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4 1 **Simulation-Based Trade-off Modeling for Indoor Infection Risk of Airborne Diseases,**
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6 2 **Energy Consumption, and Thermal Comfort**
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33 13 **Abstract**
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36 14 The transmission of airborne diseases indoors represents a significant challenge to public health.
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38 15 While enhancing ventilation can mitigate infection risks, it simultaneously escalates building
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40 16 energy consumption and alters human thermal comfort. There is limited understanding about the
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42 17 intricate interplay among 1) human health measured as exposure to pathogens and infection risk,
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44 18 2) building energy consumption as a result of different heating, ventilation, and air conditioning
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46 19 (HVAC) control strategies, and 3) human thermal comfort in different climate zones. This research
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48 20 developed a modeling framework to evaluate the trade-offs among health, energy, and human
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50 21 thermal comfort and conducted simulations using school building data, considering a variety of
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52 22 parameters in temperature, humidity, and ventilation control. Key findings revealed that indoor
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54 23 temperature profoundly influences infection risk, energy consumption, and thermal comfort.
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Ventilation rate governs the variations of infection risks and building energy usage, while indoor relative humidity demonstrated negligible impacts. Notably, thermal comfort and low infection risk can be concurrently realized, albeit at the expense of high energy consumption. Comparing the optimal and worst environment settings in a typical U.S. climate zone, a 43% decrease in infection risks and a 61% increase in thermal comfort are observed, accompanied by an over 70% increase in energy consumption. The influences and trade-offs among infection risks, energy consumption, and thermal comfort are additionally modulated by climate characteristics.

Keywords:

Health; Energy; Thermal Comfort; HVAC Control; Infection Risk; COVID-19

1 Introduction

The prolonged COVID-19 pandemic has prompted concerns regarding the establishment and maintenance of a healthy and sustainable indoor environment as schools resume full in-person instruction. Due to their crowded and inadequately ventilated nature, schools are often regarded as spaces where frequent interactions take place among students and teachers. Several studies have confirmed that the airborne route is the main pathway for the transmission of SARS-CoV-2 [1–4]. The special environmental condition of schools could accelerate the transmission of airborne diseases and lead to an outbreak during the pandemic. The indoor environment can affect the virus infectivity, survival, and the suspension time in the air. Thus, maintaining an appropriate indoor air environment in the building operation is of significance to prevent the airborne transmission of the virus. Increased ventilation rate and implementation of air filtration, as the primary mitigation measures for risk control, can dilute the aerosol concentration in the air, and result in a decrease in

infection risk [5]. In addition, recent research has demonstrated that indoor temperature and humidity can affect the transmission of the virus by aerosols since both factors are influential on the decay and deposition rate of the virus, and thus affect the survival time of the virus. Dabisch et al. [6] reported that both the temperature and air humidity will be influential on the infectivity of SARS-CoV-2 in aerosols, especially for temperature. For instance, when air humidity remains constant, the time needed for a 90% virus decay increases from 11.5 min to 19.5 min when temperature decreases from 30 °C to 10 °C. Under constant temperature, the decay rate increases from $0.6 \pm 0.6\%$ to $1.5 \pm 0.5\%$ with increased relative humidity from 20% to 70%. Bazant et al. [7] indicated air humidity can affect the drop size distributions. Thus, despite the influence on virus infectivity, relative humidity can affect the deposition rate, since the deposition rate is relevant to the virus radius. Building HVAC systems, as a primary means to regulate the indoor environment, is essential for the control of indoor disease transmission.

The HVAC sector is a significant contributor to energy consumption. According to the Commercial Buildings Energy Consumption Survey, electricity and natural gas are the primary energy sources for commercial buildings, comprising 60% and 34% of energy consumption, respectively. In terms of expenditure, commercial buildings allocated \$119 billion for electricity and \$16 billion for natural gas to fulfill their energy needs [8]. Growth in population, increasing demand for building services and occupant comfort levels, and the increased time spent in buildings will continue to increase the energy demand. Thus, improving the energy-saving efficiency of HVAC systems is an essential objective for the building operation. HVAC energy demand is directly related to the building configuration, local climate, and the indoor environment status such as internal loads and temperature setpoint [9]. Appropriate operations can reduce

energy use while maintaining a satisfactory thermal sensation and a healthy environment. However, currently, there is a lack of study that quantitatively illustrates the relationships among the above three important aspects of the indoor environment. Therefore, this paper aimed to find the relationships and investigate the tradeoff among health, energy, and thermal comfort. The tradeoff exists due to the assumable inverse relationships among variables. For example, mitigation strategies such as improved ventilation can be adopted by the operation of HVAC systems to reduce infection risks, which may lead to increased energy consumption and dissatisfied thermal sensation. As stated above, there is a tradeoff among the important aspects of school operations during the pandemic.

Existing studies have developed various models to analyze health, energy consumption, and thermal comfort in the built environment, while the tradeoff among the three aspects considering mutual-related parameters remains elusive. Two significant knowledge gaps exist in this area. The first knowledge gap is the lack of a systematic framework to investigate the influential parameters in the models of health, energy, and thermal comfort, as the linkage between these models remains elusive without consideration of mutual-related parameters. The second knowledge gap is the absence of reliable quantitative analysis for the three major aspects during the pandemic simultaneously. This is due to three primary reasons. The first reason is the unclear impact of HVAC-controlled environment factors on these models. The COVID-19 pandemic has significantly changed the requirement for the indoor environment with the consideration of the health aspect. However, the lack of real data on all the control factors and concerned aspects is a major challenge for the tradeoff analysis. In addition, current studies tend to use constants to represent the environment factors for infection estimation [10–12]. However, the actual values of

the environment factors are dynamic in terms of the HVAC settings. Second is the ignorance of the impact of occupancy settings on the infection risk. Studies tend to assume a closed space without occupancy variation during the estimating period when computing the infection risks [13–15]. This simplification in occupancy will lead to inaccuracies in the evaluation of energy and thermal sensation. Third is the ignorance of climate characteristics for the tradeoff analysis. The lack of utilization of school and climate data and the absence of a systematic framework that links the models of health, energy, and thermal comfort holds back detailed and quantitative tradeoff analysis.

To close these knowledge gaps, this paper proposes to develop a convergent framework to perform the tradeoff analysis of energy, health, and thermal comfort in the school building operation. The framework considers the impacts of various room-level control methods, including temperature, ventilation, and humidity control, on the three important aspects. Additionally, this study provides insights into how different environment factors affect health, energy consumption, and thermal comfort for buildings located in different climate zones and demonstrates the tradeoff between these aspects. The predicted results of the three major aspects are estimated based on the set values of different environment factors, and the simulation results are used as a reference to illustrate the tradeoff based on the priorities of health, cost, or comfort as determined by the facility management team. The contributions of this study are two-fold. Firstly, this research proposed a new convergent framework to computationally link models of health, energy consumption, and thermal comfort in built environments with the identification and modeling of influential and related parameters. The HVAC-controlled indoor environment and related implications of health, energy, and comfort outcomes of our proposed framework are expected to present new paradigms in sustainable

building environment assessment. Secondly, this paper quantitatively analyzed the influence of indoor environment modifications on energy consumption, infection risks, and thermal sensation in schools during the COVID-19 pandemic. Using school data, this research conducted simulations to reveal new insights regarding the trade-offs among health, energy, and thermal comfort under various control strategies and climate characteristics.

2 Literature Review

2.1 Airborne disease transmission

2.1.1 Transmission mechanism and impacts of indoor environment

Traditionally, it was believed that respiratory pathogens spread mainly through large droplets produced by coughing or sneezing, or through contact with contaminated surfaces (fomites). However, studies have shown that several respiratory pathogens, including measles [16], influenza [17], severe acute respiratory syndrome coronavirus (SARS-CoV) [18], and SARS-CoV-2 [19,20], can spread through small respiratory aerosols. These aerosols can remain suspended in the air for extended periods and travel long distances. Respiratory aerosols are small droplets that are formed when people exhale during activities such as breathing, talking, and coughing, and these droplets can dry out partially, becoming aerosols that can transmit pathogens. Studies have shown that the concentration of infectious viruses is enriched in small particles with sizes smaller than $5\ \mu m$ [21]. Such small aerosol particles are the main concern of airborne transmission, and the World Health Organization (WHO) and the US Centers for Disease Control and Prevention (CDC) have acknowledged that the inhalation of infectious aerosols is the primary transmission mode of COVID-19 [22,23].

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4 138 The transmission and persistence of infectious aerosols in the air are influenced by both the virus
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6 139 characteristics and environmental conditions. Aerosol particle size changes over time due to
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9 140 processes such as evaporation, coagulation, and deposition, impacting virus viability and
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11 141 transmission. Larger particles tend to deposit to the ground faster than smaller ones, with particles
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14 142 of 5 μm taking approximately 33 minutes to deposit from a height of 1.5 m, while those of 1 μm
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16 143 can take over 12 hours to deposit [21]. The travel distance of aerosols in indoor environments is
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19 144 influenced by the particle size, the initial velocity induced by various respiratory activities, and the
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21 145 environment factors, such as the room air velocity, controlled by natural or mechanical ventilation
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24 146 [24]. Furthermore, environment factors can significantly affect the decay mechanisms in aerosols.
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26 147 Temperature plays a critical role in virus persistence and transmission by influencing the stability
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29 148 of the composition of viruses such as proteins and lipids. Several respiratory viruses that tend to
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31 149 infect the upper airways in the respiratory tract such as influenza and SARS-CoV-2 are more stable
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34 150 in environments with lower temperatures [25,26]. Relative humidity affects the survival of viruses
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36 151 in the air through the evaporation process. Once the infectious aerosols are exhaled from the
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39 152 respiratory tract with the saturated conditions to the ambient environment, the aerosols begin to
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41 153 evaporate due to the decrease in relative humidity [27]. The sensitivity of virus persistence to the
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43 154 relative humidity is determined by both the characteristics of the virus and the ambient
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46 155 environment [21]. For instance, influenza A viruses are reported to remain active over a wide range
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48 156 of relative humidity [28], while influenza viruses prefer environments with low relative humidity
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51 157 [29]. Given the substantial influence of environment factors on virus properties, assuming a
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53 158 constant environmental condition could potentially result in an erroneous estimation of virus
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2.1.2 Transmission modeling

Mathematical models have been widely employed to estimate the airborne transmission of diseases in indoor environments. The choice of models depends on the objectives and scope of the studies. Nevertheless, some of these models may not be applicable to the simulation methods presented in this paper for estimating airborne transmission. Table 1 presents a detailed comparison of various mathematical models concerning their suitability for modeling indoor airborne transmission. In this paper, the Wells-Riley (W-R) model was adopted to simulate airborne transmission. Current models derived from the W-R model tend to assume a confined space and do not account for changes in occupancy and indoor environmental conditions. This oversimplification may not provide an accurate depiction of real-world scenarios in the context of school building operations. A revised W-R model was developed in this paper to address the knowledge gap.

