Summertime Resilience in an L-Shaped Long-Term Care Facility with Mixed Natural Ventilation and Pressurized Corridors

Chang Shu*[1], Lili Ji[1], Justin Berquist[1], Liang Grace Zhou[1]

1 Construction Research Center, National Research Council Canada
1200 Montréal Road
Ottawa, Ontario, Canada
**Corresponding author: Chang.Shu2@nrc-cnrc.gc.ca*

ABSTRACT

Climate change has exacerbated the summertime overheating in buildings, necessitating resilient adaptation strategies. Based on our previous work, which introduced a Thermal Resilience Index (TRI) ranging from Class F to Class A+ using a concept of resilient trapezoid framework, this study explores unit-level retrofit strategies for high-rise long-term care buildings. Utilizing a building simulation model validated by field data from a long-term care building located in Montreal, Canada, the thermal resilience of entire buildings and individual units is evaluated with mixed natural ventilation and pressurized corridors. The analysis highlights significant heterogeneity in units' resilience to extreme heat. The impact of different corridor ventilation configurations on room temperatures, thermal stratification across floors and unit-level thermal resilience are evaluated, following the ASHRAE standards 62.1, 62.2 and ventilation suggestions for the COVID pandemic. Results indicate that an enhanced ventilation rate in the corridor can mitigate the overheating conditions in the building, while it can yield diverse outcomes across units. These findings will inform our retrofit strategies in the field study and will be further evaluated with field-collected data.

KEYWORDS

Thermal resilience, long-term care building, ventilation, pressurized corridor, overheating

1 INTRODUCTION

Increasing global temperatures pose significant challenges to indoor environmental quality, particularly in long-term care facilities where residents are especially vulnerable to heat-related stresses. Ensuring thermal comfort in these settings is not only a matter of energy efficiency but also of health and safety. Buildings with inner corridors, where rooms are distributed along both sides, can pose ventilation challenges. A CFD simulation study (Chen et al., 2024) of an L-shaped residence with such corridors shows poor natural ventilation, their results indicated a high age of air in both the corridor and the unit rooms. Studies show that opening doors between rooms and corridors significantly boosts interzonal air exchange volume, and larger temperature differences between areas can further amplify the air exchange (Lee et al., 2016). Furthermore, this approach can also improve the thermal environment within spaces. A case study in multi-zone buildings showed that overheating is significantly reduced when windows and room doors are fully opened to facilitate cross ventilation. (Schünemann et al., 2021).

During a site visit to several long-term care buildings in Montreal, Canada, in the summer of 2019, we observed that residents often leave room doors wide open to mitigate indoor overheating (Figure 1). This practice significantly enhances the exchange of airflow between rooms and corridors. According to the ASHRAE handbook (2013), ventilation plans must address pollutants in rooms with contaminated air—such as chemistry laboratories, smoking rooms, bathrooms, hospitals, and medical facilities—because they can affect the air quality of adjacent areas. To solve this issue, a negative pressure difference between a contaminated room and its surrounding areas is required. The use of pressurized corridors (PC) has become a widespread solution for maintaining these pressure differences. However, the effectiveness of this system varies in high-rise buildings due to the stack effect, which can cause uneven ventilation, leading to under-ventilation in lower rooms, over-ventilation in upper rooms, and reduced corridor pressurization on lower floors. (Fine & Touchie, 2021).

Figure 1: Operation of room-to-corridor doors in long-term care buildings in Montreal, Canada (Photos taken during a site visit in July 2019)

Given the dual requirements for overheating relief and airflow control, it is essential to investigate mixed-mode ventilation that combines natural and mechanical pressurized corridor ventilation. The effects of this approach, involving pressurized corridors and window/door operations, on the building's thermal conditions across different floors and zone-level thermal resilience, are not yet well investigated.

This study investigated the thermal condition variations of a five-floor, L-shaped long-term care building in Montreal, Canada, through a parametric building simulation of various mixed-mode ventilation strategies. We explored how window and door openings, along with the distribution and flow rate of the pressurized corridor (PC) system, influence thermal conditions across different floors and rooms. The method for evaluating building and zonal thermal resilience developed in a previous study (Ji et al., 2023) has been applied to quantify and categorize the thermal resilience levels of rooms.

