Extended Summary of the thesis

Analyzes of selected methods for limiting the spread of air pollutants in occupied ventilated rooms

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List of appended papers

The thesis consists of 6 scientific articles listed below, categorized into chapters 2 and 3. The full texts of these papers can be found in the appendices.

Chapter 2: Ventilation strategies and smart control

Paper 1: Grygierek, Krzysztof, **Seyedkeivan Nateghi**, Joanna Ferdyn-Grygierek, and Jan Kaczmarczyk. "Controlling and limiting infection risk, thermal discomfort, and low indoor air quality in a classroom through natural ventilation controlled by smart windows." Energies 16, no. 2 (2023): 592. IF: 3, DOI: 10.3390/en16020592

Paper 2: **Nateghi, Seyedkeivan**, and Jan Kaczmarczyk. "Multi-objective optimization of window opening and thermostat control for enhanced indoor environment quality and energy efficiency in contrasting climates." Journal of Building Engineering 78 (2023): 107617. IF: 6.7, DOI: 10.1016/j.jobe.2023.107617

Paper 3: **Nateghi, Seyedkeivan**, Amirmohammad Behzadi, Jan Kaczmarczyk, Pawel Wargocki, and Sasan Sadrizadeh. "Optimal control strategy for a cutting-edge hybrid ventilation system in classrooms: Comparative analysis based on air pollution levels across cities." Building and Environment 267 (2025): 112295. IF: 7.1, DOI: 10.1016/j.buildenv.2024.112295

Chapter 3: Local strategies for infection control

Paper 4: **Nateghi, Seyedkeivan**, Jan Kaczmarczyk, Ewa Zabłocka-Godlewska, and Wioletta Przystaś. "Investigating the Impact of Physical Barriers on Air Change Effectiveness and Aerosol Transmission Under Mixing Air Distribution." Building and Environment (2025): 112676. IF: 7.1, DOI: 10.1016/j.buildenv.2025.112676

Paper 5: **Nateghi, Seyedkeivan**, and Jan Kaczmarczyk. "Compatibility of integrated physical barriers and personal exhaust ventilation with air distribution systems to mitigate airborne infection risk." Sustainable Cities and Society 103 (2024): 105282. IF: 10.5, DOI: 10.1016/j.scs.2024.105282

Paper 6: **Nateghi, Seyedkeivan**, Shahrzad Marashian, Jan Kaczmarczyk, and Sasan Sadrizadeh. "Resource-efficient design of integrated personal exhaust ventilation and physical barriers for airborne transmission mitigation: A numerical and experimental evaluation." Building and Environment 268 (2025): 112336. IF: 7.1, DOI: 10.1016/j.buildenv.2024.112336

Chapter 1: Introduction

Motivation and Background: Indoor air quality (IAQ) has emerged as a critical public health concern, particularly in densely occupied environments such as classrooms, offices, and healthcare facilities. As people spend around 90% of their time indoors, the quality of indoor air directly affects respiratory health, cognitive performance, and the transmission of infectious diseases. Despite this, many indoor spaces continue to experience inadequate ventilation—often due to outdated system designs or inappropriate operation—which fails to address current occupancy patterns and pollution sources. These limitations became especially visible during the COVID-19 pandemic, which highlighted the inability of conventional HVAC systems to mitigate airborne pathogen transmission in crowded settings. In school environments, where prolonged occupancy and close contact are common, the consequences of poor IAQ are especially pronounced. Although efforts to improve IAQ have intensified, they often focus narrowly on single objectives—such as ventilation or filtration—without considering thermal comfort, energy use, or environmental sustainability. Similarly, filtration-based strategies and widespread use of PPE, while effective in controlling contaminants, can contribute significantly to energy use, material waste, and greenhouse gas emissions. This thesis responds to that need by systematically evaluating a range of ventilation and infection control approaches, particularly in educational settings, and assessing their combined impact on health, comfort, energy demand, and sustainability.

