Indoor air modelling and infection risk assessment in a naturally ventilated patient room

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ABSTRACT

Sufficient ventilation in clinics is critical for diluting virus concentrations and lowering subsequent doses inhaled by the occupants. Several advanced simulation methods and tools for building physics and indoor air fluid dynamics are currently available in research and industry. However, in naturally ventilated buildings, indoor air distribution depends strongly on local and dynamically changing conditions, e.g., opening sizes and time, exhaust shaft location, and climatic and weather conditions. Therefore, considering the physical complexity of air and temperature distribution in natural ventilation rooms, new reliable and handy modelling techniques are required to predict infection risks of COVID-19 in typical naturally ventilated spaces.

This study includes field measurements and simulations of indoor air quality and building performance in a naturally ventilated hospital building. The indoor air model is built into the building energy simulation tool IDA-ICE to calculate air change rates in a naturally ventilated patient room. An initial data set was collected from the presurvey, architectural plans, and observations. The model was calibrated against indoor air measurements. Then, simulated air changes and room conditions were used for infection risk calculation. The virus-specific parameters of the infection risk model and human activity values are estimated separately using scientific literature studies.

According to measurements and simulations, natural ventilation is insufficient to dilute airborne impurities in this case study. Additionally, the infection risk analysis indicated that the infection emission rate had a significant impact on the results of different ventilation strategies. The combination of controlled ventilation and air purification reflects a comprehensive and proactive approach to managing infection risks in patient rooms and healthcare settings. The simulation tool can help engineers and designers explore different ventilation strategies and infection control measures.

KEYWORDS

Natural ventilation, infection risk assessment, patient room, COVID-19, dynamic simulation

1 INTRODUCTION

The COVID-19 pandemic has sparked extensive research on airborne transmission of diseases, virus properties, risk assessment and the role of ventilation technology and air purification in preventing airborne transmission in various indoor spaces. Hospitals and healthcare facilities, being high-risk environments, have been of particular interest in these studies. Multiple case studies have demonstrated that SARS-CoV-2 can remain viable in aerosols for several hours, further emphasising the significance of proper ventilation and air filtration in healthcare facilities (Izadyar and Miller, 2022; Zhao et al., 2022).

Ventilation systems in modern hospitals are designed to reduce airborne infection risks and prevent cross-infections. To ensure proper dilution of airborne viruses, patient rooms in hospital facilities must have 4-12 air exchanges per hour (ACH), as specified by corresponding standards and regulations (Lancet COVID-19 Commission, 2022). The COVID-19 pandemic has highlighted the limitations of natural ventilation in maintaining precise control over indoor air quality and airflow rates. In high-risk environments, mechanical ventilation with controlled airflow rates and appropriate filtration is often preferred to ensure infection control measures (WHO, 2021).

Despite the challenges brought to light during the COVID-19 pandemic, natural ventilation remains a common practice in hospitals, particularly in regions with warmer climates where it can be more easily implemented due to favourable weather conditions (Abbas and Dino, 2022; Fageha and Alaidroos, 2022). In addition, many hospitals, especially older ones, were designed with architectural features that promote natural ventilation, such as large windows, high ceilings, rooms and corridors aligned to facilitate cross-ventilation (WHO, 2009). Upgrading or retrofitting these healthcare facilities with mechanical ventilation might require significant structural modifications and compliance adjustments, which can be challenging for older facilities (Gilkeson et al., 2013). If upgrading the existing ventilation system is not immediately feasible, a combination of strategies may be needed to enhance ventilation and indoor air quality in healthcare facilities. This might involve optimising natural ventilation where feasible, implementing air purification technologies in specific areas, and considering mechanical ventilation for high-risk spaces (Fennelly et al., 2023). The design of such spaces requires careful consideration and planning to ensure that the combination of different options effectively promotes airflow and maintains a safe environment.

