

# A SIMULATION-BASED APPROACH TO MITIGATE DISEASE TRANSMISSION RISK FROM AEROSOL PARTICLES IN BUILDINGS

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## ABSTRACT

Understanding the role of architectural design in identifying the risk of disease transmission is essential for creating resilience in buildings. Here we used a Grasshopper simulation workflow to execute aerosol disease transmission risk estimation coupled with EnergyPlus simulation inputs to assess the impact of architectural factors on the risk of COVID-19 transmission. We simulated the risk for a simple geometry with different window configurations and geographic locations. We observed that increasing the fractional opening of a single window as well as cross ventilation design can increase the outdoor air exchange, which corresponds to substantially reduced risk of disease transmission. Furthermore, indoor relative humidity in cold climates can be significantly lower in winter due to the impacts of increased mechanical heating which translates to an increased risk of infection. We demonstrate that early architectural design decisions implicate the resultant risk of disease transmission indoors that should be prioritized in the future.

**Keywords:** COVID-19, risk analysis, EnergyPlus, healthy buildings, passive design

## 1 INTRODUCTION

Throughout history, the spread of infectious disease among humans has caused epidemics, pandemics, and endemics with widespread illness and loss of life. The COVID-19 pandemic revealed the global and

interconnected nature of modern life as well as our widespread inability to combat airborne disease transmission, which has resulted in more than 6 million deaths as of March 22, 2022 (World Health Organization 2022). Several scientists have already called for increased attention to the role of buildings and indoor environments in controlling the current pandemic as well as helping to fight against viral infectious spread in future events (Wang et al. 2021; Chan and Yanis n.d.). Given what we have learned from previous pandemics, including experiences to date with COVID-19, our strategies to combat infectious disease must be reimagined to include the role of buildings, and building design, to intentionally improve resilience and support occupant health.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes COVID-19 infection, and other pathogens such as influenza viruses, can be released into the air through respiratory activities such as breathing, coughing, speaking, singing, and sneezing (Coleman et al. 2021; Lednický et al. 2020). Aerosolized viruses do not transport solely as infectious virions, but they are embedded in aerosol particles that vary in size, ranging from nanometers to millimeters (Wang et al. 2021). Recent research has confirmed what many aerosol scientists proposed; viruses contained in smaller particles ( $< 5 \mu\text{m}$ ) can float in the air for hours and deposit in people's respiratory system, even for those individuals that were beyond a six-foot radius of the infected emitter, and still cause infection (Samet et al. 2021).

Ventilation, filtration, and indoor relative humidity (RH) are among the environmental mitigation strategies that have been shown to effectively reduce the concentration of SARS-CoV-2 virus in the air (Parhizkar et al. 2022; Prather et al. 2020). Recently, the White House characterized the role of air filtration and ventilation in reducing the risk of COVID-19 transmission indoors, emphasizing the importance of healthy building principles for creating safe indoor spaces ("Let's Clear the Air on COVID" 2022). A COVID-19 aerosol risk estimation platform was introduced in 2020 which calculates the risk of disease transmission indoors in accordance with several input parameters such as modes of emissions, deposition to indoor surfaces, ventilation rate, room volume, occupant density, and duration of exposure (Parhizkar et al. 2021). The novelty of this model is related to the concept of inhaled and deposited dose in the human's respiratory system which links aerosol physics to quantitative microbial risk assessment models. Aerodynamics and size distribution of bioaerosols constitute the fundamental framework of the SafeAirSpaces risk estimation platform (SafeAirSpaces 2020), which is an essential yet missing component of previous microbial risk assessment models. The dose-response estimated by SafeAirSpaces (~11 plaque forming units resulting in a 45% attack rate) corresponds well with a recent human challenge study that established the so-called "infectious dose" (10 TCID<sub>50</sub>) suggesting that 10 infectious virions are estimated to produce infection in ~50% of human volunteers (Killingley et al. 2022).

Since the beginning of the COVID-19 pandemic, scientists have provided useful datasets linking indoor air parameters and disease transmission. These datasets provide motivation for new research at the architectural and building operations scales to reduce disease transmission and support human health. While these data sets from aerosol physics and infection dynamics are essential to help us understand the relationship between indoor environmental factors and risk of disease transmission, the data sets alone are not enough to adequately impact architectural design or building operations practices; translation is needed. In this paper, we introduce a framework with the ability to integrate environmental health data into a building simulation-based workflow that can aid building design and operations decision-making.

