though the literature review frequently mentioned these two factors, experts did not reach minimum agreement levels. Air disinfection by using UV devices (UVGI and UV-C light) was identified as an approach when it is challenging to improve ventilation (Morawska et al., 2020). Despite its practicality and potential benefits, the use of air disinfection suggests precautions due to its impact on human health, maintenance issues, and control strategies (Morawska et al., 2020).

Monitoring IAQ during building operations was viewed as a complementary factor in avoiding the high concentration of CO_2 or as an indicator of IAQ (Allen & Macomber, 2020). Monitoring IAQ was also found to be an additional intervention if other factors such as increased ventilation rates, higher air filtration, and increased air changes were put in place since it is a challenge to detect COVID-19 airborne transmission.

The literature review confirms the importance of building operations in minimizing the risk of infection (Awada et al., 2021; Morawska et al., 2020), but this factor did not reach the minimum agreement level in the final research findings (65%). Space management (60%) and an effective O&M factor system (59%) also did not reach the minimum agreement levels.

In contrast to the literature review, which recognizes space management as essential in minimizing transmission risk and a focal point in mitigating future pandemics (Awada et al., 2021), it only received 60% agreement. As defined in Chapter 4, the space management factor could be interpreted as a temporary measure rather than a permanent one, which may explain its lower ranking. Similarly, the literature review has yet to recognize the last factor, an effective system of operation and monitoring (O&M), since it emerged during Round 1 of the Delphi Method and was emphasized to ensure the intended building performance during operations.

In addition, the literature review recognized that a combination of factors or multiple strategies is more effective in reducing the risk of transmission. For example, a combination of increased ventilation rates and UVGI (Morawska et al., 2020) can potentially double the risk reduction. Higher air filtration, such as MERV 14–16, combined with recirculation, is comparable to bringing in more outdoor air (ASHRAE, 2021a) or using advanced HVAC designs and operations practices, humidity control and spatial configurations, and human interactions (Awada et al., 2021). In addition, implementing multiple strategies in building operations is important for safer building operations during COVID-19 and future pandemics (Awada et al., 2021; Morawska et al., 2020).

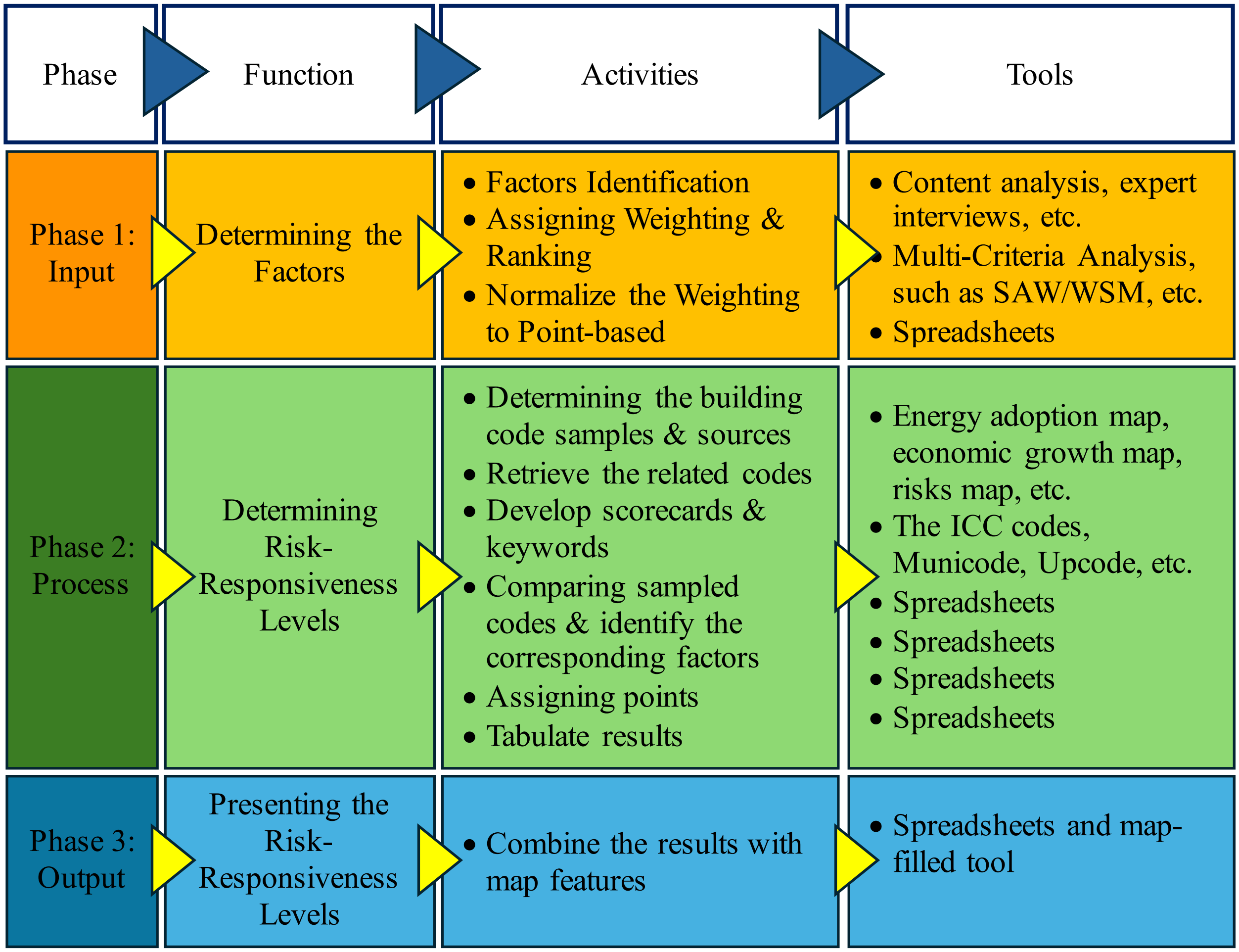
To sum up, while the literature review identified the role of each factor in mitigating the risks of airborne transmission, research findings identified that based on four criteria of prevention effectiveness, energy costs, ease of monitoring and reporting, and ease of implementation and enforcement, only five factors remain: 1) increased ventilation rates; 2) higher air filtration; 3) space design; 4) CADR and 5) bringing outdoor air.

The remaining six factors fell within a close range of median values (69% to 59%), indicating nuanced perspectives between experts in determining their importance in building codes' risk responsiveness. This could potentially be due to their perceived temporary nature or emerging status in building operations, in factors such as space management or monitoring IAQ.

5.1.2 How Do We Assess or Evaluate the Current Risk-Responsiveness Levels of Building Codes?

The assessment and evaluation of current building codes employed the risk-responsive framework (RRF) to the selected sample of states and cities. The research adhered to the three phases of RRF structure as outlined in Chapter 3 Research Methodology. In phase 1, this research involved identifying the factors that were already weighted and ranked using the MCA method (SAW/WSM). Using these factors, I proceeded to Phase 2 to determine the risk-responsive levels in the U.S. case studies. I continued with factors' assessment by examining the relevant chapters or sections in the sampled building codes and subsequently recorded the data in spreadsheets.

Next, I allocated points accordingly based on the data gathered from the sampled building codes. I summarized the code examination from sampled states and cities, displaying points received from each factor, and tabulated the results. Figure 5.2 depicts RRF structure as explained in Chapter 3 Research Methodology.



Phase	Function	Activities	Tools
Phase 1: Input	Determining the Factors	• Factors Identification • Assigning Weighting & Ranking • Normalize the Weighting to Point-based	• Content analysis, expert interviews, etc. • Multi-Criteria Analysis, such as SAW/WSM, etc. • Spreadsheets
Phase 2: Process	Determining Risk-Responsiveness Levels	• Determining the building code samples & sources • Retrieve the related codes • Develop scorecards & keywords • Comparing sampled codes & identify the corresponding factors • Assigning points • Tabulate results	• Energy adoption map, economic growth map, risks map, etc. • The ICC codes, Municode, Upcode, etc. • Spreadsheets • Spreadsheets • Spreadsheets • Spreadsheets
Phase 3: Output	Presenting the Risk-Responsiveness Levels	• Combine the results with map features	• Spreadsheets and map-filled tool

Figure 5.3 RRF Phases and Tools (Taken from Figure 3.5. RRF Phases and Tools)

In general, RRF is a useful framework for investigating the risk-responsiveness levels of building codes. It provides clear, step-by-step guidance to answer the research questions. During the development of this research, I identified several advantages and challenges. One clear advantage of using RRF is its simplicity and ease of use. Each phase’s activities are open to adjustment, and the tools can also be expanded depending on the complexity of the cases. For instance, if the research solely employs a qualitative approach, assigning weighting and ranking might not be necessary. Instead of using SAW/WSM, the MCA method could offer more options for assigning weight and rank of factors, if required.