Indoor air pollutants: Indoor pollutants—originating from both internal and external sources—can significantly impact human health, comfort, and productivity. These pollutants fall into three major categories: chemical (e.g., VOCs, CO, NO_2, ozone, formaldehyde), particulate ($PM_{2.5}$, PM_{10}), and biological (bacteria, viruses, fungi, allergens). Biological pollutants have gained particular attention during the COVID-19 pandemic due to the airborne transmission of SARS-CoV-2. In addition, carbon dioxide (CO_2), though not a direct pollutant, serves as a widely used proxy for ventilation adequacy and indoor air quality (IAQ).

Methods to mitigate spread of indoor pollutants: Maintaining a healthy indoor environment requires well-designed ventilation and supplementary strategies. Ventilation approaches include:

- Natural ventilation, which relies on passive airflow, is cost-effective but limited by climate and outdoor air quality.

- Mechanical ventilation, which offers controlled airflow and filtration, is more reliable but energy-intensive.
- Hybrid ventilation combines both, switching modes based on indoor and outdoor conditions for energy-efficient air quality management.

The type and placement of air diffusers also play a critical role in shaping airflow, influencing how pathogens disperse and whether they accumulate or are effectively removed.

- Mixing ventilation (MV) is one of the most commonly implemented ventilation strategies in indoor environments. In this approach, air is typically introduced at high velocity through ceiling diffusers or wall-mounted inlets, aiming to dilute indoor air pollutants and maintain uniform environmental conditions.
- Displacement ventilation (DV) is an alternative to mixing ventilation that supplies cooler air at low velocity near the floor level and relies on thermal stratification to transport heat and airborne contaminants upward toward ceiling-mounted exhaust outlets. This stratified airflow pattern reduces mixing between the clean air zone in the occupied region and the warmer, contaminated air rising toward the ceiling.
- Personalized ventilation (PV) is emerging as a solution for localized air supply, reducing exposure to shared pollutants. PV refers to a localized airflow approach that delivers or removes air directly within the breathing zone of occupants.

Other infection mitigation methods include:

- Personal protective equipment (PPE) such as masks and face shields, which reduce infection risk but generate waste and have limited long-term viability.
- Physical barriers like partitions can reduce short-range droplet transmission, though effectiveness depends on proper design and ventilation compatibility.
- Filtration and air cleaning technologies, including HEPA filters and portable purifiers, enhance pollutant removal but may increase pressure drop and energy use.
- Emerging technologies, including AI-driven control systems, UV-C disinfection, and real-time environmental monitoring, offer smart and responsive solutions for infection control.

Implications of IAQ management and infection control: IAQ management introduces several trade-offs:

- Thermal comfort can be compromised by high ventilation rates, especially in extreme climates.
- Energy efficiency may decrease with increased air changes or high-performance filtration.

- Environmental sustainability is challenged by the material and energy demands of many control technologies. Life Cycle Assessment (LCA) tools are increasingly used to evaluate the broader impacts of these interventions.

Objectives and scope: This thesis aims to advance the understanding and development of effective and sustainable strategies to improve IAQ and mitigate airborne infection risks, particularly in educational environments. The study seeks to balance health protection, occupant comfort, energy efficiency, and environmental sustainability within classroom environments. The primary objectives of this research are:

- Evaluating different ventilation strategies in maintaining IAQ and reducing airborne infection risks in densely occupied spaces.
- Investigating localized mitigation measures such as physical barriers, personal ventilation, mask and portable air cleaners in controlling aerosol transmission in densely occupied space.
- Analysing environmental, energy and comfort impacts with various IAQ improvement and infection control strategies.

Based on these objectives, the following questions were formulated at the outset of this work:

1) Can natural ventilation through smart windows provide sufficient indoor air quality and infection control in classroom settings?
2) What are the energy use and thermal comfort implications of natural ventilation, and how can they be optimized?
3) How can hybrid ventilation systems be designed to adapt to varying indoor and outdoor air quality conditions effectively?
4) What are the possible impacts of introducing physical barriers on ventilation effectiveness and airborne contaminant transmission in ventilated rooms?
5) Can combining local exhaust ventilation with physical barriers enhance infection control?

