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Research Paper

Geo-environmental parametric 3D models of SARS-CoV-2 virus circulation in hospital ventilation systems

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ABSTRACT

The novel coronavirus, SARS–CoeV-2, has the potential to cause natural ventilation systems in hospital environments to be rendered inadequate, not only for workers but also for people who transit through these environments even for a limited duration. Studies in the field of geosciences and engineering, when combined with appropriate technologies, allow for the possibility of reducing the impacts of the SARS-CoV-2 virus in the environment, including those of hospitals which are critical centers for healthcare. In this work, we build parametric 3D models to assess the possible circulation of the SARS-CoV-2 virus in the natural ventilation system of a hospital built to care infected patients during the COVID-19 pandemic. Building Information Modeling (BIM) was performed, generating 3D models of hospital environments utilizing Revit software for Autodesk CFD 2021. The evaluation considered dimensional analyses of 0°, 45°, 90° and 180°. The analysis of natural ventilation patterns on both internal and external surfaces and the distribution of windows in relation to the displacement dynamics of the SARS-CoV-2 virus through the air were considered. The results showed that in the external area of the hospital, the wind speed reached velocities up to 2.1 m/s when entering the building through open windows. In contact with the furniture, this value decreased to 0.78 m/s. In some internal isolation wards that house patients with COVID-19, areas that should be equipped with negative room pressure, air velocity was null. Our study provides insights into the possibility of SARS-CoV-2 contamination in internal hospital environments as well as external areas surrounding hospitals, both of which encounter high pedestrian traffic in cities worldwide.

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1. Introduction

The dynamics of atmospheric contamination by microorganisms and aggregates in ultrafine particles suspended in the air on a global scale is a frontier theme in geo-environmental studies (Silva et al., 2020; Oliveira et al., 2021; Shao et al., 2021; Silva et al., 2021). Neckel et al. (2021) reported that moving air could carry fungi, viruses and bacteria to other regions, thus spreading environmental contamination. Monitoring air quality in both indoor and outdoor environments is therefore important in terms of human health (Silva et al., 2020; Oliveira et al., 2021).

Of current paramount importance in over the globe affecting humans is the spread of and contamination of surfaces by the novel coronavirus (SARS-CoV-2). The SARS-CoV-2 virus has devastated people and their lives in many regions of the world through the respiratory syndrome known as COVID-19, which can cause severe illness leading to death (Cao et al., 2021; Jansi et al., 2021). Due to the easy and rapid transmission of SARS-CoV-2, the mortality rates in many countries in the world is alarming, in addition to generating severe negative social and economic impacts (Cao et al., 2021; Shao et al., 2021). The World Health Organization reported a global

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death toll of 3,104,743 from SARS-CoV-2 as of April 26, 2021 (WHO, 2021).

The COVID-19 pandemic has posed many different challenges for citizens and governments worldwide. Among these is the implementation of hospitals exclusively for the care of COVID-19 patients. Some of these hospitals were existing structures prior to the pandemic, whereas others are being constructed from the ground up in real time to deal with the massive, to cater to the rapid influx of patients. Modular structures have been utilized in many instances due to the shorter construction time required, given the urgency imposed by the pandemic (Perondi et al., 2020; Chen et al., 2021; Yang and Chong, 2021). One Brazilian example of this was the construction of the Independência Hospital in the State of Rio Grande do Sul’s capital city, Porto Alegre, a structure built using modules and dedicated only to the treatment of COVID-19 patients.

The present study stems from the possible displacement and transport of SARS-CoV-2 virus in ultrafine particles suspended in the hospital environment, considering the different dynamics of air movement, circulation, and internal air quality (Cao et al., 2021; Hadei et al., 2021; López et al., 2021; Shao et al., 2021). It is essential to assess the air quality in hospitals that were built quickly, and to ensure that the risks of contamination are indeed low in these facilities (Chen et al., 2021), or if the novel coronavirus is unimpeded in its ability to move throughout.

Hospitals dedicated to the treatment of patients infected with SARS-CoV-2 are in many cases, located in sectors with very high levels of the virus (Kenarkoohi et al., 2020; Ryu et al., 2020). This presents an increased risk to healthcare professionals of contracting SARS-CoV-2 throughout the course of their duties (Kenarkoohi et al., 2020; Vandercam et al., 2020; Aghalar et al. (2021) showed that the SARS-CoV-2 virus can in fact be easily transmitted through hospital ventilation systems. The source of these viral particles can range from the hospital roof to the ground level, and areas near air intakes surrounding the hospital. The transport of viral particles between regions diminishes air quality and presents a serious risk to anyone within or surrounding the hospital facility, further strengthening the COVID-19 pandemic (Robotto et al., 2021). Ultrafine particles which contain the SARS-CoV-2 virus are easily suspended in the air and have the propensity to travel great distances due to their aerodynamic diameters \( \leq 10 \mu m \) (≤PM10). SARS-CoV-2 has been found on particles even smaller than 1 \( \mu m \) (≤PM1) (López et al., 2021; Robotto et al., 2021; Shao et al., 2021).

SARS-CoV-2 transmission has been shown to occur in environments outside hospital settings through ventilation as well (Hadei et al., 2021; López et al., 2021; Robotto et al., 2021; Shao et al., 2021). For this reason, the evaluation of the internal ventilation system of hospitals with modular architecture can assess and predict possible risks of contamination through air circulation. It is also necessary to consider the consequences from the outlet of this air in areas outside and surrounding the hospital (Hadei et al., 2021; López et al., 2021).

The major objective of this manuscript is to build parametric 3D models with a view to assess the hypothetical circulation of the SARS-CoV-2 virus in the natural ventilation system in hospitals built to care for infected patients during the COVID-19 pandemic, taking a typical case in Brazil as example.

2. Materials and methods

2.1. Study area

The Independência Hospital was built and dedicated only for COVID-19 patients. The hospital grounds have a total area of 1100 m², of which approximately 385 m² constitute the total built area. It is located in the City of Porto Alegre, capital city of the State of Rio Grande do Sul, Brazil, 29°10’30’S, 51°05’00’’W. The city’s total population is just under 1.5 million, with a demographic density of 2838 inhabitants/ km² (Ibge, 2021) (Fig. 1).