2 METHODOLOGY

2.1 Overview

Figure 1 outlines the workflow used in this paper to quantify the zonal thermal resilience with different ventilation strategies. In the first step, a multi-zone building model is created based on the actual building situations and the model is validated with field measurement data. Then, in the second step, the various ventilation scenarios with mechanical pressurized corridor ventilation and natural ventilation with different window/door operations are integrated into the model. The final step involves quantifying and comparing the zonal thermal resilience for each scenario. These steps are elaborated upon in Sections 2.2, 2.3, and 2.4, respectively.

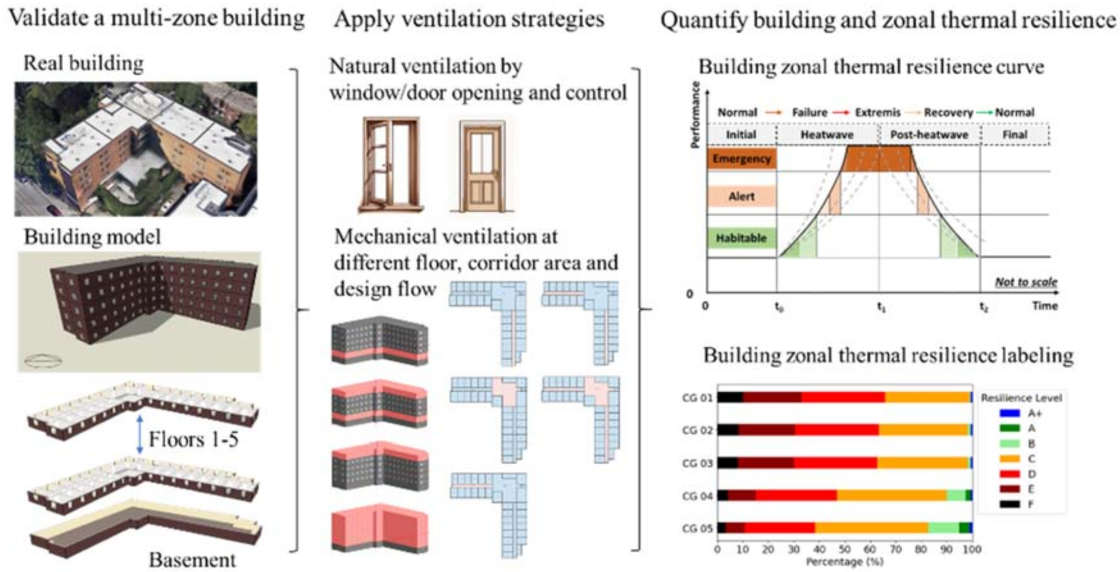


Figure 2: Workflow of quantifying the zonal thermal resilience with different ventilation strategies

2.2 Building model and validation

The building model was developed for a long-term care building constructed in the 1980s with a footage area of 817m^2, which is one of the buildings in an overheating monitoring campaign conducted in Montreal, Canada since the summer of 2020 (Wang et al., 2020). The long-term care facility is an L-shaped building with five above-ground floors and a below-grade basement, facing south. Most of the patient rooms and offices in this building are naturally ventilated, with only a few rooms equipped with window air conditioners. The first column in Figure 1 shows the map view of the building.

The indoor temperature and relative humidity (RH) were continuously monitored in selected spaces on different floors and orientations, at a 15-minute interval. The sensor accuracy is ±0.21°C for air temperature and ±2% for relative humidity (RH) (Xie et al., 2021). Weather stations were placed on the roof of this building to gather local weather information, including air temperature (± 0.21 °C), relative humidity (± 2 %), solar radiation (± 10 W/m^2), wind speed and direction, and precipitation. The measured indoor and outdoor environment data were used to calibrate and validate the building model (Ji et al., 2022a). The building parameters, architecture plan, operation schedules, and air conditioning information of the building were collected through a building survey and site visit (Wang & Shu, 2021). The unknown parameters, including envelope thermal properties, internal heat gains, and natural ventilation rate, were calibrated through a Monte Carlo method (Hoffman, 2014) based on the measured hourly indoor temperature (Ji et al., 2022a). At the room level, considering the ±0.21°C sensor accuracy for indoor air temperature measurements, the root means square error (RMSE) between the simulated and measured temperatures during calibration and validation ranged from 0.56°C to 1.13°C. Both values are well within the acceptable limit of 1.5°C suggested by previous studies. (O' Donovan et al., 2019). More details on the calibration and validation of this building can be found in the studies by Ji et al. (2022, 2023). A total of 175 thermal zones, including naturally ventilated patient rooms, stairwells, and corridors, were investigated to analyse zone-level thermal resilience for this building.

