

Transient zonal model for predicting indoor airflows in naturally ventilated buildings: a case study of hospital patient rooms

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Abstract. Proper ventilation dilutes viral concentrations and reduces infection risk. Advanced simulation methods are needed to understand indoor airflow dynamics in naturally ventilated spaces, like hospital patient rooms. Predicting airflow distribution is complex due to factors such as variable opening sizes, changing weather conditions, and exhaust shaft locations. Simulation methods, such as Computational Fluid Dynamics (CFD), building energy simulation, and analytical mathematical models are used to address these challenges. Zonal models, in particular, bridge the gap between the simplicity of standard perfectly mixed room air assumptions and the computational intensity of CFD simulations. This research presents a case study of patient rooms in a hospital located in Romania. The study focuses on validating a coarse grid zonal model implemented in the building simulation tool IDA ICE for predicting indoor airflow in patient rooms with natural ventilation. The model is validated against field measurements of indoor air parameters in the patient room. This study demonstrates the capability of a one-dimensional transient zonal model integrated into building simulation software to predict main indoor air distribution patterns. This model requires minimal prior knowledge of airflow characteristics, making it a versatile tool for predicting indoor air quality in naturally ventilated hospital buildings. The method can identify risky areas for infection control and optimise ventilation in healthcare facilities.

1 Introduction

Ventilation plays a crucial role in healthcare settings, especially in controlling infection risks. Airflow spatial distribution in patient rooms, often naturally ventilated, is complex and influenced by multiple factors. Advanced simulation methods, such as CFD and zonal models, are critical for understanding and predicting these airflow patterns. These methods help address the challenges posed by varying room configurations and external conditions [1].

While useful for overall building energy analysis, building energy simulation tools often lack the detailed airflow analysis needed for specific spaces like patient rooms [2]. In the

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evolving landscape of building performance simulation software, a significant challenge lies in accurately modelling and predicting indoor environmental quality, particularly in terms of airflow, temperature distribution, and pollutants concentration [3]. Traditional approaches to commercial building energy simulation tools often rely on the assumption that each zone within a building is well-mixed, implying uniform temperature and pollutant concentration throughout the zone's air volume. Moreover, the majority of airborne risk models assume steady-state conditions and well-mixed air in a single zone, which may lead to overestimation of infection risk or underestimation of quanta emissions, especially in poorly ventilated spaces [4].

Some tools have incorporated airflow networks to address some limitations of the standard room model. These networks calculate airflow rates between well-mixed zones and have successfully solved various engineering and design challenges. However, they are not designed to capture detailed airflows within individual rooms, limiting their effectiveness in certain applications.

CFD represents a more advanced method capable of precise airflow prediction inside rooms. Despite its detailed analysis capabilities, CFD provides precise airflow and temperature distributions. However, it requires extensive computational resources and detailed pre-knowledge of airflow patterns due to the need for a high number of grid points. This limitation becomes more significant when considering complex airflow physics, various numerical methods, and turbulence modelling approaches.

Zonal models emerge as an intermediate solution, bridging the gap between the simplistic standard room model and computationally intensive CFD. These models aim to predict air movement, temperature, and pollutant distributions with far less computational demand than CFD, making them suitable for applications like yearly simulations. Zonal models divide a room into multiple nodes, each calculating air temperature and pollutant concentration, with some models also calculating air velocity [5]. They have been employed in various studies, including examining the interaction between room space and terminal units, temperature stratification in non-industrial high-ceiling buildings, and the distribution of indoor gaseous contaminants [6]. The advantage of zonal models lies in their short computational time and their potential for integration with multizone models. However, the limitation of the zonal model lies in its inability to directly predict aerosol and particle distribution, which are critical factors in assessing airborne infection risk.

The continuous development and refinement of zonal models demonstrate a concerted effort to bridge the gap between the need for detailed environmental analysis and the practical limitations of computational resources. The incorporation of zonal models into building simulation software has seen some notable implementations. In most cases, the zonal models are based on Togari's [7] non-pressurised model zonal model that divides a room into horizontal layers to predict vertical temperature distribution. This model calculates heat and mass transfer between layers, accounting for airflows along vertical surfaces and airstreams from supply terminals. The coupling of the thermal zonal model with TRNSYS building simulation software is achieved by incorporating boundary conditions like interior surface temperature and heat transfer coefficient [8]. Once the boundary conditions are given to the zonal model, it calculates the wall currents and the heat and mass conservation equations for all the layers until convergence is reached. In IDA ICE software [9], a 1D zonal model was implemented combined with a simple flow element model. This setup is used for simulating the entire building, and its performance has been evaluated through benchmarks involving natural convection and displacement ventilation [10].