Despite its simplicity, RRF faces numerous challenges. I observed that the general time-consuming issue stemmed from the extensive use of spreadsheets during Phase 2. The use of spreadsheets has some limitations when handling text-based data, such as building code text, resulting in additional time required to complete multiple activities as stipulated in RRF simultaneously.

5.1.3 What is the Status of the U.S. Building Codes in Terms of Risk-Responsiveness Levels?

Based on the code examination of the sampled states and cities, the risk-responsiveness levels of building codes in the U.S. are considered low in mitigating airborne transmission, including COVID-19. Twenty-six states out of thirty state samples received 18 points out of 100. Only four out of the 30 sampled states received higher scores than the others: Washington (32), California (28), Nevada (28), and Wisconsin (23). These states received a relatively higher score due to the inclusion of more factors, thus resulting in more points.

From these research findings, I learned that only four factors were commonly identified from the sampled building codes: (1) ventilation rates, (2) outdoor air, (3) air change rates, and (4) space management, with none receiving the maximum points. The four highest-point states—Washington, California, Nevada, and Wisconsin—received more points for factors such as "higher air filtration," "increased air changes," and "effective system of O&M."

The city code examinations presented similar results, where four cities—Seattle, Los Angeles, Houston, and New York City—received relatively higher points than the other twenty-six. These four cities received additional points for "higher air filtration" and "effective system of O&M."

The pattern of the states and cities that received lower points is consistent with the literature review on building code adoption in the U.S. that mandates minimum requirements (Baum, 2005; Cheng, 2013; Cote & Grant, 2008; Fakunle et al., 2020; Vaughan & Turner, 2013).

The research findings found no correlation between the model code years and points received by the states, and the updates from different model codes were not related to factors in mitigating airborne transmission. Because the code is a model, states and cities (AHJs) were open to adjustments, changes, or amendments that were necessary during the adoption process.

States and cities that received relatively higher points shared similar requirements for preparedness for known hazards that can also mitigate airborne transmission, including COVID-19. Wildfires and smoke hazards might prompt the adoption of "higher air filtration" measures in relevant building codes, which share similar airborne transmission mitigation requirements. Therefore, these states received additional points for airborne transmission mitigation preparedness by having more factors in their building codes.

To conclude, the analysis of building codes across sampled states and cities in the U.S. revealed generally low levels of risk responsiveness to airborne transmission, including COVID-19. Most states scored poorly, with only four—Washington, California, Nevada, and Wisconsin—receiving relatively higher scores due to their inclusion of more factors in their codes. Ventilation rates, outdoor air, air change rates, and space management were some of the most identified factors, but they have yet to receive maximum points. Notably, the four states with the highest points also emphasized factors like higher air filtration, increased air changes, and an effective operation and monitoring system.

I observed similar trends in city code examinations, with Seattle, Los Angeles, Houston, and New York City receiving higher points. These findings were supported by the literature review, which highlighted the prevalence of minimum requirement-based code adoption in the United States. Interestingly, there was no clear association between model code years and points received by states, suggesting flexibility in the code adoption processes. Higher-scoring states and cities shared similar requirements for preparedness against known hazards like wildfires, which also respond to airborne transmission mitigation.

5.1.4 What Recommendations Can be Provided to Prepare for Similar Airborne Disease Crises in the Future?

The research findings uncovered three discussion topics for building codes to mitigate airborne transmission in the future: (1) maintaining building design and operation; (2) higher requirements for emergencies; and (3) the best compliance paths for factors. The following text discusses these three topics in more detail.

5.1.4.1 Maintaining Building Design and Operation

The research findings identified several challenges in maintaining building design and operation, albeit with the potential to mitigate indoor airborne transmission, including COVID-19. First, building design and operation phases are critical for minimizing transmission risks, and current building codes focus primarily on design and construction. Second, a system of enforcement is necessary to ensure that building operations perform as intended. Lastly, the limited knowledge of building owners and operators during the building operation phase poses a challenge to maintaining building performance.

Based on these findings, I developed three scenarios for maintaining design and operation:

1) Availability of design and operation codes
2) Availability of an enforcement system
3) Knowledge improvements for building owners and operators

First, the availability of design and operation codes for four factors out of eleven were agreed upon as contributing to a successful design and operation implementation: increased ventilation rates, bringing in outdoor air, increased ACH, and higher air filtration. Compared to the literature review in Chapter 2, this finding is consistent with the use of advanced HVAC design and operations practices (Awada et al., 2021) in dealing with the transmission risk of COVID-19 in buildings in the future.

Furthermore, the literature review underscored the significance of building design and operation, with a focus on engineering, as crucial component in mitigating similar disasters such as air pollution at the same time (Megahed & Ghoneim, 2021). However, this finding raises additional questions about other factors that have yet to receive expert agreements to mitigate the transmission risks.

In the second scenario, the local government enforcement system was limited, which could only support the “higher air filtration” factor in building design and operation. Given the literature review in Chapter 2 has not yet discussed the role of local governments’ enforcement systems, this finding is quite concerning. Because it reveals further questions on how to ensure other factors’ inclusion in future building codes that also obtain support from the local government enforcement systems. Alternatively, we could rephrase the question to focus on establishing an enforcement system for other factors in future building codes, which would guarantee the building’s performance during operations as intended in the design phase.

The third scenario included knowledge improvement for building owners and operators in the “monitoring IAQ” factor, which could have contributed to successful building design and operations. The literature review did not address the role of the building’s stakeholders, such as building owners and building operators, in maintaining building performance. This finding offers new perspectives on shared responsibility in the post-construction phase. This question was developed based on the Round 1 Delphi result, which emphasizes the challenges of maintaining building performance during operations as intended in the design phase, where the operations are no longer under the responsibility of the building designer. This finding highlighted an opportunity that, since building owners and operators have expressed concern regarding monitoring IAQ, any building problems related to indoor air quality, including changes in CO_2 level as a proxy to detect COVID-19 transmission in buildings, could be anticipated and mitigated earlier.

5.1.4.2 Higher Requirements for Emergencies

The research findings revealed that experts did not agree on whether building codes should mandate higher requirements, despite unanimous agreement that the risk of COVID-19 in office buildings would persist. Experts unanimously agreed that higher requirements in building codes are necessary and supported the implementation of a dual operation mode, which includes both normal and emergency functioning. However, the experts could not reach a consensus on whether the higher requirements should be incorporated directly into the building codes or outlined in separate guidelines.

The literature consistently showed higher requirements than codes, particularly in building rating tools associated with indoor air quality, such as increased ventilation rates and higher air filtration in Fitwel and WELL, corresponding to COVID-19, respectively. The literature review underlined that the building codes' objective is to address public safety and health and minimize casualties and economic losses by mandating minimum requirements for buildings (Baum, 2005; Cheng, 2013; Cote & Grant, 2008; Fakunle et al., 2020; Vaughan & Turner, 2013).

In the past, building codes in the U.S. have been gradually revised and improved in response to numerous hazards. Since the risks of airborne transmission of COVID-19 continue to be a concern, this finding underscores the urgency to accommodate higher requirements into building codes in the future. However, current building code practices in the U.S. aim to balance optimal safety and economic feasibility by mandating minimum requirements (Cote & Grant, 2008). Introducing higher requirements into building codes might disrupt these efforts.

5.1.4.3 The Best Compliance Path for Factors

The research findings revealed that performance-based path outperforms prescriptive path in terms of the code compliance to implement the factors. Although there are small differences, the research findings also identified three factors that worked best in both prescriptive and performance-based settings: bringing more outdoor air, increasing ventilation rates, and increasing ACH. Two other factors in the performance-based path—CADR and the effective system of O&M—did not include in the prescriptive path, while higher air filtration in the prescriptive path, did not include in the performance-based path. Table 5.3 lists the comparison between agreed-upon factors in performance-based and prescriptive paths.