This hospital building was built using modular construction over a period of 30 days, with 60 beds, at a cost of R$ 10.4 million, allocated by the private sector. The hospital is not characterized as a field hospital, since its structure was handed over to the public health network and will remain in operation after the COVID-19 pandemic. The hospital is operated in its entirety through the Unified Health System (SUS) of Brazil, which provides care to the population free of charge. The hospital opened on June 15, 2020.

In this study, we evaluated the natural ventilation patterns in one of the collective rooms where COVID-19 patients are treated (Fig. 2A). Each room, illustrated in Fig. 2B, has an area of 47.3 m², of which 6.83 m² consists of an enclosed bathroom. Two types of windows can also be identified (window A (1.20 m × 1.20 m) and window B (0.81 m × 0.81 m). The external wooden lattice structure shown in Fig. 2C has the following dimensions: 0.03 m × 1.42 m, separated by 0.12 m between each lattice rung (Fig. 2D). In the case of our object of study, parametric 3D projection is considered to yield an innovative representation of the modular structure, as the pre-assembled structures are fitted together to make up the finished hospital building (Chen et al., 2021).

Only the flow of natural air was considered in this simulation due to the lack of information on the proprietary HVAC system installed in and utilized for the structure (Lou et al., 2020). Hospital recommendations regarding safety during the COVID-19 pandemic were followed when designing the methodology of this study. The alternative paradigm, considered as a parameter of analysis, is the direction and velocity of the local air (Chen et al., 2019; Ahmed et al., 2021; Aviv et al., 2021). Consequently, it was found out that the wind velocity in Porto Alegre usually varies between 5 km/h and 10 km/h (1.4 m/s and 2.8 m/s) (Fig. 3) (INMET, 2016; Meteoblue, 2021). For this reason, we adopted a mean of 2.1 m/s for this study.

2.2. BIM modeling method

From BIM (Building Information Modeling) model, the file with the extension “.rte” was exported directly from Revit to the Autodesk CFD 2021 software, through the “Add-Ins” ribbon (Calautit et al., 2020; Kim et al., 2020). This made it possible to model in 3D geometry in the Revit model in a parametric way; considering parameters and constructive interfaces in relation to the types of modular materials that make up the building as related to air speed (Mousa et al., 2017; Porras-Amores et al., 2019; Calautit et al., 2020).

The Autodesk CFD software has been used by many researchers around the world. For example, a CFD simulation of natural ventilation performance inside a room, entering through a fresh air valve, in Lublin, Poland, was made and compared with experimental data (Raczkowski et al., 2019). The authors found out that the CFD simulation could predict thermal performance of naturally ventilated room precisely. In another example, wind velocity was analyzed inside a wood house in Tomohon, Nort Sulawesi (Kristianto et al., 2014). After setting up the inlet boundary conditions, the authors were able to define the optimal cases for wind velocity inside the building.

In order to validate the process of the model generated in this study, the procedure used by the authors Nalamwar et al. (2017), Johansson and Wasim (2020), Utkucu and Sözer (2020) was adopted. This procedure involves the following steps: (a) imply the model elements geometry to decrease the mesh size needed...
to obtain proper results in shorter times; (b) after importing the model in Autodesk CFD, define the materials with its parameters and assign them to the elements in the model; (c) define the boundary conditions like the velocity of air; (d) generate a proper mesh that ensures the software makes correct calculations in small or curve shapes. For this step, the “Autosize” mesh option of Auto-

**Fig. 1.** Location of Independência Hospital in the City of Porto Alegre, Brazil (IBGE, 2021).

**Fig. 2.** Internal layout of the Independência Hospital, with parametric 3D projection of the room selected for the internal ventilation study. (A) Internal layout of the collective room. (B) View of the external wooden lattice structure (C) and the external dimensions of the wooden lattice structure (D).
desk CFD was first utilized to obtain an initial mesh and then refined where necessary with the “Diagnostics” and “Regions” tools of the mentioned software; (e) set the solving parameters, like the turbulence model and magnitudes that are looked for. In the three studied cases (Nalamwar et al., 2017; Johansson and Wasim, 2020; Utkucu and Sözer, 2020), the authors used the k-ε turbulence model. Besides, the official website of the Autodesk CFD (2021) recommends the case that fits better with each model, where a table explains that the k-ε model is the default one which works adequately for most applications. For this reason, we adopted the same turbulence model. (f) set the coordinates of control points where the user wants to obtain the results in that specific point. In older versions of the software, for instance Autodesk CFD (2019), this step must be done before the simulation has started.

The validation of the CFD was based on an external volume generated to simulate the air (Das et al., 2016). The inlet air velocity and direction were defined with the criterion of 2.1 m/s, whereas the outlet of the air volume was defined with a static gage pressure of 0. To simulate a free-space environment, it was necessary to assign Slip/Symmetry to the top and sides of the air volume. This analysis considered the geometry of the input model and determines the mesh size and distribution on every edge, surface, and volume in the model. This process considers geometric curvature, gradients, and proximity to neighboring geometry, which requires a finer mesh. In the model analyzed in this research, an automatic mesh size (Fig. 4A) was first generated, which was reviewed with the diagnostic tool in order to find the elements that needed a refined mesh (Fig. 4B), like at the external wooden lattice structure and the border of the windows. Consequently, the final mesh without the external wooden lattice have approximate 380,000 elements and the mesh with the external wooden lattice have 720,000 elements, as presented in Fig. 5.

The analysis in this study was simplified in order to calculate the natural air flow identified through distribution points. Window A (Fig. 2) was a sliding window, which means that it can be opened to a maximum of only half (50%) of its width, while window B is protruding, which means that it can be fully opened. Analyses were carried out with wind blowing from the four directions shown in Fig. 6 (0°, 45°, 90° and 180°). All windows were considered open to their maximum amount (recalling that some were only able to be opened 50%), in addition to some alternative cases utilizing only the 0° wind direction scenario. When considering the dimensions of the mesh and the parameters searched, between 200 and 400 iterations were required for the calculations of natural ventilation.