Table 1. Comparison of Mathematical models for the estimation of airborne disease transmission in indoor environments.

Mathematical models	Description	Advantages	Disadvantages	Reference
SIR	Characterizes the fraction of population (susceptible, infectious, recovered) getting infected that varies over time	Used to analyze the transmission in a population	Simplified assumptions for the population; Require to combine other models to describe airborne transmission	[30,31]
SEIR	Introduces a new compartment 'E' for exposed people compared with SIR model	Included more state and parameters to provide reliable prediction for the transmission in a population.	May fail to describe airborne disease alone; more complex and requires assumptions compared with SIR model	[32,33]
Dose response model	Estimates airborne transmission risks given the dose of infectious aerosols deposited in the	More reliable with the use of other models to acquire the deposited	High complexity model; Can only be applied to sophisticated simulation of	[34–37]

	respiratory tracts of susceptible people	pathogens in respiratory tracts	environment and well- studied viruses	
Wells-Riley model	Illustrates the hypothetical concentration of virus- laden aerosols and estimates the probability of infection transmission	Comprehensive and well-structured, widely adopted to various viruses; Relatively simple to use	May oversimplify and lead to limited accuracy	[38–41]

2.2 Energy consumption and thermal comfort

The environment factors are essential for occupant thermal comfort. Achieving thermal comfort is vital for human well-being, satisfaction, and performance, and is an essential consideration in building design and operation [42]. To estimate occupant thermal comfort, the most popular model was proposed by P.O. Fanger [43]. The model takes into account all the thermal factors in the environment to predict thermal comfort, expressed as the largest possible percentage of a given group of people. The predicted mean vote (PMV) model has become an internationally recognized tool for estimating the predicted mean thermal perception of occupants. According to Fanger's definition, PMV is the index that indicates the mean thermal sensation vote for any combinations of thermal factors, human activities, and clothing levels for a large group of people. The results of the PMV model are demonstrated by the ASHRAE 7-point thermal sensation scale, which ranges from "cold" to "hot," with results ranging from -3 to +3 [44]. The PMV index can be computed using Eq. 1, where M is the metabolic rate, and L is the thermal load defined as the difference between the human internal heat production and the heat loss to the environment due to evaporation.

$$PMV = (0.303 e^{-0.036M} + 0.028) L \quad (1)$$

Human thermal comfort perception is significantly impacted by indoor air temperature, which, if not set appropriately, can lead to negative effects such as low performance and health problems

such as shivering, inattentiveness, and muscular tension [45]. The relative humidity level is also related to indoor thermal comfort. Inadequate air humidity levels can cause dry skin and throat irritation. A recent study has indicated that a low-humidity environment can significantly increase the degree of fatigue in undergraduate students compared to a high-humidity environment [46]. Additionally, different ventilation modes can affect thermal comfort. Fan et al. [47] reported that various non-uniform ventilation modes can decrease the floor-to-ceiling temperature difference and increase thermal comfort by 45%. However, unsteady ventilation modes may result in lower thermal comfort levels.

The principal objective of HVAC systems is to uphold thermal comfort, which necessitates energy consumption for heating and cooling purposes. Energy consumption is largely influenced by both external weather conditions (e.g., outside air temperature, relative humidity, and wind characteristics) and internal conditions (e.g., occupancy, heat flow, and moisture flow). HVAC systems regulate indoor air temperature and moisture levels to maintain them within desired thresholds [48]. During the pandemic, the need for increased room ventilation leads to a further increase in building energy demand.

2.3 Tradeoff studies

Several recent researches have investigated the tradeoffs between energy consumption, infection risks, and thermal comfort. Mokhtari et al. [49] examined the effect of occupant distribution on energy consumption and COVID-19 infections using a university building, and the optimal occupant distribution pattern was found to reduce the number of infectors and building energy consumption. Jung et al. [50] demonstrated the potential for energy efficiency gains by integrating

personal thermal comfort models into building operational conditions. Risbeck et al. [51] proposed dynamical optimization models to estimate indoor airborne transmission risk and building energy consumption based on HVAC controller setpoints and a weather forecast. They found that infection risk and energy-efficient disinfection measures varied significantly across different spaces and were heavily dependent on the season. Guo et al. [52] developed a quantitative model to balance infection risk and energy consumption, resulting in a 13.7% reduction in energy consumption on weekdays and 45.1% on weekends when considering the combined effects of multiple mitigation measures. However, there lack the studies that analyze the tradeoff for all three major aspects (e.g., infection risk, energy consumption, and thermal comfort), and the tradeoff analysis over different climate zones remains elusive.

3 Methodology

The proposed framework consists of three phases: preparation, simulation, and tradeoff analysis, as illustrated in Figure 1. During the preparation phase, U.S. school data was gathered and prepared for both simulation and risk modeling, and building models were edited to incorporate energy and thermal comfort simulation. The selection of weather data is contingent on the climate zone in which the building is situated. The simulation phase involved utilizing the simulation methods to produce energy and comfort-related outcomes, as well as incorporating disease data of the SARS-CoV-2 virus into risk models to simulate infection risk outcomes. The tradeoff analysis phase analyzed the outcomes generated by the simulation models and compared them to explain the observed phenomenon. The methodology utilized quantitative analysis and simulation to obtain a comprehensive understanding of the tradeoff between infection risk, energy consumption, and thermal comfort in U.S. schools.

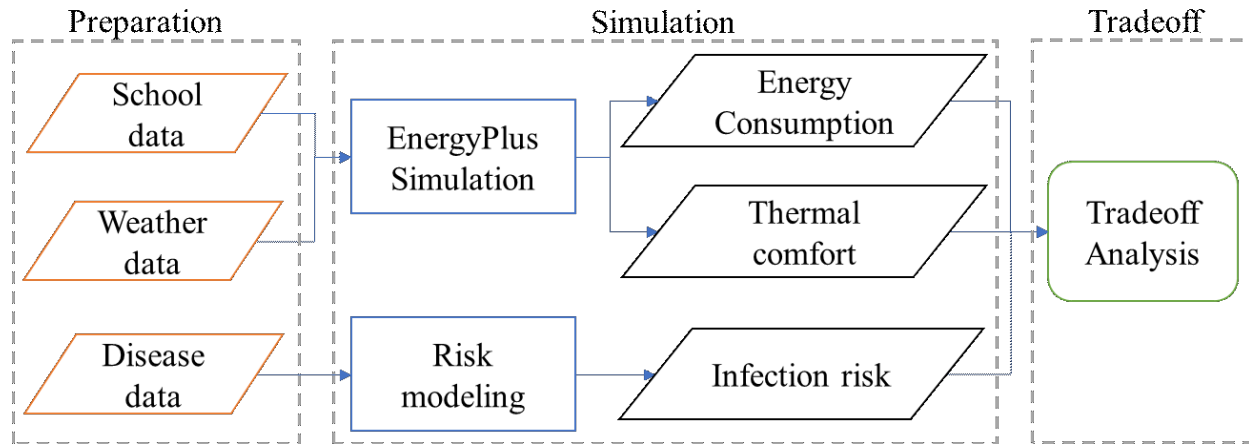


Figure 1. Framework of research methodology.

3.1 Data and model preparation

In this paper, a reference building model of a primary school, developed by the Department of Energy (DOE) [53], was used for simulation. DOE has developed 16 baseline building models, which represent approximately 70% of the US commercial building stock. The reference building model used in this study was derived from one of the commercial prototype buildings and was modified based on Standard 90.1 and International Energy Conservation Code (IECC) evolve [54]. The weather data for the 16 climate zones corresponding to the building models were utilized respectively. The zone-specified parameters such as zone area, height, and infiltration were retrieved from the building model as inputs for risk assessment. The disease data, such as the epidemiological parameters of COVID-19 were obtained from relevant literature to compute the infection risks.

3.2 Simulation

Figure 2 illustrates the data processing and simulation methodology. The simulation methodology encompasses three aspects: 1) environment modeling, i.e., physics-based building modeling with

indoor environment control; 2) occupancy/human modeling, i.e., setting occupancy and operation schedules, which is used as inputs to the risk model; 3) Health modeling, including the estimation of viral-specific parameters (e.g., viral decay rate, viral deposition rate, and viral removal rate) and local prevalence. The simulation for energy consumption and thermal comfort is based on environment modeling and occupancy/human modeling, and the simulation for infection risk relies on health modeling. The simulation outcomes obtained under various settings of environment variables will be utilized for tradeoff analysis, whereby the tradeoff relationship is represented by blue circular arrows.

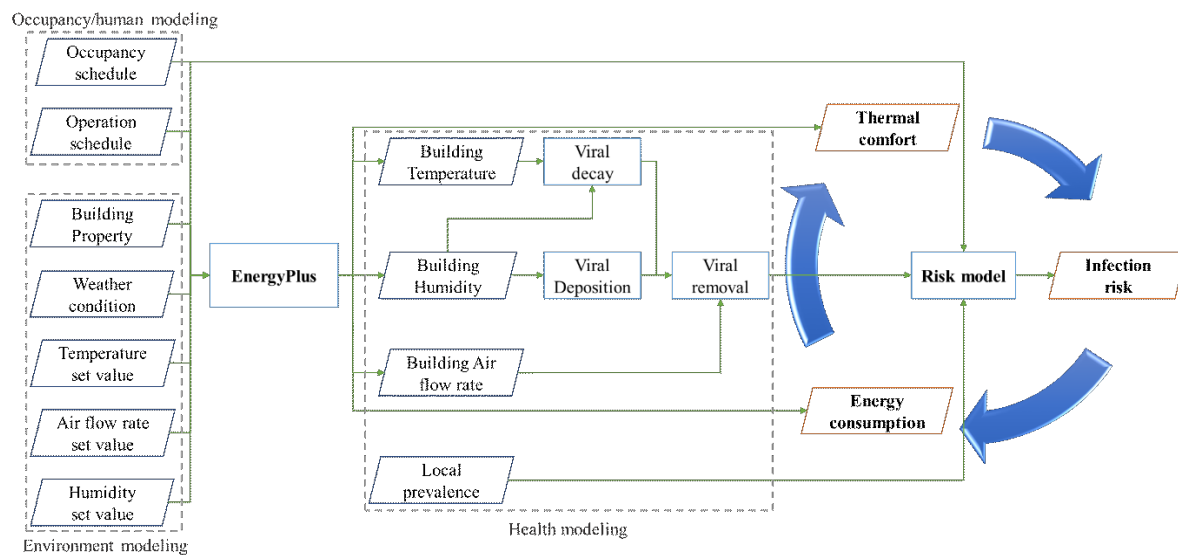


Figure 2. Data processing and simulation methodology for tradeoff analysis.