## **2 METHODOLOGY**

Passive design strategies such as natural ventilation are among well characterized methods to influence and often improve indoor thermal comfort and reduce buildings' energy consumption (Aflaki et al. 2015; Barbosa, Ip, and Southall 2015; de Gracia et al. 2015; de Dear and Brager 2001). Moreover, natural ventilation can result in increased outdoor air exchange, helping to reduce risk of disease transmission indoors (Aviv et al. 2021; Dietz et al. 2020). We therefore hypothesize that architectural parameters such as the configuration of windows and percentage of operability can be specifically designed to decrease the risk of disease transmission and support healthier indoor spaces.

Building design specifications such as window opening size, material, and site location determine the levels of indoor relative humidity and abundance of Ultraviolet B-rays (UV-B) indoors, which directly translate to alternate scenarios of disease transmission risk. To better understand how architectural design decision can impact the risk of acquiring COVID-19 infection in indoor spaces, we created a bridge between EnergyPlus & OpenStudio simulation engines and the SafeAirSpaces airborne disease transmission risk estimation platform. The workflow is visually presented in Figure 1. Using this workflow, we simulate the risk of acquiring infection within a simple architectural design case study with different window configuration, and in different site locations.

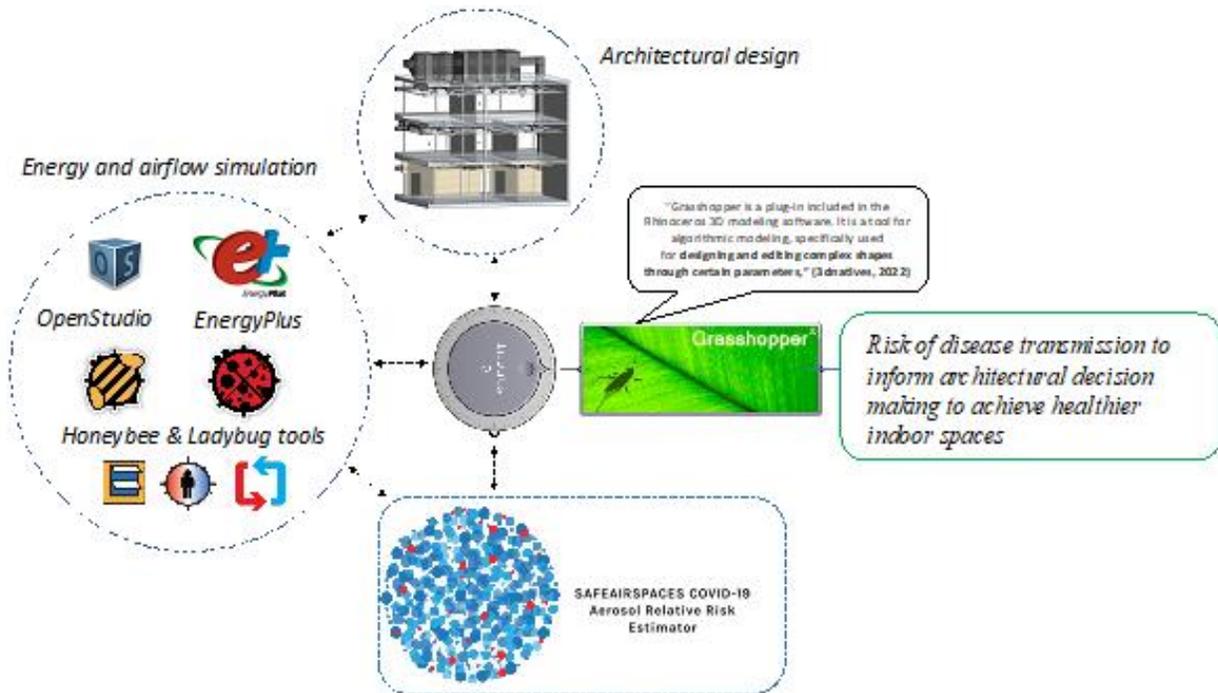


Figure 1: Simulation workflow (energy and simulation figures are courtesy of Ladybug tools (“Ladybug Tools” 2021))