It is important to mention that CFD does not allow for the modification of any component, unlike Revit. Therefore, once the model is imported into CFD, some useful tools allow us to not only identify edges that can be merged and small objects to be eliminated, but also to fill in some voids or create an external volume in order to adequately simulate the natural air flow within the room (Calautit et al., 2020; Kim et al., 2020).

After assigning the appropriate material to each element and texture for a better approximation of the actual structure, the boundary conditions were configured according to the aforementioned wind angles, considering wind inflow and outflow (Mousa et al., 2017; Porras-Amores et al., 2019; Calautit et al., 2020). To define air flow, a side surface of the generated external volume is selected as the normal direction in which the air is moving. The opposite side of the modular structure is then assigned a pressure of 0 Pa, while the sides and top of the structure must be assigned as “Slip/Symmetry” to adequately simulate the environment.

2.3. K-means grouping from the points collected for ventilation analysis

Cluster analysis consists of a high-level method assigned to detect protrusions; multivariate techniques that aim to aggregate objects based on the similarities of their characteristics; and an analysis based on proximity, which makes it possible to understand the geophysical relationships of structures in a given environment (Jing et al., 2021; Zhang et al., 2021). The structural design elements of Independência Hospital exhibit high internal homogeneity and high external heterogeneity.

The grouping algorithms utilized were optimized for the identification of hidden structures in data sets (Jing et al., 2021; Zhang et al., 2021). The identified structure is translated into group memberships corresponding to an unspecified technique and, as such,
the membership information is not known or used as a priority input. Thus, the algorithm recognizes similarities and defines classes (Ueda et al., 2020; Zhou et al., 2020). According to Ueda et al. (2020) and Zhou et al. (2020), once the clusters are defined, it is possible to choose the most representative object of a given group. Thus, K-means proceeds iteratively starting with an initial solution, the random configuration of cluster centroids obtained through the points collected in the study area, are grouped randomly in raster cells. In the relocation stage, each cell is allocated to the nearest centroid (Zhou et al., 2020). In the recalculation step, each centroid is shifted to the mean of the coordinates of the cells allocated to that centroid. The iteration process is interrupted when the mean minimum square distance (MSSD) cannot be further reduced or when the improvements become less than a specified threshold for the object under study.

Eleven control points were selected to gather data for different scenarios, with a wind direction of 0° (Fig. 6). Data from three different plans were collected for further analysis. A grid was defined with points separated by 0.5 m to calculate the magnitude of the wind speed in different positions inside and outside the room. This “grid” was used at 3 different heights: 0.5 m above the floor, half the height of the room (1.27 m) and 0.5 m below the ceiling. In addition, four scenarios were analyzed: (1) all windows opened fully with the outer wooden lattice structure; (2) all windows opened fully without the outer wooden lattice structure; (3) all windows opened halfway (50%) with the outer wooden lattice structure and (4) all windows opened halfway (50%) without the external wooden lattice structure. These scenarios were chosen as they have the greatest variations in magnitude of airflow velocity and values within the room.

Two properties are used to better define the quality of the data cluster, compression and separation (Ueda et al., 2020; Zhou et al., 2020). Clusters have good compression when the data points are close to each other. The clusters were well separated when they were far apart. The validation indices assess the quality of clustering solutions, and two visualization techniques were adopted, distribution histograms and boxplots (Ueda et al., 2020; Zhou et al., 2020).

These construction-related data sets were brought together and organized into a single database. The database is analyzed to identify the number of building characteristics, the number of repeated data entries and the integrity of the data sets. Data cleansing is necessary in order to create a complete data set, which is used as an input for clustering algorithms (Stavroulakis et al., 2020; Ueda et al., 2020). This is necessary as some cluster procedures cannot handle missing values (Cai et al., 2020; Stavroulakis et al., 2020). Missing data removal procedures were performed, which resulted in a decreased number of available entries. Subsequently, the analysis was performed using JASP software, version 0.14.1.0, to demonstrate possible displacement of SARS-CoV-2 particles in the built structure of the hospital and its surroundings, through the analysis of points...
of intensity of the levels of displacement of natural ventilation. The Cao et al. (2021) and Jansi et al. (2021) studies prove the ease of displacement of SARS-CoV-2 through the air, through ultra-fine microparticles.

3. Results and discussion

3.1. Natural ventilation analysis

The results yielded interactions of 300 relationships that occurred in the analyzed space; thus, we place high relevance and reliability of these data on the intensity of natural ventilation, which does not depend on the thermal insulation characteristics of the modular structure (Li and Chen, 2020). In Fig. 7, the representation of the existing dynamics of inlets, air circulation and wind exit can be visualized, noting that the circulation of natural ventilation inside the building is of less intensity.

The consequence for this environment is that it can consistently concentrate the SARS-CoV-2 virus as long as COVID-19 patients are within the room and actively shedding virus particles, which explains the occurrence of contamination among health professionals working in these hospital environments (Kenarkoohi et al., 2020; Vandercam et al., 2020; Noorimotlagh et al., 2021). Noorimotlagh et al. (2021) demonstrated that the transmission of SARS-CoV-2 outdoors occurs almost exclusively by air, mainly through ultrafine particles suspended in the air (Cao et al., 2021; Hadei et al., 2021; López et al., 2021; Shao et al., 2021).

Several studies have examined indoor airflow within constructions and buildings driven exclusively by the influence of natural external winds (Liu and Lee, 2020; Cui et al., 2021; Hirose et al., 2021; Maroni et al., 2021; Matour et al., 2021). Fig. 8 shows the initial simulation of wind velocity vectors blowing directly at the structure. Fig. 9 demonstrates the change in wind direction and

![Fig. 5. Final mesh applied for the model. (a) Plan view. (b) Profile view and front view.](image)

![Fig. 6. Diagram of the hospital room under study with arrows indicating airflow direction at Independência Hospital.](image)
speed as caused by the wooden lattice structure placed in front of the open windows in the structure.