Virus risk assessment in naturally-ventilated indoor spaces is a complex and multifaceted problem that involves various aspects of building physics and understanding the characteristics of the specific virus in question. The transient nature of natural ventilation, combined with fluctuating outdoor and indoor conditions, makes simulation of these spaces computationally intensive and requires advanced modelling techniques. In engineering applications, it is critical to balance the level of detail in the simulation model with computational resources to meet the simulation goal. To overcome these challenges, researchers and engineers often adopt a combination of simplified modelling techniques, empirical correlations, and advanced indoor air simulation tools (Moghadam et al., 2023). When assessing virus risk in naturally ventilated settings, researchers often use a combination of building energy simulation, fluid dynamics, and contaminant transportation to determine optimal ventilation design. The design scenarios calculated by such models typically represent the effect of different building types and climate zones (Tognon et al., 2023), positions of inlet and outlet (Abbas and Dino, 2022), optimised window opening control (Grygierek et al., 2022) and occupancy scenarios (Fageha and Alaidroos, 2022) on airborne infection risk. In such design models, Wells-Riley models are commonly used to assess the impact of ventilation strategies, filtration systems, occupancy patterns, and other controls on the risk of infection transmission (Kurnitski et al., 2023).

The case studies in simulation research on virus risk with natural ventilation are usually made for educational buildings, offices, and commercial and residential buildings (Moghadam et al., 2023). However, there is a lack of evidence-based studies in hospital facilities that are strategically important and may not be closed in case of a pandemic.

This research aims to develop a straightforward engineering methodology to evaluate virus risk in naturally vented healthcare facilities. It will also provide options for possible ventilation and air purification strategies. The following sections present an infection risk assessment case study in a naturally ventilated patient room. This case study utilised measurements of indoor air parameters, dynamic simulation of natural ventilation performance and virus risk assessment. Finally, infection risk-based solutions are described using ventilation strategies and air purification combinations.

2 CASE STUDY

This case study is based on an analysis of ventilation and air purification solutions in the Matei Bals Hospital patient room in Romania, Bucharest. Background information about the case building was collected during the pre-study phase of the research (Figure 1). The hospital building has brick walls and large windows. A closed hallway separates the patient rooms on opposite sides of the building. The studied patient room is located on the second floor of a four-storey Covid Ward building. The patient room is designed for two patients. The building is ventilated only by natural ventilation, with fresh outdoor air supplied by infiltration and openings and exhaust air removed by an exhaust shaft. The patient's room is heated by a water radiator under the window connected to the district heating system.

The pre-study survey provided information about building use, approximate window opening schedules and occupancy in the patient room. In addition, information on possible diseases of patients and disinfection methods and other measures to prevent disease spread were revealed. The window opening schedule was claimed to be every two hours for fifteen minutes. A face mask is required for all hospital personnel and patients. In the infection isolation rooms, personnel wear protective suits. Hospital spaces can spread viruses due to the absence of a controlled ventilation system and air purification. Thus, further research included fresh air exchange and virus risk analysis in dynamic conditions. In addition to the survey, cloud-based indoor air quality (IAQ) monitoring was performed in the pre-study phase. Indoor air parameters fluctuated highly during the measurements. Also, measurement data quality was highly dependent on the internet connection. Therefore, further research included on-site indoor air measurements to check the quality of the data loggers.

The possible technological solutions applied in the study included the combination of portable air purifiers with existing natural ventilation. Mechanical ventilation option was also checked in the infection risk calculation.

