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Environmental data monitoring and infection risks in UK care-homes in the context of COVID-19

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ABSTRACT

The COVID-19 pandemic drew attention to the critical role of building ventilation as a measure for controlling infection transmission. With the substantial number of COVID-19 outbreaks in care homes worldwide, the effectiveness of ventilation is an important consideration for infection control and wider exposure to indoor air pollutants. In this study, we used IoT-based sensors in two residential care homes to evaluate ventilation in various areas, including bedrooms, corridors, and communal spaces. Our monitoring focused on carbon dioxide (CO_2) levels as a proxy for ventilation, as well as temperature and humidity, during the spring of 2022. We also developed a ventilation model using the software CONTAM and coupled it with an infection risk model to assess airborne transmission risks under different weather and occupancy conditions. Our results suggest that ventilation is generally adequate based on UK COVID-19 guidelines at the time, with CO_2 below 800 ppm for the majority of the time, and opening windows in communal spaces in elderly care environments can help preserve indoor ventilation during periods of high occupancy. However, modelling data suggests that low CO_2 values may be indicative of low occupancy in many spaces and therefore ventilation rates may not be sufficient to mitigate infection transmission. Encouraging positive ventilation behaviours in staff and residents, potentially supported by visible CO_2 monitors, and taking additional precautions such as using air cleaners, enabling additional window openings or staff wearing masks during outbreaks and periods of high disease prevalence is likely to be beneficial for resident and staff health.

1. Introduction

The risk of COVID-19 transmission is now well recognized to be increased in poorly ventilated areas. The SARS-CoV-2 virus, and other viruses such as influenza, are transmitted by aerosols and are far more contagious in indoor air than outdoors [1]. Even if an infected individual leaves an environment, the virus may remain in the air for some time [2]. Beyond infection transmission, wider aspects of indoor air quality (IAQ) are well recognized to be important for health. Poor indoor air quality and indoor air pollution harm both physical and mental health [3–6]. Circa 13.7 million deaths per year are linked to our work and home environments and air quality. Analysis of the Global Burden of (n=87) risk factors in 204 countries and territories [7] highlighted indoor air pollution as a top ten mortality risk factor globally. In some cases, the indoor environment is twice as polluted as the outdoor environment [8]. Poor IAQ has immediate and longer-term effects. Short-term exposure may mean irritated eyes, nose, and throat, but longer-term effects are more significant such as asthma, and other breathing diseases [9,10]. IAQ is complex and is affected by contextual, occupant, and building-related (COB) factors [11].

Ventilation is a key strategy in reducing exposure to airborne viruses, and diluting indoor pollutant sources. The role of fresh air in mitigating disease is not new. In 1857, Florence Nightingale wrote, “The want of fresh air may be detected in the appearance of patients sooner than any other want. No care or luxury will compensate indeed for its absence. Unless the air within the ward can be kept as fresh as it is without, the patients had better be away [12]”. Despite ventilation’s central role in promoting healthy workplaces, schools, hospitals, and care homes, its use is variable, particularly in naturally ventilated buildings and during the winter. Carbon dioxide (CO_2) levels in a

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building are a significant predictor of ventilation rate, and monitoring of CO_2 has been widely recommended during the pandemic as a means of enabling better natural ventilation of buildings [13,14]. The primary source of CO_2 in indoor environments is human metabolism. CO_2 concentration increases with the number of occupants and also varies depending on their age and activity [15]. Ventilation helps lower indoor CO_2 concentrations when there are no other gas sources. So-called "Sick Building Syndrome" is more likely in environments with high CO_2 concentrations over extended periods [16].

Care homes are environments that may be susceptible to poor ventilation and indoor air quality. Residents are often elderly and vulnerable and may require higher indoor temperatures for comfort than in many buildings. Aside from the widespread use of communal facilities such as dining rooms that can facilitate airborne infection, frequent use of personal care products, household cleansers, bactericides, and proximity to combustion sources in kitchens can reduce air quality. Surprisingly little empirical data exists on the extent, variability and effects of ventilation in care homes. In our previous study [17], two care homes in the Yorkshire area of the UK were monitored with a limited number of CO_2 sensors. The current study focuses on ventilation in care homes through systematic monitoring of two UK residential care homes (with nursing) for elderly people by using multiple sensors to measure CO_2 , temperature and humidity over a UK Spring period. We present and compare data on this monitoring for a range of different locations in the two homes including bedrooms, corridors and communal areas. We also present an infection risk model based on [2], that uses the modelling tool CONTAM to simulate airflow between spaces to inform a transient Wells-Riley model to predict infectious airborne quanta concentration and assess potential exposure risk. We use this model to demonstrate how ventilation conditions for environmental and occupancy scenarios typical of a care home can influence the likelihood of airborne disease transmission.