2.3 Ventilation case design

Table 1: Designed cases of natural and mechanical ventilation strategies

Natural ventilation (NV)	Window opening	5%		10%		15%
	Window control	$(T_{in} > T_{setpoint26})$ & $(T_{in} > T_{out})$				
	Door opening · time	2.5%		50%		100%
	Door control	$(T_{in} > T_{setpoint26})$ & $(T_{in} > T_{corridor})$		$(T_{in} > T_{setpoint26})$ & $(T_{in} > T_{out})$		
Mechanical ventilation (MV)	MV floor	1	5	1+5	1+2+3+4+5	
						
	MV corridor	Right	Center	Left	Right+Left	Right+Center+Left
						
	MV design flow	$0.3L/s/m^2$ *	0.35ACH **	3ACH ***	6ACH ***	

* ASHRAE 62.1-2019: Ventilation for Acceptable Indoor Air Quality, 2019.
** ASHRAE 62.2-2016: Ventilation and Acceptable Indoor Air Quality in Residential Buildings, 2016.
*** Salimifard P., Jones E., Allen J. "Portable Air Cleaners: Selection and Application Considerations for COVID-19 Risk Reduction." Harvard T.H. Chan School of Public Health Healthy Buildings Program, August, 2020.

Table 2: Cases grouped by MV design flow

Case group (CG)	Number of cases	Total number of zones	NV/MV	MV design flow
01	18	3150	NV	0
02	486	85050	NV+MV	$0.3L/s/m^2$
03	486	85050	NV+MV	0.35ACH
04	486	85050	NV+MV	3ACH
05	486	85050	NV+MV	6ACH

To assess the impact of various ventilation strategies on zone-level thermal resilience, 1962 models were created. Of these, 18 were naturally ventilated (NV), while 1944 combined natural and mechanical ventilation (NV+MV). As detailed in Table 1, for the NV cases, the exterior windows and internal doors connecting each bedroom zone to the corridor in each zone are set with three possible opening percentages. The windows are opened when the indoor temperature (T_{in}) is higher than the setpoint temperature of 26°C and at the same time higher than the outdoor temperature (T_{out}). The doors are controlled by two possible strategies: a) they are opened when the indoor temperature is higher than both the setpoint temperature of 26°C and the corridor temperature ($T_{corridor}$), b) they are opened when the indoor temperature higher than both the setpoint temperature of 26°C and the outdoor temperature (T_{out}).

In NV+MV cases, alongside natural ventilation controls, mechanical ventilation from the corridors is distributed across different floors and various areas within each floor. Four potential mechanical ventilation (MV) design flows were considered, adhering to both standard ventilation requirements and enhanced protocols for COVID-19 risk reduction. (ASHRAE, 2022, 2022; Salimifard et al., 2020). The cases are organized into five groups (CG01 to CG05), categorized by different mechanical ventilation (MV) design flow rates as detailed in Table 2.

2.4 Thermal resilience quantification

The zone-level thermal resilience quantification method for multi-zone buildings was developed by the study of Ji et al. (2023). There are four main steps in the quantification of building thermal resilience, 1) confirming of the thermal performance indicator, 2) constructing the thermal resilience curve, 3) calculating the thermal resilience quantification index, and 4) labelling the thermal resilience level.