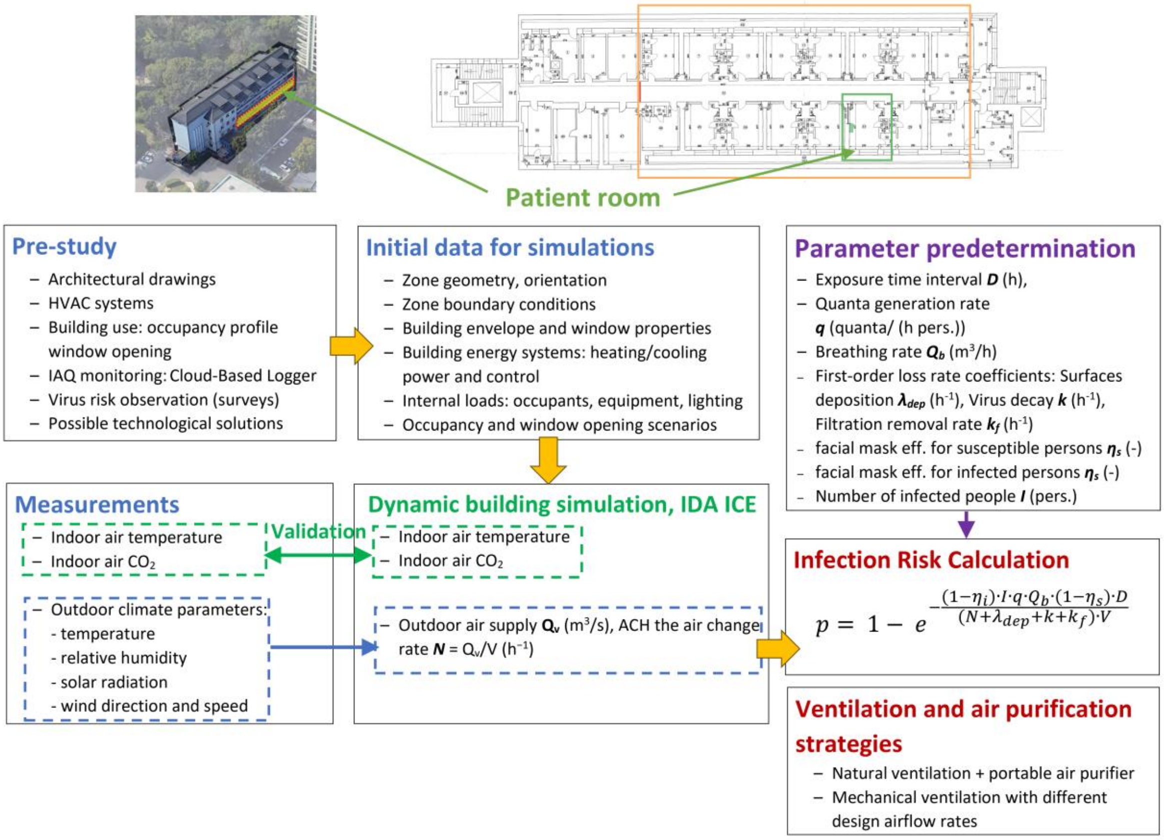

Figure 1: Case study algorithm and methods

3 METHODS

The methods applied in this section describe the research methods that followed the pre-study phase, including measurements of indoor air parameters, dynamic building simulation and infection risk calculation.

3.1 Indoor air measurements

The indoor air temperatures and CO_2 levels were measured with the cloud-based IAQ monitoring service SmartWatcher® and data loggers Onset HOBO®. The cloud-based IAQ monitoring portable device SmartWatcher® was located on the internal wall at a height of 2 meters. Three data loggers Onset HOBO® were placed on the tripod at three heights 0.5 m, 1.0 m and 1.5 m (Figure 2). In addition, during the measuring campaign the air purifier ISEC Kullas® was installed between the patient beds. The air purifier was working at 60% power, providing CADR 192 m^3/h.