Table 5.3. Comparison Between Agreed Factors in Performance-based and Prescriptive Paths

Performance-based		Prescriptive	
Factors	Median Values	Factors	Median Values
Clean air delivery rates	8	Higher air filtration	7
Increased ventilation rates	8	Bringing OA	7
Bringing OA	7	Increased ACH	7
Effective system of O&M	7	Increased ventilation rates	7
Increased ACH	7		

The literature review identified the prescriptive path as a widely accepted code that is relatively easy to implement and verify. The prescriptive path specifies materials, methods, details, or building components required to comply with the code (Cote & Grant, 2008), while performance-based allows flexibility for building designers to comply with outlines to achieve the objectives. It also encourages innovative solutions to pursue higher performance levels with specific requirements (Rossberg & Leon, 2013). Literature has emphasized the association of performance-based paths in addressing future risks and hazards such as energy efficiency, climate change, and earthquakes (Babrauskas, 2000; Burby & May, 1999; Cote & Grant, 2008; Eisenberg, 2016; Rossberg & Leon, 2013).

The experts agreed that three factors a) increased ventilation rates; b) bringing outdoor air; and c) increased air change rates, will perform best in either performance-based or prescriptive paths. Upon comparing the prescriptive and performance-based characteristics in the literature review, it becomes clear that these three factors have both prescriptive and performance-based advantages. These advantages include their relative ease of implementation and verification, providing building designers with the flexibility to comply and strive for higher performance levels. This finding also emphasizes the shared benefits of two compliance paths to mitigate the future risks of airborne transmission. This finding emphasized that implementing factors may not need to be contained solely as prescriptive or performance-based paths but as a combination of both to successfully mitigate future airborne transmission risks.

The findings revealed that two factors, CADR and increased ventilation rates in performance-based settings, received higher median values than others. These higher median values indicate that, when compared to other factors in the performance-based path, both factors were found to work more successfully or perform better than others.

While increased ventilation rates are the most discussed topic to address COVID-19 risks in indoor settings in the literature review, CADR emerged during Delphi Round 1 and Round 2. The expert agreed that even though CADR was introduced later, this factor performs similarly or works successfully with increased ventilation rates in a performance-based path.

To sum up, the research findings on recommendations for future building codes involved three discussion topics: (1) maintaining building design and operation; (2) higher requirements for emergencies; and (3) compliance paths for factors. First, challenges in maintaining design and operation include the need for design and operation codes beyond the current building codes, which primarily focus on design requirements. Second, while experts agreed that the transmission risk continues even after the pandemic officially ends, there is no need to include higher requirements in building codes. Experts did not reach an agreement on the best way to implement higher requirements for mitigating airborne transmission, whether in separate documents or guidelines. Finally, this research found that the performance-based compliance path was found outperformed the prescriptive path, with three factors: a) bringing outdoor air, b) increasing ventilation rates, and c) increasing air change rates, which were effective in both compliance paths. These findings suggest that a combination of compliance paths may most effectively mitigate future airborne transmission risks. In addition, the similar results of performance-based and prescriptive paths on some factors indicate that combining these two paths could increase efficacy in mitigating airborne transmission.

Chapter 6. CONCLUSION

Based on the discussions presented in Chapter 5, I continue to transition to the final chapter, where I will synthesize the key findings, discuss the broader policy implications, and provide concluding remarks in Chapter 6. This chapter will summarize the key findings in relation to the research objectives and questions, as well as the contributions to the body of knowledge. The study's limitations and questions for future research will also be discussed.

6.1 SUMMARY OF KEY FINDINGS

This research aimed to develop a framework to assess the current condition of existing building codes for office buildings, present the results, and investigate how these codes could be more responsive to the risks of airborne transmission, including COVID-19. However, even though building codes are essential in ensuring occupant safety and health, there is a need for more discussions and an overall lack of knowledge regarding how building codes would respond and be more responsive to a future pandemic.

Regarding the first research question, which focuses on factors that determine a building's risk-responsiveness, this research conducted two activities: a) the development of criteria for factor evaluation; and b) the weighting and ranking process. This research employed experts' comments to develop the criteria for factor examinations. These include prevention effectiveness, associated energy costs, ease of monitoring and reporting, and lastly, ease of implementation and enforcement. These criteria were used to evaluate factors' relative weight of importance using the SAW/WSM method. Based on the weighting and ranking, eleven final factors were identified. Five factors exceed the minimum agreement level of 70%, while the remaining six range between 69-59%.

The five factors that exceed the minimum threshold are: a) increased ventilation rates; b) higher air filtration; c) spade design; d) clean air delivery rates (CADR), and e) bringing outdoor air.

The six remaining factors are: a) increased ACH; b) air disinfection; c) monitoring IAQ; d) compliance with operation standards and guidelines; e) space management; and f) an effective system of operation and monitoring. Despite the literature review supporting these factors' contribution to mitigating airborne transmission risks, including COVID-19, the close range of remaining factors suggests a nuanced perspective in determining their importance in building codes' risk responsiveness.

In response to the second research question about assessing or evaluating building risk responsiveness levels, I used RRF as a framework to guide the step-by-step actions required. I completed all three RRF phases, starting with the factor identification from content analysis, expert interviews, and two rounds of the Delphi method and finalizing them using the SAW/WSM method. Next, I proceeded with code examinations, including assigning scores and recording the data in spreadsheets. Lastly, I presented the results based on the assigned scores to the sampled states and cities in the U.S. case studies. Despite its simplicity, RRF can be time-consuming due to the extensive use of spreadsheets. Additionally, the limitations of spreadsheets in handling text-based data, such as building codes, can make it challenging to perform multiple activities simultaneously.

Regarding the risk-responsiveness levels across various states and cities in the U.S., the research findings indicate that, in general, most states and cities exhibited low building code risk responsiveness levels, with a few exceptions. States that received higher points, such as Washington, California, Nevada, and Wisconsin, scored relatively higher due to the inclusion of relevant factors in their building codes.

Ventilation rates, outdoor air, air change rates (ACH), and space management were commonly identified across codes. However, none of these factors received maximum points. The states with the highest points also had higher air filtration, increased ACH, and an effective O&M system.

Similar findings were noted in city-level code examinations, with cities such as Seattle, Los Angeles, Houston, and New York City scoring higher points. When compared to the literature review, these findings underscored the widespread adoption of minimum-requirement-based code adoption in the U.S. states and cities. Those states and cities that scored higher often had requirements that prepared them against known hazards, such as wildfires, contributing to their readiness to mitigate airborne transmission risks. From the healthy building perspective, the adoption of health-focused factors such as higher air filtration in responding to disasters that share similar requirements with mitigating airborne transmission risks, including COVID-19, underscores the potential integration of these factors to improve the building codes' risk responsiveness in the future.

Responding to the question on recommendations that can be provided to prepare for similar airborne diseases, this research revealed three critical areas for future building codes to mitigate airborne transmission: (1) maintaining building design and operation; (2) higher requirements for emergencies; and (3) the best compliance paths for factors in building codes.

While maintaining building design and operations is essential to mitigating indoor airborne transmission, there were challenges and the potential to ensure building operations performed as intended during the design phase. The research revealed three scenarios related to maintaining building design and operation: a) availability of design and operation building codes; b) availability of an enforcement system; and c) knowledge improvements for building owners and operators.

This research identified that the availability of design and operation codes could contribute to the successful implementation of four factors out of a total of eleven:

1) Increased ventilation rates
2) Bringing outdoor air
3) Increased ACH
4) Higher Air Filtration

Despite the literature review's support for these factors' contribution to maintaining building performance as intended in design, this finding highlights challenges in how the remaining factors could support building performance during operations to mitigate airborne transmission.

Regarding the second scenario, which involves the availability of an enforcement system, this research identified that only one factor, "higher air filtration," could receive support from local enforcement systems, e.g., inspection, reporting, and penalties by the local government. This underscores the limit support local governments provide in contributing to successful building design and operation. This research then identified challenges in including other factors in future building codes that also receive support from the local government enforcement systems.

In the context of the third scenario, this research identified that knowledge improvement for building owners and operators on the "monitoring IAQ" factor could offer a new perspective on maintaining building design and operation. This finding also provides fresh insights into the shared responsibility in the post-construction phase. The goal is to maintain building performance during operations as intended in the design phase, where the operations are no longer directly under the responsibility of the building designer.

Responding to the second critical area, on higher requirements for emergencies, this research found that experts did not reach an agreement on the inclusion of higher requirements for emergencies such as COVID-19, even though the risk of transmission remains. Despite the literature review's endorsement of the building codes’ objective to enhance public safety and health and minimize casualties and economic losses, it is believed that the current viewpoint still mandates the minimum requirements. Furthermore, current building code practices continue to attempt to balance optimum safety and economic feasibility, thereby hindering the assumed burden in the future.