Figs. 8–11 demonstrate the drop in internal air velocity due to the change in direction of the air flow from the wooden lattice structure. In addition, the CFD allows us to view the trajectory of the air flow within the room. Air moving within this highly infectious environment may contain suspended particles containing the SARS-CoV-2 virus (Cao et al., 2021; Jansi et al., 2021). Gatheeshgar et al. (2021) emphasized that one potential solution to mitigate the spread of SARS-CoV-2 in hospital environments is the greater use of modular partitions, capable of directing air circulation to the windows and exhausting it to the external atmosphere. Care must be taken, however, to avoid creating exterior areas in which tainted air can be concentrated, exposing hospital visitors or personnel to potentially dangerous conditions. It is impossible to estimate the amount of SARS-CoV-2 suspended in ultrafine particles present in the air, which varies according to the focus of a possible contamination (Shao et al., 2021). Hence in this study, we assume the existence of contamination probabilities because a built environment responsible for the SARS-CoV-2 treatment, reinforcing the studies by Shao et al. (2021) which showed that SARS-CoV-2 can be suspended in the air for a long time.

Air flow was shown to enter the two windows of the hospital room and move along the room’s walls, while in the bathroom it enters and exits through the single window. Furniture within the room had a noticeable impact on air velocity, slowing air flow along the Y axis and diverting flows to the X and Z axes. The positioning of room furniture must be considered, as it clearly affects the entry of air flow into the environment (Mora-Pérez et al., 2015; Xu et al., 2021).
Areas of low velocity were present within the room, even reaching values close to 0 m/s in places. These areas present the highest overall risk to human health when infectious agents may be contained or suspended in the air (Shao et al., 2021). For adequate health concerns, especially among COVID-19 patients, the entire room must be adequately ventilated (Lane et al., 2020; Gottesman et al., 2021). Air was shown to flow throughout the entire room and exit through both windows overall, so there is a noticeable contribution from natural ventilation.

Our analyses of different scenarios considered 11 overall control points from where data were gathered (Fig. 11), based on the need to assess the environment in more detail (Ahmed et al., 2021; Aviv et al., 2021; Matour et al., 2021). These points were selected as they have the greatest variations in the magnitude of the velocity of the internal air flow (Ahmed et al., 2021; Matour et al., 2021).

The highest internal air velocity result from any scenario tested was Point 1 in the 90° scenario, displaying a value of 1.21 m/s (recall the exterior air velocity of 2.1 m/s). Point 2 yielded a value of 0.50 m/s in the same scenario (Table 1) (Fig. 12). This analysis was completed with all three-room windows fully open. According to Vassella et al. (2021) the evaluation of the intensity of natural ventilation is extremely important in order to analyze the indoor air quality (IAQ), as air contaminants such as the SARS-CoV-2 virus are contained in that flow.

Table 2 lists internal air flow velocities at all the 11 points within the room in the 0° wind source direction scenario. Some variations of the 0° scenario were also made. The same previous analysis was done on all windows, which were kept fully open for the first variation, but closed by 50% for the second. Some variations included the external wooden lattice structure while others...
The space between each horizontal table in the room was doubled at one point. The results can be seen in Table 2. Finally, a comparison is presented between Window B when it is fully open and a case when it is open only 50%.

The influence of the air flow direction observed in each scenario is notable. Although each of these scenarios has zones where the airflow velocity has high values, the 0° scenario appears to be the most balanced overall as there are not many zones where the velocity decreases to very low values. However, in all scenarios very low velocity is noticeable, reaching values close to zero in some scenarios in the shower area, inside of the private bathroom. Great variations between each control point are also noticeable due to the behavior of the air flow inside the room. Even at low velocity, air flows in three dimensions on the X, Y and Z axes. The lack of natural ventilation in the room’s private bathrooms present more than just an inconvenience due to unpleasant odors (Tung et al., 2010). Barker and Jones (2005) have shown that aerosolized particles enter the air with every flush of the toilet, causing both surface and air contamination with fecal matter particles, microorganisms and viruses. This is not generally an issue for healthy individuals with a fully functioning immune system but presents a real danger in a hospital setting for patients who may be immunocompromised (Shao et al., 2021). Shao et al. (2021) showed that the spread of aerosols containing SARS-CoV-2 viruses...
in the toilet flush has become one of the forms of virus transmission between individuals, even impacting healthy people who are not immunocompromised.

3.2. Cluster analysis applied to sampled points of natural ventilation

The greater precision of the variations that occur in natural ventilation in this study was based on the use of a virtual “grid” with 198 points located at the following three heights above the ground level: 0.5 m, 1.27 m and 2.04 m. Sample points were conducted in triplicate, totaling 594 sample points for calculating and modeling the velocity of internal air flow powered only by natural ventilation, with Cluster analyses in different locations both inside and outside of the room. The choice of the three heights (0.5 m,

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### Table 1

Simulated internal air velocity (m/s) at all 11 points in the analyzed room at Independência Hospital.

| Points | 0°  | 45° | 90° | 180° |
|--------|-----|-----|-----|------|
| 1      | 0.78| 0.84| 1.21| 0.19 |
| 2      | 0.50| 0.56| 0.49| 0.16 |
| 3      | 0.22| 0.32| 0.11| 0.06 |
| 4      | 0.11| 0.02| 0.00| 0.03 |
| 5      | 0.04| 0.01| 0.00| 0.00 |
| 6      | 0.05| 0.10| 0.00| 0.02 |
| 7      | 0.01| 0.04| 0.02| 0.00 |
| 8      | 0.07| 0.00| 0.05| 0.01 |
| 9      | 0.04| 0.00| 0.04| 0.00 |
| 10     | 0.12| 0.00| 0.04| 0.02 |
| 11     | 0.26| 0.15| 0.19| 0.05 |

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### Table 2

Internal air velocities (m/s) resulting from variations to the original 0° scenario.

