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Microbial Contamination and Ventilation Strategies in HVAC Systems: A Case-Study Assessment of Infection Risk, Energy Consumption, and Thermal Comfort

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Abstract

Heating, ventilation, and air conditioning (HVAC) systems are essential for indoor air quality and thermal comfort but can simultaneously act as vectors for microbial contamination, particularly bacteria and fungi. While the COVID-19 pandemic intensified focus on airborne viral transmission, bacterial and fungal contamination in indoor environments remains a persistent and significant health risk. This study presents a detailed case study of a restaurant HVAC system, analysing the impact of different ventilation strategies on bacterial contamination, infection transmission risk, energy consumption, and thermal comfort. By focusing on a real-world application, the research evaluates practical challenges and trade-offs associated with HVAC operation modifications aimed at mitigating microbial risks while maintaining acceptable energy and comfort levels. The research compares three operational scenarios: normal operation with air recirculation, 24 h operation with 100% outdoor air, and extended operation periods. Results demonstrate that while strategies emphasizing outdoor air intake and extended operation reduce infection probability by up to 60–65%, they simultaneously increase energy consumption by over 1700% and compromise thermal comfort parameters. In the h24 case, the pre-heat coil rises from 2421.7 to 43,923.7 kWh and the post-heat coil from 24,812.8 to 152,970.4 kWh, while the Plus 2 h strategy reduces the energy penalty by roughly 42–51% with respect to the h24 case. The findings are contextualized within current research on bacterial and fungal risks in HVAC systems, highlighting the critical need for balanced ventilation strategies that integrate health protection, energy efficiency, and comfort considerations.

Keywords: TRNSYS; building energy simulation; HVAC systems; air change ventilation; indoor air quality; thermal comfort

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1. Introduction

The relationship between indoor air quality (IAQ) and human health has become increasingly prominent in recent years, especially following global health events that underscored the airborne transmission of pathogens. People spend roughly 90% of their time indoors, making the quality of indoor air a critical determinant of overall health and well-being. Heating, ventilation, and air conditioning (HVAC) systems are designed to ensure thermal comfort and adequate ventilation but can also serve as vectors for microbial contamination, including bacteria and fungi, which have long been recognized as significant health hazards [1,2]. In this context, HVAC-related microbial contamination may be associated with three main mechanisms: microbial growth within poorly maintained components, indoor transport through recirculated air, and contaminant dilution through outdoor-air renewal. The present study focuses on the latter two mechanisms.

Bacterial and fungal contaminants in indoor environments contribute to a spectrum of health issues such as respiratory infections, allergic reactions, and "sick building syndrome" [3,4]. These microbial agents continuously affect residential, commercial, and healthcare facilities, posing a persistent public health risk irrespective of episodic viral outbreaks [5]. For example, Legionella pneumophila, Staphylococcus aureus, Aspergillus species, and Penicillium species have been frequently isolated from HVAC components, particularly in poorly maintained systems [6,7].

However, the focus on viral transmission during the pandemic has overshadowed a longstanding and equally critical issue: bacterial and fungal contamination in HVAC systems. These microbial contaminants have been recognized as significant health hazards for decades, contributing to respiratory diseases, allergic reactions, and sick building syndrome. Unlike viral outbreaks which occur episodically, bacterial and fungal contamination represents a continuous threat to indoor air quality, affecting building occupants across residential, commercial, and healthcare settings.

During the COVID-19 pandemic, worldwide, various organizations issued guidelines in order to limit the contagiousness of the virus. The main place in which the outbreak occur is in indoor spaces in which people share the air and there is the major viral infection [8]. In this context, the main aim of the guidelines is to curtail the possibility of infection in indoor spaces, and the HVAC system plays an important role. The objective of this technology is to maintain a healthy and comfortable indoor environment using the most efficient components in order to limit energy consumption. Ventilation systems provide clean air by exchanging indoor and outdoor air and filtering it. Often, air-conditioning systems can recirculate the air with or without mixing it with outdoor air [9]. Poor ventilation in indoor spaces is associated with increased transmission of respiratory infections [10].

Ventilation strategies, including increasing the outdoor air fraction and minimizing air recirculation, are widely recommended to reduce microbial transmission indoors [11,12]. However, these measures often entail significant increases in energy consumption and can affect indoor thermal comfort, posing challenges to sustainable building operation [13,14]. The optimization of HVAC operational parameters must therefore carefully balance the competing objectives of health protection, energy efficiency, and occupant comfort [15].