SARS-CoV-2 and other airborne pathogens can be released into the air through aerosolized particles during human respiratory activities such as breathing, coughing, speaking, singing, and sneezing (Coleman et al. 2021; Wang et al. 2021; Asadi et al. 2019). The SafeAirSpaces model features the ability to include exhaled bioaerosol across a range of size distribution bins (spanning  $1\ \mu\text{m}$  –  $5\ \mu\text{m}$ ) from infected individuals as well as particle fate mechanisms indoors (Parhizkar et al. 2021). The insertion of control options (increasing ventilation, application of face masks, in-room filtration, viral inactivation, etc.) are employed as viral loss terms in the form of differential mass balance equations, and produce a numeric probability of infection of susceptible individuals in the space through alternate scenarios using different environmental and occupational characteristics.

Inhalation of virus-laden particles is the primary cause of airborne infection (Hinds 2012; “Let’s Clear the Air on COVID” 2022). Therefore, we emphasize measuring (and reducing) “inhaled deposited dose” for several scenarios involving one or more infected person(s) emitting aerosol particles in indoor spaces within our simulation platform. The novelty of the SafeAirSpaces model used in this study is that it estimates the fraction of rebreathed air from an infected emitter, and more specifically, the inhaled and deposited dose in susceptible individuals’ respiratory systems within the shared air space. The model predicts particle deposition in three major parts of receptors’ respiratory system (1= extrathoracic region, 2 = tracheobronchial region, 3 = alveolar region) and converts these to total volume of particles deposited, summed for each different particle size bin, and reports the inhaled and deposited volume of deposited

particles in picoliters. Therefore, a range of common building simulation parameters can be used with the SafeAirSpaces platform to estimate the related changes in disease transmission risk profiles.

## **2.1 Simulation Parameters**

The case study used in this paper is a one-story building that measures 7 m (~23 ft) long, 5 m (~16 ft) wide, and 2.7 m (~9 ft) high, with total volume of 95 m<sup>3</sup> (~1022 ft<sup>3</sup>) and contains 4 occupants who are performing office activities. The occupants' skin evaporation and exhaled breath are considered in the resultant indoor RH in all cases. Simulations were conducted in Rhinoceros 7.0. and the Grasshopper plug-in. A generic office program defined with an "ideal load" air system was assigned as a default parameter in Honeybee to complete the room model for all cases. The ideal load air system component in EnergyPlus provides required outside air intake and heat exchange (heating and/or cooling) at 100% efficiency without needing to specify air loops, water loops, etc. to produce a supply air system that meets specified conditions. A generic office template was used to define occupancy patterns as well as mechanical conditioning including heating and cooling set-points. The ventilation control component used setpoints to maintain indoor temperatures between 20°C and 26 °C. Furthermore, natural ventilation was allowed when outdoor temperatures were between 19°C and 28 °C.

For cases 1- 8 (Figure 2), we simulated the risk of infection for 12 months of a year in the city of Eugene ,OR, using average Air Changes per Hour (ACH) and RH of each month between 08:00 – 16:00 (M-F) when occupancy profile was  $\geq 0.5$  in Honeybee occupancy schedule (section 2.1.1). We later used 8760 hourly simulation outputs of ACH and RH for case 1 and case 7 (Figure 2) to calculate risk of COVID-19 infection in the city of Eugene, OR and Boston, MA during occupied hours (section 2.1.2). One high-emitter with emission values defined in Parhizkar et al (2021) was considered as index emitter throughout all simulations (Parhizkar et al. 2021). The outdoor air exchange was calculated by summing natural ventilation through windows, mechanical ventilation, as well as infiltration from OpenStudio simulation outputs in Honeybee.

### **2.1.1 Natural Ventilation**

According to window size, orientation, and fraction of openings, the following cases were considered for the study of natural ventilation on the risk of COVID-19 transmission in a building (Figure 2):

- 1- One southern window closed;
- 2- One southern window, 25% operable;
- 3- One southern window, 50% operable;
- 4- One southern window, 75% operable;
- 5- One southern large window (2X), 50% operable;
- 6- 2 southern windows, 50% operable with cross-ventilation (both located on one side);
- 7- 2 windows, 50% operable with cross-ventilation on south and west façades (located on two sides).
- 8- 2 windows, 50% operable with cross-ventilation on south and north façades (located on two sides).