| Points | 2 open windows | 2 closed windows | 1 closed window | Without wood lattice | Modified wood lattice |
|--------|----------------|------------------|-----------------|----------------------|-----------------------|
| 1      | 0.78           | 0.73             | 0.74            | 0.84                 | 0.77                  |
| 2      | 0.50           | 0.45             | 0.47            | 0.49                 | 0.49                  |
| 3      | 0.22           | 0.00             | 0.19            | 0.17                 | 0.20                  |
| 4      | 0.11           | 0.00             | 0.11            | 0.05                 | 0.08                  |
| 5      | 0.04           | 0.00             | 0.04            | 0.00                 | 0.03                  |
| 6      | 0.05           | 0.00             | 0.04            | 0.00                 | 0.04                  |
| 7      | 0.01           | 0.00             | 0.01            | 0.00                 | 0.00                  |
| 8      | 0.07           | 0.00             | 0.00            | 0.01                 | 0.04                  |
| 9      | 0.04           | 0.00             | 0.00            | 0.00                 | 0.01                  |
| 10     | 0.12           | 0.00             | 0.00            | 0.05                 | 0.08                  |
| 11     | 0.26           | 0.00             | 0.00            | 0.16                 | 0.23                  |
1.27 m and 2.04 m) utilized for Independência Hospital was based on the work of Silva et al. (2020) and Oliveira et al. (2021), who consider the presence of contamination in ultrafine particles suspended in the air. The three specific heights were derived from the human scale – heights at which air would enter the respiratory system of average sized humans (Shao et al., 2021).

Four additional scenarios were analyzed for the room sampled at Independência Hospital: (i) fully opened windows with the outer wooden lattice structure, (ii) fully opened windows without the outer wooden lattice structure, (iii) half opened (50%) windows with the outer wooden lattice structure and (iv) half opened (50%) windows without the outer wooden lattice structure, all with a 0° initial wind direction.

The K-means analysis fits a model that presents the fit score for the model, where K = 4 consists of the groupings assigned to each data set, totaling 594 samples. According to Ly and Cornelisse (2019), R² is the ratio between the sums of squares and the total sums of squares. The closer the value is to 1, the better the fit. The observed R² of 0.95 demonstrates great reliability in the study results. The silhouette index varied from –1 to 1, and the value of K = 4 clusters was 0.88, showing a high tendency for grouping, according to the established variables. The high tendency of grouping between the variables analyzed refers to the occurrence of a relationship that continues sequentially in the “grid” of points analyzed in its different layers, which varies by the height determined for analysis (Ueda et al., 2020; Zhou et al., 2020). Thus, we observed that to optimize the relationship between K and AIC, the ideal model is K = 3.

Table 3 shows the cluster sizes, the variability within each cluster in terms of the sum of squares, the proportion of explained heterogeneity within the cluster, and silhouette index. Regarding the size, Cluster 3 presents a high number of points. As for the analysis of the proportion explained within the cluster heterogeneity, the greatest heterogeneity corresponds to 1, it is observed that Cluster 2 with 0.53203 has the highest proportion of heterogeneity. The sum of squares also deals with the total distribution between the clusters, thus verifying the representativeness of each cluster in the studied set, and Cluster 2 presents a high proportion of the sum of squares of 56.86011, despite having 56 points. The Silhouette Index demonstrates homogeneity and cohesion, the closer to 1, the better the result. Cluster 3 presents indices of 0.96037, and thus, they represent high homogeneity and cohesion, the closer the value is to 1, the better the reliability of the result (Ly and Cornelisse, 2019). These values also demonstrate heterogeneities between the points analyzed (Ueda et al., 2020; Zhou et al., 2020).

Table 4 shows the cluster means for each predictor variable. Scenario 1 has 100% open windows with an external wooden wall, the highest speeds were obtained in cluster 2, with a value of 2.55849. For scenario 2 where windows are 100% open without the external wooden wall, cluster 2 was more significant. For scenario 3 the windows 50% open with the external wall made of wood, cluster 2 also had a higher average of higher speed. Scenario 4, where the windows are 50% open without the external wooden wall, the averages were higher in Cluster 2. Through the analysis of natural ventilation that moves between windows, it is possible to perceive the influence on these air exchanges and variations in external temperature for the building's internal environments (Vassella et al., 2021).

Natural ventilation for the treatment of individuals infected with SARS-CoV-2 is paramount and cross ventilation in and around hospital beds is recommended by the medical community (Shao et al., 2021). The best option to achieve this is openings that would be able to change the speed of the air flow combined with a powered system such as a HVAC system (Wang et al., 2021). In this relationship, Fig. 13 shows density based on the Gaussian kernel, smoothing the canopy height distributions (>0 m) based on a stratified random sample from each cluster, so the frequency of natural ventilation can be compared based on the analyzed scenarios. As each cluster has a specific color, the legend describes the color assignments in greater detail. For each graph it is possible to view the densities of the clusters in each variable, and the resulting overlap when they occur. This reflects the apices of each of the variables captured in each cluster.

Fig. 13 presents the smoothed Gaussian kernel-based density plots of the canopy height distributions (>0 m) based on a stratified random sample from each cluster. Each Cluster has a specific color, and the legend describes the cluster’s color assignments in more detail. For each graph it is possible to visualize the densities of the clusters in each variable, and the overlaps when they occur. How this reflects the apices of each of the variables captured in each cluster. Fig. 13 shows airflow velocity and values inside the room in relation to the following: scenario 1 with 100% open windows and external wooden wall (Fig. 13A), Scenario 2 with the windows 50% open and without the external wooden wall. Cluster 3 conforms the internal points, it is possible to observe that it has the highest density, that is, the largest number of points, another characteristic is the concentration of air velocity, regardless of the proposed scenario (Fig. 13D). In Scenario 2 (Fig. 13B) with the windows 100% open and without the external wooden wall, Cluster 2 presents greater amplitude. On the other hand, in Scenario 3 (Fig. 13C) with the windows 50% open and with the external wooden wall has the smallest amplitude in air velocity values.

When considering the variations in the analyzed clusters, the dynamics of natural ventilation become more intense when the windows are open. Thus, it can be assumed that the intensities of natural ventilation can transport SARS-CoV-2 viral particles to other hospital environments, or even to the external areas (Carratu et al., 2020; Abrahão et al., 2021), surrounding Independência Hospital.