To address these questions, several hypotheses are proposed:

- Natural ventilation through smart windows may control infection risk when there is not access to mechanical ventilation.
- Conducting multi objective optimization on defined parameters of ventilation system may lead to control IAQ, thermal comfort and energy demand simultaneously.
- Controlled integration of natural and mechanical ventilation (Hybrid ventilation) can improve indoor environmental quality and reduce energy use.

- Physical barriers can reduce airborne transmission risk between occupants.
- Local control strategies such as personal exhaust ventilation combined with physical barriers can significantly reduce exposure to airborne contaminants.

In pursuit of these objectives and hypotheses, this thesis is structured around a series of six peer-reviewed publications and one additional study that collectively form the foundation of the research. The works are presented in a logical sequence, beginning with advanced natural ventilation control, followed by the integration of hybrid and mechanical systems, and continuing with experimental and numerical assessments of local infection mitigation strategies such as physical barriers and personal exhaust ventilation. The final component of the thesis comprises a life cycle assessment (LCA) study that evaluates the environmental impact of various infection control strategies.

Chapter 2: Ventilation strategies and smart control

Scope and Methodology: This chapter synthesizes three studies (Papers 1–3) dedicated to the development, optimization, and evaluation of smart and hybrid ventilation strategies in classrooms. All three studies use a consistent simulation environment: a top-floor classroom in a three-story energy-efficient school building. The building envelope included insulated walls and floors, and double-glazed windows. Different ventilation configurations were simulated—natural ventilation using stack effect and infiltration, and mechanical systems using a packaged terminal heat pump (PTHP) with filters. Occupancy was modelled for 30 students, with internal heat and CO_2 generation standardized. Clothing insulation and lighting activation were tailored to local climatic conditions in Warsaw, Bangkok, Delhi, and Stockholm. These consistent assumptions allow meaningful cross-case comparisons and robust conclusions.

Smart window control for natural ventilation: Paper 1 focused on the design of a smart window control algorithm, operating based on indoor CO_2 levels, temperature, and infection risk. The system adjusted window positions (tilt or open) in response to defined thresholds, minimizing hours with thermal discomfort (PMV outside −0.7 to +0.7), poor air quality (CO_2 > 1200 ppm), and elevated reproduction number ($R_0 > 1$). Various scenarios were simulated to assess the effect of interventions like mask usage, air cleaners, and reduced occupancy. Findings revealed that conventional manual window opening resulted in severe CO_2 accumulation (>2500 ppm), while the smart controller reduced concentrations to acceptable levels (600–1200 ppm) for 80% of occupied hours. However, despite improved IAQ and comfort, infection risk remained high. Including R_0 in the control logic produced only a modest improvement in infection control. Additional measures, such as air cleaners and mask usage, proved essential: two air cleaners reduced time with $R_0 > 1$ to just 1.6%, and halving classroom occupancy achieved similar performance. Energy penalties were observed—particularly a 190% increase in heating demand—highlighting the tension between IAQ and energy sustainability. The study concluded that natural ventilation optimization alone is insufficient for infection control in densely occupied classrooms.

Multi-Objective optimization of window and thermostat setpoints: Paper 2 expanded the window control strategy through a multi-objective genetic algorithm that simultaneously optimized five parameters: heating/cooling thermostat setpoints, window opening temperatures, and window opening area. The study considered three objectives—annual energy demand, average CO_2 concentration, and thermal comfort (PPD)—across two contrasting climates: Warsaw and Bangkok. The results showed the existence of trade-offs between objectives. In Warsaw, optimizing for IAQ often increased energy use due to the heating demands of winter, whereas in Bangkok, without heating needs, better compromises were achievable. Selected cases based on different weightings for objective functions during optimization showed that priority-driven optimization matters. Case 3, assigning equal importance to all objectives, achieved the best overall balance. Case 4, favouring energy savings, maintained higher thermostat thresholds and reduced window opening duration. Case 5, prioritizing IAQ, used opening window for a longer time.