Most existing studies focus on mechanically ventilated spaces or use oversimplified natural ventilation models. Simulating buildings with only natural ventilation requires models that effectively capture complex air movement driven by natural forces like wind and temperature differences. In such simulations, sophisticated infiltration models are essential

for both predicting air movement and assessing building performance [11]. This study aims to fill this gap by developing and validating a transient zonal model integrated into the building simulation tool IDA ICE for predicting indoor airflow in naturally ventilated hospital patient rooms.

2 Case study

This case study is based on the analysis of ventilation and air purification solutions in the Matei Bals Institute for Infectious Diseases patient room in Bucharest, Romania (Figure 1). The hospital building has brick walls and large windows and was built at the beginning of the 20th century. A closed corridor separates the patient rooms on opposite sides of the building. The studied patient room, the Intensive Care Unit (ICU), is located on the second floor of a four-story hospital building. The building relies solely on natural ventilation, achieved through the infiltration of fresh air from the outdoors and openings, with exhaust air being expelled through an exhaust shaft. The patient's room is heated by a fan coil placed under the window and connected to the district heating system. The preliminary survey collected details about how the building is used, rough timings for windows opening, and room occupancy. Information about patients' illnesses, disinfection practices, and other preventative measures against disease spread was also obtained. It was noted that windows are opened every two hours for fifteen minutes. The absence of a controlled ventilation system and air purification in the hospital could facilitate airborne virus transmission. Therefore, further research focused on indoor air parameters and thermal comfort measurements and simulations. In addition, different simulation methods for indoor air distribution are checked. This study has been conducted on the transient zonal models of indoor air distribution, which will be integrated into the building simulation software IDA ICE.

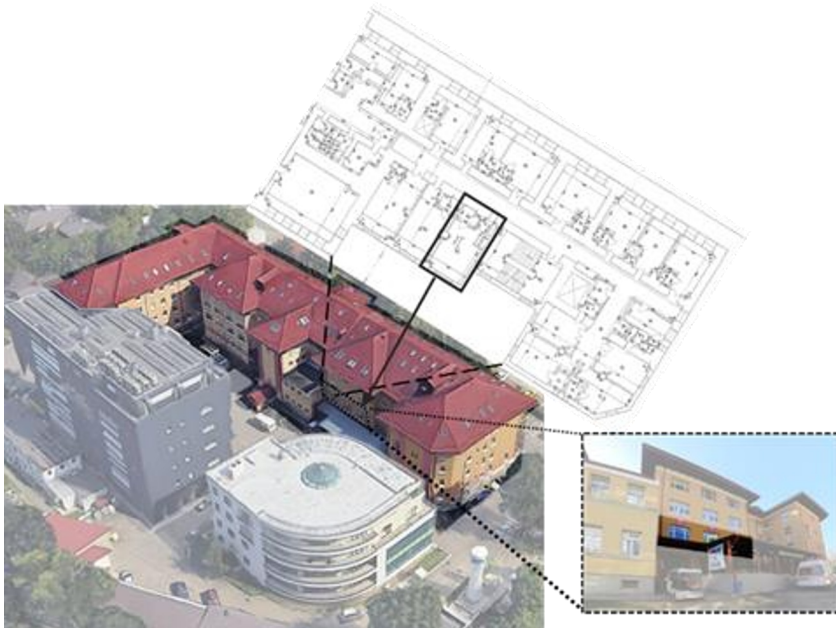


Fig. 1. Location of the ICU room in Matei Bals hospital building.

3 Methods

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

3.1 Indoor air measurements

The indoor air temperatures and were measured with the cloud-based indoor air quality (IAQ) monitoring service SmartWatcher® and data loggers Onset HOBO® (Table 1).