The contamination of particles of SARS-CoV-2 occur on surfaces and as suspended in the air in both the external and internal environments of hospitals and is therefore a contributor to the continued expansion of the COVID-19 pandemic (Cao et al., 2021; Hadei et al., 2021; López et al., 2021; Shao et al., 2021; Wang et al., 2021). Transmission of this virus does not occur only by contact or proximity between individuals, but by ultrafine particles suspended in the air. These airborne particles are susceptible to movement from one region to another based on the intensity of wind’s velocity. According to Silva et al. (2020) and Oliveira et al. (2021) air quality studies on a global scale are indispensable. Therefore, our study as well as the work of Carratu et al. (2020) alert that natural ventilation in hospitals dedicated primarily or solely to the care of patients infected with SARS-CoV-2, requires proactive design and...
preventative care, as these are environments that concentrate high amounts of viral particles in the air and allow those particles to settle onto surfaces if air flow velocity is not adequate.

4. Conclusions

Airflow within the sampled sector of Independência Hospital, driven by natural ventilation and wind action, was analyzed in a modular form with 3D projection in BIM. When windows are fully in the open position, natural ventilation at times displayed an inability to maintain recommended amounts of adequate ventilation for COVID-19 patients. Wind patterns and velocity also vary according to the season and meteorological factors, so it is difficult to maintain consistency when relying only on the local weather patterns to ventilate rooms.

The analysis of clusters demonstrated the variations of natural ventilation between the sampled points, which enabled a better understanding of the wind's intensity and velocity. For a future work, we recommend evaluating different turbulence models. Blocken (2018) summarized that some of the most used turbulence models in building simulation are available in these options: the standard k-ԑ, the RNG k-ԑ and some k-ԑ models. This author indicates that the RNG k-ԑ model is slightly more accurate than the standard k-ԑ, but requires more computational hardware. The official website of Autodesk CFD (2021) recommends beginning with the standard k-ԑ model and then switch to RNG after when the flow is mostly converged.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abrahão, J.S., Sacchetto, I., Rezende, J.M., Rodrigues, R.A.L., Crispim, A.P.C., Moura, C., Mendoça, D.C., Reis, E., Souza, F., Oliveira, G.F.G., 2021. Detection of SARS-CoV-2 RNA on public surfaces in a densely populated urban area of Brazil: a potential tool for monitoring the circulation of infected patients. Sci. Total Environ. 766, 142665.

Aghalari, Z., Dahms, H.U., Sosa-Hernandez, J.E., Oyervides-Muñoz, M.A., Parra-Saldívar, R., 2021. Evaluation of SARS-CoV-2 transmission through indoor air in hospitals and prevention methods: a systematic review. Environ. Res. 195, 110841.

Ahmed, T., Kumar, P., Mottet, L., 2021. Natural ventilation in warm climates: the challenges of thermal comfort, heatwave resilience and indoor air quality. Renew. Sustain. Energy Rev. 138, 110669.

Autodesk CFD, 2021. Turbulence. Autodesk CFD 2021. Turbulent (the default) to simulate turbulent flow. https://help.autodesk.com/view/SCDSE/2021/ENU/?guid=641937-MD09-1409-8335-520B1A20557F.

Aviv, D., Chen, K.W., Teitelbaum, E., Sheppard, D., Pantelic, J., Bysaneyk, A., Meggers, F., 2021. A fresh (air) look at ventilation for COVID-19: estimating the global energy savings potential of coupling natural ventilation with novel radiant cooling strategies. Appl. Energy 292, 116848.

Barker, I., Jones, M.V., 2005. The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet. J. Appl. Microbiol. 99, 339–347.

Blocken, B., 2018. LES over RANS in building simulation for outdoor and indoor applications: a foreground conclusion? Build. Simul. 11, 821–870.

Cai, W., Zhao, J.Y., Zhu, M., 2020. A real time methodology of cluster-system theory-based reliability estimation using k-means clustering. Reliab. Eng. Syst. Saf. 202, 106445.

Calautit, J.K., O’Connor, D., Tien, P.W., Wei, S.Y., Pantua, C.A.J., Hughes, B., 2020. Development of a natural ventilation windcatcher with passive heat recovery wheel for mild-cold climates: CFD and experimental analysis. Renew. Energy 160, 465–482.

Cao, Y.X., Shao, L.Y., Jones, T., Oliveira, M.L.S., Ge, S., Feng, X., Silva, L.F.O., Bérubé, K., 2021. Multiple relationships between aerosol and COVID-19: a framework for global studies. Gondwana Res. 93, 243–251.

Carraturo, F., Giudice, C.D., Morelli, M., Cerrillo, V., Libralato, G., Galdiero, E., Guida, M., 2020. Persistence of SARS-CoV-2 in the environment and COVID-19 transmission risk from environmental matrices and surfaces. Environ. Pollut. 265, 115101.

Chen, J.I., Biager, C.S., Augenbroe, G., Song, X.Y., 2019. Impact of outdoor air quality on the natural ventilation usage of commercial buildings in the US. Appl. Energy 235, 673–684.

Chen, L.K., Yuan, R.P., Ji, X.J., Lu, X.Y., Xiao, J., Tao, J.B., Kang, X., Li, X., He, Z.H., Quan, S., 2021. Modular composite building in urgent emergency engineering projects: a case study of accelerated design and construction of Wuhan thunder god mountain/Leishenshan Hospital to covid-19 pandemic. Autom. Constr. 124, 103555.

Cui, P.Y., Zhang, Y., Chen, W.Q., Zhang, J.H., Luo, Y., Huang, Y.D., 2021. Wind-tunnel studies on the characteristics of indoor/outdoor airflow and pollutant exchange in a building cluster. J. Wind. Eng. Ind. Aeronodyn. 214, 104645.

Das, S., Deen, N.G., Kuipers, J.A.M., 2016. Direct numerical simulation for flow and heat transfer through random open-cell solid foams: development of an IBM based CFD model. Catal. Today 273, 140–150.