In terms of the third critical area, the best compliance path, the research revealed that performance-based approaches outperformed prescriptive paths for implementing the factors. Interestingly, the research findings also identified three factors that worked best in both prescriptive and performance-based settings: bringing more outdoor air, increasing ventilation rates, and increasing ACH.

When comparing the prescriptive and performance-based characteristics in the literature review, it becomes clear that these three factors have both prescriptive and performance-based advantages. These include their relative ease of implementation and verification; providing building designers with the flexibility to comply and strive for higher performance levels. This research highlighted that it is not necessary to confine implementing factors to prescriptive or performance-based paths but rather combine them to successfully mitigate future airborne transmission risks.

6.2 RESEARCH IMPLICATIONS TO POLICY MAKING

The research findings have identified several significant implications for the development of building codes in the U.S. to enhance public health and safety against the future health risks of airborne transmission.

1) Enhanced RRF

The development of RRF underscored the need for building codes to be more responsive to emerging health risks. Policymakers should consider integrating this framework into existing building codes to systematically identify and address risk factors associated with airborne transmission diseases, including COVID-19.

2) Performance-based and Prescriptive approaches

   The findings suggest that combining performance-based and prescriptive paths can enhance the effectiveness of building codes. Policymakers should promote this approach, allowing greater flexibility and innovation in building design while maintaining stringent safety requirements. Specific measures such as increased ventilation rates, higher air filtration, and effective space management should be emphasized in policy improvements.

3) Dual operating modes

   This research underscores the importance of incorporating dual operating modes, normal and emergency, into building codes. This flexibility allows buildings to adapt to different risk levels, particularly responding to risks that require similar responses such as wildfires and airborne transmission. Considering the potential cost impact, policymakers should further investigate the inclusion of emergency provisions in building codes to ensure that buildings can swiftly transition to a heightened state of readiness during health crises.

4) Interdisciplinary collaboration

   The adoption and implementation of risk-responsive building codes require collaboration among various stakeholders, including government agencies, industry professionals, and academic researchers. Policymakers should facilitate interdisciplinary partnerships and create platforms for knowledge sharing to ensure that building codes are continuously updated based on the latest research and technological advancements.

5) Long-term impact of emergency provisions

   This research emphasizes the importance of integrating emergency provisions into building codes. Policymakers should evaluate the long-term impact of such provisions by conducting cost-benefit analyses and scenario planning to establish the most effective strategies for promoting safer and healthier building practices.

Incorporating these research findings into policy development can strengthen U.S. building codes to better safeguard public health and safety against current and future airborne health threats.

6.3 RESEARCH CONTRIBUTION

This research contributes to the increased understanding of how building codes can be more responsive in the future to the risks of airborne transmission, including COVID-19. Building codes are mandatory requirements for safer and healthier building practices, so linking the risks of airborne transmission to future practices is critical. Furthermore, learning about previous airborne transmissions, such as SARS and MERS, as well as the recent COVID-19, emphasizes that future risks could and should be mitigated.

One of the main contributions of this research is the development of the Risk-Responsive Framework (RRF), which demonstrates how to determine the risk-responsiveness factors and examine the building codes' risk-responsiveness levels. I used a three-phased RRF structure to guide factor identification, determine risk-responsiveness levels, and present the results. Despite its limitations, RRF can be utilized in various case studies and enhanced it with more advanced tools.

Aside from RRF, I have submitted and disseminated the research findings in academia and industry through multiple publications, including:

- One conference paper was presented at the CI and CRC joint conference 2024 in Des Moines, Iowa, from March 20 to 23, 2024, titled "Benchmarking Healthy Building Requirements in Mitigating Airborne Transmission Diseases Such as COVID-19: Identifying the Gaps between Current Codes and Building Rating Tools. " This paper is available online at https://doi.org/10.1061/9780784485293.077.
- Two conference papers accepted at the World Building Congress WBC2025, May 19–23, 2025 at Purdue University, U.S. The first proposed title is "Examining the Risk-Responsiveness Levels of the US Building Codes for Healthier and Safer Future Building Practices" and the second proposed title is "Developing Future Building Code Criteria for Safer and Healthier Office Building Practices: Lessons Learned from COVID-19."

6.4 RESEARCH LIMITATIONS

While conducting this research, I discovered a number of limitations, ranging from representativeness to methodology to research process limitations. This first limitation pertains to sample representativeness, as the majority of the experts who participated were largely from the Pacific Northwest area, and the responses collected might represent a largely Pacific Northwest context, thus leading to unintentional bias during data collection and analysis. The experts were selected through an extensive desk study, internet searching, and recommendations from other experts to avoid selection bias and represent the broader expert community relevant to building practices, including international and national professional associations such as ASHRAE.

It should be noted that during the Delphi method, some experts decided not to continue to Round 2. To prevent attrition and ensure consistency and validity, I invited other experts with similar backgrounds and experiences to participate. In Round 2, each question was accompanied by the results from Round 1 to maintain information transparency and keep the experts informed. This effort helped maintain sample representativeness and ensures consistency and validity of this research.

The second limitation was the lack of language fluency experienced during interviews and data analysis. The experts who participated in this research were knowledgeable professionals with varying levels of expertise and well-versed in technical conversation. Therefore, this research required additional time to review and interpret their comments and concerns.

The third limitation pertained to the methodology regarding the use of the Delphi method for data collection. The iterative nature of the Delphi method requires at least two rounds of surveys or questionnaire distribution, which is time-consuming, especially when managing reminders to experts about the deadline. Additional challenges in time allocation were identified during data analysis, where delays in data collection impacted data analysis and results development.

Then, regarding the limited quantitative data analysis, the use of SAW/WSM in determining factor weighting and ranking as a quantitative data analysis procedure is also considered a limitation. SAW/WSM is one of the simplest MCA methods, and is known for its flexibility when combined with other methods in MCA analyses. However, MCA is widely applied in various fields, including transportation and logistics, building performance, project management, and environment management, using various established weighting methods. Therefore, to achieve more robust future research in mixed qualitative and quantitative methods, it should consider other advanced techniques for MCA beyond using SAW/WSM.

Finally, the findings from this study may not be readily generalizable to other countries. The case studies in this research emphasized the context of a developed country, such as the U.S., with an established building code adoption process. The representation of building code developers, engineers, academicians, researchers, and AHJs in the case studies might differ in other countries' contexts. Therefore, we should exercise caution when generalizing these research findings to other countries, even though RRF could be replicated.

6.5 FUTURE RESEARCH OPPORTUNITIES

Building codes ensure occupants' safety and health during building operations by meeting the minimum requirements. The building code adoption process in the U.S. involves many stakeholders, including building code model developers, professionals and engineers' associations, and AHJs at state and city levels. Therefore, based on the research findings, I identified several opportunities for future research.

The first opportunity would be to discuss the effectiveness of building codes during emergencies. Experts differed in their opinions on the emergencies, emphasizing the potential for flexibility in dual operating modes: normal and emergency. Experts believe that as long as the risks are not present, there is no need to include emergency requirements. However, since the risks of airborne transmission remain, along with those related to climate change, such as wildfires, further research exploring how effectively current building codes address these risks would be very insightful. This could involve retrospective analyses of recent events to evaluate which building code provisions were most beneficial.

Another research opportunity could be related to the long-term impact of emergency provisions in building codes. Research could assess the long-term effects of integrating dual modes of operations, including emergency provisions, into permanent building codes against separate, temporary measures. This research might include a cost-benefit analysis and scenario planning model.

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APPENDIX A THE EXPERT INTERVIEW QUESTIONS

CONSENT PAGE

Developing a Framework for Risk-Responsive Building Codes of Office Buildings: A Healthy Building Perspective

Dear Mr./Ms.,

With this letter, I invite you to participate in the interview: *Developing a Framework for Risk-Responsive Building Codes of Office Buildings: A Healthy Building Perspective*.

As a black swan event, the ongoing COVID-19 global pandemic has changed the perspective on the design and operation of office buildings in terms of occupants' health and safety, sizing changes in space management, engineering, and operation. My preliminary investigation of related building codes to office use indicates that the codes are less responsive to the risk of COVID-19 transmission. Therefore, this research aims to 1) Evaluate the gaps between current codes and expected future codes in terms of risk responsiveness for design and operation, 2) Determine the risk-responsiveness level of the building code requirements for office buildings, and 3) Provide recommendations to improve risk responsiveness level in preparation for future public health crises.