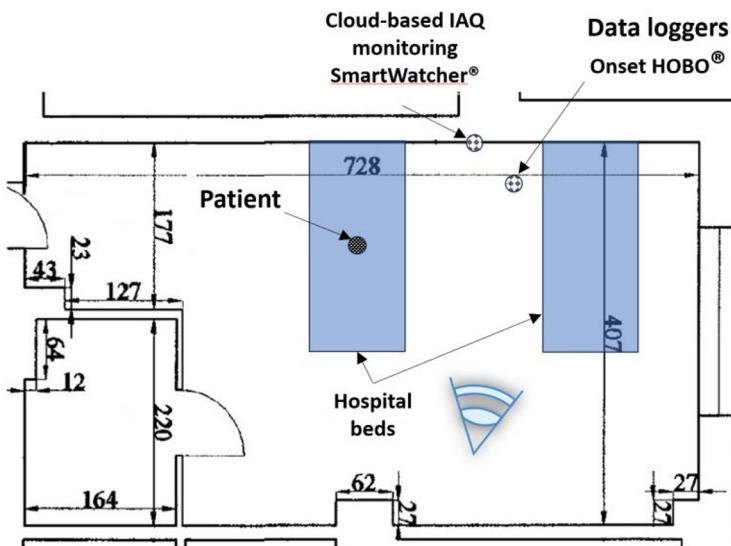
The SmartWatcher® IAQ Monitoring Service is a cloud-based service that monitors indoor air quality in real time. The monitoring service collects data every minute and stores it in the cloud every 10 minutes. The data loggers, Onset HOBO®, were configured with a one-minute measurement interval and stored data in the logger's built-in memory, which was later retrieved via Universal Serial Bus (USB). Outdoor air measurements were taken from the National Air Quality Monitoring Network in Bucharest.

Table 1. Indoor air temperature measuring devices.

	SmartWatcher®	Onset HOBO®
	tair °C	tair °C
Range	-10 to 50 °C	0 to 50 °C
Accuracy	±0.1 °C	±0.21 °C
Resolution	0.1 °C	0.024 °C at 25 °C

The cloud-based IAQ monitoring portable device SmartWatcher® was located on the internal wall at a height of 1 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).

a)



b)

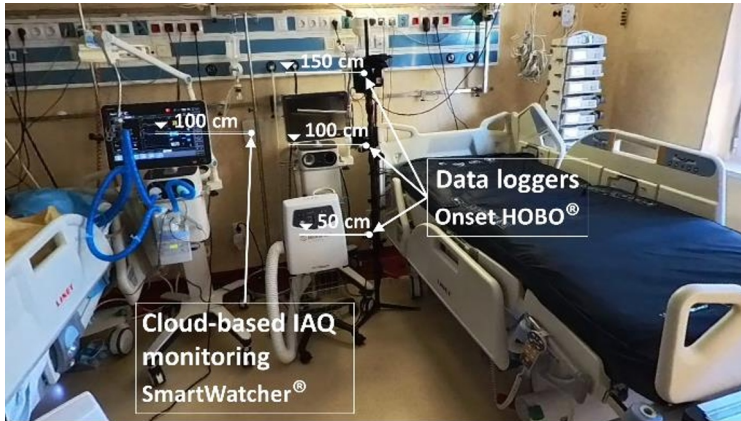


Fig. 2. The location of the measuring devices in the ICU room: a) floor plan and b) photo.

3.2 IDA ICE zonal model

The transient zonal model incorporated into IDA-ICE software in our study marks a significant advancement in indoor environmental simulation (Figure 3). The model integrates enhancements in geometry computation and temperature gradient estimation. It involves computing view factors for complex geometries and integrating flow element models for specific room features like heating sources and ventilation terminals. The model used climate data to simulate outdoor conditions. 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 was considered as a source of recirculating air and heat gain from equipment. To achieve an average indoor air temperature of 21 °C, a zone heat balance was calculated to determine the fancoil heating power. 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.

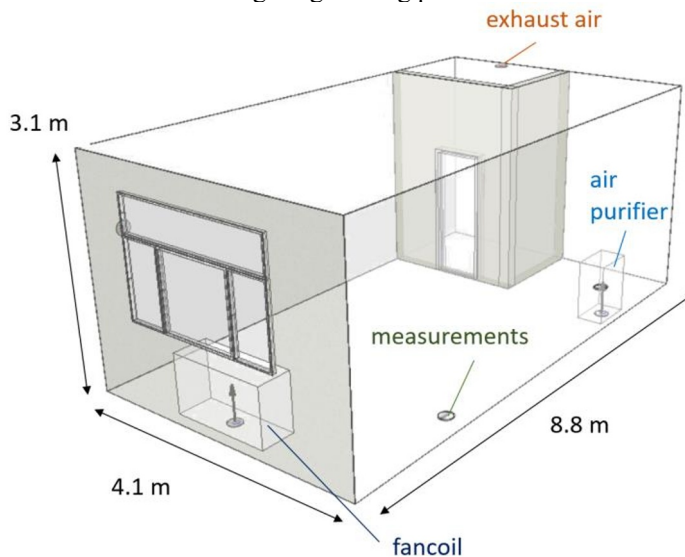


Fig. 3. IDA ICE model layout of the ICU room.