Gathiekhari, P., Poologanathan, K., Ganalan, S., Shyha, I., Sherlock, P., Rajanayagam, H., Nagaratnam, B., 2021. Development of affordable steel-framed modular buildings for emergency situations (Covid-19): Structure 31, 862–875.

Gottesman, T., Fedorovsky, R., Yerushalmi, R., Lellouche, J., Nutman, A., 2021. An outbreak of carbapenem-resistant Acinetobacter baumannii in a COVID-19 dedicated hospital. J. Infect. Prev. Pract. 3, (1) 100113.

Hadei, M., Mohebbi, S.R., Hopke, P.K., Shahsavani, A., Bazzazpour, S., Alipour, M., Jafari, A.J., Bandpey, A.M., Zali, A., Yarahmadi, M., 2021. Presence of SARS-CoV-2 in the air of public places and transportation. Atmos. Pollut. Res. 12 (3), 302–306.

Hirose, C., Regaya, N., Hagishima, A., Tanimoto, J., 2021. Indoor airflow and thermal comfort in a cross-ventilated building within an urban-like block array using large-eddy simulations. Build. Environ. 196, 107811.

IBGE (Brazilian Institute of Geography and Statistics). 2021. Brazilian Institute of Geography and Statistics. Demographic Data of 2021 - Brazil. https://cidades.ibge.gov.br/.

INMET (Brazilian Institute of Meteorology). 2016. Climate archives. http://www.inmet.gov.br/projetee/dados-climaticos/.

Jansi, R.S., Khusro, A., Agastian, P., Alfarhan, A., Al-Dhabi, N.A., Arasu, M.V., Rajagopal, R., Barcelo, D., Al-Tamimi, A., 2021. Emerging paradigms of viral diseases and paramount role of natural resources as antiviral agents. Sci. Total Environ. 759, 152045.

Joshi, P.K., Bose, S., 2021. Modular composite building in urgent emergency engineering projects: a case study of accelerated design and construction of Wuhan thunder god mountain/Leishenshan Hospital to covid-19 pandemic. Structure 31, 862–875.

Jing, J.K., Ke, S.Z., Li, T.J., Wang, T., 2021. Energy method of geophysical logging lithology based on K-means dynamic clustering analysis. Environ. Technol. Innov. 23, 101534.

Johansson, E., Wasm, M., 2020. Wind comfort and solar access in a coastal development in Malmö, Sweden. Urban Clim. 33, 100645.

Kenarkoohi, A., Noorimotlagh, Z., Farahi, S., Amorloei, A., Mirzaee, S.A., Pakzad, I., Bastani, E., 2020. Hospital indoor air quality monitoring for the detection of SARS-CoV-2 (COVID-19) virus. Sci. Total Environ. 748, 141324.

Kim, R.W., Hong, S.W., Norton, T., Amon, T., Youssef, A., Berckmans, D., Lee, I.B., 2020. Computational fluid dynamics for non-experts: development of a user-friendly CFD simulator (Hnv-Sys) for natural ventilation design applications. Biosyst. Eng. 199, 232–246.
Kristianto, M.A., Utama, N.A., Fathoni, A.M., 2014. Analyzing indoor environment of Minahasa Traditional House Using CFD. Procedia Environ. Sci. 20, 172–179.

Lane, M.A., Brownson, E.A., Morgan, J.S., Babiker, A., Vanairsdale, S.A., Lyon, G.M., Mehta, A.K., Ingersoll, J.M., Lindsley, W.C., Kraft, C.S., 2020. Bioaerosol sampling of a ventilated patient with COVID-19. Am. J. Infect. Control 48 (12), 1540–1542.

Li, Y., Chen, L., 2020. A study on database of modular facade retrofitting building envelope. Energy Build. 214, 105826.

Liu, T., Lee, W.L., 2020. Evaluating the influence of transom window designs on natural ventilation in high-rise residential buildings in Hong Kong. Sustain. Cities Soc. 62, 102406.

López, J.H., Romo, A.S., Molina, D.C., Hernández, C.A., Cureño, Á.B.C., Acosta, M.A., Gaxiola, C.A.A., Félix, M.J.S., Galván, T.G., 2021. Detection of Sars-Cov-2 in the air of two hospitals in Hermosillo, Sonora, Mexico, utilizing a low-cost environmental monitoring system. J. Glob. Infect. Dis. 102, 478–482.

Lou, L., Shou, D.H., Park, H., Wu, Y.S., Hui, X.N., Yang, R.G., Kan, E.C., Fan, J.T., 2020. Thermoelectric air conditioning undergarment for personal thermal management and HVAC energy saving. Energy Build. 225, 110374.

Ly, A., Cornelisse, J., 2019. How to train a machine learning model in Jasp: Clustering. https://jasp-stats.org/2019/11/19/how-to-train-a-machine-learning-model-in-jasp-clustering/.

Maroni, D., Cardoso, G.T., Neckel, A., Maculan, L.S., Oliveira, M.L.S., Bodah, E.T., Bodah, B.W., Santosh, M., 2021. Land surface temperature and vegetation index as a proxy to microclimate. J. Environ. Chem. Eng. 9, (4) 105796.

Mator, S., Garcia-Hansen, V., Omrani, S., Hassanli, S., Droegemueller, R., 2021. Wind-driven ventilation of Double Skin Facades with vertical openings: effects of opening configurations. Build. Environ. 196, 107804.

Meteoblue, 2021. Wind rose of Porto Alegre. https://www.meteoblue.com/es/tiempo/archivo/windrose/.

Morá-Pérez, M., Guillén-Guillamón, L., López-Jiménez, P.A., 2015. Computational analysis of wind interactions for comparing different buildings sites in terms of natural ventilation. Adv. Eng. Softw. 88, 73–82.

Mousa, W.A.Y., Lang, W., Auer, T., Yousef, W.A., 2017. A pattern recognition approach for modeling the air change rates in naturally ventilated buildings from limited steady-state CFD simulations. Energy Build. 155, 54–65.

Nalamwar, M., Parbat, D., Singh, D., 2017. Study of effect of windows location on ventilation by CFD Simulation. Int. J. Civ. Eng. Technol. 8 (7), 521–531.