This interview is part of my doctoral dissertation as a Ph.D. Candidate of the College of Built Environments, Department of Construction Management at the University of Washington (UW). In this interview, I will investigate building professionals' opinions and expertise on the impact of the COVID-19 pandemic on office buildings, the role of building codes, requirements relevant to COVID-19 mitigation, and how building codes could and should mitigate risk for users in future pandemics.

Your participation in this interview is entirely voluntary. You may decline the questions you do not wish to answer. Your responses will remain confidential and anonymous. The interview process will be documented with a post-interview transcript and video recorded with the participant's consent.

Your decision to participate will not affect your job or any benefits you receive now or future. The University of Washington will keep this study's data confidential following its policy on academic integrity. Your participation is greatly appreciated and will be an essential part of the study results and future publications resulting from this study.

If you have any questions about this study, please contact us. Information on human subjects' rights in research is available through the UW's Institutional Review Board at hsdinfo@uw.edu or www.washington.edu/research/hsd/.

Thank you,

Novi T.I. Bramono (nbramono@uw.edu)

Dr. Hyun Woo "Chris" Lee (hyunwlee@uw.edu)

College of Built Environments - Department of Construction Management
University of Washington, Seattle - WA
(M) 206 452 9482
(Z) 528 242 791

INTERVIEW QUESTIONS

Ver 2

1) How does the current COVID-19 pandemic affect office buildings in office design and operation?
2) How do you see the current building code requirements for office buildings playing a role in responding to current and future pandemics? In what ways could and should building codes prevent airborne disease transmissions such as COVID-19 or SARS?
3) What is your opinion on current building codes that focus primarily on a building's design? Do you think that codes should include the operation side? Or both?
4) What is your opinion on the current "prescriptive" code's ability to respond to this pandemic? And how does it compare with other code types, such as "performance-based" and "hybrid" codes, specifically in preparing for ongoing and future health crises?
5) In the recent healthy buildings literature, some healthy building foundations are associated with multiple strategies for mitigating the airborne transmission of COVID-19, such as higher ventilation rates, higher air filtration levels, and maintaining indoor air quality. How do you see these requirements in current building codes?
6) Are there any requirements in the current building codes that should be added or improved to be more responsive to the infection risks of COVID-19 or future airborne diseases?
7) Please refer to the provided Table 1 in Attachment I on the next page in responding to this question. Based on your experience prior to and during the COVID-19 pandemic, how do you see the significance of factors listed in Table 1 in influencing future building codes for office buildings and office spaces? Are the factors listed in Table 1 sufficient to determine appropriate requirements for office buildings and office spaces as reflected in building codes to prepare for a future pandemic, or are there others?

Attachment

Table 1. Examined Factors Relevant to Address COVID-19 in Office Buildings

Factors	Aims	Sources
Space management	Aims to limit the number of occupants in working space considering the risk of infection. The strategies include barriers or partitions in crowded spaces, or workspace configurations to maintain a perceived safer distance between occupants.	(AIA, 2020b, 2020a; CDC, 2020d; OSHA, 2020), (AIA, 2020b, 2020a; OSHA, 2020), (AIA, 2020a, 2020a; CDC, 2020d), (AIA, 2020b, 2020a; Awada et al., 2021; OSHA, 2020), (Morawska et al., 2020), (BOMA International, 2022)
Ventilation	Aims to at least to meet acceptable indoor quality, or higher through non-engineering strategies such as optimizing natural ventilation and operable windows, and engineering controls strategies such as increased outdoor air, increased ventilation rates and increased air changes.	(AIA, 2020b, 2020b; Dietz et al., 2020; Morawska et al., 2020; Xu et al., 2020), windows (AIA, 2020b, 2020a), (AIA, 2020b, 2020a; Morawska et al., 2020; OSHA, 2020, Li, 2020), (Awada et al., 2021), (NIOSH, 2022)
Air filtration	Aims to capture smaller particles, including viruses, in reducing the risk of transmission. The use of at least MERV -13 rated air filter, instead of default MERV-8, could increase the system efficacy in removing viruses. Portable air filter such as HEPA, could be utilized in higher air risk area.	(AIA, 2020b, 2020a; ASHRAE, 2020, 2021b; Xu et al., 2020), (Faulkner et al., 2021), (AIA, 2020b, 2020a; CDC, 2021a; Faulkner et al., 2021; Morawska et al., 2020; Sloan Brittain et al., 2020; Xu et al., 2020)
Temperature and RH	Maintain temperature and RH in certain range aims to limit the spread of viruses' survivability.	(AIA, 2020b, 2020a; Dietz et al., 2020; Faulkner et al., 2021), (AIA, 2020b, 2020a)
Monitoring indoor air quality	Monitoring temperature and RH, and CO_2 regularly were suggested aiming for an early detection of problems and immediate resolve.	(Eykelbosh, 2021), (Li et al., 2020), (AIA, 2020a)
Air disinfection	The use of UV technology to disinfect air aims to minimize the risk of infection, such as a supplemental UV germicidal irradiation for mechanical paths or un upper room for high-risk indoor setting or crowded spaces. A UV light is considered effective but has safety concerns to human health.	(AIA, 2020b, 2020a), (Dietz et al., 2020)
Building operation compliance	Aims to operate office buildings to reduce the risk of infection, particularly in re-opening phase. The strategies include to perform systems equipment, systems and operation protocols for safer operation in compliance with engineering guidelines, such as ASHRAE.	(AIA, 2020b, 2020a; Areno, 2020; CDC, 2020d).

Factors	Aims	Sources
Cleaning and disinfection management	Aims to minimize the risk of infection through surface cleanings, or for frequently touched surfaces during building operation.	(AIA, 2020a, 2020b; CDC, 2020d)
Occupant tracing management	Aims to minimize the spread of infection by asking occupants to sign in on dedicated application to track and minimize the infection among occupants	(AIA, 2020b; CDC, 2020d)

APPENDIX B DELPHI ROUND 1 QUESTIONNAIRE

Delphi Survey:
Developing a Framework for Risk-Responsive Building Codes of Office Buildings: A Healthy Building Perspective

Overview
Thank you for participating in this survey. It aims to gather data from experts/professionals in building practices on the factors that will be used as determinants for a new framework to evaluate building codes' risk-responsiveness level in mitigating COVID-19 in the future.

This survey is part of Novi Bramono's dissertation in the Built Environment Ph.D. program at the College of the Built Environments, University of Washington. Your response will provide valuable insights as we examine the risk-responsiveness criteria for the new framework.

This survey will take approximately 10-15 minutes to complete. Once we have received responses from all participants, we will collate and summarize findings and formulate a brief second round questionnaire. You will receive a notification in the next two months indicating the first round is finalized and the second round will start. If consensus has not yet been reached in the second round questionnaire, we will send the third as the last round. Your survey participation and responses will be strictly confidential to the research team and will not be divulged to any outside party, including other survey participants.

If you have any questions, please contact Novi Bramono at nbramono@uw.edu.

Introduction

The COVID-19 pandemic has impacted office buildings, contributed to a changed perspective on office design and operation, and emphasized a safer and healthier working space for occupants. As a result, office buildings need to be adaptive and adjust for the future of work to minimize such health risks. Recent literature reviews have identified some assumed factors that are important for office building design and operation in mitigating the risk of airborne illness infection. These factors include:

Table 1. Factors Identified for Mitigating COVID-19 to Office Buildings

Factors	Objectives
Space management	Aims to provide a safer distance to the occupants, e.g., physical barriers, maintaining 6-feet space distancing, and limit the room's density
Ventilation	Aims to provide more indoor fresh air, e.g., increased ventilation rates, indoor airflow, air changes, and higher outdoor air fractions to help dilute indoor contaminants.
Air filtration	aims to increase the air filtration level to minimize the risk of infection by replacing the current MERV filters with at least MERV 13, using additional HEPA filters, or portable air filters in a higher-risk area.
Temperature and Relative Humidity (RH)	Aims to control the temperature and RH levels to reduce the possibility of the virus traveling over a long distance. The recommended temperature is in the range 62.6-64.4° F and 40-60% of RH
Air disinfection	Aims to minimize risk in crowded space using ultraviolet germicidal irradiation (UVGI) in high-risk indoor settings, such as crowded spaces, where people must take off masks, and areas where it is difficult to maintain a safe distance.
Monitoring indoor air quality	Aims to monitor temperature, RH, and CO2 levels regularly to indicate the number of occupants and the need for fresh outdoor air.
Compliance with operation standards	Aims to maintain building performance in reducing infection risk during operation by meeting ASHRAE standard(s) and guidelines, e.g., running the HVAC system 2 hours before and after occupation, performing system commissioning for the equipment, and maintaining ventilation effectiveness in required spaces, etc.
Cleaning and disinfection management	Aims to reduce the spread of pathogens by having cleaning protocols and performing routine daily cleaning protocol in frequently touched surfaces
Occupant tracing management	Aims to minimize the spread of infection by asking occupants to sign in on dedicated application to track and minimize the infection among occupants

From a healthy building perspective, achieving and maintaining indoor air quality is essential. Increased ventilation rates, increased air filtration, temperature, and relative humidity control are associated with creating a healthier, safer working environments that increase occupants' productivity. These align with the factors in mitigating COVID-19 in an office setting.