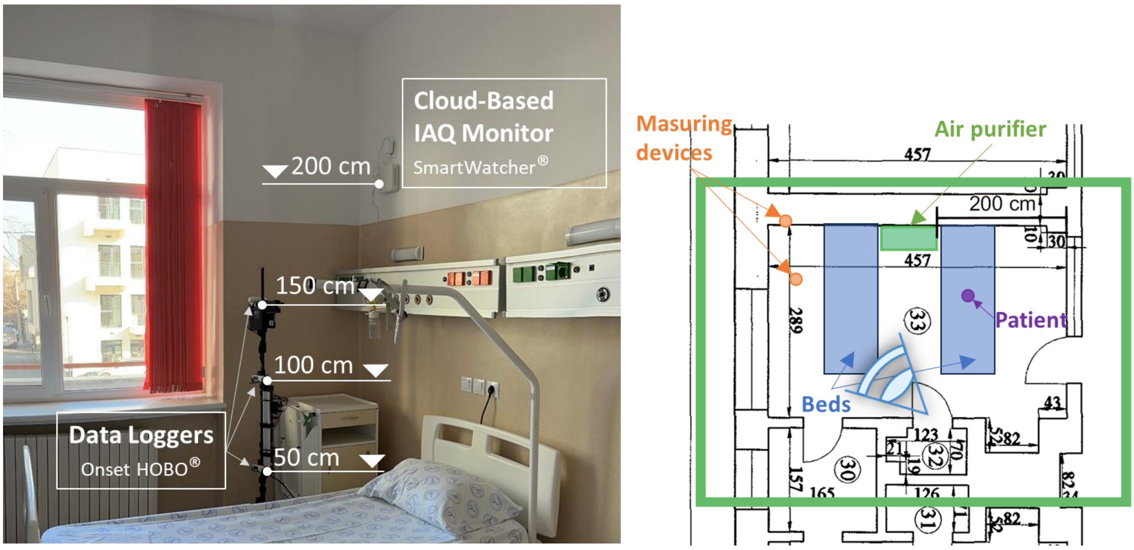

Figure 2: Patient room layout and location of the measuring devices

The SmartWatcher® IAQ Monitoring Service is a cloud-based indoor air quality monitoring service showing real-time values for the investigated parameters. The monitoring service collects data every 1 minute and stores it in the cloud every 10 minutes. The data loggers Onset HOBO® were also configured with a one-minute measurement interval. The logger's built-in memory was used to store data, which was later retrieved via USB. The outdoor air measurements were taken from the local meteorological institute, National Air Quality Monitoring Network in Bucharest. The measuring devices were validated at VTT Technical Research Centre of Finland Ltd. (https://www.vttresearch.com/en). Table 1 shows the technical parameters of the temperature and carbon dioxide sensors of the measuring devices.

Table 1: Measuring devices

	SmartWatcher®		**Onset HOBO®**	
	Air temperature °C	**CO_2 ppm**	**Air temperature °C**	**CO_2 ppm**
Range	-10 to 50 °C	0 – 10000 ppm	0 to 50 °C	0 – 5000 ppm
Accuracy	±0.1 °C	±3% of reading, ±30 ppm	±0.21°C	±50 ppm ±5% of reading at 25°C
Resolution	0.1 °C	1 ppm	0.024°C at 25°C	1 ppm

3.2 Dynamic building simulation

This section describes the initial data for dynamic simulation and the methodology for calculating the dynamic airflow rates in a naturally ventilated patient room. Figure 3 presents the initial simulation data in IDA ICE building simulation tool (Bring et al., 2000). The model utilised measured climate data to simulate the outdoor conditions. The room layout and outdoor climate parameters were measured during the measurement campaign. The parameters of the building envelope, exhaust shaft, and heat gain from lighting and equipment were estimated based on visual observation. In the building simulation, the air purifier acts as a source of recirculating air and heat gain from equipment. A zone heat balance was calculated in order to reach an average indoor air temperature of 21 °C to determine the heating power of the water radiator. Since the control and power of the heater were unknown, circuit water temperatures of 70°C at the inlet and 40°C at return were chosen based on average engineering practice. As it was not possible to observe and detect window opening times in hospital facilities, window openings were not considered in the current simulation. In addition, possible window openings didn't affect indoor air measurements, which indicates short window opening times.