Furthermore, environmental factors such as temperature, relative humidity, and the presence of organic matter within HVAC systems strongly influence microbial proliferation and survival [16,17]. Maintenance practices and filter efficiency also play essential roles in mitigating microbial contamination [18,19]. Despite growing awareness, the integration of microbiological risk mitigation with energy and comfort considerations remains an area with several unresolved questions and ongoing research [20,21].

To address these challenges, this work focuses on an in-depth case study of a restaurant HVAC system. Such a case study approach allows a comprehensive analysis of actual building operations, occupant density, and ventilation scenarios, providing practical insights into the effectiveness and limitations of infection control measures in real settings. While the findings are specific to this type of building, they offer useful reference points for similar commercial establishments and highlight the need for context-sensitive HVAC management strategies.

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State of the Art in HVAC-Associated Microbial Contamination

Microbial contamination in HVAC systems is a well-documented phenomenon with substantial implications for indoor air quality and occupant health [22]. Comprehensive reviews have characterized HVAC units as hotspots for microbial colonization due to favourable microenvironments created by moisture, temperature, and organic dust accumulation [23,24]. Various bacterial and fungal species, including both opportunistic pathogens and allergenic fungi, have been detected in components such as filters, cooling coils, and ductwork [25,26].

Studies indicate aerosolized microbial concentrations in indoor air range widely, from 102 to over 104 colony forming units per cubic meter (CFU/m^3), influenced by HVAC operation and maintenance quality [27,28]. For instance, research in hospital environments has highlighted the presence of antibiotic-resistant bacterial strains facilitated by HVAC airflows, increasing the risk of nosocomial infections [29]. Residential and office buildings similarly report microbial contamination associated with occupant complaints and health symptoms [30,31].

Environmental parameters critical to microbial growth in HVAC include temperatures typically between 10 °C and 35 °C, relative humidity above 60%, and nutrient availability, factors that vary seasonally and by building use [32,33]. Inadequate maintenance, such as infrequent filter replacement and improper cleaning, exacerbates these issues [33].

Technological interventions for microbial mitigation in HVAC range from high-efficiency particulate air (HEPA) and Minimum Efficiency Reporting Value (MERV) filters, ultraviolet germicidal irradiation (UVGI), and photocatalytic oxidation to antimicrobial coatings inside ductwork [34–37]. The effectiveness of these measures depends on system design, operational protocols, and regular maintenance [38]. In healthcare settings, combined strategies have shown promise for reducing airborne microbial loads and transmission risk [39].

Ventilation strategy optimization remains a key research topic, particularly the trade-offs between increasing outdoor air ventilation for pathogen dilution and the subsequent rise in heating and cooling loads [40,41]. Advanced controls and real-time monitoring systems are emerging to dynamically balance these factors, enabling responsive HVAC operation that prioritizes both health and energy efficiency [42,43].

Innovative approaches also explore the integration of indoor air quality sensors and the development of predictive models to guide ventilation management and microbial risk mitigation [44,45]. Despite advances, knowledge gaps persist regarding long-term efficacy, cost-benefit analyses, and occupant health outcome correlations [46].

Addressing these challenges requires multidisciplinary research bridging microbiology, building science, and systems engineering to develop evidence-based HVAC guidelines that ensure safe, comfortable, and sustainable indoor environments [47,48].

Despite extensive research, significant knowledge gaps remain regarding optimal ventilation strategies that balance microbial contamination control with energy efficiency and thermal comfort requirements. Most existing studies focus on either health outcomes or energy performance in isolation, with limited research providing integrated analyses of these competing objectives.

2. Materials and Methods

2.1. Methodology

The objective of the paper is to assess the thermal consumption, the thermal comfort variation and the microbial risk reduction inside a building varying the changing air of an HVAC system. The method consists in taking into account an HVAC system designed for a building that consider the return air that is mixed with the external air. In order to reduce the probability of infection, in accordance to the main directive of local (AICARR [49]) and international (REHVA [50]) organizations, it is possible to analyse three different scenarios:

1. Normal case: considering the changing air given by the UNI 10339 [51] during working hours (8 am to 5 pm) and using the return air as normal operation of the HVAC pre-COVID-19;
2. h24 case: this scenario avoids the adoption of return air and take all the necessary from the exterior. Furthermore, the HVAC system is turned on all day long (24 h/day), and the crowding is reduced to 0.25 in order to maintain the correct distance among people;
3. Plus 2 h case: this scenario is equal to the H24 case, but the HVAC is turned on 2 h before and after work hours (6 am to 7 pm).