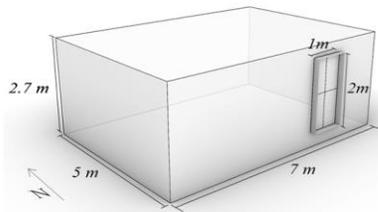
For all simulations listed above, a minimum mechanical ventilation of ~0.5-2 ACH was provided to maintain indoor temperature within the specified temperature range.

### **2.1.2 Indoor Relative Humidity**

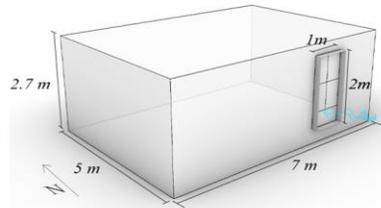
During winter months (especially in colder climates), indoor spaces often experience excessive dryness which is attributed to the correlation between temperature and humidity: sensible heating is associated with

decreased RH levels (“Health Risk in Winter: Modern Buildings Often Leads to a Desert-like Environment in Living Spaces” 2016). Therefore, we simulated the same building in two geographic locations: Eugene, Oregon, and Boston, Massachusetts. To observe the impact of outdoor RH on resultant indoor RH, a minimum mechanical ventilation of  $\sim 0.5\text{-}2$  ACH was provided to keep the temperature within the range specified and windows were considered to be closed for all hours in both locations. We used a mechanistic model developed by Dabisch et al (2021) that quantifies the impact of RH on SARS-CoV-2 infectious decay (Dabisch et al. 2021). We updated the SafeAirSpaces risk estimation platform to include a RH SARS-CoV-2 viral inactivation feature based upon published data of inactivation rates across a range of RH levels (Dabisch et al. 2021). Therefore, the half-life of SARS-CoV-2 can be expressed as decay rate as explained previously (Parhizkar et al. 2021).

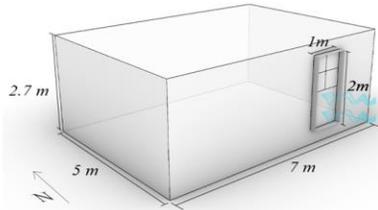
Case 1 (Window closed)



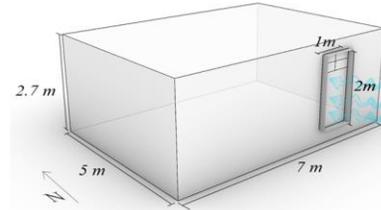
Case 2 (Southern window 25% open)



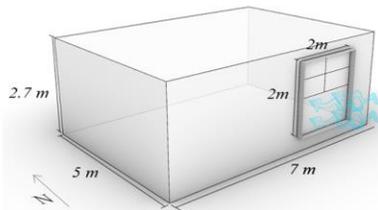
Case 3 (Southern window 50% open)



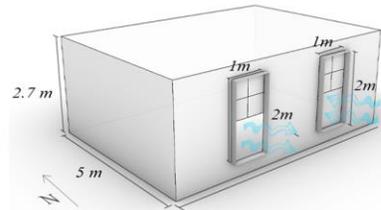
Case 4 (Southern window 75% open)



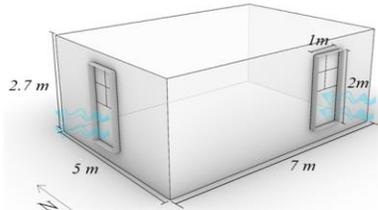
Case 5 (Enlarged southern window 50% open)



Case 6 (2 southern windows 50% open with CV)



Case 7 (2 southern & western windows 50% open with CV)



Case 8 (2 southern & northern windows 50% open with CV)

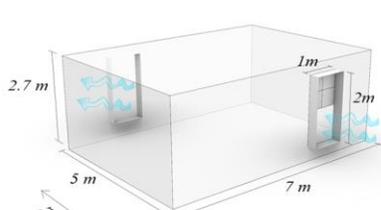


Figure 2: Spatial parameters of case studies for indoor simulation of COVID-19 transmission