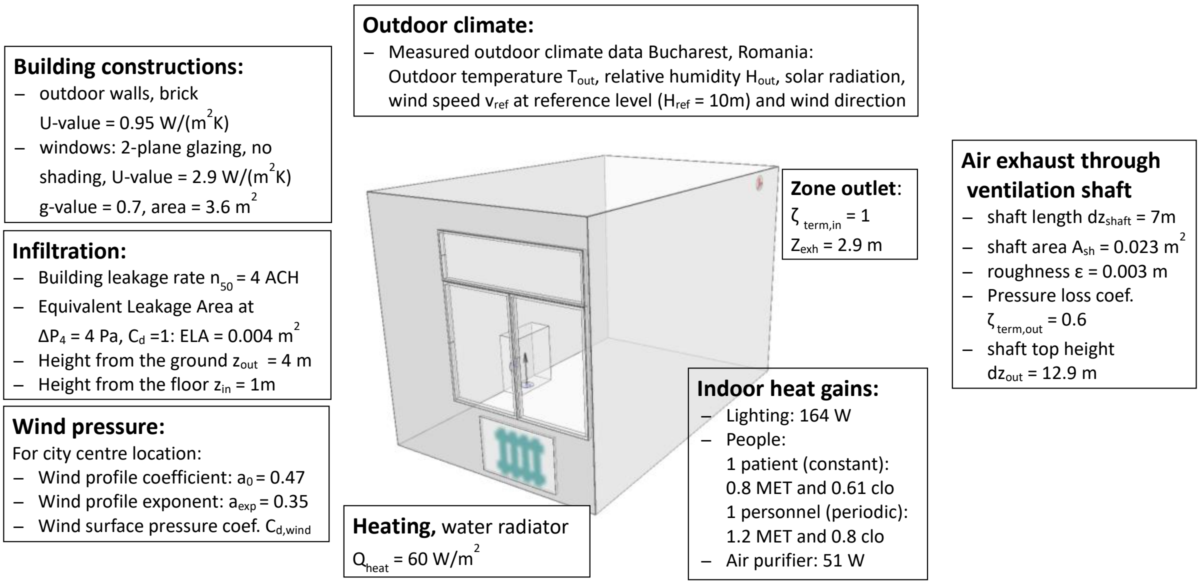

Figure 3: Initial values for dynamic simulation

Air supply was estimated through wind-driven infiltration and air leakage due to pressure differences. The infiltration rate was estimated based on measurement in a building with similar year of construction in Romania (Iordache and Catalina, 2012). In the model, the combined envelope leak area is distributed on all external walls, at z_{in} = 1 m above floor level. The wind pressure variation across the building's surfaces was estimated using wind pressure coefficients $C_{d,wind}$, calculated for the city centre location. The pressure difference through the leakages dp_{out-in} was defined as:

$$dp_{out-in} = (P_{in} - \rho_{in} \cdot g \cdot z_{in}) - \left(P_{air} + 0.5 \cdot C_{d,wind} \cdot \rho_{out} \cdot v_{wind}^2 - \rho_{out} \cdot g \cdot z_{out}\right) \quad (1)$$

where: P_{in} [Pa] is the static pressure of indoor, ρ_{in} [kg/m^3] is indoor air density; P_{air} [Pa] is the atmospheric air pressure; ρ_{out} [kg/m^3] is indoor air density.
The local wind velocity at the roof height v_{wind} was calculated with the Eq. 2. Wind profile exponents a_0 and a_{exp} are used for wind speed correction from the reference height H_{ref}.

$$v_{wind} = a_0 \cdot v_{ref}(H_{build.}/H_{ref})^{a_{exp}} \quad (1)$$

where H_{ref} [m] is height of meteorological wind measurements, $H_{ref} = 10$ m; H_{build} is the height of the building, m.
The mass flow $m_{out\text{-}in}$ [kg/s] through the infiltration was calculated with the power law equation:

$$m_{out-in} = c \cdot dp_{out-in}{}^{n} \quad (3)$$

where n [-] is the flow exponent, which is a dimensionless parameter representing the non-linearity of the airflow regime, n = 0.6; c [kg/(s Pa^n)] is the power-law coefficient, which is calculated from the equivalent leakage area (ELA) as:

$$c = ELA \frac{\sqrt{2\Delta P_4 \cdot \rho_{20°C}}}{\Delta P_4{}^{0.6}} \approx 1.35 \cdot ELA \quad (4)$$