Table 1 summarizes the operating schedules and main characteristics of the three HVAC scenarios considered in the analysis.

Table 1. Summary of the HVAC operating scenarios analysed in the study. The infection-risk analysis for the outdoor-air-only scenarios was carried out considering air change rates between 7.7 and 10 1/h.

Scenario	Main Operating Characteristic	Outdoor Air/Recirculation	Crowding	Number of Occupants
Normal case	Operation during occupancy hours (8 am–5 pm)	Outdoor air according to UNI 10339 + return air	0.35 people/m^2	70
h24 case	24 h operation	100% outdoor air	0.25 people/m^2	50
Plus 2 h case	Extended operation before and after occupancy	100% outdoor air	0.25 people/m^2	50

The heating and cooling demands of the building are obtained through a numerical model implemented in TRNSYS. This model was necessary in order to quantify the variation of the energy consumption by adopting the given scenarios for microbial risk reduction. To further improve the transparency of the modelling assumptions, Table 2 summarizes the main input parameters adopted in the present study together with their role in the simulations and their source or justification. This additional table is intended to distinguish the parameters directly imposed by the model from those derived from the case-study configuration.

Table 2. Main modelling inputs and assumptions adopted in the study.

Parameter	Value/Setting	Source/Justification
Building use	Restaurant	Selected application of the study
Building location	Rome, Italy	Case-study definition
Floor area	200 m^2	Case-study geometry
Internal height	3 m	Case-study geometry
Indoor volume	600 m^3	Derived from geometry
Occupancy schedule	8 am–5 pm	Case-study assumption
Normal-case occupancy	70 people	Scenario definition
h24 and Plus 2 h occupancy	50 people	Reduced crowding scenario

Table 2. *Cont.*

Parameter	Value/Setting	Source/Justification
Normal-case crowding	0.35 people/m^2	Scenario definition
h24 and Plus 2 h crowding	0.25 people/m^2	Scenario definition
Normal-case ventilation rate	10 L/s per occupant	UNI 10339
Normal-case changing air	7.7 1/h	Derived from the simulated case
Outdoor air strategy (Normal)	Outdoor air + return air	Pre-COVID reference configuration
Outdoor air strategy (h24/Plus 2 h)	100% outdoor air	Infection-risk mitigation scenarios
Weather input	TRNSYS Type 109	Rome weather file used in the simulation
Infection-risk model	Jimenez/Miller/Wells-Riley/Buonanno approach	References [52–56]
Event duration	1.5 h	Case-study definition
Breathing rate	0.66 m^3/h	Case-study definition
Quanta exhalation rate	60.5 1/h	Case-study definition
Thermal comfort index	PMV	Results methodology
Fan control	On/off thermostat logic	TRNSYS implementation
Heating coil control	Internal bypass/setpoint logic	TRNSYS Type 670 implementation
Filter efficiency	Not explicitly modelled as an independent parameter	Not part of the present sensitivity analysis
Direct field calibration	Not available	Results interpreted through literature benchmarking

The probability of infection was estimated through a model implemented by Jimenez, available online [52]. The model combines three different types of calculations implemented by Miller er al. [56], Wells-Riley [53], and Buonanno et al. [54,55]: quanta generation by the infectious source, time-dependent indoor concentration/removal calculations, and the Wells-Riley probability of infection with the corresponding expected number of new infected people.

The adopted modelling framework should therefore be interpreted as a scenario-comparison tool aimed at consistently evaluating the relative effect of different HVAC operating strategies on infection risk, energy demand, and thermal comfort within the selected restaurant case study. In this sense, the methodology is not intended to provide direct field-calibrated predictions for the analysed building, but rather to compare alternative operating conditions under a transparent and internally consistent set of assumptions.

2.2. Case Study

The case study is composed by a building with a single flat with an area of 200 m^2 (20 m $\times$ 10 m) and a height of 3 m. The building use is for a restaurant, and it is situated in Rome (Italy). The thermal characteristics of the buildings are reported in Table 3. The simulations were performed on an annual basis using the Rome weather file managed in TRNSYS 16 through TYPE 109.