The IDA ICE software for building simulation [9] includes several models to simulate natural ventilation. These models encompass various aspects: an infiltration (leak) model to simulate air leakage into and out of the building, a model for two-directional flow through large openings to represent the exchange of air through doors and windows, a stack effect model to capture the movement of air due to temperature-induced density differences, and multi-zonal flows to simulate the movement of air across different areas or zones within the building (Figure 4).

The zonal airflow model in IDA ICE is based on the non-pressurized zonal model formulated by Togari [7]. The zonal model divides the room into several horizontal layers with uniform air temperature per layer and negligible velocity. The time derivative of the air temperature in each layer is calculated based on energy conservation in an open system and the mass flow exchanged between layers. The model also handles boundary layers along walls and the thermal plume generated by heat emitters, which affect the mass flows and thermal stratification within the room. The trajectory of each flow element is computed using differential equations with appropriate initial conditions.

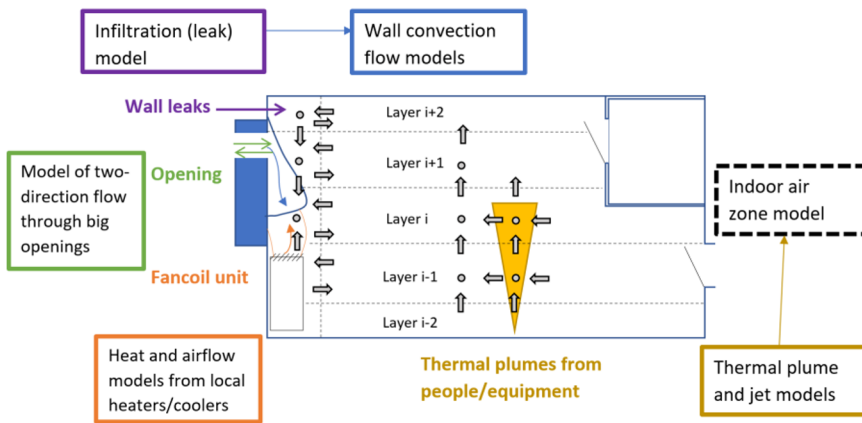


Fig. 4. IDA ICE zonal model of indoor air, heat and mass transfer.

The 1D layered finite difference model [7] allows for the computation of temperature stratification, with a focus on mass flow between layers and the thermal plume generated by heat emitters. An explicit Euler method integrates the conservation of energy. For each layer (i), the conservation of mass can be expressed in the following way:

$$\dot{m}_{lay,i} = \dot{m}_{lay,i-1} + \dot{m}_{flow,i} \quad (1)$$

where i is the layer number, from floor upward; $\dot{m}_{lay,i}$ is the air mass flow from layer (i) to layer (i+1), kg/s; $\dot{m}_{flow,i}$ is the net mass flow from all the flow elements to layer (i).

A finite volume method is used to discretize the conservation of energy in space. This allows us to calculate the time derivative of the air temperature T_i in each layer (Eq. 2):

$$\frac{\rho V_i c_p dT}{dt} = (\dot{Q}_{cond,i} - \dot{Q}_{cond,i-1}) + (\dot{Q}_{trans,i} - \dot{Q}_{trans,i-1}) + \dot{Q}_{flow,i} \quad (2)$$

where ρ is the air density, V_i is the air volume of layer (i) and $C_{p,eff}$ is the effective specific heat of layer (i) in [kJ/K.kg]. $\dot{Q}_{cond,i}$ is the heat flux from layer (i) to layer (i+1) generated by thermal conduction. $\dot{Q}_{trans,i}$ is the heat transported from layer (i) to layer (i+1). $\dot{Q}_{flow,i}$ is net energy input to layer (i) from all the flow elements.