### 3 RESULTS

#### 3.1 The Impact of Window Design on the Risk of COVID-19 Infection

The simulation of different window design iterations shows that the size and fraction of window openings can substantially increase the outdoor air exchange rate during moderate and warm seasons in the city of Eugene, Oregon (Figure 3A). According to Figure 3A, increasing the fraction of opening of a single window from 0% to 75% results in an increased outdoor air exchange from ~1.8 ACH (0% operable) to ~4 ACH (75% operable), leading to 10% decrease (~44% to ~35%) on the risk of transmission (Figure 3C). We also observed that increasing the fraction of window opening from 0% to 75% had negligible impact on indoor RH (0.3% increase) which was considered in risk calculations. One important takeaway from Figure 3A is the substantial impact of cross ventilation through two adjacent windows as compared to the air exchange rate of a single large window with same size and operable fraction (50%). While a large window on south façade with 50% opening provided an average ACH of 4.3 during warm months (Figure 2, Case 5), a similar open area split between two windows on the same wall (south façade) or between the south façade and either the west or north façades, provided an average ACH of ~20-25 due to the impact of natural ventilation in June, July, and August (Figure 2, Cases 6, 7, and 8).

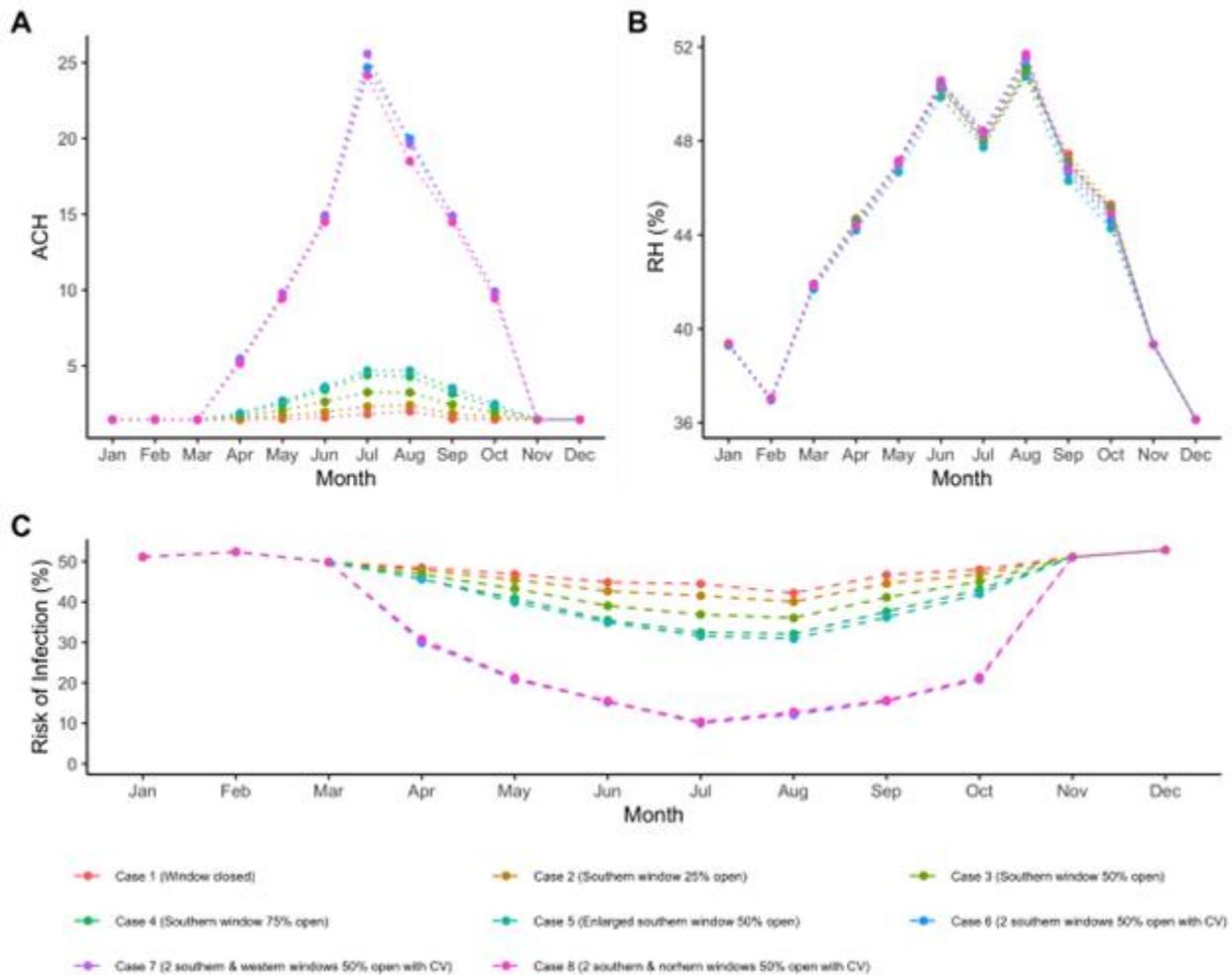


Figure 3: The impact of natural ventilation on risk of COVID-19 infection in Eugene, OR; A) Outdoor air exchange levels for different window configurations, B) Indoor RH levels for different window configurations and C) Risk of infection for different