Table 3. Characteristics of opaque and transparent elements of the chosen building envelope.

	Thickness (m)	Transmittance (W/m^{2}K)	g-Value (−)
External Wall	0.4	0.879	-
Roof	0.21	0.628	-
Pavement	0.545	1.193	-
Window	0.004	5.16	0.682

An HVAC system designed specifically for use in the building was considered. The air handling unit is composed by the component shown in the Figure 1. The external air is mixed with the return air from the building and is subjected to a pre-heat coil, humidification, cooling coil, and post-heat coil, depending on the season, before it is put in the building.

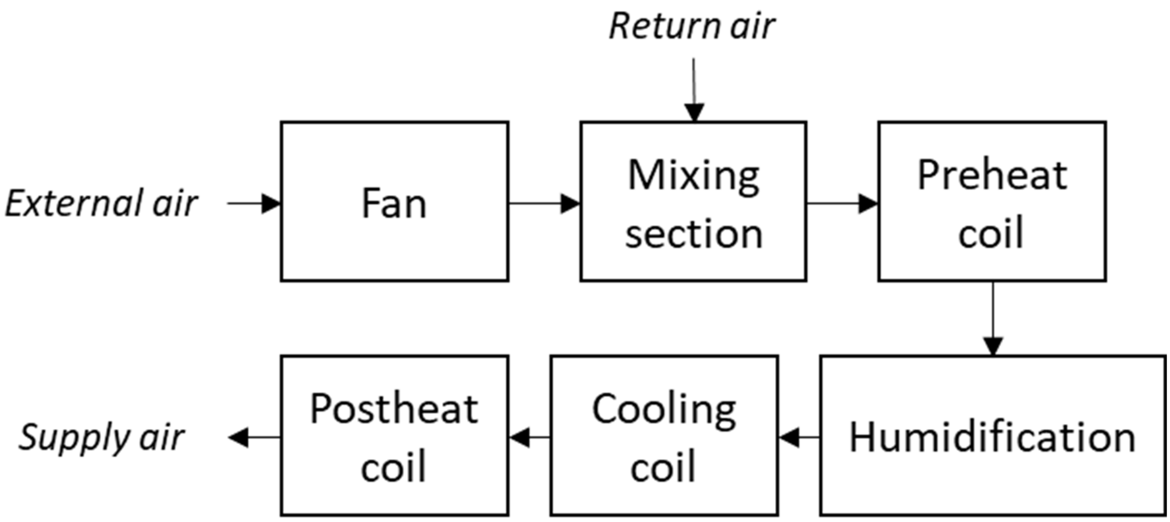

Figure 1. Block diagram of the air handling unit used in the building.

The parameters used in the model of Jimenez [52] for the probability of infection are reported in Table 4. Furthermore, the analysis is given for two types of contests: 1 infected person, or 13% of people infected inside the building. The first case is considered the minimum scenario, while the second case is related to the average quantity of infected people based on a strep test analysed in Italy during the second wave of contagion that was recorded from October to December 2020.

Table 4. Parameters used for the Jimenez model [52].

Parameter	Value	Unit
Volume	600	m^3
Duration of event	1.5	h
Changing air	4.5–10	1/h
Total number of people present	70–50	-
Breathing rate	0.66	m^3/h
Quanta exhalation rate	60.5	1/h

2.3. TRNSYS Building Model Setup

As outlined in the previous section, the simulation of the building was developed using TRNSYS 16 with the TYPE 56 module, renamed “Reference Building”. TRNSYS is a transient system simulation environment widely used for building and HVAC analyses.

This type loads a file that contains all the previously specified geometric and physical characteristics of the building; it was constructed in TRNSYS BUILD.

The weather data are managed through TYPE 109, renamed as “Weather Database”. This element reads meteorological data from an input file at regular time intervals.

The “Psychrometer” module receives dry bulb temperature and relative humidity as inputs to calculate the corresponding properties of moist air. TYPE 69, renamed “Diffuse Sky and Ground Radiation Sum”, is used to determine the effective sky temperature, which is crucial for longwave radiation exchange calculations. The module renamed “Ground” models the energy transfer from the building floor to the underlying soil.

These modules are interconnected with green arrows on the diagram, representing the flow of thermal information and allowing the simulation to reflect real-time heat losses and gains based on external weather conditions.

For the ventilation system, red arrows denote the movement of air between the various system components leading up to the Reference Building module.