4 Results

4.1 Measured and simulated indoor air temperatures

The IDA-ICE model was used to simulate air temperatures, which were then compared to actual measurements to validate the building simulation model. Figure 4 shows that the simulated air temperatures were quite similar to the measured results. The building has a ventilation coefficient of 0.9 to 1.1 air exchanger per hour (ACH), due to the natural ventilation system. As the air currents are mainly influenced by the outdoor air temperature, the simulated air circulation was higher at night when the outside air was colder, as shown in Figure 5. The slight differences (around 1°C) between HOBO data loggers and Smartwatcher monitoring readings were attributed to the sensors' different vertical locations. The zonal model, capable of predicting vertical temperature stratification, was used to simulate air temperatures at a height of 1 meter.

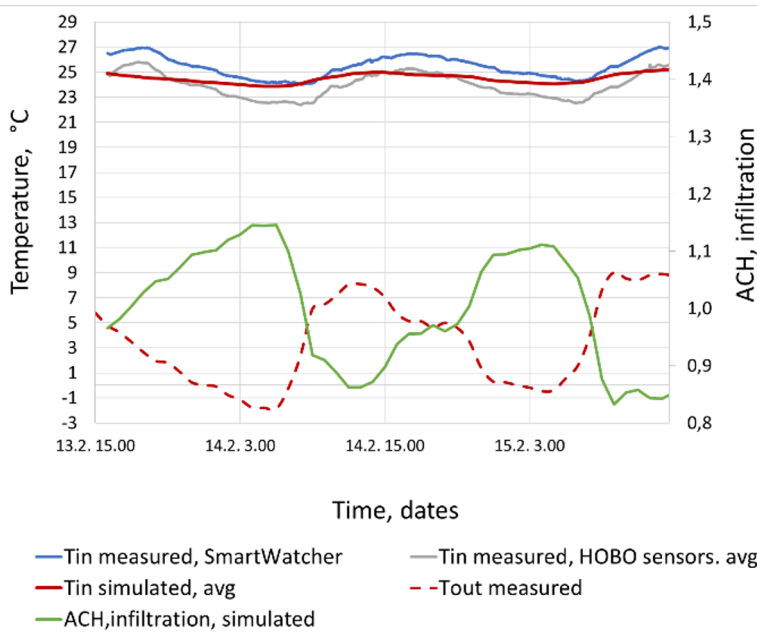


Fig. 5. Measured and simulated indoor air temperatures.

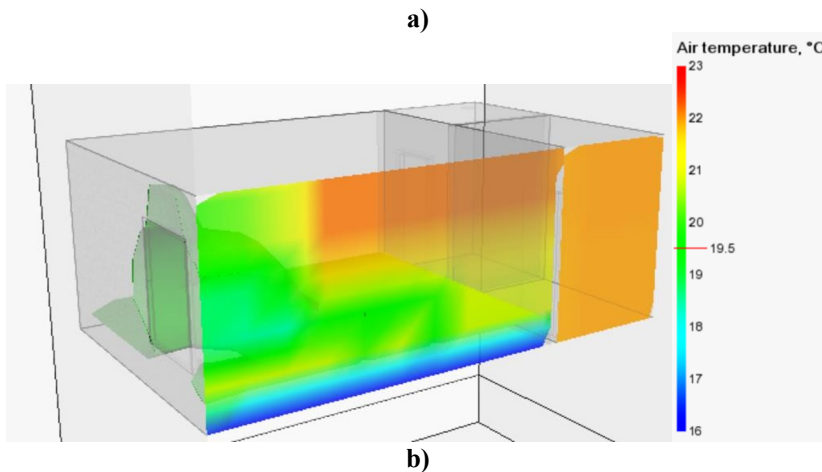
4.2 Indoor air parameter distribution simulated with the zonal model

Figure 6 presents the temperature and velocity distribution within the patient room simulated using the building simulation tool IDA ICE with the transient zonal model. The air distribution dynamics depicted in the simulation highlight the effect of brief window openings on indoor air movement. Such openings can drastically alter the airflow patterns, potentially affecting both temperature control and the spread of infections. Rapid air mixing due to window openings may help to flush out pathogens and reduce infection risk, but it can also create unpredictable temperature layers and airflow paths that need to be carefully managed in sensitive environments like ICUs.