Hybrid ventilation with outdoor pollution constraints: Paper 3 addressed limitations of natural ventilation in polluted urban areas by proposing a smart hybrid ventilation strategy, controlled via an Energy Management System (EMS). The EMS dynamically toggled between natural and mechanical ventilation based on indoor temperature and real-time outdoor $PM_{2.5}$ and NO_2 concentrations. Mechanical ventilation used a PTHP system with filters that degraded in efficiency over time, prompting periodic replacement. Natural ventilation was enabled only when outdoor conditions were safe, according to thresholds defined per city (e.g., $PM_{2.5}$ limit of 60 $\mu g/m^3$ in Delhi, 40 in Warsaw, 15 in Stockholm). Simulations revealed that outdoor air pollution significantly constrained natural ventilation. In Delhi, natural ventilation was permitted for only 11% of the year; Warsaw allowed 44%, and Stockholm 31%. These differences stemmed from both pollution levels and threshold values. Despite Stockholm's cleaner air, Warsaw's less restrictive thresholds resulted in more window operation. Optimization outcomes showed the hybrid strategy significantly outperformed both mechanical-only and non-hybrid ventilation models. Energy savings reached 65% in Warsaw, 57% in Stockholm, and 13% in Delhi, relative to the mechanical-only base case. Indoor CO_2

concentrations improved substantially—Warsaw moved from Category III to 43% of the year in Category I air quality; Stockholm and Delhi showed improvements as well. Thermal comfort, while slightly reduced in some optimized cases, remained within acceptable levels, with 99% compliance in Delhi and over 80% in the European cities.

Chapter 3: Local strategies for infection control

Scope and Objectives: This chapter explores the design, evaluation, and optimization of localized infection control strategies, with a focus on physical barriers (PB) and personal exhaust (PE) ventilation systems. The first study (Paper 4) focuses on the impact of desk-mounted physical barriers on airflow patterns and aerosol dispersion under mixing ventilation conditions. It examines how partitions influence ventilation efficiency, quantified by air change effectiveness (ACE), and their unintended effects on pollutant recirculation and stagnation zones. Paper 5 builds on this foundation by introducing a combined PB+PE strategy. It assesses the integrated system's performance across multiple air distribution types—mixing and displacement ventilation—demonstrating that effectiveness depends heavily on airflow directionality and pollutant capture mechanics. The final study (Paper 6) extends the investigation into sustainability by combining experimental validation and computational fluid dynamics (CFD) simulations. The aim is to optimize the PB+PE system design, balancing performance and resource efficiency through adjustments in barrier height and exhaust airflow.

Methods and Experimental design: The chapter employs tracer gas analysis (CO_2 and N_2O), aerosol and bioaerosol measurements, and CFD modeling. Tracer gas decay methods were used to calculate ACE; aerosol experiments employed a Collison nebulizer, while bioaerosol tests used *Micrococcus luteus* as a biological surrogate. CFD simulations included the Discrete Phase Model (DPM) to track particle trajectories, incorporating Brownian motion and Stokes number-based behaviors. All studies were conducted in a full-scale laboratory classroom mock-up. Six thermally active dummies simulated occupants, and modular desk layouts allowed flexible configuration. Ventilation parameters (air change rate of 3 h^{-1}, supply air at 20°C, and relative humidity at 40%) were kept constant. Several ventilation schemes were implemented, including three mixing strategies (MV1–MV3) and one displacement ventilation system (DV), allowing comparative evaluation.