The following modules were used to simulate the HVAC system:

- TYPE 648 (“Plenum Air Chamber”): Models the recirculation section, with control over recirculation and outdoor flow rates and air properties.
- TYPE 662 (“Variable Speed Fan”): Represents the fan with an internal on/off controller.
- TYPE 670 (“Air Heating Coil”): Simulates heating coils with an internal bypass damper which is activated when the inlet air temperature exceeds the setpoint. This type was applied for both pre-heating and post-heating coils.
- TYPE 641 (“Adiabatic Humidifier”): Used to simulate humidification through adiabatic processes.
- TYPE 752 (“Cooling Coil”): Models the cooling coil. Air passes through the coil, where a refrigerant fluid can be considered; it accounts for the bypass factor, mixing saturated air that comes into contact with the coil with unsaturated air.

The TRNSYS building model setup is shown in Figure 2.

For air supply modelling, TRNSYS BUILD’s “Ventilation Type Manager” function was activated, with input conditions set according to the output air properties downstream of the post-heating coil. Before the post-heating coil connection, a calculator performed the conversion of airflow units from kg/s to air changes per hour (ACH). This allowed the model to represent the ventilation management logic consistently within the corresponding TRNSYS BUILD input structure.

For temperature control, a thermostat was employed to send a signal to the on/off fan, activating it according to the indoor air temperature measured in the simulated environment.

Although the present study does not include a dedicated field-monitoring campaign for direct calibration in the analysed restaurant, the modelling workflow was benchmarked against recent published studies investigating the same interaction among ventilation strategy, infection risk, energy performance, and thermal comfort. Recent simulation, experimental, and review studies consistently show that increased outdoor air use generally reduces infection risk while often increasing HVAC energy demand and, depending on the adopted strategy, affecting thermal comfort [57–62]. Accordingly, the present model outputs are discussed in the revised manuscript as literature-benchmarked results rather than as directly field-validated absolute predictions.

Overall, the methodological workflow combines building-energy simulation, infection-risk estimation, and thermal comfort assessment within a single case-study framework, allowing the three performance dimensions to be compared consistently under different HVAC operating scenarios.