For a single day, the cross ventilation can increase the outdoor air exchange up to ~25 ACH which corresponds to substantially reduced risk of transmission (Figure 3C). While providing 25 ACH of mechanical ventilation for a space with +1000 ft<sup>2</sup> floor area comes with extensive energy use, natural ventilation can provide sufficient air exchange rate with significantly reduced risk of infection for many hours of the year without increased energy consumption or comfort concerns. By contrast, risk of COVID-19 transmission in all scenarios was higher in winter months because of the lack of natural ventilation through window openings. In addition to lower ACH, our simulation shows lower RH in winter months to be another contributing factor for higher risk of COVID-19 transmission during colder climates. We investigate the role of RH more thoroughly in the next section. These results highlight the importance of natural ventilation in moderate seasons and raises concern related to higher risk of disease transmission in winter months. Increased risks should be addressed through engineering risk reduction strategies such as in-room HEPA filtration or increased zonal ACH, increase outside air fraction and high-efficiency MERV filters for recirculated air fraction.

### **3.2 The Impact of Outdoor Climate on the Risk of Infection in 2 Sites**

As previously discussed, building location can impact the risk of infection in various ways. More mild climates provide the opportunity to activate natural ventilation in buildings more frequently, which could significantly reduce the risk of disease transmission. In colder climates, buildings are often designed to be more airtight to support indoor thermal satisfaction as well as reduced energy use. To study the impact of RH through geography, we simulated Cases 1 and 7 (Figure 2) in a cold (Boston, MA) and moderate (Eugene, OR) climate. Figure 4B shows that for the same building located in a cold climate (Boston), the indoor RH can be significantly lower in winter due to increased sensible heating through HVAC, when compared to a mild climate such as the city of Eugene, Oregon. As shown in Figure 4C, risk of infection is significantly lower in the city of Eugene in winter months when windows are closed due to higher RH levels. The simulation of Case 7 resulted in lower risk of transmission due to higher ACH and RH levels in both climates.