3.2.1 Simulation of energy consumption and thermal comfort

EnergyPlus was used to estimate building energy consumption and thermal comfort. Ventilation rate, relative humidity level, and temperature were the three focused environment factors in this study, which were controlled as needed in the simulation. These three factors are identified as the key influential variables for thermal comfort, energy, and health [49,55]. Besides the settings

relevant to the control of environment factors, the default settings of the reference building model were applied for energy and thermal comfort simulation. Figure 3 shows the 3-D geometry of the reference building model.

The building model used in this study is a single-story building structure consisting of 25 zones, including a bathroom, a cafeteria, a computer laboratory, corridors, a gymnasium, a kitchen, a library, a lobby, a mechanical room, offices, and classrooms classified into four distinct types. The building features steel-framed exterior walls and roofs insulated entirely above deck (IEAD) with non-residential insulation. The window-to-wall ratio is 0.35, and the overall total floor area is 6871 m^2 . The building employs both gas and electricity as its primary fuel sources. The HVAC system for the reference model employs both constant air volume (CAV) and variable air volume (VAV) systems, depending on the functionality of the building zones. The heating system utilizes both gas boilers and gas furnaces, while the cooling system is a packaged air conditioning unit (PACU). Further details of the DOE reference model are presented in Table 2, where the key parameters that vary across different climate zones are summarized. HVAC sizing, HVAC efficiency, and fan maximum flow rate vary according to building zone and climate zone. The values presented in the table represent the range retrieved from all zones in the building that correspond to the given climate zones. The table also outlines the installation of economizers. Other key parameters, such as building infiltration, lighting density, appliance density, occupancy fraction, and economizer maximum limit dry bulb temperature, remain constant across all climate zones, with values of 0.00133 $m^3/s * m^2$, 9.68–21.52 W/m^2 , 4–25.29 W/m^2 , 0–0.95, and 28 °C, respectively.

Table 2. Key parameters of the DOE reference model in different climate zones [53].

Climate zone	1A	2A	2B	3A	3B-CA	3B	3C	4A
R-value (exterior walls)	0.32	1.17	0.73	1.36	0.80	1.10	1.36	1.98
R-value (roof)	2.38	2.67	3.83	2.44	1.76	3.66	2.00	3.03
AC (kW) Heating (kW)	[20.62, 204.32]	[17.59, 170.31]	[16.45, 157.70]	[18.00, 169.11]	[19.83, 150.77]	[14.52, 133.12]	[20.68, 151.32]	[15.54, 138.26]
AC (COP)	[32.15, 440.67]	[36.20, 451.59]	[28.57, 363.53]	[39.97, 472.75]	[32.16, 442.62]	[27.26, 351.00]	[47.24, 534.37]	[38.42, 433.08]
Economizer	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5
Fan max flow rate	-	-	- / Diff dry bulb	-	Diff dry bulb	- / Diff dry bulb	Diff dry bulb	-
Climate zone 4B	[0.2, 8.23]	[0.2, 6.86]	[0.2, 6.35]	[0.20, 6.9]	[0.20, 8.02]	[0.20, 5.82]	[0.20, 9.04]	[0.20, 5.57]
R-value (exterior walls)	1.76	1.92	2.15	2.15	2.71	2.44	3.04	3.91
R-value (roof)	2.99	2.75	3.38	3.51	3.97	3.65	4.41	5.75
AC (kW) Heating (kW)	[14.40, 97.58]	[11.59, 99.88]	[14.99, 129.43]	[12.99, 85.08]	[14.17, 114.16]	[10.37, 85.44]	[12.23, 116.09]	[8.14, 93.38]
AC (COP)	[30.46, 347.96]	[27.77, 376.05]	[43.29, 467.19]	[32.51, 336.32]	[44.22, 439.91]	[36.90, 414.54]	[39.05, 433.79]	[48.31, 663.20]
Economizer	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5	3.23, 3.3, 3.5
Fan max flow rate	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
Climate zone 8	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb	- / Diff dry bulb
Climate zone 7	[0.20, 5.52]	[0.20, 5.5]	[0.20, 5.21]	[0.20, 4.6]	[0.20, 4.6]	[0.20, 5.16]	[0.20, 4.68]	[0.20, 5.64]

Diff dry bulb: All zones in the reference building model are equipped with differential dry bulb economizers.

- / Diff dry bulb: Some zones are not equipped with economizers, while others have differential dry bulb economizers.

-: Economizer is not equipped in any of the zones of the reference building model.

The unit of R-value is $m^2 \cdot kW$.

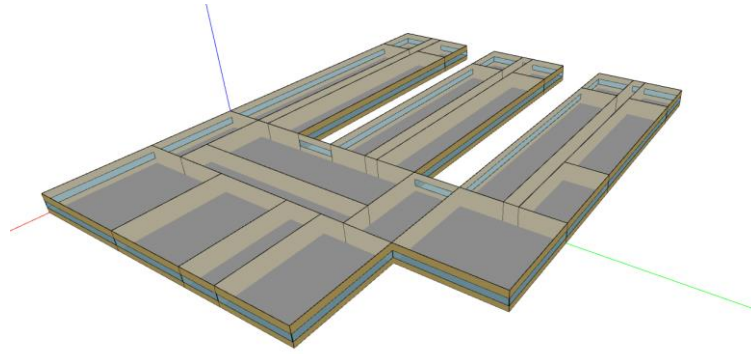


Figure 3. 3-D geometry of the reference building model [53].

In order to manipulate environmental conditions, the minimum ventilation rate of each room can be adjusted to regulate room ventilation rates. For humidity control, the original HVAC system of the reference building model cannot adjust the level of relative humidity in each room. Our simulation incorporated the addition of humidifiers and dehumidifiers to the HVAC system to facilitate indoor air humidity control. The humidifiers are electrically heated, self-contained steam humidifiers. Each humidifier was set to provide at most $4 * 10^{-5} m^3/s$ water flow rate to humidify the room air [56]. The dehumidifiers were conventional mechanical dehumidifiers. This system uses a direct expansion cooling coil to cool and dehumidify the airstream. Default settings of this equipment were utilized, with the ability to dehumidify airstreams ranging from 10°F to 95°F. The humidifiers were connected to each HVAC branch, with one humidifier allocated for each branch, while the dehumidifiers were positioned in each zone and connected to the zone's exhaust fan. The relative humidity level of each zone was detected by a humidistat and regulated by the humidity ratio setpoint. Economizers were installed in five of the seven HVAC branches. The HVAC system was set to operate from 6:00 to 21:00 during weekdays and to shut down at other times and on non-working days. With the implementation of specific controller settings of

the indoor environment, the hourly room temperature, humidity, and air flow rate were simulated, which enabled the prediction of the building energy consumption and room thermal comfort.

3.2.2 Modeling of airborne disease transmission

As stated in Section 2.1.2, the W-R equation can be used to estimate the indoor airborne transmission of an infectious agent using Eq. 2 [38,39].

$$P_{infection} = 1 - e^{-\bar{\mu}} \quad (2)$$

Where $P_{infection}$ is the probability of a susceptible person being infected, and $\bar{\mu}$ is the number of quanta breathed by a susceptible person.

Azimi et al. [57] considered several school microenvironments or spaces and developed a model based on the W-R equation to estimate the transmission risk of infectious aerosols between students when one index case is present in the school. The average number of quanta inhaled by a susceptible student during a typical school day is estimated using Eq. 3.

$$\bar{\mu} = \frac{1}{N_{total}} * \bar{p} * \sum_i \int_0^{\bar{t}_i} N_i(\tau) C_{quanta,i}(\tau) d\tau \quad (3)$$

i : Index of the spaces, which are classroom and common area.

N_{total} : Total number of students.

$N_i(\tau)$: Number of students in space i .

$\bar{p}$: Average inhalation rate (m^3 /hour), set as $10.59 m^3/day$ according to [58], which is estimated as the average breathing rate for students from 6 to 11 years.

$\bar{t}_i$: Average time students stay in space i .

$C_{quanta,i}(\tau)$: Concentration of quanta in space i , τ hours after the index case is present in space i (quanta/ m^3).

$C_{quanta,i}(\tau)$ can be estimated using Eq. 4 [57].

$$C_{quanta,i}(\tau) = \frac{Iq}{V_i K_{total,i}} (1 - e^{-K_{total,i}\tau}) \quad (4)$$

I : Number of infectors

q : quanta generation rate (quanta/hour)

V_i : Volume of space i (m^3)

$K_{total,i}$: Total removal rate of infectious viruses in space i (per hour), and is computed using Eq.

5.

$$K_{total,i} = \lambda_{infiltration,i} + \lambda_{ventilation,i} + k_{deposition} + k_{decay} \quad (5)$$

$\lambda_{infiltration,i}$: Natural ventilation rate or infiltration air exchange rate in space i (per hour).

$\lambda_{ventilation,i}$: Mechanical ventilation rate of the HVAC system in space i (per hour).

$k_{deposition}$: Deposition rate of infectious particles in space i (per hour). The viral deposition rate is computed based on the radius of the infectious particles, which is varied according to the room relative humidity, and can be calculated using Eq. 6 and Eq. 7 [7].

k_{decay} : decay rate for viral infectivity in space i (per hour).

$$r = r_0 * \sqrt[3]{0.4/(1 - RH)} \quad (6)$$

$$k_{deposition} = 2\Delta\rho g r^2 / (9\mu_a H) \quad (7)$$

The viral decay rate can be estimated by a series of empirical equations related to relative humidity and temperature, which is shown in Eq. 8–13 [59].

$$k_{decay} = 16.9803 + 0.0622E_s - 0.796p_v - 21.95V_s \quad (8)$$

$$E_s = (1.007T - 0.026) + C_m(2501 + 1.84T) \quad (9)$$

$$p_v = \frac{RH * p_s}{100} \quad (10)$$

$$V_s = (0.287 + 0.461C_m) \left(\frac{273.15 + T}{p_b} \right) \quad (11)$$

$$C_m = \frac{0.622p_v}{p_b - p_v} \quad (12)$$

$$p_s = 0.61078e^{\frac{17.2694T}{T+237.99}} \quad (13)$$

Where T is the room air temperature ($^{\circ}\text{C}$), RH is room relative humidity, E_s represents specific enthalpy (kJ/kg), p_v is the vapor pressure (kPa), p_s is the saturated vapor pressure (kPa), V_s is the specific volume per kilogram of dry air (m^3/kg), C_m is the moisture content, and p_b is the barometric pressure (101.325 kPa).