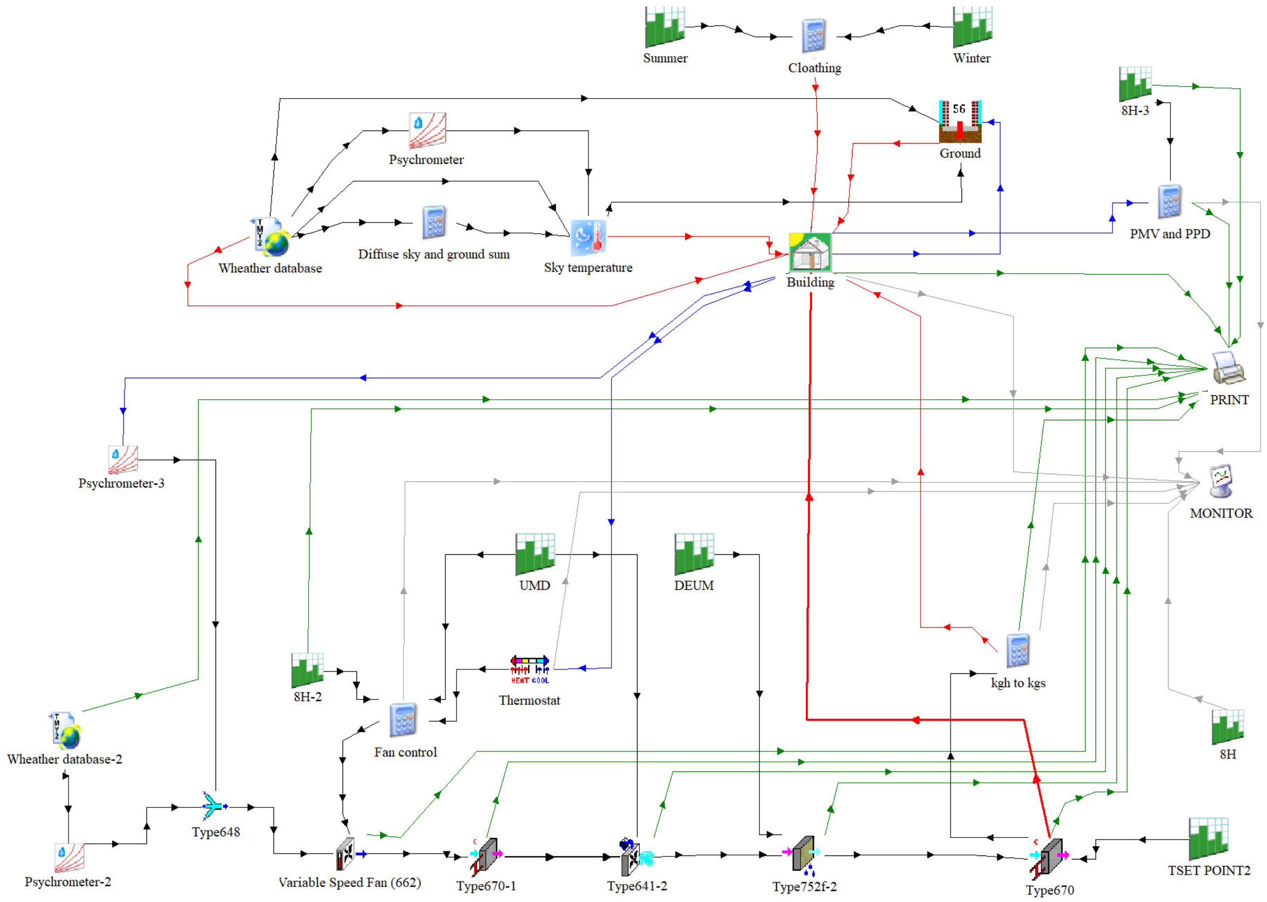

Figure 2. TRNSYS Studio setup of the simulation model. Red lines indicate inputs to the building model, with the bold red line representing the HVAC system output supplied to the building model. Blue lines represent outputs from the building model. Green lines correspond to outputs from the numerical model exported to an external Excel file for post-processing. Gray lines indicate variables monitored during the simulations. Black lines represent connections among TRNSYS types.

3. Results

3.1. Analysis of Building Thermal Performances

The building thermal behaviour was simulated using the TRNSYS 16 software to evaluate HVAC system performance according to the directive UNI 10339, which prescribes ventilation rates specific to restaurant use. The baseline (Normal) case employs a ventilation rate of 10 L/s per occupant, with an occupancy density of 0.35 persons per square meter. As shown in Table 5, the Normal case serves as a reference representing the system originally designed for the building and operated during occupancy hours only (8 am to 5 pm). The other cases (h24 and plus 2 h) are based on the Normal case in which the return air, turning on of the system, and the crowding (the number of occupant are 50 people based on a crowding of 0.25 people/m^2) are modified.

Table 6 presents energy usage for the air handling unit under three scenarios: Normal operation with air recirculation, 24 h operation with 100% outdoor air (H24 case), and extended operation with earlier start/stop times (Plus 2 h case). Table 7 show the percentage difference between the cases.

Table 5. Main results of the Normal case.

Parameter	Value	Unit
Heating load	9.29	kW
Cooling load	8.99	kW
External air flow	0.9	kg/s
Return air flow	0.6	kg/s
Supply air flow	1.5	kg/s
Time of occupancy	8 am–5 pm	-
Crowding	0.35	people/m^2
Number of occupants	70	people
Changing air	7.7	1/h

Table 6. Air handling unit energy consumption.

	Normal Case (kWh)	H24 Case (kWh)	Plus 2 h Case (kWh)
Fan	4486.8	19,593.2	10,612.9
Pre-heat coil	2421.7	43,923.7	21,486.9
Cooling coil	45,709.4	142,581.9	82,848.4
Post-heat coil	24,812.8	152,970.4	82,380.3

Table 7. Percentage difference of air handling unit energy consumption.

	Normal-H24 Case	Normal-Plus 2 h Case	Plus 2 h-H24 Case
Fan	337%	137%	−46%
Pre-heat coil	1714%	787%	−51%
Cooling coil	212%	81%	−42%
Post-heat coil	516%	232%	−46%

The results reveal a marked increment in energy consumption moving from Normal to H24 and Plus 2 h cases, with increases ranging from 81% to over 1700%. The Plus 2 h scenario reduces total energy consumption by roughly half compared to H24 but remains substantially higher than Normal. This result is due to the shorter operating schedule outside the occupancy period: both H24 and Plus 2 h avoid recirculation during occupancy, but the H24 case conditions 100% outdoor air during the whole day.