The interaction between the upward hotter air flow from the fancoil and the downward cooler flow near the windows in an ICU patient room, as part of the zonal model simulation

using IDA ICE, presents a complex dynamic of indoor air distribution (Figure 6). The interaction between these opposing air flows can lead to thermal stratification, where layers of different temperatures form, typically warmer air above and cooler air below. It results in vertical temperature stratification, especially during cooler outdoor air, with warmer air near the ceiling and cooler air near the floor. The average room temperature might fall within the comfort range, but localized areas could experience discomfort due to uneven heating (Figure 6a). When a window opening causes a significant draft in cold outdoor conditions, the vertical momentum of an under-window fancoil may be insufficient to counter the cooler downward airflow. This can result in lower temperatures near the floor, a steeper vertical temperature gradient, and increased air velocity in the occupied zone. Such conditions can lead to undesirable air mixing, potentially enhancing the distribution of infected aerosol particles and posing a risk in healthcare settings.

An ICU patient room's thermal dynamics are further complicated by horizontal temperature stratification in addition to vertical stratification. The model also mirrored the air velocity patterns observed, capturing the nuances of airflow within the room, including areas of stagnation and high flow (Figure 6b). Fan coil units significantly affected indoor air distribution and increased turbulence, which may influence disease spread in a closed environment. The airflow from these units can disrupt the stratified layers of air, mixing potentially contaminated air throughout the room. This can lead to increased exposure risk, especially in areas where people are stationary for long periods, such as hospital rooms. Proper placement and use of fan coils are essential to minimize these risks and ensure efficient air mixing without contributing to the spread of diseases [12].



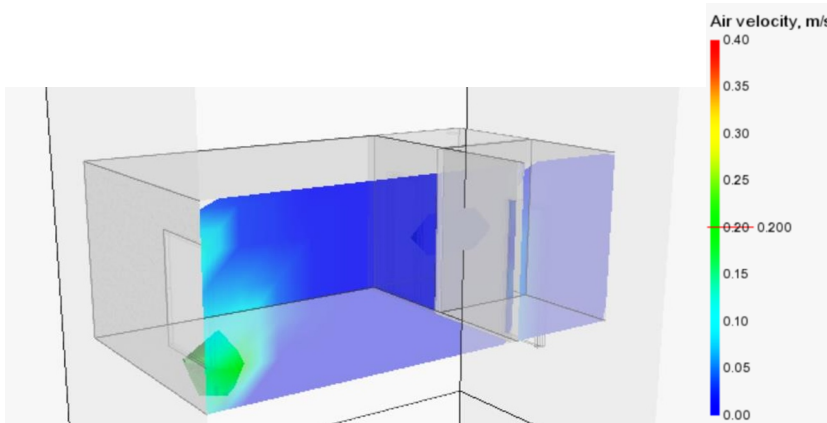


Fig. 5. Simulated a) indoor air temperature and b) velocity distribution

5 Discussion

The model offers a balance between CFD detailed predictions and the simplicity of standard mixed-room models. It provides a more practical approach to real-world applications, especially in settings with limited computational resources. The study acknowledged variations due to external factors like fluctuating outdoor conditions, which can be explored in future research. While reducing computational time, the models do not solve the momentum equation, introducing certain limitations to their applicability to predicting the particle distribution that is critical in infection risk assessment [13].

The use of split systems and fan coil units for air conditioning and heating in healthcare settings is generally discouraged due to maintenance difficulties, inadequate filtration, and the creation of turbulence which could increase infection risk [12]. For COVID-19 patient areas, especially where aerosol-generating procedures occur, some alternatives should be considered. If these units must be used, measures like creating negative pressure in the room and careful cleaning between patients are recommended. Additionally, the units should run at minimum velocity to lessen turbulence, and airflow should be directed away from direct contact with individuals.

The model contributes significantly to the field of indoor air quality, particularly in understanding and optimising airflow in naturally ventilated spaces [12]. Its versatility and minimal requirement for prior airflow knowledge make it a promising tool for architects, engineers, and healthcare facility managers. Further research could refine the model, especially in its application to different room configurations and varying external conditions.

6 Conclusions

The comprehensive analysis of the ventilation and air purification solutions in the ICU patient room at the Matei Bals Hospital in Bucharest, Romania, using the IDA ICE building simulation tool, has provided valuable insights into the complex dynamics of air flow and temperature distribution within a healthcare setting. High degree of correlation was observed between the measured and simulated data for both temperature and air velocity. The zonal model successfully replicated the temperature gradients observed in the actual measurements. It accurately depicted the influence of the fancoil unit and natural ventilation through windows. The model also mirrored the air velocity patterns observed, capturing the nuances of airflow within the room, including areas of stagnation and high flow. This research bridges

the gap between complex, resource-intensive methods like CFD and oversimplified approaches, offering a balanced, efficient alternative for indoor airflow analysis in healthcare settings.

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