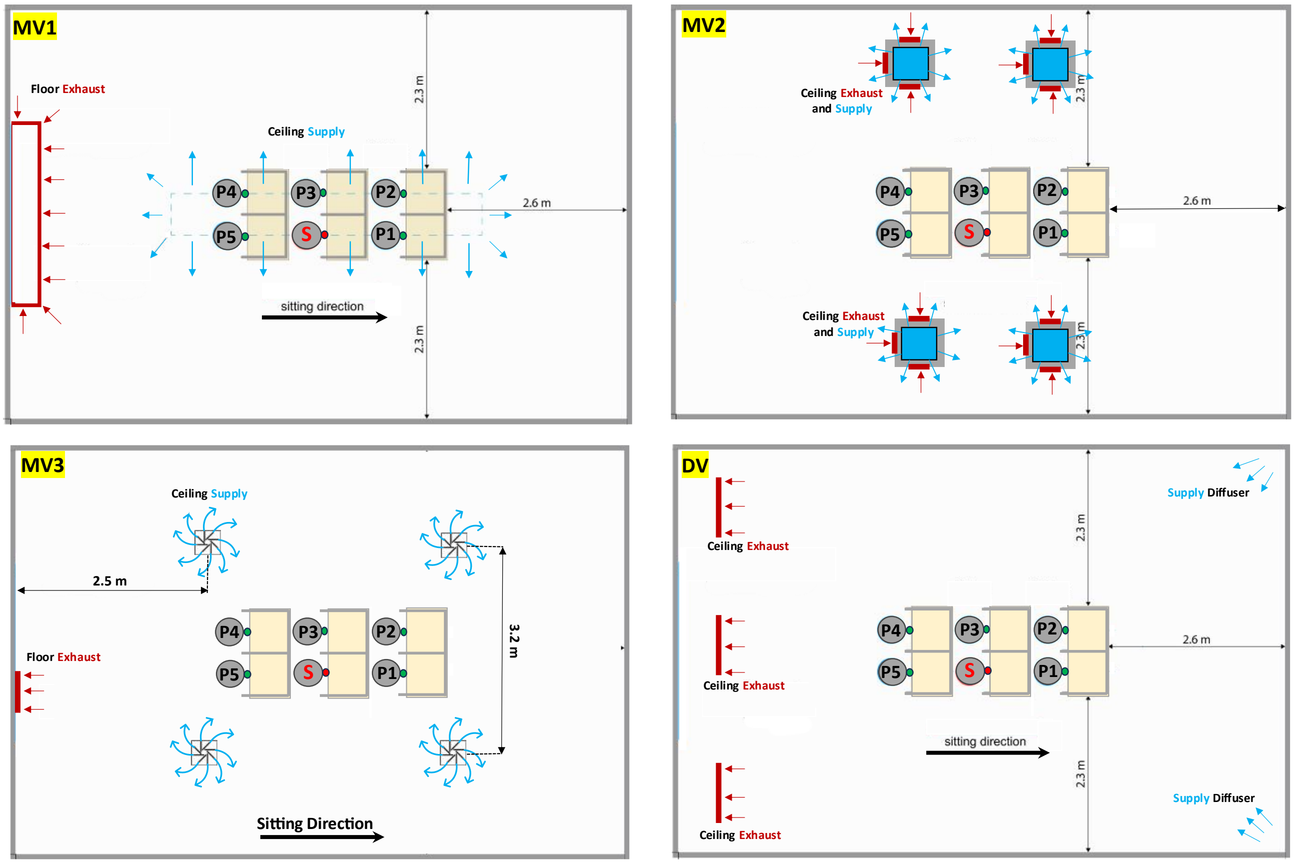

Fig. 7. Test room arrangement with four different air distributions[1]: MV1, MV2, MV3, and DV