For the school buildings, the occupancy schedule specifies the hourly occupancy for each room. In addition, the indoor environment such as temperature, humidity, and air flow rate, is subject to continuous changes over time for each room. In this paper, to account for the time-dependent parameters, the value of μ was calculated with 1-hour time step. $\mu(t)$ indicates the number of quanta breathed by a susceptible student from time t to $t + 1$, and is estimated using Eq. 14. This equation assumes that the quanta generated before time t are all inhaled by susceptible hosts.

$$\mu(t) = \frac{1}{N_{total}(t)} \times \bar{p} \times \sum_i (N_i(t) \int_t^{t+1} C_{quanta,i}(t, \tau) d\tau) \quad (14)$$

$$C_{quanta}(t) = \frac{I_i(t)q}{VK_{total,i}(t)} (1 - e^{-K_{total,i}(t)}) \quad (15)$$

$$K_{total,i}(t) = \lambda_{infiltration,i}(t) + \lambda_{ventilation,i}(t) + k_{deposition}(t) + k_{decay}(t) \quad (16)$$

t : Time step with step size of one hour from t_0 . $t \in t_0, t_0 + 1, \dots, t_n - 1$. t_n is the end of operation hour.

$N_{total}(t)$: Total number of students in schools at time t . $N_{total}(t) = \sum_i N_i(t)$.

$N_i(t)$: Number of students in space i at time step t , which is achieved from room occupancy schedule.

$I_i(t)$: Number of index cases at time step t in space i .

$\lambda_{infiltration,i}(t)$: Natural air ventilation rate or infiltration air exchange rate in space i (per hour), retrieved from the EnergyPlus model.

$\lambda_{ventilation,i}(t)$: Mechanical ventilation rate of the HVAC system in space i (per hour), retrieved from the simulation result of the hourly room air flow rate.

$k_{deposition}(t)$: Deposition rate of infectious particles in space i (per hour), which is computed based on the room air relative humidity retrieved from the hourly simulation result.

$k_{decay}(t)$: decay rate for viral infectivity in space i (per hour), which is computed based on the room temperature and relative humidity retrieved from the hourly simulation result.

$$I_i(t) = prevalence * N_i(t) \quad (17)$$

q : quanta generation rate, set as 142 *quanta/h* according to the study conducted by Buonanno et al. [10].

V_i : Volume of space i (m^3)

$K_{total,i}(t)$: Total removal rate of infectious viruses in space i at time t (per hour).

prevalence: Local infection rate (%), assumed to be 5%.

The average infection risk for a student staying in the school for an hour is calculated using Eq.

18. P is the infection risk for a typical school day.

$$\mu_n = \sum_{t=t_0}^{t_n-1} \mu(t) \quad (18)$$

$$P = 1 - e^{-\mu_n} \quad (19)$$

μ_n indicates the total number of quanta breathed by a susceptible student during a typical school day. P is the infection risk of a typical school day.

3.3 Tradeoff analysis

To perform the tradeoff analysis, different sets of environment parameters were identified and evaluated to aid school facility managers in decision making for HVAC operation. For temperature control, the thermostat placed in each room regulates the heating and cooling setpoints. In the simulation, five groups of cooling and heating setpoints were adopted, including [24°C, 24°C], [25°C, 23°C], [26°C, 22°C], [27°C, 21°C], and [28°C, 20°C]. The increased differences between cooling and heating setpoints were set to ensure the workload of the HVAC system decreasing both in winter and summertime, and to better understand the relationship between thermal comfort and energy use. Therefore, the cooling setpoint should increase while the heating setpoint should decrease simultaneously. For humidity control, the ranges of the set values were specified to define the minimum and maximum values of the room relative humidity, and were regulated via the humidistat in each room. Four humidity ranges were used, which were [30%, 40%], [40%, 50%], [50%, 60%], and [60%, 70%], since the indoor comfort range is typically between 30% and 60% relative humidity. Furthermore, relative humidity in northern U.S. cities is approximately 30%, while in southern cities it can reach 70% [60]. For ventilation control, the set values were identified as the designed minimum outdoor air flow rate in each room. Four values of the ventilation rate were considered: 2 air changes per hour (ACH), 4 ACH, 6 ACH, and 8 ACH. Research indicates that the average air change rate in U.S. school classrooms is 2 ACH [61], and during the pandemic, the classroom ventilation rate should be increased according to CDC instructions [62]. In total, 80

combinations of set values (5 temperature set values $\times$ 4 humidity set values $\times$ 4 ventilation set values) were generated, resulting in 80 simulation runs for analysis.

The simulation process leverages EnergyPlus to model indoor dynamics and PMV values in the hourly resolution and annual building energy consumption based on the building and environment configurations. The annual average values for each environment factor were computed as the average of the hourly results. For thermal comfort, the predicted mean vote (PMV) model was used, with PMV indexes ranging from -3 to +3, representing cold to hot thermal sensations on the ASHRAE thermal sense scale. Neutral thermal conditions are achieved at a PMV index of 0. In this study, the annual average result for thermal comfort was computed as the average of the absolute value of the hourly results, considering the consequences of both the positive and negative values of the PMV index. The trade-off analysis considered annual building energy consumption, annual average thermal comfort, and infection risks on a typical school day within the year.

To simulate infection risks, the number of quanta inhaled by a susceptible individual during a typical school day was computed, with details provided in Section 3.2.2 and illustrated in Figure 2. This calculation was performed using a 1-hour time step, taking into account the school population, occupancy schedule, and simulated hourly results of the environment factors. Specifically, the number of infectors was estimated based on occupancy schedule and local epidemic prevalence; The virus total removal rate was estimated based on hourly result values of the environment factors, including the room temperature, humidity, and ventilation, which affect the viral decay, deposition and decay, and removal rates, respectively. The total number of quanta inhaled by a susceptible student during a school day was determined by summing the hourly

breathed quanta, and the infection risk of a typical school day was estimated based on the total quanta inhalation.

To conclude, in the tradeoff analysis, temperature, humidity, and air flow rate are the variables representing different indoor environments. The three aspects of consideration, i.e., energy consumption, infection risk, and occupant thermal comfort were simulated based on set values of the three environment factors. The tradeoff analysis is presented at the building level with the averaged modeling results over all building zones.

4 Results

In this paper, simulations were conducted to model building energy consumption, thermal comfort, and infection risks using building reference models representative of their respective climate zones. The results show that the general tradeoff patterns between the three aspects and the relationships between the aspects and environment factors are similar. Therefore, in Sections 4.1 and 4.2, the simulation of a building located in climate zone 5A with a cool and humid climate was chosen as a representative case to illustrate the result of the tradeoff analysis. The reason for selecting climate zone 5A was its extensive geographic coverage, as well as its recognized status as a representative of a typical climate within the United States.

4.1 Impact of environment factors

This study involved specifying different set values for the room air flow rate, humidity, and temperature as environment factors, resulting in 80 simulation runs and corresponding simulation results of health, energy consumption, and thermal comfort sensation. The results of the three

aspects are annual building energy consumption, average daily infection risk, and average occupant thermal comfort for a year. The relationships between the environment factors and the three aspects are shown in Figure 4. Specifically, figure 4(a-c) demonstrate the impact of temperature set values on the infection risk, building energy, and thermal comfort, respectively. Likewise, Figure 4(d-f) depict the impact of air flow rate, and Figure 4(g-i) demonstrate the impact of humidity. The results indicate that lowering cooling setpoints leads to a decrease in infection risks, as the increased cooling load of the HVAC system could lead to an increase in economizer operation. Since the economizer introduces a massive amount of outdoor air, it is advantageous in reducing infection risks. Furthermore, an increase in the differences between heating and cooling setpoints results in decreased building energy consumption due to the decrease in both heating and cooling load. Temperature setpoints also significantly impact thermal comfort sensation, with an increase in temperature deviation from neutral temperature resulting in higher PMV values, indicating greater dissatisfaction with the thermal environment. A linear relationship between air flow rate and infection risk was observed, as increased ventilation leads to the dilution of indoor air and a subsequent decrease in infection risk. In addition, increased ventilation leads to increased energy consumption, with a near-linear relationship between ventilation and building energy consumption. The impact of air flow rate on thermal comfort was found to be minor. Finally, the effects of air humidity on the three aspects were found to be insignificant for this climate zone.

Figure 4(a-c) utilized color schemes to identify the distinct effects of environment factors. It can be inferred that, holding the air flow rate constant, decreasing cooling setpoints results in an increase in infection risks and a decrease in energy consumption. Similarly, at constant temperature setpoints, an increase in air flow rate is correlated with a reduction in infection risks and increased

energy use. Temperature setpoints are the dominant factor in determining thermal comfort, while the impact of ventilation and humidity is minimal.

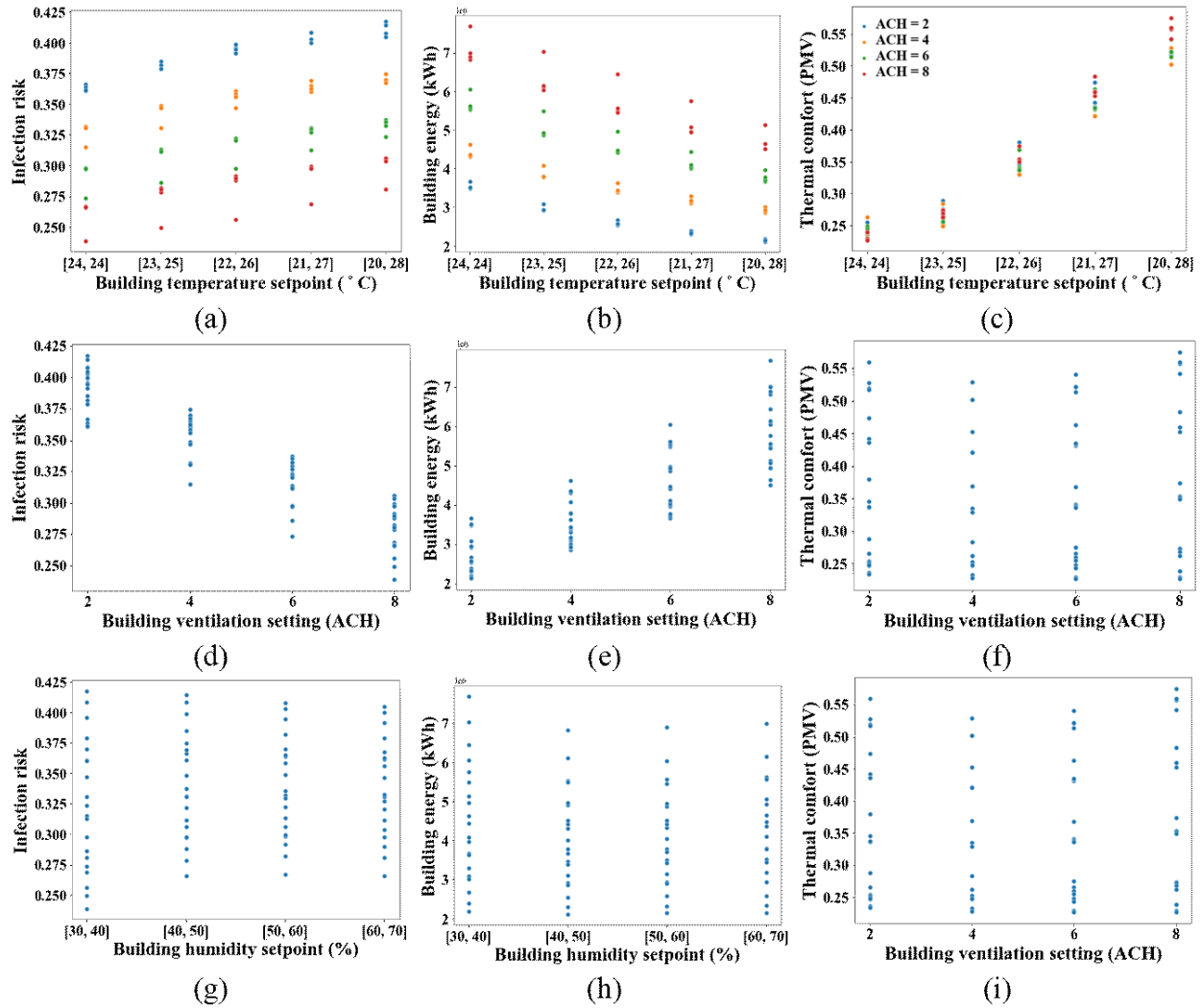


Figure 4. The impact of environment factors on energy consumption, infection risk, and thermal comfort.