The pressure differences from the indoor air through the exhaust shaft consist of the components related to buoyancy flows from the floor to outlet terminal $dp_{in\text{-}shaft}$, airflow inside the shaft dp_{shaft} the air outlet from the shaft towards the outdoor air $dp_{shaft\text{-}out}$ (Eq. 5-7):

$$dp_{in-shaft} = \left(P_{in\_floor} - \rho_{in} \cdot g \cdot z_{exh}\right) - P_{term,in} \quad (5)$$
$$dp_{shaft} = P_{shaft1} - P_{shaft2} - dz_{shaft} \cdot g \cdot \rho_{shaft} \quad (6)$$
$$dp_{shaft-out} = P_{term,out} - \left(P_{out,roof} - \rho_{out} \cdot g \cdot dz_{out}\right) \quad (7)$$

where P_{in_floor} [Pa] is the static pressure at the floor level; $P_{term,in}$ [Pa] is the static pressure at the outlet terminal in the room; P_{shaft1} and P_{shaft2} [Pa] are the static pressures on the bottom and top of the shaft respectively; $P_{term,out}$ [Pa] is the static pressure at the terminal on the top of the exhaust shaft; $P_{out,roof}$ [Pa] is the outdoor air pressure at the roof level.
The equation Eq.8 defines the mass flow $m_{in\text{-}out}$ [kg/s] through the exhaust shaft from indoor air, taking into account head pressure losses at the outlet terminal $\zeta_{term,in}$ and exhaust grill $\zeta_{term,out}$, as well as friction losses inside the shaft. Based on the flow regime depending on Reynolds number Re, surface roughness ε, and shaft dimensions A_{sh}, friction losses are presented within the combined coefficient C_{tot} (ASHRAE, 2017).

$$m_{in-out} = A_{sh}\sqrt{2 \cdot \rho_{20°C}} \cdot \left(\sqrt{\frac{dp_{in-outlet}}{\zeta_{term,in}}} + \sqrt{\frac{dp_{shaft-out}}{\zeta_{term,out}}}\right) + C_{tot}\sqrt{dp_{shaft}} \quad (8)$$

$$C_{tot} = f(Re, \varepsilon, A_{sh})$$

Therefore, the ventilation rate calculation involves estimating the infiltration rate into a room due to buoyancy (stack effect) and wind-driven forces in IDA ICE building simulation software. The software uses wind profile equations and wind pressure coefficients to estimate outdoor wind speed at varying heights relevant to the building's characteristics. The stack effect takes into account differences in temperature between indoor and outdoor air, as well as pressure losses in the exhaust shaft. The calculated ventilation rates are used in the infection risk estimation described in the following Section 3.3.

3.3 Infection risk model

Infection risk calculations were conducted using the Wells-Riley model (Eq.9), which is widely used in ventilation design and indoor air quality studies to estimate infection risk, especially in the context of infectious respiratory diseases such as influenza and COVID-19. The model parameters were chosen from the latest literature (Kurnitski et al., 2023).

$$p = 1 - e^{-\frac{(1-\eta_i)\cdot I \cdot q \cdot Q_b \cdot (1-\eta_S)\cdot D}{(N+\lambda_{dep}+k+k_f)\cdot V}} \quad (9)$$

Due to the sensitivity of the Wells-Riley model to quanta emission rates, the study examined the effects of different emission rates on the probability of infection transmission in indoor spaces in the absence of facial masks (η_s =0 and η_i = 0) using a range of quanta emission rates from 2 to 10 quanta/hour per person (Table 2). Simulations were conducted under conditions in which one infectious (I =1) and one susceptible person were constantly present.
A dynamic airflow calculation was used to simulate infection risk in natural ventilated conditions with and without the air purifier (ISEC Kullas). In addition, the mechanical ventilation cases without air purifiers were calculated with the recommended minimum (4 ACH) and maximum (12 ACH) air exchanges for patient rooms (Lancet COVID-19 Commission, 2022).

Table 2: Infection risk model parameters

Parameter	Unit	Value
Quanta generation rate per infectious person q	quanta/(h pers)	2 – 10
Breathing rate for resting people Q_b	m^3/h	0.5
Surfaces deposition loss rate λ_{dep}	1/h	0.6
Filtration removal rate from portable air purifier k_f	1/h	4.5

4 RESULTS

This section describes the results of the study. First, the measurements of indoor air temperatures and carbon dioxide were analysed and compared with the simulation results. The calculated air flow in natural ventilation was presented with the correlation to outdoor air measurements. Finally, the infection risk methodology and calculation result were shown for different parameter ranges and ventilation solutions.