Effects of Physical Barriers on Ventilation and Aerosol Transport: Paper 4 evaluated the standalone effect of acrylic desk partitions on airflow and aerosol dispersion. Two ventilation schemes (MV2 and MV3) were tested, with and without barriers. Results showed that physical barriers can disrupt airflow uniformity, particularly under systems like MV2 with less turbulent mixing. Local ACE values decreased significantly at certain points when barriers were present, indicating stagnation zones where contaminants may accumulate. Aerosol concentration reduction (CR) analysis revealed mixed results. Under MV3's swirling flow, barriers consistently reduced aerosol concentrations (CR > 0.6), while MV2 showed negative CR values at downstream positions—suggesting that barriers redirected pollutants toward susceptible occupants. Bioaerosol results aligned with these trends. In MV2, CFU counts dropped near the source but increased at lateral and rear positions. MV3 showed more balanced reductions, confirming that the effectiveness of PBs is strongly dependent on airflow design. These findings underscore the context-dependent utility of physical barriers: they can be

[1] The naming convention for ventilation systems in this thesis differs from that used in the corresponding publications.

effective when well-aligned with the ventilation pattern but may worsen exposure when airflow is weak or misdirected.

Performance of Integrated PE+PB Systems under Different Ventilation Types: Paper 5 introduced a combined PE+PB system, designed to extract contaminated air directly from the source zone. Tests were conducted under three ventilation schemes (MV1, MV2, DV), comparing multiple configurations: baseline (no control), PB only, and PB+PE. The PB-only setup showed mixed results. Under DV and MV2, barriers reduced exposure by up to 63%, but under MV1, they worsened conditions—doubling pollutant concentration next to the source (P2), indicating recirculation and entrapment due to barrier obstruction. When PE was added at 9 L/s per person, exposure dropped consistently across all setups. In MV1, PE reduced N_2O levels at P2 by 60%, neutralizing the barrier's negative impact. PE+PB also performed strongly under DV, further enhancing its already superior performance. Flow rate analysis revealed that 9 L/s/person was an effective operating point, offering substantial improvements over 4 L/s without incurring the complexity and energy penalties associated with 12 L/s.

Design Optimization of PE+PB for Resource Efficiency: In Paper 6, the focus shifted to optimizing the PE+PB system for sustainable performance. CFD simulations were validated against experimental data and used to study airflow, thermal plumes, and particle removal efficiency under MV3 conditions. The primary objective was to determine the minimum barrier height and exhaust flow rate needed to maintain high effectiveness. Key results showed that reducing barrier height from 65 cm to 45 cm resulted in only a 5% reduction in particle removal efficiency. Dropping further to 25 cm led to a larger performance decline (RAR ≈ 0.83), suggesting 45 cm as a practical and resource-efficient design. Similarly, decreasing exhaust flow from 9 to 6 L/s resulted in only a minor efficiency drop (6%), while further reduction compromised performance. Overall, Paper 6 demonstrated that substantial material and energy savings are achievable without sacrificing infection control if the system is properly optimized. The validated CFD framework also provides a tool for future scaling and customization in diverse room layouts or ventilation conditions.

Chapter 4: Life cycle assessment of infection control strategies

Scope and Objectives: While the COVID-19 pandemic intensified the development and deployment of various control strategies—ranging from ventilation upgrades to personal protective equipment—most evaluations focus solely on health-related performance, often ignoring the long-term environmental consequences. This chapter fills that gap by applying a life cycle assessment (LCA) methodology to examine the environmental impacts of different infection control strategies.

Methods and Framework: A comprehensive LCA was conducted using OpenLCA (v2.3.1) and the Environmental Footprint (EF) v3.0 database. The analysis adopted a cradle-to-grave system boundary, encompassing raw material extraction, production, usage, and disposal. Environmental impacts were quantified using a two-stage process of normalization and weighting to convert diverse impact categories into a unified performance score measured in Points (Pt). Three primary strategies were modelled in detail:

- **Air Cleaners**: Two portable HEPA-filtered devices, with continuous operation and regular filter replacements.
- **Disposable Masks**: Daily use by 30 students during school hours.
- **Integrated PE+PB System**: Based on the experimentally validated setup from Chapter 3, involving acrylic partitions and localized exhaust units.