4.2 Tradeoff among health, energy, and thermal comfort

The tradeoff was analyzed based on the 80 simulation runs of the three major aspects, and is illustrated in Figure 5, which presents a 3-dimensional view of the relationship between the three aspects and the 2-dimensional representations between each two aspects, as shown in Figures 5(b-

d). The color of each point in the figures represents the value of the other aspect, with darker colors indicating smaller values. The results demonstrate that there are tradeoffs between energy consumption and thermal comfort, and between infection risk and thermal comfort. The detailed relations are shown in Figure 6. There is a near-linear relationship between energy consumption and PMV values, indicating that increased energy consumption leads to improved thermal comfort. In addition, a near-linear relationship is observed between decreased infection risk and increased thermal satisfaction for the same room ventilation rate. The increased deviation from neutral temperature will lead to reduced operating hours of HVAC and more a dissatisfied environment for occupants. The tradeoff between infection risk and energy consumption is shown to be nearly linear, as increasing the air flow rate to decrease infection risk also increases energy consumption. Therefore, increased energy consumption can lead to reduced infection risk and improved thermal comfort simultaneously.

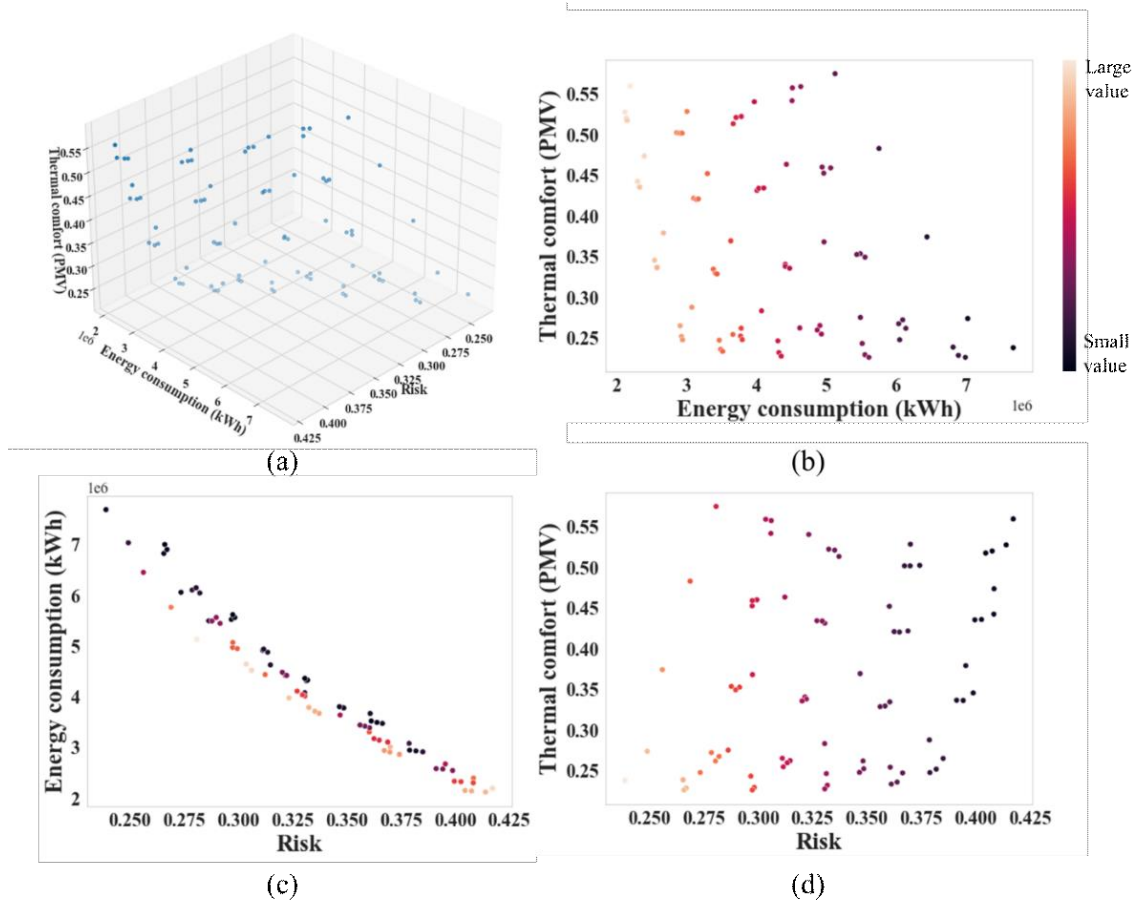


Figure 5. Tradeoff among energy consumption, infection risk, and thermal comfort.

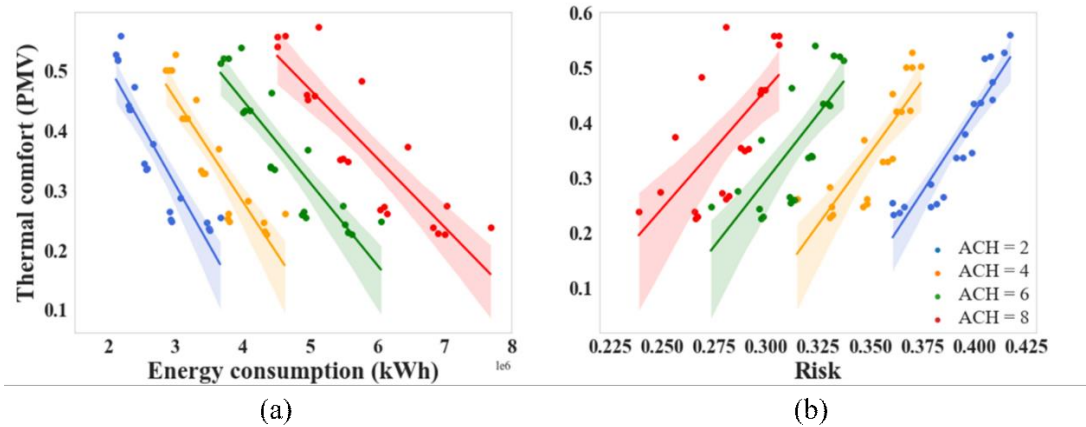


Figure 6. (a). The relationship between building energy consumption and thermal comfort with controlled ventilation. (b). The relationship between infection risk and thermal comfort with controlled ventilation.

4.3 Analysis for buildings in different climate zones

A nationwide assessment of energy, risk, and thermal comfort was conducted to analyze the impact of climate characteristics on buildings across the U.S. The findings indicate that the overall tradeoff patterns and the relationships between environment factors and the concerned aspects are similar for buildings located in different climate zones under most circumstances. The results suggest that an increase in building energy consumption can lead to improved thermal sensation and reduced infection risks. However, the simulated outcomes of the three aspects vary significantly across different climate zones. Figure 7 displays the distributions of the average values of infection risks, building energy consumption, and thermal comfort with different set values of environment factors in the climate zones. The median values presented in the boxplots provide an intuitive illustration of the impact of climate on the three aspects, and the variation in the simulated results indicates the influence of different set values of environment factors.

Regarding energy consumption, buildings located in cold climates tend to consume more energy, and the range of simulated energy consumption is larger compared with those in warm climates. For instance, the energy consumption in zone 1A is less than half of that in zone 7, and the range of the energy consumption in zone 1A is reduced by 36% compared to zone 7. In subarctic climates, the annual median energy consumption and the corresponding range reach the highest values over all climate zones. In warm climates, the heating and cooling load are usually mild due to the small difference between indoor and outdoor environment. Hence, changing setpoints will not produce discernible influences on energy consumption, leading to smaller variances in energy use. While in colder climates with large temperature differences between indoor and outdoor environment, any decrease in the heating temperature setpoint will lead to an observable reduction in energy

consumption. Hence, the variances of energy use in cold climates tend to be larger. For hot climate zones, the VAV system can help reduce energy consumption. Regarding thermal comfort, buildings in mild climate zones are more likely to achieve better thermal sensation than those in hot or cold climates. For instance, in zone 2A and zone 8, representing very hot and subarctic climates respectively, the median PMV values are around 0.63 and 0.65. Mixed climates like Zone 4A and 4B achieve satisfactory thermal sensation with a median value of 0.3. The spread of the data tends to decrease from extremely hot or cold climates to mild climates, indicating that although the deviation of the temperature setpoints increases, the indoor temperature remains around neutral temperature in mild climates. Improper indoor temperature settings are more likely to result in thermal dissatisfaction in hot or cold climates. As for infection risks, the median and variation of the simulated result values are not subject to change significantly across different climate zones. Room ventilation rate dominates this aspect compared with the other environment factors, which is not varied significantly over most climate zones. Consequently, infection risks do not vary significantly across different climate zones, except in very hot regions. Buildings in climate zone 1A exhibit the lowest infection risks due to higher ventilation rate associated with much longer cooling season and economizer operation hours that introduce a larger volume of outdoor air intake to dilute the infection virus. Generally, buildings in climate zone 1A require cooling almost all through the year, compared to limited summer cooling months in other climate zones (e.g., June to August as the cooling season in climate zone 5A). With the setting of maximum limit dry bulb temperature of economizer operation in reference buildings, the economizer will diligently operate to introduce natural cooling from November to May in climate zone 1A when outdoor temperature falls in the appropriate operation range. While in other climate zones, the