Building codes mandate building requirements for safer and healthier building practices and evolved gradually from the previous disasters to mitigate future risks. With COVID-19 and airborne illnesses risk is continuing, therefore, it is important for building codes to anticipate the risk in the future.

This study aims to develop a new framework to evaluate factors that determine the risk-responsiveness level of current codes in response to airborne diseases. Based on this evaluation, suggestions for code improvements will be developed.

In this Round 1, the study will ask:

- What factors are relevant to mitigate COVID-19 in office buildings
- Which factors should be included in office design and operation
- What factors that should be included in the proposed code evaluation framework
- Which codes should have been evaluated
- What types of codes are more responsive in mitigating the future risks
- What scopes that should be included to the future building code
- What adjustment allowed in the code during emergency
- What guidelines that should be available for the code
- What supports that should be available for code enforcement

Please complete this questionnaire by indicating how much you agree or disagree with each of the following statements based on each factor and their descriptions.

A. Factors relevant to mitigate COVID-19 in office buildings. From the literature, there are several factors identified to mitigate COVID-19 in office buildings. These factors vary from space management, ventilation, air filtration, temperature and relative humidity, air disinfection, indoor air quality, compliance with the operation standards, cleaning and disinfection management and occupant tracing management.

Statement A. Please state your opinion by giving (X) on whether these factors are relevant, or not relevant, to mitigate COVID-19 in office buildings.

Factors	Relevant	Not Relevant
Space management		
Ventilation		
Air filtration		
Temperature and Relative Humidity (RH)		
Air disinfection		
Monitoring indoor air quality		
Compliance with operation standards		
Cleaning and disinfection management		
Occupant tracing management		

Please write your comments or feedback, if any:

……….

B. Scope of future building codes. Office building design and operation are two continuing phases for buildings to maintain their ability to provide a safe and healthy working environment. Design requirements are the primary references for building construction, while requirements for building operation address building performance compliance according to the design requirements. Having these two phases regulated in building codes will contribute to safer and healthier office building practices in the future.

Statement B. Building codes need to regulate BOTH design requirements AND operational requirements.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedback, if any:

……

C. Factors relevant to office design and operation. COVID-19 has changed the perspective on how buildings are designed and operated.

Statement C. Please state your opinion by selecting the factors that are most relevant to building design AND/OR building operation in light of COVID-19. Factors can be selected for both categories.

Factors	Design	Operation
Space management		
Ventilation		
Air filtration		
Temperature and Relative Humidity (RH)		
Air disinfection		
Monitoring indoor air quality		
Compliance to operation standards		
Cleaning and disinfection management		
Occupant tracing management		

Please write your comments or feedbacks, if any:

……

D. Future building codes. To anticipate future risks and make the building code more responsive, we aim to understand which factors are most important to address in future building codes.

Statement D1. It is important to include space management to provide a safer distance between occupants in the office setting (e.g., installing physical barriers, maintaining 6-feet minimal distancing, limiting the room's density, etc.) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedback, if any:

……

Statement D2. It is important to mandate higher ventilation rates in occupied zones of office spaces than ASHRAE 62.1 Ventilation for Acceptable Indoor Air Quality (e.g., 30% or 60 % higher) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedback, if any:

……

Statement D3. It is important to mandate higher air changes per hour in an occupied zone (e.g., from 4 ACH to 6 ACH) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedbacks, if any:

……

Statement D4. It is important to mandate a higher air filtration level (e.g., changing the existing filter level to at least MERV 13 or HEPA filter and a portable HEPA filter for a higher risk spaces) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedback, if any:

……

Statement D5. It is important to include temperature and humidity settings in an acceptable range to minimize airborne disease transmission (e.g., temperature between 62.6 F to 64.4 F and RH between 40 to 60 %) in future building code.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
○	○	○	○	○

Please write your comments or feedback, if any:

……

Statement D6. It is important to mandate an air disinfection requirement (e.g., UV germicidal irradiation device/UVGI) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

Statement D7. In future building codes, it is important to require the maintenance of ventilation effectiveness by supplying the ventilation rates without any disturbance for occupied spaces during office operation.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

Statement D8. It is important to require monitoring indoor air quality (e.g., CO, CO2, PM 2.5, PM 10, etc.) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

Statement D9. It is important to require maintaining temperature between 62.6° F to 64.4° F (17° to 18° C) and relative humidity of 40-60 % to reduce the indoor infection risk in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

Statement D10. Please state your opinion whether these standard/guidelines are relevant or not relevant for building operation in the future building code.

Standard/Guidelines	Relevant	Not relevant
ASHRAE standard 180-2018 Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems		
ASHRAE's Core Recommendation for Reducing Airborne Infectious Aerosol Exposure (October 19, 2021)		
ASHRAE's Guidance for Re-Opening Buildings (September 2021)		
ASHRAE's In-Room Air Cleaner Guidance for Reducing COVID-19 in Air in Your Space/Room (January 21, 2021)		
ASHRAE's Guidance for Building Operations During COVID-19 Pandemic (May 2020)		

Please write your comments or feedback, if any:

……

Statement D11. It is important to require cleaning and disinfection management in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

Statement D12. It is important to use a contact tracing system to alert exposed occupants to minimize further risk of infection in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

E. **Relevant codes.** Among all of the codes, commercial and mechanical codes are the ones that closely associated with office buildings. Both commercial codes and mechanical codes contain provisions that are relevant to mitigate COVID-19. These two codes are complimentary in regulating indoor air strategies such as temperature and humidity, ventilation, ventilation rates, air changes, etc.

Statement E. Any adjustments or improvements relevant to COVID-19 mitigation strategies should address both commercial building codes and mechanical codes since both contain important mitigation strategies for airborne diseases.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

………

F. Type of codes. Building codes are generally categorized into the following three types, as summarized in Table 2 below:

Table 2. Three types of code

Prescriptive	These require each building component to be built to a certain standard. Most building codes are generally written in this type.
Performance-based	These require a whole building to perform to a certain standard. Performance-based code requires additional efforts to ensure performance compliance.
Hybrid	These are a mix between prescriptive and performance-based code. In general, allows some requirements to be written as performance-based, while most are written prescriptively.

Statement F. Please indicate your opinion on which type of code that MOST SUITABLE for the following factors for mitigating COVID-19 in office buildings:

Factors	Prescriptive	Performance-based	Hybrid
Space management			
Ventilation			
Temperature and Relative Humidity (RH)			
Air disinfection			
Monitoring indoor air quality			
Compliance with operation standards			
Cleaning and disinfection management			
Occupant tracing management			

Please write your comments or feedback, if any:

………

G. Emergency preparedness. Anticipating more emergencies and increased hazard risk in the future, such as COVID-19, wildfires, smoke, etc., office buildings will need to prepare their system to supply better quality air than the mandated requirements in the non-emergency situation.

Statement G. Do you agree or disagree with the following statement: Building codes need to mandate higher requirements (e.g., via increased ventilation rates, higher air filtration levels, more frequent air changes, etc.) during emergency and hazard situation.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

H. Code guidelines. Building codes should be written formally with sufficient levels of explanations for interpretation. Adding code guidelines that offer additional explanations, details, visualization, or examples would help the code users (e.g., building designers, local government officers, etc.) to understand the requirements better.

Statement H. Do you agree or disagree with the following statement: It is important to include coding guidelines (e.g., additional explanation, detail, visualization, or examples) in future building codes.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……

I. Available support. One of the critical success factors in enforcing building codes is the availability of support from relevant stakeholders, as summarized in Table 3 below.