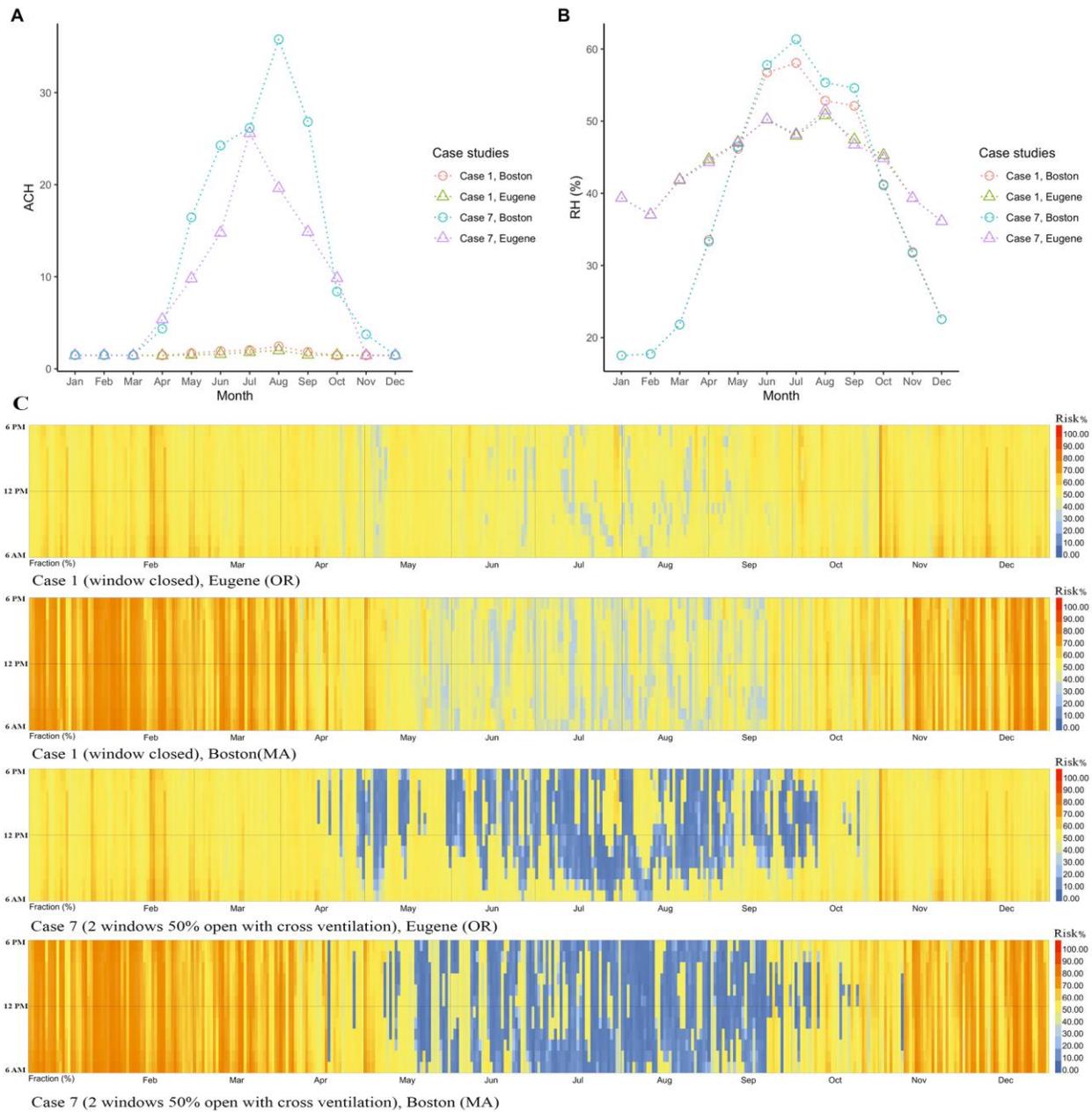


Figure 4: The impact of geography on risk of COVID-19 infection; A) Outdoor air exchange levels for different locations and window configurations, B) Relative humidity levels associated with local climate and C) Risk of infection for the city of Eugene and Boston

#### 4 CONCLUSION

In this paper, we demonstrated that simple decisions in architectural design (such as the number, size, and operability of windows) as well as geographic location, can result in alternate disease transmission risk scenarios using a simulation-based workflow. We presented a parametric approach to study disease transmission indoors, using data provided in an available aerosol disease transmission risk estimation platform (Parhizkar et al. 2021). In addition to the variables presented in this paper, our proposed platform (using the Grasshopper plug-in) will provide architects and building researchers with opportunities to study a wide range of additional building design and operations variables that may influence disease transmission

risk and therefore indoor health such as HVAC system design. Previous studies conducted comprehensive literature reviews and concluded that human and spatial parameters such as occupant-introduced perturbations, opening and closing of interior apertures, size and placement of interior objects, and indoor occupant density and movements can change the steady-state conditions to a transient-flow system (Mousavi and Bhattacharya 2022; Shih, Chiu, and Wang 2007). According to our understanding of disease transmission indoors, airflow patterns can induce additional momentum on virus-laden particles that can change the trajectory of aerosol transmission, all of which can be assessed during design phase. Moreover, building massing and spatial planning can significantly alter the environmental factors which consequently impact disease transmission in indoor spaces. Therefore, human health, and specifically risk of disease transmission within buildings, needs to be considered from the initial schematic design phase to the specification of interior finishes, enclosure systems, and mechanical and electrical control systems. Modeling spatial and temporal analyses of the indoor microenvironment (and specifically, aspects of the indoor microbiome), is logistically challenging and computationally expensive through CFD analysis techniques. Therefore, our proposed methodology is a cost-effective way to quantify indoor microenvironmental impacts on the dispersion and transport of airborne contaminants (including virus-laden particles in future studies) in the Rhino/Grasshopper simulation environment. This workflow allows designers to parameterize additional architectural variables and test a wide range of design interventions as they pertain to the risk of disease transmission at the room and building scale.

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