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4 542 economizer are only active in summer months or shoulder seasons. Hence, the total economizer
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7 543 operation hours and ventilation rate are significantly larger in zone 1A than other climate zones.
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11 545 The influence of humidity setpoints on energy consumption is negligible except for regions with
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14 546 high humidity levels, such as zone 1A. In these areas, energy consumption reduces with the
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16 547 increase of humidity setpoint. For instance, in zone 1A, the average annual energy consumption
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19 548 decreases by 49% when the humidity setpoint is raised from [30%, 40%] to [60%, 70%]. The
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21 549 prominent influence of humidity setpoint on HVAC energy use in zone 1A results from the
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24 550 extremely humid climate, where raising the humidity setpoint reduces the energy required for
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26 551 dehumidification.
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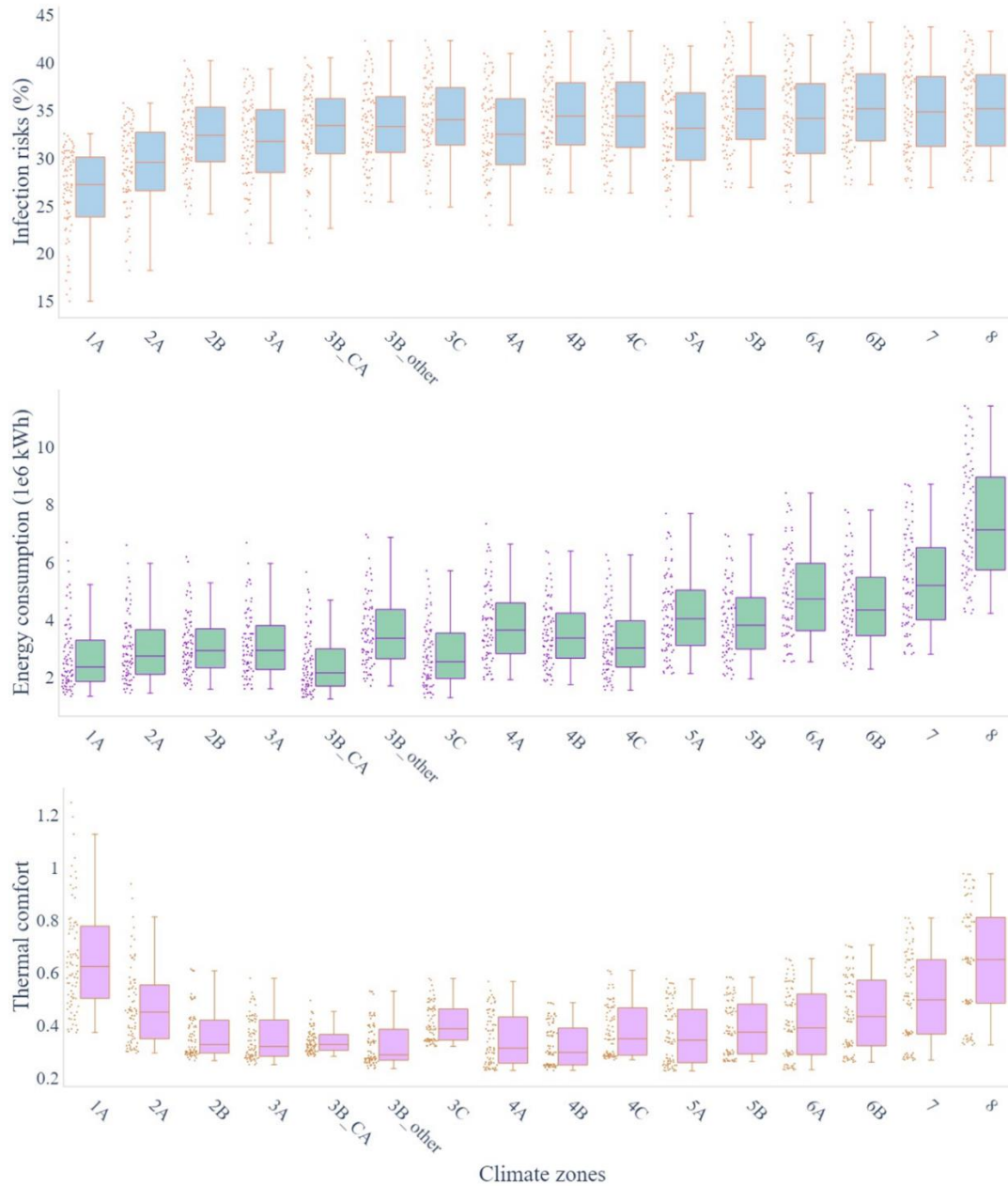


Figure 7. The distribution of infection risks, energy consumption, and thermal comfort in 16 climate zones.

5 Discussion

This study investigates the impact of various indoor environment factors on three critical aspects that are of concern for school management teams during the COVID-19 pandemic: building energy

consumption, thermal comfort, and infection risks. To illustrate the tradeoff analysis and the interrelationships between environment factors and the aforementioned aspects, a representative building model of a primary school was employed. Furthermore, climate data from 16 different zones in the U.S. developed by the Department of Energy (DOE) were incorporated into the simulation to highlight the influence of climate characteristics. By controlling the indoor environment, the study obtained the results of health, energy consumption, and thermal comfort sensation based on the building characteristics and climate data.

5.1 Influence of environment factors

The results suggest that the environment factors have a certain degree of influence on the concerned factors. Room ventilation rate and temperature setpoints are identified as the two key factors that affect energy use in all climate zones, with room ventilation being the most significant factor. In most climate zones, humidity has minimal impact on building energy consumption, except for humid zones like 1A, where the energy use of dehumidifiers can be influential. To reduce infection risks, decreasing cooling temperature setpoints and increasing ventilation rates are effective measures. However, indoor temperature alone does not significantly affect infection risks. Lowering the cooling setpoint can increase the cooling load of the HVAC system and the operation hours of economizers to bring in more outdoor air for cooling purposes, thus influencing infection risks. Room ventilation rate dominates the changes in building infection risks and energy consumption, and both have near-linear and positive relationships. These findings align with recent studies that also indicate the significant impact of ventilation on the infection risks of SARS-CoV-2 [1,5,11]. The study further suggests that increased temperature deviation from the neutral temperature reduces thermal sensation satisfaction, and the influence of room ventilation on

thermal sensation is minimal. This result conclusion is similar to the study proposed by Miranda et al. [55], who investigated the influence of ventilation on thermal comfort in classrooms during COVID-19. The study concludes that room ventilation does not have a decisive influence on comfort when the temperature is above 12 °C. The effect of room air relative humidity is not significant to infection risks and thermal sensation, which is consistent with the conclusions of other studies. For instance, Zuo et al. [63] indicated that the increase in relative humidity from 50% to 70% at 26 °C had trivial influences on physiological responses and thermal comfort.

5.2 Impact of considering health aspect on building operation

The COVID-19 pandemic has introduced health considerations as a new dimension to building operations, which are closely associated with thermal comfort and energy use. The study reveals a clear linear relationship between infection risks and energy consumption, which can be attributed to the dominant effect of room ventilation rate on both aspects. Moreover, a near-linear relationship between infection risks and thermal satisfaction is observed due to the working principle of VAV systems. Therefore, there are evident tradeoffs among the three dimensions, indicating that the lowest infection risk and optimal thermal sensation can be achieved by setting appropriate indoor conditions, such as utilizing the maximum ventilation rate and setting cooling and heating temperature setpoints to 24°C. The appropriate indoor temperature can achieve satisfactory thermal sensation based on the PMV model, while increasing energy consumption through reduced cooling setpoint and increased ventilation can both decrease the infection risk.

The ASHRAE 62.1-2019 standard regulated the minimum ventilation rate for classrooms as 10 cfm/person and $0.12 \text{ cfm}/ft^2$. According to the building characteristics and occupancy schedule,

the room minimum ventilation rate is between 0.54 ACH to 3.56 ACH for the prototype primary school building. During the pandemic, CDC encourages increasing room ventilation as much as possible [62], and according to the study conducted by Guo et al. [52], the requirements for fresh air ventilation rate ranges from 0.8 ACH to 5.75 ACH given the characteristics of the reference building. Taking zone 5A for example, the increase of ventilation rate by 1 ACH implies an increase in energy use by 19.7%. The implications of ventilation rate on energy use do not vary significantly across different climates.

5.3 Impact of climate characteristics on the relationships of three aspects

According to the analysis based on the weather data of different climate zones, it is concluded that climate characteristics can have influential impacts on the concerned factors. In cold climate zones, the building energy consumption is sensitive to the adjustment in temperature setpoints. On the contrary, energy consumption in hot and warm climate zones is relatively low, and increasing the cooling setpoint has a less efficient impact on energy savings than decreasing the heating setpoint in cold climates. Regarding thermal comfort sensation, occupants in buildings located in cold and hot climate zones (e.g., 1A, 2A, 6A, 6B, 7, and 8) are more likely to experience discomfort. Therefore, facility management teams must implement more restrictive temperature set values around the neutral temperature to maintain a comfortable indoor environment for such buildings. However, the effect of temperature control is not as significant for some mild climate zones, including 3B-CA, 3C, and 5A, where thermal sensation variation is minor, and restricted temperature control could result in a significant increase in energy consumption for marginal improvements in thermal comfort. Regarding the infection risks, climate characteristics do not appear to have a significant influence except for zones with extremely hot weather. Therefore, in

order to establish a healthy indoor environment in buildings located in other climate zones, it is imperative to implement alternative mitigation measures such as air filtration and social distancing.

This study highlights the interdependent nature of energy consumption, infection risks, and thermal comfort in building operations. The findings suggest a near-linear relationship between energy consumption and thermal comfort across all climate zones with constant ventilation levels, as a result of considerable influence of temperature settings. Similarly, with constant ventilation levels, there is a near-linear relationship exists between infection risks and thermal comfort, attributable to the increased cooling load that necessitates additional outdoor air additional cold air from central air handling units and more economizer operation. There is a clear linear relationship between infection risks and energy consumption attributable to building ventilation and temperature setpoints that affect both factors linearly, and an insignificant effect of relative humidity on these two aspects.