Neckel, A., Korceński, C., Kujawa, H.A., Silva, L.S.d., Prezotto, F., Amarion, A.W.L., Maculan, L.S., Gondaçaes, A.C., Bodah, E.T., Bodah, B.W., 2021. Hazardous elements in the soil of urban cemeteries; constructive solutions aimed at sustainability. Cemphere 262, 128248.

Nooirirotzaghi, B., Jafarmadzadeh, N., Martinez, S.S., Mirzaee, S.A., 2021. A systematic review of possible airborne transmission of the COVID-19 virus (SARS-CoV-2) in the indoor air environment. Environ. Res. 193, 110612.

Oliveira, M.L.S., Neckel, A., Pinto, D., Maculan, L.S., Zanchett, M.R.D., Silva, L.F.O., 2021. Air pollutants and their degradation of a historic building in the largest metropolitan area in Latin America. Cemphere 277, 130286.

Perondi, B., Miethke-Morais, A., Montal, A.C., Harima, L., Segurado, A.C., 2020. Setting up hospital care provision to patients with COVID-19: lessons learnt at a 2400-bed academic tertiary center in São Paulo, Brazil. Braz. J. Infect. Dis. 24 (6), 570–574.

Porras-Amores, C., Mazarrón, F.R., Cañas, I., Sáez, P.V., 2019. Natural ventilation analysis in an underground construction: CFD simulation and experimental validation. Tunn. Undergr. Space Technol. 90, 162–173.

Raczkowski, A., Suchorab, Z., Brzyski, P., 2019. Computational fluid dynamics simulation of thermal comfort in naturally ventilated room. MATEC Web Conf. 252, 04007.

Robotto, A., Quagliano, P., Lembo, D., Morello, M., Brizio, E., Bardi, L., Civra, A., 2021. SARS-CoV-2 and indoor/outdoor air samples: a methodological approach to have consistent and comparable results. Environ. Res. 195, 110847.

Ryu, B.H., Cho, Y., Cho, O.H., Hong, S.I., Kim, S., Lee, S., 2020. Environmental contamination of SARS-CoV-2 during the COVID-19 outbreak in South Korea. Am. J. Infect. Control 48 (8), 875–879.

Shao, L., Ge, S., Jones, T., Santosh, M., Silva, L.F.O., Cao, Y.X., Oliveira, M.L.S., Zhang, M., Bérubé, K., 2021. The role of airborne particles and environmental considerations in the transmission of SARS-CoV-2. Geosci. Front. 12, 101189.

Silva, L.F.O., Pinto, D., Neckel, A., Dotto, G.L., Oliveira, M.L.S., 2020. The impact of air pollution on the rate of degradation of the fortress of Florianópolis Island, Brazil. Chemosphere 251, 126838.

Silva, L.F., Santosh, M., Schindler, M., Gasparotto, J., Dotto, G.L., Oliveira, M.L., Hochella Jr, M.F., 2021. Nanoparticles in fossil and mineral fuel sectors and their impact on environment and human health: a review and perspective. Gondwana Res. 82, 184–201.

Stavroulakis, P.J., Papadimitriou, S., Tsionumas, V., Koliousis, I.G., Riza, E., Tsirikou, F., 2020. Exploratory spatial analysis of maritime clusters. Mar. Policy 120, 104125.

Tung, Y.C., Shih, Y.C., Hu, S.C., Chang, Y.L., 2010. Experimental performance investigation of ventilation schemes in a private bathroom. Build. Environ. 45 (1), 243–251.

Ueda, R.M., Souza, A.M., Menezes, R.M.C.P., 2020. How macroeconomic variables affect admission and dismissal in the Brazilian electro-electronic sector: a var-based model and cluster analysis. Phys. A: Stat. Mech. Appl. 557, 124872.

Utzkuc, D., Sözer, H., 2020. An evaluation process for natural ventilation using a scenario-based multi-criteria and multi-interaction analysis. Energy Rep. 6, 644–661.

Vandercam, G., Simon, A., Scohy, A., Belkhir, L., Kahamba, B., Rodriguez-Villalobos, H., Yombi, J.C., 2020. Clinical characteristics and humoral immune response in healthcare workers with COVID-19 in a teaching hospital in Belgium. J. Hosp. Infect. 106 (4), 713–720.

Vassella, C.C., Koch, J., Henzi, A., Jordan, A., Waeder, R., Iannaccone, R., Charrière, R., 2021. From spontaneous to strategic natural window ventilation: improving indoor air quality in Swiss schools. Int. J. Hyg. Environ. Health 234, 113746.

Wang, Z.F., Wang, Y.Z., Yang, Z.W., Wu, H.K., Liang, J.Y., Liang, H.W., Lin, H.M., Chen, R.C., Ou, Y.E., Wang, F.Y., Wang, Y., Wang, Y., Luo, W.Z., Li, N.J., Li, Z.T., Xie, J.K., Jiang, M., Li, S.Y., 2021. The use of non-invasive ventilation in COVID-19: a systematic review. J. Glob. Infect. Dis. 106, 254–261.

WHO (World Health Organization), 2021. WHO Coronavirus Disease (COVID-19) Dashboard. https://covid19.who.int/.

Xu, F., Xu, S.Z., Passe, U., Canapathysubramanian, B., 2021. Computational study of natural ventilation in a sustainable building with complex geometry. Sustain. Energy Technol. Assess. 45, 101153.

Yang, S.S., Chong, Z.H., 2021. Smart city projects against COVID-19: quantitative evidence from china. Sustain. Cities Soc. 70, 102897.

Zhang, Y.Y., Wang, H.J., Lv, Dong, X., Zhang, P., 2021. Capturing the grouping and compactness of high-level semantic feature for saliency detection. Neural Netw. 142, 351–362.

Zhou, S.G., Zhou, K.F., Wang, J.L., 2020. Geochemical metallogenic potential based on cluster analysis: a new method to extract valuable information for mineral exploration from geochemical data. J. Appl. Geochem. 122, 142, 351-362.