Table 3. Example of support for code enforcement

Training	Aims to improve local staff's knowledge for better understanding of code compliance
Funding	Aims to improve the local agencies', including additional staffing for better code enforcement
Technical support	Aims to solve technical issues that require assistance, e.g., e.g., a helpline, code training, guide on prescriptive and performance code, quick references, FAQ library, and/or a contact list of experts, etc.

Statement I. The availability of support from relevant stakeholders is one of the essential factors in successfully implementing building code requirements and standards.

Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
O	O	O	O	O

Please write your comments or feedback, if any:

……….

APPENDIX C DELPHI ROUND 2 QUESTIONNAIRE

Page 1. Welcome to Delphi Survey Round 2

I am honored to invite you to participate in the second round survey of my study to determine the factors for a risk-responsive building code framework. Thank you for your continued feedback.

The Round 1 Survey was successfully completed in December 2022. It involved collecting feedback from invited experts and professionals regarding the factors of risk-responsive building codes in mitigating airborne transmission, including COVID-19, in office buildings in the future. The responses were extensive, thorough, and very helpful.

In this second round, the results of the first round of feedback are presented with areas for your feedback related to the emerging perceptions. Then, questions will be asked based on these results.

This survey will take approximately 15 minutes to complete. Please finalize your responses within three weeks after receiving this invitation.

Your participation and responses will be strictly confidential and will not be divulged to any outside party, including other survey participants. An anonymized report of the Delphi Survey will be accessible to participants approximately three months after the Dissertation report is finalized.

This study has been reviewed by the University of Washington's Institutional Review Board No. STUDY00015394 and has qualified for exempt status. Don't hesitate to contact me at nbramono@uw.edu if you have any questions.

Sincerely yours,
Novi Bramono (Bram)
nbramono@uw.edu
College of the Built Environments
University of Washington, Seattle

Page 2. Email address

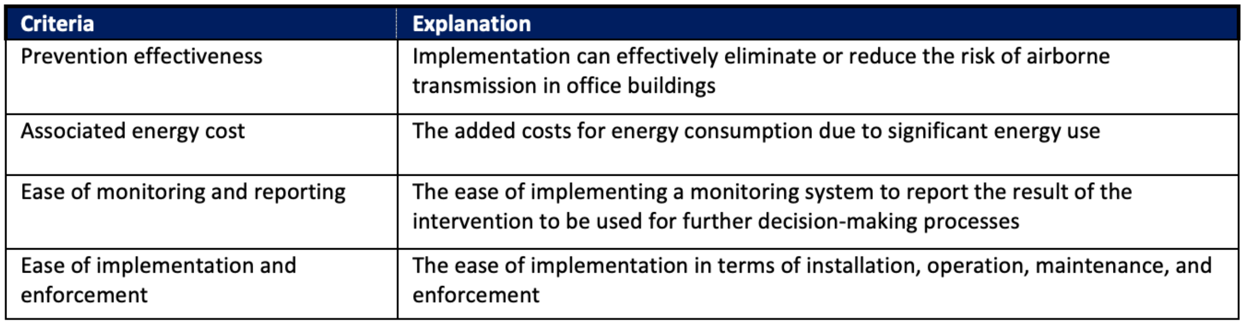
Please include your email address in the text box below.

Page 3. Criteria

Question 1: Criteria for Factors

In the first round, participants provided feedback on the proposed factors for a risk-responsive building code framework. The following criteria for evaluating the factors in risk responsive building code framework were developed based on the Round 1 Survey:

Table 1. Criteria for evaluating factors



Criteria	Explanation
Prevention effectiveness	Implementation can effectively eliminate or reduce the risk of airborne transmission in office buildings
Associated energy cost	The added costs for energy consumption due to significant energy use
Ease of monitoring and reporting	The ease of implementing a monitoring system to report the result of the intervention to be used for further decision-making processes
Ease of implementation and enforcement	The ease of implementation in terms of installation, operation, maintenance, and enforcement

The following question is based on the feedback received from participants. The next question will use the evaluating factors to assess the factors in the risk-responsive building code framework.

In this question, I'm asking you to indicate your opinion of each criterion's relative weight of importance. Please enter number for each criterion, totaling 100, in the boxes below.

Each number entered represents a percentage (%). For example: 10 means 10%, 25 means 25%, etc. A larger number means that one criterion has more importance than others. And the sum of all numbers entered should add up to 100, which represents = 100 %.

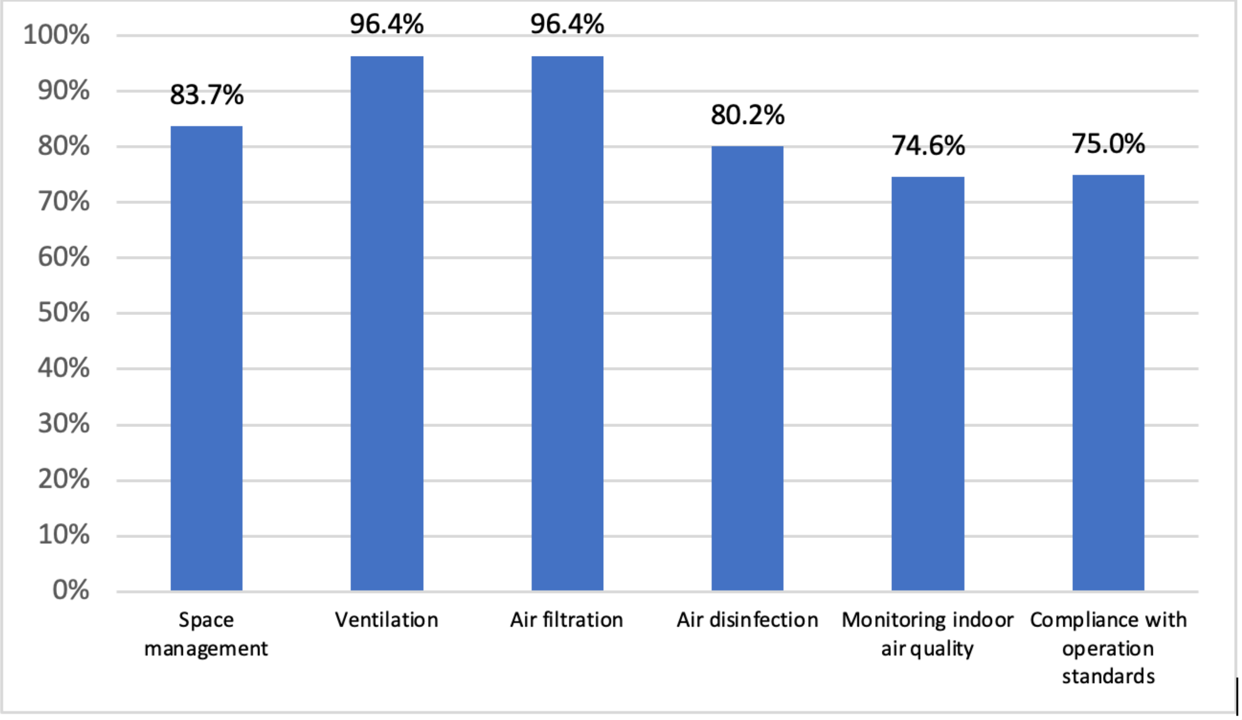
Criteria	Relative weight
Prevention effectiveness	
Associated energy cost	
Ease of monitoring and reporting	
Ease of implementation and enforcement	

Page 4. Assessment of factors

Question 2: Assessing the factors

In Round 1, participants were invited to provide their opinion on the most relevant factors related to office buildings' design and operation in mitigating airborne transmission, including COVID-19. The following figure represents the distribution of the responses of the most relevant factors.

Figure 1. Relevant Factors in Office Building Design and Operations
Number of Respondents = 14



Participants were invited to provide comments on the list of factors and some more factors that could be included. The following table summarizes key responses from participant's responses.