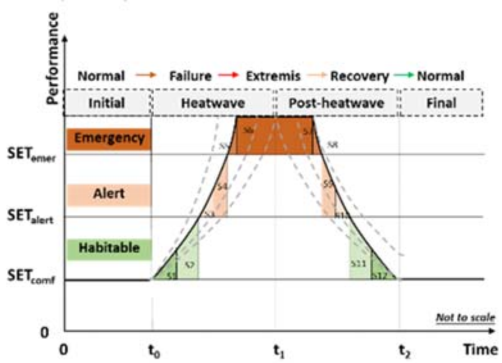
In step one, the thermal performance indicator chosen should represent the thermal performance of each thermal zone. In this study, the Standard Effective Temperature (SET) was selected as the heat-stress index. SET is calculated using environmental parameters such as air temperature, relative humidity, mean radiant temperature, and airflow speed, as well as human parameters like activity and clothing levels, based on a two-node physiological model. In step two, the resilience trapezoid profile (Figure 2 a) is employed to construct the thermal resilience curve. This curve captures the timing and extent of system failure, duration of the extreme state, and recovery to a normal state. The building thermal resilience trapezoid consists of two periods—the heatwave period and the post-heatwave period—and includes three thresholds (SET_{comf} = 24.12 °C, SET_{alert} = 28.12 °C, SET_{emer} = 32.12 °C), and three hazard levels (habitable level, alert level, emergency level). In step three, the zone-level thermal resilience index (TRI_z) is calculated by Equation (1)

$$TRI_z = WSETH_{z,0}/WSETH_z \quad (1)$$

where $WSETH_{z,0}$ is the zone thermal resilience of a reference case. In this study, the reference case for other building settings is a natural ventilation scenario with 5 % window opening, 2.5 % door opening, and controlled by (T_{in} > 26 °C) & (T_{in} > $T_{corridor}$). $WSETH_z$ is the thermal resilience of a studied zone, which can be calculated by Equation (2)

$$WSETH_z = \sum_1^{12} WSETH_i = \sum_1^{12} SETH_i W_{1,i} W_{2,i} W_{3,i} \quad (2)$$

where i is the segment number of the 12 segments separated by the two periods, three hazard levels, and exposure time at each hazard level, $SETH_i$ is the integration of SET above its hazard threshold over time, $W_{1,i}, W_{2,i}, W_{3,i}$ are the penalty coefficients that the higher the penalty coefficient, the more difficult for the building to recover from exposure to heat.
In step four, according to the value of TRI_z, each zone can be labelled by their resilience class from Class F to Class A+ (Figure 2 b). More detailed explanations can be found in the study of Ji et al. (2023).



(a)

Label	TRI	Resilience improvement
Class A+	(10.0, +∞)	>90%
Class A	(3.3, 10.0]	70%-90%
Class B	(2.0, 3.3]	50%-70%
Class C	(1.4, 2.0]	30%-50%
Class D	(1.1,1.4]	10%-30%
Class E	(1.0, 1.1]	0-10%
Class F	(0,1.0]	No improvement

(b)

Figure 3: (a) Conceptual thermal resilience profile and (b) thermal resilience labelling system (Ji et al., 2023)

2.5 Study period and weather data

The simulation in this study focused on a heatwave event occurred in Montreal, Canada in the summer of 2018, from June 30 to July 05, which resulted in 66 heat-related deaths (Lamothe et al., 2019). The weather data was collected from hourly measurements from a weather station located in the urban area of Montreal (Shu et al., 2022). The air temperature, relative humidity, wind speed, wind direction, solar radiation, and precipitation were collected and converted to an EPW format for input to the Energyplus (DOE, 2022) building simulation model.

3 RESULTS

3.1 Physical environment changes in buildings

Figure 3 shows the averaged physical parameters (temperature and relative humidity) of all cases in each case group. It can be noted that the indoor temperature (T) is reduced with the increase of mechanical ventilation design flow rate (Figure 3 a). The reduction in temperature is more notable in CG04 (PC ACH=3) and CG05 (PC ACH =6) than CG02 (PC flow rate = 0.3L/s/m^2) and CG03 (PC ACH = 0.35). The averaged RH in each case group is comparable while CG04 and CG05 present slightly higher RH due to the increased introduction of outdoor air.