The energy demand hike is primarily attributable to heating and cooling loads driven by increased outdoor air intake and extended system run times. These findings highlight the inherent trade-off between enhanced ventilation for infection risk mitigation and elevated energy consumption, underscoring the need for balanced operational strategies.

3.2. Analysis of Thermal Comfort

Thermal comfort was evaluated using the Predicted Mean Vote (PMV) index during occupancy hours (8 am to 5 pm). A positive PMV value denotes a feeling of warmth, and conversely, a negative PMV value indicates a feeling of coldness for occupants, while an ideal PMV value would be 0. Table 8 reports the cumulative hours in which the PMV is inside the thermal stress category for the three cases.

The Normal scenario exhibits the most favourable comfort conditions, with over 2800 h within the neutral comfort range. In contrast, the H24 and Plus 2 h cases show substantial increases in hours categorized as slightly cold or cold, indicating a degradation of occupant comfort linked to the altered HVAC operation and disabled temperature control mechanisms as per guidelines.

Table 8. Cumulative hours inside the thermal stress category of PMV index.

	Normal Case	H24 Case	Plus 2 h Case
Very hot	0	0	0
Hot	0	0	0
Slightly warm	160	18	6
Neutral	2814	2307	2550
Slightly cold	309	870	697
Cold	2	90	32
Very cold	0	0	0

Such thermal comfort compromises must be carefully weighed against infection control benefits to avoid adverse effects on occupant well-being and productivity.

3.3. Analysis of Probability of Infection

In a confined space like a restaurant the probability of infection strictly depends on the number of infected people that are inside. In order to investigate a reasonable contagiousness that can occur, two types of contests were taken into account: 1 infected person, or 13% of people infected inside the building. The first case is considered the minimum scenario, while the second case is related to the average quantity of infected people based on strep test analysed in Italy during the second wave of contagion that was recorded from October to December 2020. Table 9 shows the probability of infections and the number of new infected people for the two scenarios. These results consider the H24 or Plus 2 h cases that give the same values because they are strictly related to the use of recirculation air.

Table 9. Probability of infection and number of new infected people for the analysed contagion scenarios.

<table>
<tr><th></th><th></th><th colspan="4">Changing Air</th></tr>
<tr><th></th><th></th><th>7.7</th><th>8</th><th>9</th><th>10</th></tr>
<tr><td rowspan="2">Probability of infection (%)</td><td>1 infected person</td><td>1.01</td><td>0.98</td><td>0.89</td><td>0.82</td></tr>
<tr><td>13% of people infected</td><td>6.21</td><td>6.03</td><td>5.51</td><td>5.08</td></tr>
<tr><td rowspan="2">Number of people infected (people)</td><td>1 infected person</td><td>0.5</td><td>0.5</td><td>0.4</td><td>0.4</td></tr>
<tr><td>13% of people infected</td><td>3.1</td><td>3.0</td><td>2.8</td><td>2.5</td></tr>
</table>

For the normal case, in which there is the return air, the probability of infection is 12.77% in the case of 13% of people infected; that means 8.9 new infected people, considering that the number of occupancy is 70 people, and the changing air is 7.7 1/h (see Table 4). Furthermore, the results of Table 8 consider the possibility of increasing the changing air inside the restaurant showing that there is a slight decrease of the probability of infection and consequently of newly infected people. It is worth noticing that in the minimum scenario (1 infected person), in the case study considered, the number of new infected people is less than the unit value, that is, the contagiousness can't increase exponentially. Furthermore, varying the changing air can slightly reduce the probability of infection in the case of 13% of people infected, and there isn't a significant variation for the 1 infected person case.

This substantial infection risk mitigation confirms the effectiveness of increased outdoor air ventilation and extended system operation, albeit at the cost of compromised thermal comfort and high energy consumption.

4. Discussions

The results confirm the critical tension between infection control measures and system energy efficiency. While guidelines stressing 100% outdoor air and extended system runtime significantly reduce infection risk, they generate a substantial increase in HVAC energy demand and may compromise indoor thermal comfort.