There are several limitations to be acknowledged in this paper. Firstly, the study focuses on the tradeoffs among annual infection risks, thermal comfort, and energy consumption. Nonetheless, it is imperative to note that the outcomes and corresponding values of the environment factors may vary with a diverse simulation period. Consequently, future studies should consider the seasonal impact on the three aspects as well as the HVAC operation strategies. Secondly, while this study provides trade-off relationships, it does not present a single optimal solution that considers all three aspects. Therefore, further research is necessary to develop an optimization method that provides intuitive decision-making suggestions. Thirdly, the present study was conducted based on simulations of a reference building model. Therefore, it is essential to acknowledge that the

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4 651 simulated results may differ from actual situations. Future studies may develop building models
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6 652 based on detailed information of a specific school to acquire more accurate results.
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9 653 10 11 654 **6 Conclusion** 12 13

14 655 The prolonged COVID-19 pandemic has prompted school management teams to prioritize
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16 656 maintaining a healthy and sustainable indoor environment through effective HVAC system control.
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18 657 This paper presents a tradeoff analysis of three crucial aspects of the built environment during the
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21 658 pandemic: health, energy consumption, and thermal comfort. A novel and convergent framework
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24 659 was developed to perform a quantitative analysis of the intricate tradeoff relationships between
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26 660 these aspects, taking into account the influence of dynamic environment factors and fluctuations
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29 661 in occupancy. The study used EnergyPlus to simulate building energy consumption and occupant
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31 662 thermal comfort, and a revised Wells-Riley model was developed to estimate indoor airborne
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33 663 infection risks. The simulation was carried out across all climate zones in the U.S. to account for
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36 664 the diverse range of climate characteristics.
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41 666 A case study utilizing a reference building model of a primary school was conducted to
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43 667 demonstrate the framework. The analysis investigated the effects of various environment factors
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46 668 regulated through the HVAC systems on health, energy consumption, and thermal comfort. The
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48 669 examined environment factors comprised temperature, humidity, and air flow rate, and their set
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51 670 values were determined based on practical operation ranges. The study concludes that variations
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53 671 in the set values of environment factors, in addition to the environment factors themselves, have a
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56 672 significant impact on the three key aspects of indoor environments: health, energy consumption,
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58 673 and thermal comfort. These impacts are influenced by the HVAC system and climate
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characteristics. The optimal thermal comfort and lowest infection risk can be achieved simultaneously with the highest energy consumption. Taking zone 5A as an example, the infection risks decrease by 43%, and the thermal satisfaction increases by 61% when using the optimal environment settings (e.g., highest ventilation rate and neutral temperature) compared to the worst environment settings (e.g., lowest ventilation rate and largest deviation from neutral temperature). However, the increase of ventilation rate by 1 ACH implies an increase in energy use by 19.7%, and an increase of over 70% energy consumption is observed when comparing the two scenarios. Therefore, the school budget is the main restriction to achieve a healthy environment and thermal comfort. To lower the energy cost, reducing ventilation is more effective than increasing the temperature variation. The effectiveness of the change in environment factors varies over different climate zones. For instance, increasing the deviation of the temperature setpoints from neutral setpoints can significantly reduce the energy consumption of buildings located in cold climate zones, while the effect of hot and warm climate zones on energy saving is not that significant. For the tradeoff among the three major aspects, the findings suggest a near-linear relationship between energy consumption and thermal comfort, as well as between infection risks and thermal comfort when the ventilation level is constant. Additionally, there exists a distinct linear relationship between infection risks and energy consumption.

Although this study focuses on the tradeoff relationship between energy consumption, thermal comfort perception, and infection risks for U.S. primary schools during the COVID-19 pandemic, The generalizability of the framework is not limited to COVID-19 and can be extended to other infectious diseases. Furthermore, it can incorporate other important aspects to cater to the specific needs of other countries and facilities, thereby contributing to the maintenance of a sustainable

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697 indoor environment. In order to ensure accuracy and relevance in practical implementation, the
698 detailed building model can be tailored to account for specific building envelopes and HVAC
699 configurations in a given context.

Acknowledgement

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Reference

- [1] G. Buonanno, L. Morawska, L. Stabile, Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications, MedRxiv. (2020).
- [2] L. Morawska, D. K. Milton, It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19), Clin. Infect. Dis. 71 (2020) 2311–2313.
<https://doi.org/10.1093/CID/CIAA939>.
- [3] J. Shen, M. Kong, B. Dong, M. J. Birnkrant, J. Zhang, Airborne transmission of SARS-CoV-2 in indoor environments: A comprehensive review, Htps://Doi.Org/10.1080/23744731.2021.1977693. 27 (2021) 1331–1367.
<https://doi.org/10.1080/23744731.2021.1977693>.
- [4] L. Setti, F. Passarini, G. De Gennaro, P. Barbieri, M. G. Perrone, M. Borelli, J. Palmisani, A. Di Gilio, P. Piscitelli, A. Miani, Airborne transmission route of covid-19: Why 2 meters/6 feet of inter-personal distance could not be enough, Int. J. Environ. Res. Public Health. 17 (2020). <https://doi.org/10.3390/ijerph17082932>.
- [5] Y. Xu, J. Cai, S. Li, Q. He, S. Zhu, Airborne infection risks of SARS-CoV-2 in U.S. schools and impacts of different intervention strategies, Sustain. Cities Soc. 74 (2021) 103188. <https://doi.org/10.1016/J.SCS.2021.103188>.
- [6] P. Dabisch, M. Schuit, A. Herzog, K. Beck, S. Wood, M. Krause, D. Miller, W. Weaver,

- 1
2
3
4 723 D. Freeburger, I. Hooper, B. Green, G. Williams, B. Holland, J. Bohannon, V. Wahl, J.
5
6 724 Yolitz, M. Hevey, S. Ratnesar-Shumate, The influence of temperature, humidity, and
7
8
9 725 simulated sunlight on the infectivity of SARS-CoV-2 in aerosols,
10
11 726 <https://doi.org/10.1080/02786826.2020.1829536>. 55 (2020) 142–153.
12
13
14 727 <https://doi.org/10.1080/02786826.2020.1829536>.
15
16 728 [7] M. Z. Bazant, J. W. M. Bush, A guideline to limit indoor airborne transmission of
17
18
19 729 COVID-19, *Proc. Natl. Acad. Sci. U. S. A.* 118 (2021).
20
21 730 <https://doi.org/10.1073/PNAS.2018995118/-/DCSUPPLEMENTAL>.
22
23 731 [8] Energy Information Administration (EIA), Commercial Buildings Energy Consumption
24
25
26 732 Survey (CBECS). <https://www.eia.gov/consumption/commercial/> (accessed April 9,
27
28 733 2023).
29
30
31 734 [9] H.W. Lin, T. Hong, On variations of space-heating energy use in office buildings, *Appl.*
32
33 735 *Energy*. 111 (2013) 515–528. <https://doi.org/10.1016/J.APENERGY.2013.05.040>.
34
35
36 736 [10] G. Buonanno, L. Stabile, L. Morawska, Estimation of airborne viral emission: quanta
37
38 737 emission rate of SARS-CoV-2 for infection risk assessment, *Environ. Int.* (2020) 105794.
39
40
41 738 [11] H. Dai, B. Zhao, Association of the infection probability of COVID-19 with ventilation
42
43 739 rates in confined spaces, *Build. Simul.* 13 (2020) 1321–1327.
44
45 740 <https://doi.org/10.1007/s12273-020-0703-5>.
46
47
48 741 [12] L. Rocha-Melogno, K. Crank, M. H. Bergin, G. C. Gray, K. Bibby, M. A. Deshusses,
49
50 742 Quantitative risk assessment of COVID-19 aerosol transmission indoors: a mechanistic
51
52 743 stochastic web application, [https://doi-](https://doi.org/10.1080/09593330.2021.1998228)
53
54 744 [Org.Utk.Idm.Oclc.Org/10.1080/09593330.2021.1998228](https://doi.org/10.1080/09593330.2021.1998228). (2021).
55
56
57 745 <https://doi.org/10.1080/09593330.2021.1998228>.
58
59
60
61
62
63
64
65

- [13] A. O' Donovan, P.D. O' Sullivan, The impact of retrofitted ventilation approaches on long-range airborne infection risk for lecture room environments: design stage methodology and application, *J. Build. Eng.* 68 (2023) 106044. <https://doi.org/10.1016/J.JOBE.2023.106044>.
- [14] A. Harrichandra, A. M. Ierardi, B. Pavilonis, An estimation of airborne SARS-CoV-2 infection transmission risk in New York City nail salons, *Toxicol. Ind. Health.* 36 (2020) 634–643. <https://doi.org/10.1177/0748233720964650>.
- [15] Q. Zhao, Y. Qi, M. M.Wali, A method for assessing the COVID-19 infection risk of riding public transit, *Int. J. Transp. Sci. Technol.* 12 (2023) 301–314. <https://doi.org/10.1016/J.IJTST.2022.07.001>.
- [16] W. E. Bischoff, R. J. McNall, M. W. Blevins, J. L. Turner, E. N. Lopareva, P. A. Rota, J. R. Stehle, Detection of Measles Virus RNA in Air and Surface Specimens in a Hospital Setting, *J. Infect. Dis.* 213 (2016) 600–603. <https://doi.org/10.1093/INFDIS/JIV465>.
- [17] R. Tellier, Review of Aerosol Transmission of Influenza A Virus, *Emerg. Infect. Dis.* 12 (2006) 1657. <https://doi.org/10.3201/EID1211.060426>.
- [18] I. T. S. Yu, Y. Li, W. Wong, W. Tam, M. Phil, A. T. Chan, J. H. W. Lee, D. Y. C. Leung, T. Ho, Evidence of Airborne Transmission of the Severe Acute Respiratory Syndrome Virus, <https://doi.org/10.1056/NEJMoa032867>. 350 (2004) 1731–1739. <https://doi.org/10.1056/NEJMOA032867>.
- [19] J. S. Kutter, D. de Meulder, T. M. Bestebroer, P. Lexmond, A. Mulders, M. Richard, R.A.M. Fouchier, S. Herfst, SARS-CoV and SARS-CoV-2 are transmitted through the air between ferrets over more than one meter distance, *Nat. Commun.* 2021 121. 12 (2021) 1–8. <https://doi.org/10.1038/s41467-021-21918-6>.

- [20] Y. Li, H. Qian, J. Hang, X. Chen, P. Cheng, H. Ling, S. Wang, P. Liang, J. Li, S. Xiao, J. Wei, L. Liu, B. J. Cowling, M. Kang, Probable airborne transmission of SARS-CoV-2 in a poorly ventilated restaurant, *Build. Environ.* 196 (2021) 107788.
<https://doi.org/10.1016/J.BUILDENV.2021.107788>.
- [21] C. C. Wang, K. A. Prather, J. Sznitman, J. L. Jimenez, S. S. Lakdawala, Z. Tufekci, L.C. Marr, Airborne transmission of respiratory viruses, *Science* (80-.). 373 (2021).
<https://doi.org/10.1126/SCIENCE.ABD9149/ASSET/C3B6AAC0-E7B3-43F8-9047-C04940ED3887/ASSETS/IMAGES/LARGE/SCIENCE.ABD9149-F5.JPG>.
- [22] WHO, Transmission of SARS-CoV-2: implications for infection prevention precautions, (2020). <https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions>.
- [23] CDC, SARS-CoV-2 Transmission, (2021). <https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html>.
- [24] D. Parienta, L. Morawska, G. R. Johnson, Z. D. Ristovski, M. Hargreaves, K. Mengersen, S. Corbett, C. Y. H. Chao, Y. Li, D. Katoshevski, Theoretical analysis of the motion and evaporation of exhaled respiratory droplets of mixed composition, *J. Aerosol Sci.* 42 (2011) 1–10. <https://doi.org/10.1016/J.JAEROSCI.2010.10.005>.
- [25] A. W. H. Chin, J. T. S. Chu, M. R. A. Perera, K. P. Y. Hui, H. L. Yen, M. C. W. Chan, M. Peiris, L. L. M. Poon, Stability of SARS-CoV-2 in different environmental conditions, *The Lancet Microbe.* 1 (2020) e10. [https://doi.org/10.1016/S2666-5247\(20\)30003-3](https://doi.org/10.1016/S2666-5247(20)30003-3).
- [26] M. Moriyama, W. J. Hugentobler, A. Iwasaki, Seasonality of Respiratory Viral Infections, <https://doi.org/10.1146/Annurev-Virology-012420-022445>. 7 (2020) 83–101.
<https://doi.org/10.1146/ANNUREV-VIROLOGY-012420-022445>.