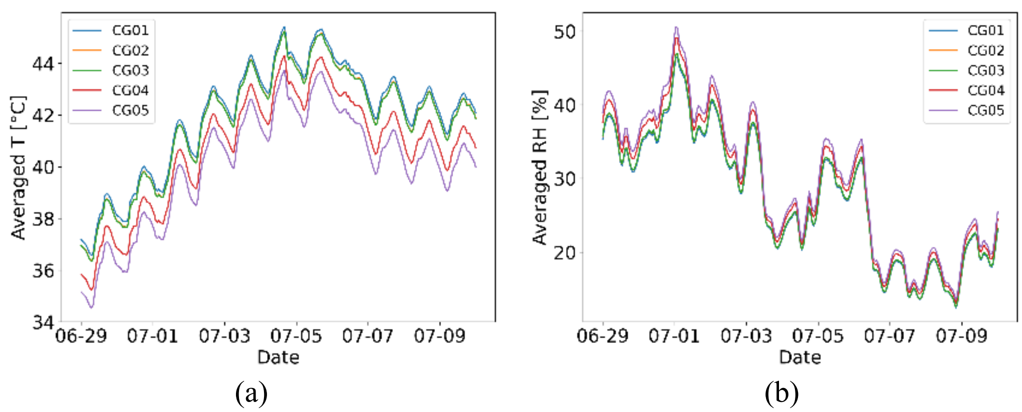


Figure 4: The averaged (a) zone means air temperature (T) (b) zone mean relative humidity (RH) of each case group

3.2 Thermal stratification

Thermal index SET is calculated for each zone based on the calculated T, RH, mean radiant temperature (T_{mrt}) and an assumed air flow of 0.1m/s, an occupant metabolic rate of 1.2 met, a clothing level of 0.5clo, and a body surface area of 1.8258m^2. The difference of SET in zones on Floors 2-5 with the SET in zones on Floor 1 is calculated to show the vertical thermal stratification in the building as presented in Figure 4. Notably, the SET difference is reduced from CG01 to CG05, as the increase of MV design flow rate suppressed the thermal stratification.

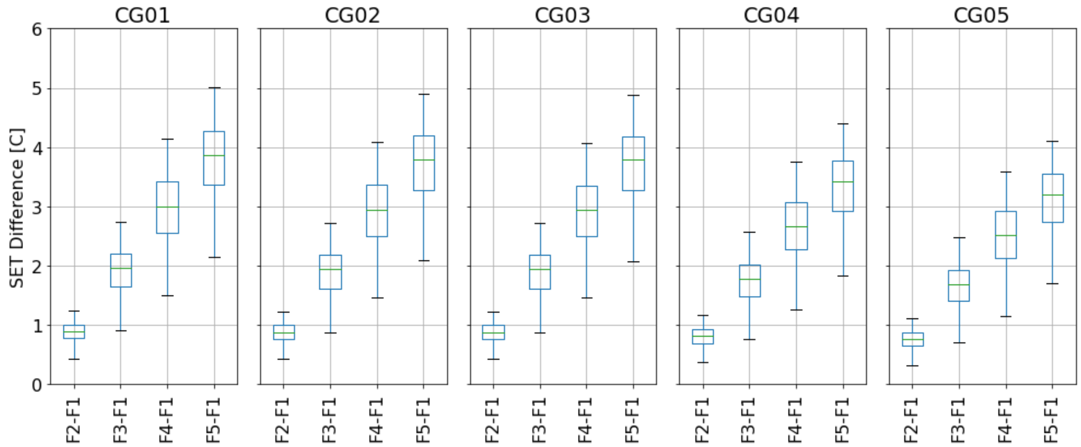


Figure 5: Distribution of the SET difference between floors 2-5 and floor 1 for each case group

3.3 Thermal zone resilience

Following the thermal resilience labelling method in Section 2.4, the TRIz in each zone of each case is calculated for their resilience level labelling. Figure 5 shows the percentage of zones in different resilience levels for each case group. With an increased MV design flow rate, more zones achieve a higher resilience label. Compared to CG01 (the reference natural ventilation scenario), CG05 (PC ACH=6) can reduce the zones in Class F from 10% to less than 3% and increase the zones of Class A+, A, B and C from 34% to more than 60%. This means that compared to the reference natural ventilation case, the thermal resilience of more than half of zones are improved by at least 30%.