4.1 Measured and simulated parameters of indoor air

The air temperatures and CO_2 levels simulated by IDA-ICE-model was compared with measurements in order to validate the building simulation model (Figure 3). The simulated air temperatures were closer to the measurement result, especially at the SmartWatcher measuring point. The temperature measured by HOBO sensors was about 1 °C higher than the simulated temperature measured by SmartWatcher (Figure 3a). This could be due to the local effect of internal heat gain sources and heating system controls that were not taken into account when calculating the heat balance. Also, the sensors' sensitive elements faced different angles toward solar radiation, heat gain sources, and airflow distribution, which resulted in different fluctuation patterns. In addition, a rapid temperature rise of 1 °C occurred due to reflected solar radiation around the same time (around 3:20 pm). Solar radiation from the eastern-facing window affected HOBO measurements in the early morning (7-8 am). Generally, the simulation model is able to capture the main patterns for indoor air temperature changes.
As the outdoor air temperature mainly determined the natural driving force for airflow, simulated air changes per hour were higher at night when the outside air was colder. Air exchanges also impacted indoor CO_2 distribution, resulting in minimal levels at night and maximum levels during the day (Figure 3b). The measured indoor CO_2 levels tended to vary throughout the day based on occupant activities, ventilation rates, and other environmental

conditions that were difficult the record and simulate. However, the model is able to present the main tendencies of dynamically changing CO_2 and calculate the mean averaged values. As a result of the validation of dynamic building simulations with measurements, it can be concluded that the simulation model is capable of predicting the thermal and mass balance with the desired level of accuracy.

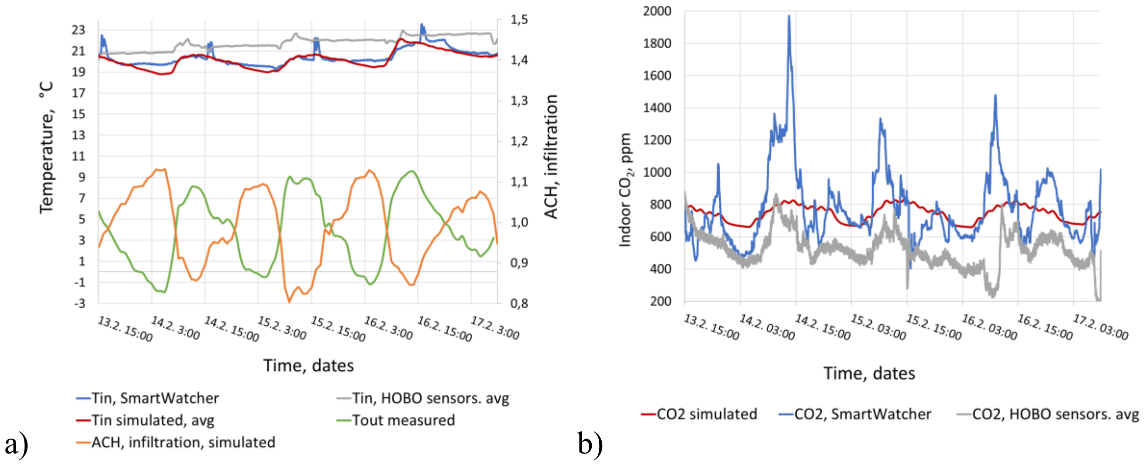

Figure 3: Measured and simulated indoor air temperatures (a) and CO_2 (b)

4.2 Infection probability calculation

Infection probabilities were calculated before and after air purifiers were installed in the patient room (Figure 4a). Infection risk results with lower quanta are more sensitive to changes in airflow rates. According to the calculations, the air purifier with 2 quanta/h pers is more effective than the one with higher quanta values. It might be because the air purifier's ability to remove infectious particles is more noticeable when emissions are lower. In cases where emission rates are higher, the air purifier might not be able to remove particles from the air as quickly as they are being emitted.

Figure 4b shows the increase in infection risk with different ventilation systems and adding the air purifier. Predictably, with natural ventilation alone the infection probability is the highest. The use of a mechanical ventilation system with a high air exchange ACH 12 demonstrates the best efficiency in reducing infection risk across different quanta emission rates. However, mechanical ventilation with lower ACH might have limitations in effectively reducing infection risk, especially in scenarios where quanta emission rates are high. In the studied case, natural ventilation combined with an air purifier can be efficient even in scenarios with high quanta emission rates.