- [27] W. Yang, L. C. Marr, Dynamics of Airborne Influenza A Viruses Indoors and Dependence on Humidity, PLoS One. 6 (2011) e21481.
<https://doi.org/10.1371/JOURNAL.PONE.0021481>.
- [28] K. A. Kormuth, K. Lin, A.J. Prussin, E. P. Vejerano, A. J. Tiwari, S. S. Cox, M. M. Myerburg, S. S. Lakdawala, L. C. Marr, Influenza Virus Infectivity Is Retained in Aerosols and Droplets Independent of Relative Humidity, J. Infect. Dis. 218 (2018) 739.
<https://doi.org/10.1093/INFDIS/JIY221>.
- [29] A. C. Lowen, J. Steel, S. Mubareka, P. Palese, High Temperature (30°C) Blocks Aerosol but Not Contact Transmission of Influenza Virus, J. Virol. 82 (2008) 5650.
<https://doi.org/10.1128/JVI.00325-08>.
- [30] C. M. Liao, C. F. Chang, H. M. Liang, A Probabilistic Transmission Dynamic Model to Assess Indoor Airborne Infection Risks, Risk Anal. 25 (2005) 1097–1107.
<https://doi.org/10.1111/J.1539-6924.2005.00663.X>.
- [31] R. T. Chen, G. M. Goldbaum, S. G. F. Wassilak, L. E. Markowitz, W. A. Orenstein, An Explosive Point-Source Measles Outbreak in a Highly Vaccinated Populationmodes of Transmission and Risk Factors for Disease, Am. J. Epidemiol. 129 (1989) 173–182.
<https://doi.org/10.1093/OXFORDJOURNALS.AJE.A115106>.
- [32] W. O. Kermack, A. G. McKendrick, A Contribution to the Mathematical Theory of Epidemics, Proc. R. Soc. London. Ser. A, Contain. Pap. a Math. Phys. Character. 115 (1927) 700–721. <https://doi.org/10.1098/RSPA.1927.0118>.
- [33] P. Harjule, V. Tiwari, A. Kumar, Mathematical models to predict COVID-19 outbreak : An interim review, <https://doi.org/10.1080/09720502.2020.1848316>. 24 (2021) 259–284. <https://doi.org/10.1080/09720502.2020.1848316>.

- [34] K. S. Crump, D. G. Hoel, C. H. Langley, R. Peto, Fundamental carcinogenic processes and their implications for low dose risk assessment - PubMed, *Cancer Res.* (1976) 2973–2979.
- [35] C. Chen, W. Liu, C. H. Lin, Q. Chen, A Markov Chain Model for Predicting Transient Particle Transport in Enclosed Environments, *Build. Environ.* 90 (2015) 30–36.
<https://doi.org/10.1016/J.BUILDENV.2015.03.024>.
- [36] M. F. King, C. J. Noakes, P. A. Sleight, Modeling Environmental Contamination in Hospital Single- and Four-Bed Rooms, *Indoor Air.* 25 (2015) 694–707.
<https://doi.org/10.1111/INA.12186>.
- [37] M. Nicas, R. M. Jones, Relative Contributions of Four Exposure Pathways to Influenza Infection Risk, *Risk Anal.* 29 (2009) 1292–1303. <https://doi.org/10.1111/J.1539-6924.2009.01253.X>.
- [38] M. W. Wells, Ventilation in the Spread of Chickenpox and Measles within School Rooms, *J. Am. Med. Assoc.* 129 (1945) 197–200.
<https://doi.org/10.1001/JAMA.1945.02860370019006>.
- [39] E. C. Riley, G. Murphy, R. L. Riley, Airborne Spread of Measles in a Suburban Elementary School, *Am. J. Epidemiol.* 107 (1978) 421–432.
<https://doi.org/10.1093/oxfordjournals.aje.a112560>.
- [40] S. N. Rudnick, D. K. Milton, Risk of Indoor Airborne Infection Transmission Estimated from Carbon Dioxide Concentration, *Indoor Air.* 13 (2003) 237–245.
<https://doi.org/10.1034/J.1600-0668.2003.00189.X>.
- [41] G. N. Sze To, C. Y. H. Chao, Review and Comparison between the Wells–Riley and Dose-Response Approaches to Risk Assessment of Infectious Respiratory Diseases,

- Indoor Air. 20 (2010) 2–16.
- [42] J. Van Hoof, Forty Years of Fanger’s Model of Thermal Comfort: Comfort for all?, Indoor Air. 18 (2008) 182–201. <https://doi.org/10.1111/J.1600-0668.2007.00516.X>.
- [43] P. O. Fanger, Thermal Comfort. Analysis and Applications in Environmental Engineering, Therm. Comf. Anal. Appl. Environ. Eng. (1970).
- [44] S. 55-2017 ASHRAE, Thermal Environmental Conditions for Human Occupancy, Am. Soc. Heating, Refrig. Air-Conditioning Eng, Atlanta, USA, 2017.
- [45] A. Shajahan, C. H. Culp, B. Williamson, Effects of Indoor Environmental Parameters Related to Building Heating, Ventilation, and Air Conditioning Systems on Patients’ Medical Outcomes: A Review of Scientific Research on Hospital Buildings, Indoor Air. 29 (2019) 161. <https://doi.org/10.1111/INA.12531>.
- [46] C. Liu, Y. Zhang, L. Sun, W. Gao, X. Jing, W. Ye, Influence of Indoor Air Temperature and Relative Humidity on Learning Performance of Undergraduates, Case Stud. Therm. Eng. 28 (2021) 101458. <https://doi.org/10.1016/J.CSITE.2021.101458>.
- [47] M. Fan, Z. Fu, J. Wang, Z. Wang, H. Suo, X. Kong, H. Li, A Review of Different Ventilation Modes on Thermal Comfort, Air Quality and Virus Spread Control, Build. Environ. 212 (2022) 108831. <https://doi.org/10.1016/J.BUILDENV.2022.108831>.
- [48] V. S. K. V. Harish, A. Kumar, A Review on Modeling and Simulation of Building Energy Systems, Renew. Sustain. Energy Rev. 56 (2016) 1272–1292. <https://doi.org/10.1016/J.RSER.2015.12.040>.
- [49] R. Mokhtari, M. H. Jahangir, The Effect of Occupant Distribution on Energy Consumption and COVID-19 Infection in Buildings: A Case Study Of University Building, Build. Environ. 190 (2021) 107561.

- <https://doi.org/10.1016/J.BUILDENV.2020.107561>.
- [50] W. Jung, F. Jazizadeh, Energy Saving Potentials of Integrating Personal Thermal Comfort Models for Control of Building Systems: Comprehensive Quantification Through Combinatorial Consideration of Influential Parameters, *Appl. Energy*. 268 (2020). <https://doi.org/10.1016/J.APENERGY.2020.114882>.
- [51] M. J. Risbeck, M. Z. Bazant, Z. Jiang, Y. M. Lee, K. H. Drees, J. D. Douglas, Modeling and Multiobjective Optimization of Indoor Airborne Disease Transmission Risk and Associated Energy Consumption for Building HVAC Systems, *Energy Build.* 253 (2021). <https://doi.org/10.1016/J.ENBUILD.2021.111497>.
- [52] Y. Guo, N. Zhang, T. Hu, Z. Wang, Y. Zhang, Optimization of Energy Efficiency and COVID-19 Pandemic Control in Different Indoor Environments, *Energy Build.* 261 (2022) 111954. <https://doi.org/10.1016/J.ENBUILD.2022.111954>.
- [53] DOE, Commercial Reference Buildings, (2012). <https://www.energy.gov/eere/buildings/existing-commercial-reference-buildings-constructed-or-after-1980>.
- [54] ASHRAE, Energy Standard for Buildings Except Low-Rise Residential Buildings, Inc., Atlanta, GA, USA, 2019.
- [55] M. T. Miranda, P. Romero, V. Valero-Amaro, J. I. Arranz, I. Montero, Ventilation Conditions and Their Influence on Thermal Comfort in Examination Classrooms in Times of COVID-19. A Case Study in a Spanish Area with Mediterranean Climate, *Int. J. Hyg. Environ. Health.* 240 (2022) 113910. <https://doi.org/10.1016/J.IJHEH.2021.113910>.
- [56] DOE, Input Output Reference, EnergyPlus, 2021.
- [57] P. Azimi, Z. Keshavarz, J. G. C. Cedeno Laurent, J. G. Allen, Estimating the Nationwide

- transmission risk of Measles in US Schools and Impacts of Vaccination and Supplemental
Infection Control Strategies, *BMC Infect. Dis.* 20 (2020). <https://doi.org/10.1186/S12879-020-05200-6>.
- [58] EPA, *Exposure Factors Handbook 2011 Edition (Final Report)*, Washington, DC, 2011.
- [59] C. B. Beggs, E. J. Avital, A Psychrometric Model to Assess the Biological Decay of the SARS-CoV-2 Virus in Aerosols, *PeerJ.* 9 (2021). <https://doi.org/10.7717/PEERJ.11024>.
- [60] M. Luo, Z. Wang, G. Brager, B. Cao, Y. Zhu, Indoor Climate Experience, Migration, and Thermal Comfort Expectation in Buildings, *Build. Environ.* 141 (2018) 262–272. <https://doi.org/10.1016/J.BUILDENV.2018.05.047>.
- [61] S. Batterman, F. C. Su, A. Wald, F. Watkins, C. Godwin, G. Thun, Ventilation Rates in Recently Constructed U.S. School Classrooms, *Indoor Air.* 27 (2017) 880–890. <https://doi.org/10.1111/ina.12384>.
- [62] CDC, *Ventilation in Schools and Child Care Programs*, (2021). <https://www.cdc.gov/coronavirus/2019-ncov/community/schools-childcare/ventilation.html>.
- [63] C. Zuo, L. Luo, W. Liu, Effects of Increased Humidity on Physiological Responses, Thermal Comfort, Perceived Air Quality, and Sick Building Syndrome Symptoms at Elevated Indoor Temperatures for Subjects in a Hot-Humid Climate, *Indoor Air.* 31 (2021) 524–540. <https://doi.org/10.1111/INA.12739>.