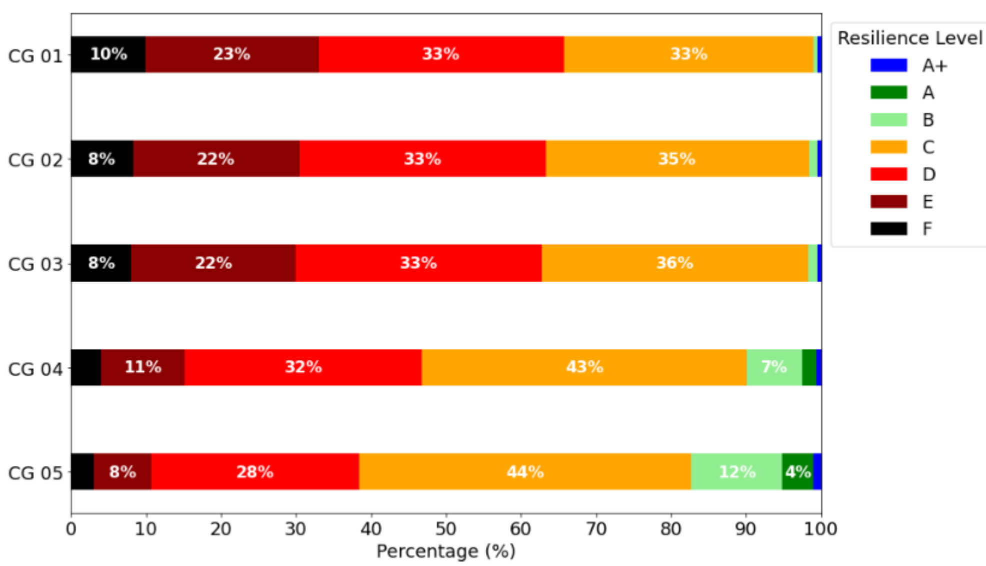


Figure 6: Percentage of zones in different classes of resilience levels in each case group

4 CONCLUSIONS

This study investigates how mixed-mode ventilation, combining pressurized corridors and natural ventilation, impacts thermal conditions and zone-level thermal resilience in an L-shaped, five-floor long-term care building. A parametric analysis of 1,962 scenarios, varying corridor ventilation and window/door controls are simulated and analysed. Preliminary conclusions are as follows.

- The introduction of corridor ventilation reduces the overall indoor temperature and a higher air supply rate in the corridor can enhance the thermal resilience of the units.
- The thermal stratification in this building is suppressed by the increased corridor ventilation design flow rate.
- Compared to scenarios using only natural ventilation, mixed-mode ventilation with pressurized corridors enhances thermal resilience in over half of the zones by at least 30%.

The current study only focuses on the impact of corridor ventilation rates on the overheating conditions and thermal resilience in different units. The distribution of air supply vents and the operation of windows and doors will be further discussed in subsequent research.

5 ACKNOWLEDGEMENTS

This research was funded by the Resilient Residential Retrofit (R^3) theme of the Climate Resilient Built Environment Initiative (CRBE) of the National Research Council Canada (NRCC) and received support from the seventh wave of Postdoctoral Fellowship (PDF) program of the NRCC.

6 REFERENCES

ASHRAE. (2022). *ANSI/ASHRAE Standard 62.1: Ventilation and Acceptable Indoor Air Quality*. www.ashrae.org/technology.

ASHRAE. (2022). *ANSI/ASHRAE Standard 62.2: Ventilation and Acceptable Indoor Air Quality in Residential Buildings*. www.ashrae.org

ASHRAE handbook. (2013). *Health care facilities*. www.healthdesign.com.au/haad.hfg/

Chen, S., Fan, Z., He, L., Ma, S., & Liu, J. (2024). Ventilation benefit assessment of space organization design for 'L' type inner corridor buildings. *Building and Environment*, *253*. https://doi.org/10.1016/j.buildenv.2024.111327

DOE. (2022). *EnergyPlus 22.1.0*. https://energyplus.net/

Fine, J. P., & Touchie, M. F. (2021). Evaluating ventilation system retrofits for high-rise residential buildings using a CONTAM model. *Building and Environment*, *205*. https://doi.org/10.1016/j.buildenv.2021.108292

Hoffman. (2014). *The No-U-Turn Sampler: Adaptively Setting Path Lengths in Hamiltonian Monte Carlo*. *15*, 1593–1623.