Table 2. Updated List of Factors

Number of responses = 14

Factors	Summary
Higher air filtration	Using a higher air filtration, e.g., MERV 14, with a focus more on the filtration of recirculated air
Bringing outdoor air	Bringing an equivalent outdoor air or, if required, more outdoor air during building operation
An effective system of operation and monitoring	Performing tests and demonstrating an effective system operation and monitoring for a safer building operation
Clean air delivery rates	Requiring a particular rate for air cleaners, which measure the amount of clean air in a fixed amount of time, to indicate the effectiveness in removing small airborne particles
Space design	Minimizing the movement of the pathogen in a space setting, e.g., by installing a low-speed air diffuser at 30 fps or less or installing low wall or floor return
Space management	Limiting the number of occupants in a space, e.g., by setting a maximum occupancy in occupied spaces or space distancing for relatively denser spaces, such as in workstations or call centers
Monitoring indoor air quality	Monitoring levels of indoor contaminants, primarily CO_2, to indicate how well the indoor ventilation in space, and other pollutants, e.g., CO, PM 2.5, VOCs
Air disinfection	Using air disinfection technology, e.g., upper room ultraviolet germicidal irradiation (UVGI), which is preferable for high-risk indoor settings and crowded spaces, spaces with insufficient or no mechanical HVAC systems, or spaces with inadequate natural ventilation
Increased air change rates	Using higher air change rates, e.g., higher than typical 2 to 3 per hour for office spaces, to minimize the risk of infection
Increased ventilation rates	Using higher ventilation rates, e.g., higher than typical 20 cfm/person for office spaces, to minimize the risk of infection
Compliance with operation standards and guidelines	Operating buildings in accordance with specific guides to minimize the risk of infection, e.g., ASHRAE Core Recommendations for Reducing Airborne Infectious Aerosol Exposure (October 2021) and ASHRAE Building Readiness (May 2022) or the updated version

In the following question, I'm asking you to indicate your judgments of these factors in relationship to various criteria.

Please indicate your judgment by selecting a number with a range of 0-10, where 0 = "Not at all important" and 10 = "Extremely important."

Criteria Factors	Prevention effectiveness	Associated energy cost	Ease of monitoring and reporting	Ease of implementation and enforcement
Higher air filtration				
Bringing outdoor air				
Effective system of operation and monitoring				
Clean air delivery rates				
Space design				
Space management				
Monitoring indoor air quality				
Air disinfection				
Increased air change rates				
Increased ventilation rates				
Compliance with operation standards and guidelines				

**Note: In survey format, all blue boxes are dropdown menu to choose a number between 0-10*

If you have any comments, please provide them in the comment box below.

Page 5. Design and operation

Question 3: Maintain Building Design and Operation

In Round 1, participants were asked if building codes needed to regulate the design and operational requirements for mitigating the risk of indoor airborne transmission. The result shows that participants expressed challenges in maintaining design requirements in building operations phase.

Below is a summary of perspectives expressed by participants:

- Design and operation phases have been recognized as essential in mitigating the risk of airborne disease transmission. However, current building codes are primarily for design and construction.
- Operational performance needs to be enforced to ensure buildings perform as intended. Achieving operational performance during the operation phase will require dedicated enforcement, inspection, and reporting systems, with penalties by local authorities.
- Building owners and operators have limited knowledge in maintaining design requirements after buildings are completed, thus making it challenging to maintain building performance as intended during the operational phase.

Based on this feedback, I'm asking you to indicate your judgments regarding the factors in relationship to various conditions below on the likeliness of a successful building design and operation in mitigating the risk.

Please indicate your judgments on the following conditions by entering a number between 0 to 10, where 0 = “Not at all likely to be successful” and 10 = "Extremely likely to be successful.”

Conditions Factors	Availability of design codes and operation codes	Availability of operational performance enforcement system e.g., inspection, reporting and penalties	Availability of knowledge improvements for building owners and operators after completion
Higher air filtration			
Bringing outdoor air			
Effective system of operation and monitoring			
Clean air delivery rates			
Space design			
Space management			
Monitoring indoor air quality			
Air disinfection			
Increased air change rates			
Increased ventilation rates			
Compliance with operation standards and guidelines			

Note: In survey format, all blue boxes are dropdown menu to choose a number between 0-10

If you have any comments, please provide them in the comment box below.

Page 6. Emergency Situation

Question 4: Higher Requirements for Emergency Situations

In Round 1, I asked the participants their judgments on whether building codes need to mandate higher requirements, e.g., increased ventilation rates, higher air filtration, more frequent air changes, etc., during emergencies and hazardous situations.

Participants responded as follows: 50% indicated agreement, 36% neither agreed nor disagreed, and 14% indicated disagreement.

Below is a summary of perspectives expressed by participants:

- Buildings would be better to have more than one operating mode: normal mode and emergency mode. Under the emergency, having higher requirements would be acceptable.
- Building codes are not necessarily included higher requirements than standards unless the risk is present and frequently happens.
- Code changes are not necessarily required, depending on the risk or hazards, even if the risk or hazard is present. Changes in building code must consider the energy use and cost impact.

Based on the response’s summary, the following questions ask about the likeliness of the continuing risk of airborne transmission, whether building codes should address the risk, whether higher requirements in codes would be necessary, and whether building codes should allow normal and emergency mode operation.

Please indicate your judgments on the following questions by entering a number between 0 to 10, where <u>0 = “Not at all likely” and 10 = "Most likely.”</u>

Questions	Likeliness
Do you think that the airborne transmission risk such as COVID-19 in office buildings will continue?	
Do you think that building codes should address the risk?	
Do you think that having higher or more stringent requirements in building codes would be able to adequately anticipate risks in the future?	
In your opinion, with having a normal mode of operation and an emergency mode of operation mode would be able to mitigate the risk of infection?	

*<u>*Note: In survey format, all blue boxes are dropdown menu to choose a number between 0-10</u>*

If you have any comments, please provide them in the comment box below.

What would be the best way to accommodate the higher or more stringent requirements for emergencies? Please indicate your judgment by selecting one of the following statements.

O	Higher or more stringent requirements are included in building codes, but only activated during emergencies and inactivated during normal operations
O	Building code recognizes emergency situations, but refers to other documents or relevant guidelines for implementation as long as necessary
O	There is no need to include or recognize higher or more stringent requirements for emergency in building codes
O	Neutral – I don’t have any comments
O	Other, please specify: ……

Page7. Path of Compliance

Question 5: Paths of Compliance

In Round 1, I asked participants to select what would be the best type of code to implement the factors. Based on the participant's comments, the associated question has been revised.

In general, there are two primary paths of compliance with building code requirements: prescriptive path and performance-based path. Here is a summary of those two paths in the Table 3 below:

Table 3. Summary of compliance path for building codes

Prescriptive path	Performance-based path
• Typically accepted type of building codes • Specify the materials, details, components, and methods • Each element of the buildings has a minimum acceptable standards or must adhere to current standards • For example, when reviewing energy codes, prescriptive tables require a specific different type of wall and roof construction across different climate zones, a typical list of minimum R and U-values • The prescriptive path does not require conducting calculations and merely following a chart or specifications in the codes • Compliance with prescriptive path codes does not mandate post-construction accountability	• Outline the objectives to be met, e.g., the amount of energy use intensity or amount of carbon saving • Allow some flexibility for building designers to comply • Encourage innovative solutions to pursue higher performance levels, e.g., energy performance, responsiveness to earthquakes, fire, or climate change • Recognized some challenges, e.g., the scale of the project, additional costs verification method, and the capacity of the building inspectors • Requires a calculation or modeling against an acceptable baseline or performance metric • Compliance with performance-based path codes requires periodic measurement throughout the life of the building

In this question, please indicate your opinion on the best path for these factors in_mitigating airborne transmission for office buildings.

Please indicate your judgments by providing a number between 0 and 10, where 0 = "Not working at all" and 10 = "Working successfully."

Compliance path Factors	Prescriptive path	Performance-based path
Higher air filtration		
Bringing outdoor air		
Effective system of operation and monitoring		
Clean air delivery rates		
Space design		
Space management		
Monitoring indoor air quality		
Air disinfection		
Increased air change rates		
Increased ventilation rates		
Compliance with operation standards and guidelines		

**Note: In survey format, all blue boxes are dropdown menu to choose a number between 0-10*

If you have any comments, please provide them in the comment box below.

Anything else you would like to share? Please provide them in the comment box below.

Page8. End

Thank you for your participation in my survey. It's very much appreciated. Please contact me if there are any questions or concerns.

VITA

Novi Triadi Iman Bramono was born in 1977 in Semarang, Indonesia. He obtained a bachelor's degree in architecture in 2002 from Soegijapranata Catholic University in Semarang, Indonesia. In 2011, he completed his master's degree in urban management and development, specializing in urban environmental management, at the Institute for Housing and Urban Development Studies, Erasmus University in Rotterdam, NL, with funding from the StuNed Program. Bram began his Ph.D. studies in the Department of Construction Management at the College of Built Environments in 2020 with a scholarship from the Indonesian Endowment Fund for Education (LPDP).