Each strategy was applied to a classroom of 30 students operating for 6 hours a day, 5 days a week, over a 9-month school year. All cases assumed a constant background ventilation rate of 148 L/s (3 ACH) via mechanical mixing ventilation. Transportation impacts were excluded due to minimal contribution, as supported by prior research.

Infection Risk Analysis: The health effectiveness of each strategy was evaluated using the Wells-Riley model, focusing on the basic reproduction number (R_0) as a measure of infection probability over a typical 45-minute lesson. The results clearly differentiated the performance of various scenarios:

- Case 1 (Ventilation only): $R_0 > 1.25$ (highest risk)
- Case 2 (Ventilation + Air Cleaners): $R_0 \approx 0.75$
- Case 3 (Ventilation + Masks): $R_0 \approx 0.45$
- Case 4 (Ventilation + Masks + Air Cleaners): $R_0 \approx 0.27$
- Case 5 (Ventilation + PE+PB): $R_0 \approx 0.36$

These findings confirm that multi-layered strategies (Case 4) offer the most robust infection control but also highlight the strong performance of PE+PB.

Total Environmental Footprint: The LCA results were aggregated into single-point impact scores (Pt) for each strategy:

- Case 1 (Ventilation only): ~0.06 Pt (lowest impact)
- Case 2 (Ventilation + Air Cleaners): ~0.12 Pt
- Case 3 (Ventilation + Masks): ~0.27 Pt
- Case 4 (Ventilation + Masks + Air Cleaners): ~0.33 Pt (highest impact)
- Case 5 (Ventilation + PE+PB): ~0.14 Pt

These findings clearly show that disposable masks, while effective for infection control, carry the highest environmental burdens. In contrast, air cleaners and PE+PB systems offer a significantly sustainable approach.

Weighted Trade-Off Analysis: To integrate infection risk and environmental impact into a unified decision-making framework, a dual-criteria composite index (F_{ws}) was developed. This function allows for flexible prioritization between infection control (R_0) and environmental burden (Pt), depending on the application context. Results showed that:

- When environmental impact is prioritized, ventilation-only (Case 1) appears optimal despite limited infection protection.
- When infection control is prioritized, PE+PB (Case 5) was the best strategy, though case 4 had the lowest infection risk.
- When equal weighting is applied, PE+PB (Case 5) becomes the optimal solution, offering strong infection mitigation with moderate environmental impact.

This chapter demonstrates that there is no single universally optimal strategy for indoor infection control. Notably:

- Disposable masks provide strong protection but are environmentally intensive.
- PE+PB systems offer localized control with lower long-term impacts.
- Air purifiers balance moderate energy use with solid infection mitigation.
- Ventilation alone is environmentally benign but insufficient for infection prevention.

Chapter 5: Conclusions

This thesis presents a comprehensive investigation into strategies for improving indoor environmental quality and mitigating airborne infection risks, with a particular focus on classrooms. The main findings of this thesis confirm that:

- Natural ventilation via smart windows improves IAQ and thermal comfort, but cannot alone ensure sufficient infection control, particularly in densely occupied spaces like classrooms.
- Multi-objective optimization of smart window operation and thermostat setpoints enables a balanced trade-off between energy use, thermal comfort, and indoor air quality across various climates.
- Controlling outdoor pollution penetration through an optimized hybrid ventilation significantly improves indoor air quality, energy use, and thermal comfort across various climates with different pollution levels.
- Physical barriers can alter airflow patterns and improve containment of exhaled aerosols, but their efficiency is highly dependent on the operation of air distribution systems and occupants' location.
- Combining physical barriers with personal exhaust ventilation, regardless of ventilation type and occupant location, significantly reduces airborne transmission by capturing contaminants at the source
- The resource-efficient design for integrated personal exhaust ventilation and physical barriers offered lower material and energy use while keeping high contaminant removal efficiency.
- A comparative life cycle assessment of infection mitigation strategies revealed that physical barriers with personal exhaust ventilation achieved the most balanced strategy, offering strong infection reduction with moderate environmental impact.