Ji, L., Shu, C., Hou, D., Laouadi, A., Leon, L., & Lacasse, M. (2022a). Predicting indoor air temperatures by calibrating building thermal model with coupled airflow networks. *2022: CLIMA 2022 The 14th REHVA HVAC World Congress*, 1–8. https://doi.org/https://doi.org/10.34641/clima.2022.340

Ji, L., Shu, C., Hou, D., Laouadi, A., Leon, L., & Lacasse, M. (2022b). Predicting indoor air temperatures by calibrating building thermal model with coupled airflow networks. *2022: CLIMA 2022 The 14th REHVA HVAC World Congress*, 1–8. https://doi.org/https://doi.org/10.34641/clima.2022.340

Ji, L., Shu, C., Laouadi, A., Lacasse, M., & Wang, L. (Leon). (2023). Quantifying improvement of building and zone level thermal resilience by cooling retrofits against summertime heat events. *Building and Environment*, *229*. https://doi.org/10.1016/j.buildenv.2022.109914

Lamothe, F., Roy, M., & Racine-Hamel, S.-É. (2019). *Enquête épidémiologique - Vague de chaleur à l'été 2018 à Montréal*. https://doi.org/https://santemontreal.qc.ca/fileadmin/user_upload/Uploads/tx_asssmpublications/pdf/publications/

Lee, S., Park, B., & Kurabuchi, T. (2016). Numerical evaluation of influence of door opening on interzonal air exchange. *Building and Environment*, *102*, 230–242. https://doi.org/10.1016/j.buildenv.2016.03.017

Leon, L., Shu, C., Ge, H., Zmeureanu, R., Lacasse, M., & Leroyer, S. (2020). Assessment of summertime overheating conditions in vulnerable buildings in Montréal. *2nd International Conference on New Horizons in Green Civil Engineering (NHICE-02), Victoria, BC, Canada, April 29 – May 01, 2020*, *November*, 2–5.

O' Donovan, A., O' Sullivan, P. D., & Murphy, M. D. (2019). Predicting air temperatures in a naturally ventilated nearly zero energy building: Calibration, validation, analysis and approaches. *Applied Energy*, *250*(May), 991–1010. https://doi.org/10.1016/j.apenergy.2019.04.082

Salimifard, P., Jones E., & Allen J. (2020). *Portable Air Cleaners: Selection and Application Considerations for COVID-19 Risk Reduction*.

Schünemann, C., Schiela, D., & Ortlepp, R. (2021). How window ventilation behaviour affects the heat resilience in multi-residential buildings. *Building and Environment*, *202*. https://doi.org/10.1016/j.buildenv.2021.107987

Shu, C., Gaur, A., Wang, L. (Leon), Bartko, M., Laouadi, A., Ji, L., & Lacasse, M. (2022). Added value of convection permitting climate modelling in urban overheating assessments. *Building and Environment*, *207*(PA), 108415. https://doi.org/10.1016/j.buildenv.2021.108415

Wang, L. (Leon), & Shu, C. (2021). Chapter 2: Assessment of the Effect of Urban Heat Island on Buildings. In N. Enteria, M. Santamouris, & U. Eicker (Eds.), *Urban Heat Island (UHI) Mitigation. Advances in 21st Century Human Settlements*. Spinger.

Xie, Z., Shu, C., Reich, B. Z., Wang, L., Baril, D., Ji, L., Yang, S., Bai, X., Zmeureanu, R., Lacasse, M., Wang, L., & Ge, H. (2021). A field study on summertime overheating of six schools in Montreal Canada. *Journal of Physics: Conference Series*, *2069*(1). https://doi.org/10.1088/1742-6596/2069/1/012168