This general trade-off is consistent with recent literature. Xu et al. [61] developed a simulation-based framework explicitly linking infection risk, energy consumption, and thermal comfort, showing that lower infection risk and improved comfort can be achieved only at the expense of higher energy use. In the present restaurant case, the same direction emerges more sharply: the outdoor-air-only strategies reduce infection probability by about 60–65%, but they also produce a strong increase in HVAC energy consumption and a reduction in neutral PMV hours. At the same time, more advanced air distribution strategies can outperform conventional mixing approaches. Kong et al. [57] reported that interactive cascade ventilation improved indoor air quality, thermal neutrality, and infection control compared with conventional reference systems, while Li et al. [62] experimentally showed that alternative ventilation layouts in dense classrooms can reduce peak infection risk while also improving energy utilization. Compared with these studies, the present work indicates that simply suppressing recirculation and extending operation time is effective for infection-risk mitigation, but it is not necessarily the most balanced solution from an energy and comfort perspective.

The literature also confirms that the balance among infection control, thermal comfort, and energy use is highly dependent on climate, season, and system configuration. Maiques et al. [59] showed in Mediterranean educational buildings that mechanical ventilation strategies can ensure indoor air quality and thermal comfort with lower HVAC demand than less controlled ventilation modes, while CO_2-based control can further reduce energy use. This climatic sensitivity is relevant for the present Rome case study, where the penalty of conditioning outdoor air is one of the main reasons why the h24 and Plus 2 h scenarios become energetically critical. Similarly, Luo et al. [60] found that natural ventilation can maintain both low infection risk and acceptable comfort under mild conditions, whereas in summer and winter mechanical ventilation is required; however, recirculating air-conditioning increased infection risk, and filtration strongly reduced it. This point is especially relevant for the present study because the main difference between the Normal scenario and the alternative scenarios is precisely the suppression of return-air recirculation. In addition, Jahromi et al. [58] analysed the effect of different recirculation ratios on thermal comfort and indoor air quality and validated their numerical model against experimental and numerical benchmark data, further supporting the importance of recirculation as a governing parameter. Taken together, these studies support the physical plausibility of the trends obtained here, even though the numerical values remain case-specific.

A further implication of the comparison with recent studies is that static ventilation strategies are rarely optimal across all operating conditions. Giraldo-Pérez et al. [63] showed that adaptive control can reduce unnecessary ventilation effort compared with standard fixed-rate approaches, while recent reviews by Zhang and Lin [64] and Huang and Hughes [65] indicate that advanced ventilation and control strategies are increasingly moving toward adaptive, occupancy-aware, and multi-objective operation in order to balance indoor air quality, infection-risk control, thermal comfort, and energy performance. In this sense, the present manuscript contributes as a bounded case study: it does not claim a universally optimal solution, but it clearly shows that using 100% outdoor air as a blanket strategy can lower infection risk while simultaneously creating substantial energy and comfort penalties. The comparison with the recent literature suggests that more balanced solutions may require combinations of moderated ventilation, filtration, real-time monitoring, and predictive or demand-based control rather than a single maximization of outdoor air intake.

Finally, the present work remains a modelling study and does not include field measurements of pathogen load or bioaerosol concentrations in the analysed restaurant. For this reason, the absolute values of infection probability and thermal comfort cannot be independently validated on-site within the current study. However, the consistency of the obtained trends with recent simulation, experimental, and observational studies [57–65] provides external support for the interpretation of the results. Future work should therefore move in two parallel directions: first, validation through field monitoring in real restaurant environments; second, the assessment of hybrid mitigation strategies that combine ventilation, filtration, and adaptive control in order to reduce infection risk without incurring the full energy penalty associated with prolonged 100% outdoor-air operation.

5. Conclusions

This study analysed the impact of ventilation strategies aimed at reducing microbial contamination and infection risk within a restaurant HVAC system. The comparative scenarios demonstrated a clear trade-off: eliminating air recirculation and extending system operation reduces infection probabilities by approximately 60–65% during conditions of moderate contagion but yields energy consumptions up to 17 times higher than baseline operation and significant declines in thermal comfort.

These findings underscore the necessity for an integrated, multidisciplinary approach to HVAC system design and management that harmonizes health protection, energy efficiency, and occupant comfort. Adoption of advanced air cleaning technologies, dynamic operational control informed by real-time environmental sensing, and stringent maintenance protocols are essential to achieving this balance.

Future work should focus on developing adaptive HVAC systems capable of responding in real time to indoor microbial challenges while minimizing energy penalties. Moreover, addressing microbial diversity beyond viral and bacterial pathogens, understanding long-term health implications of indoor air quality, and refining guidelines for diverse building uses remain key research priorities.

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