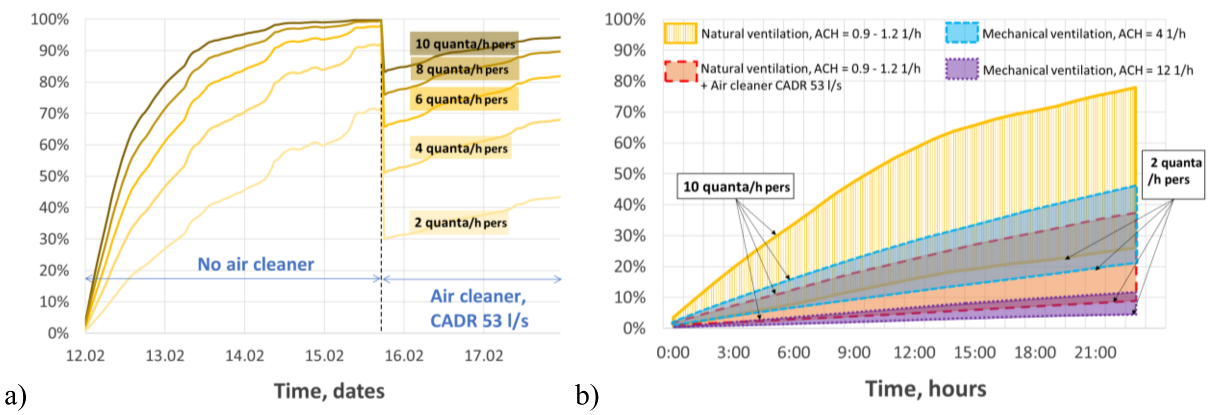

Figure 4: Infection risk probability during the measuring period (a) and withing a day of exposure (b)

5 DISCUSSION

Accurate field measurements and precise simulations in real-world hospital facilities often encounter different challenges, such as limited data availability and difficulties in obtaining accurate building information. Building simulations allow you to explore various scenarios, interventions, and technologies in a controlled environment, while measurements can be used for validation and separate analysis.

Natural ventilation simulation accuracy depends on modelling assumptions. Small changes in input parameters or boundary conditions can lead to significant results differences. Validating simulation results with real-world measurements can be complex, especially for large and complex buildings with varying conditions. In this case, advanced models like CFD can be used to better understand the airflow behaviour of a building.

Within hospital settings, the Wells-Riley infection risk model has significant limitations since it does not consider disease-specific parameters, assumes a uniform distribution of infection particles, and is not suitable for dynamic scenarios. However, it is still possible to apply this model to estimate safe spaces and infection risk-based ventilation design.

While air purifiers can effectively reduce infection risks by removing airborne particles, including infectious agents, they might not inherently improve all aspects of indoor air quality (VOCs, humidity or temperature in the indoor environment). Thus, air purifiers should be used in conjunction with other measures such as ventilation, proper maintenance of the HVAC system, and other air cleaning measures.

6 CONCLUSIONS

This study investigated a naturally ventilated patient room in Bucharest, Romania. Indoor air measurements and building simulations were combined with an infection risk assessment to investigate possible ventilation and air purification technologies. A simulation model for the studied room was developed using IDA ICE software and validated with measurements. In the simulation model, dynamic airflow rates with natural ventilation were calculated and applied to infection risk estimation. These findings emphasise the significance of both emission rates and airflow rates when assessing the effectiveness of air purifiers and ventilation technologies. The results show that natural ventilation alone is not able to sufficiently dilute airborne impurities. A combined ventilation strategy and air purification are required in patient rooms to prevent infection. The simulation tool developed can be used for infection risk analysis in engineering applications to optimise hospital design and operation. The research contributes to the understanding of infection risk in indoor environments and enables finding optimised ventilation and air purification strategies to reduce the spread of airborne infectious diseases.

7 ACKNOWLEDGEMENTS

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