2. State-of-the-art

2.1. Risks within care homes

Care homes were a key focus for the COVID-19 policy response worldwide due to the significant role they play in the provision of care for one of the most vulnerable population sectors, and the fact that they were identified as a high-risk setting for the consequences of COVID-19 [18]. The COVID-19 pandemic severely affected residents in care homes in the United Kingdom. Significant increases in the number of excess deaths in care homes in the first and second waves of 2020/21 were seen, and studies carried out in England, Scotland, and Wales up to the summer of 2020, evaluated this early excess mortality [19]. By the end of the first wave in England and Wales (August 2020), the Office for National Statistics (ONS) estimated that nearly one-third of all deaths among care home residents had been caused by COVID-19 [20]. These deaths among care home residents accounted for approximately 40% of all COVID-19 deaths in England and Wales [21]. The rapid spread of COVID-19 in care homes with nursing has resulted in tragic consequences for residents and revealed significant gaps in monitoring, observation, awareness, and resources for interventions to prevent the transmission of infectious diseases [22,23] such as improved ventilation and air filtration. The impact of the COVID-19 pandemic on the risk of outbreak and death among care home residents in England has not yet been comprehensively investigated and placed in the context of indoor air quality and assessment of ventilation.

Residents of care homes with nursing typically spend the vast majority of their time indoors, which can subject them to any indoor air pollutants for long periods [8,24–26]. The majority of nursing home residents are over 65 years old [27] and commonly have underlying chronic health conditions and weak immune systems, which may make them more vulnerable to the impacts of airborne pollutants [26,28,29]. Concentrations of indoor gaseous and particle air pollution in nursing homes have been shown to frequently surpass those found in surrounding outside areas [30].

Awareness of ventilation in care homes has only been considered in a relatively small number of studies, most of which are closely related to human beings' physical and mental health because care homes residents and elderly people typically spend 80%–91% of their time in indoor environments [31,32]. Even at low concentrations, long-term and continued exposure to indoor air pollution may negatively impact health, well-being, and quality of life, as well as increasing hospitalization and unscheduled acute care visits [33–35]. A study across seven European countries with over 600 residents in 50 care homes indicated that even moderate reductions in indoor air quality were associated with poorer respiratory health of elderly residents, with greater impacts for those over 80 years old [36]. A small number of studies have considered thermal comfort in care homes [37], including measurement of ventilation and temperature conditions [38] which indicated overheating in 80% of resident rooms and limited ventilation due to small window openings for security. Studies in the USA [39] and the Netherlands [40] associated poor ventilation in care homes with outbreaks of influenza and COVID-19, respectively.

2.2. CO_2 as a proxy for ventilation

In the context of enclosed spaces, the significance of ventilation, including its role in preventing the spread of pollutants, viruses, and bioeffluents, has long been recognized and extensively studied within the scientific community [41,42]. However, the advent of the COVID-19 pandemic has sparked renewed interest in this subject [43–46], given the pivotal role that ventilation plays in reducing infection risks in enclosed spaces and environments [47,48]. This has led various stakeholders, health organizations, and the scientific community to question existing ventilation standards. There is a growing consensus that boosting outdoor ventilation and increasing airflow rates could be helpful not only for reducing the risk of COVID-19 transmission, but also for mitigating future pandemic risks, and enhancing overall safety in our indoor living environments [49,50]. Consequently, while the COVID-19 pandemic may be waning, the focus on the role of ventilation in buildings appears to be entering a new phase [51]. The scientific community is increasingly advocating for revisions to current standards, emphasizing the need to enhance ventilation flow rates [52].

During the pandemic, the measurement of CO_2 as a proxy for ventilation levels in indoor spaces and other indoor settings received increased attention [13]. According to [14], the measurement of indoor CO_2 concentration is important because it allows for analysis of ventilation provision in buildings and the associated risks of long-distance airborne virus transmission, as CO_2 can be used as a proxy for exhaled breath, which may contain suspended aerosols containing viral particles.

High concentrations of CO_2 in an indoor environment can indicate insufficient ventilation, high occupancy relative to the space volume, or a mixture of the two, and high-resolution and long duration CO_2 monitoring allows a basic air quality classification to be made for quick and efficient space assessment [53].Whereas the CO_2 concentrations provide an indicator of ventilation efficiency and can be used in models that attempt to predict the risk of airborne transmission, it is extremely difficult to identify specific transmission occurrences, and the majority of research does not include a microbiological assessment of indoor environments [54]. It is also important to note that, while CO_2 can be a useful indicator, it is not a comprehensive indicator of indoor air quality and it is challenging to use data to calculate ventilation rates directly [55].

Pre-pandemic, a CO_2 range of 800 to 1000 ppm has been considered to be indicative of an acceptable building outdoor air ventilation rate in many countries [53]. In response to the COVID-19 pandemic, various new guidelines and standards have been introduced with the aim of reducing the transmission of airborne diseases. In the UK,

Table 1
Classification of air quality bands from A through G and the corresponding to CO_2 concentrations [54].

Air quality (CO_2 level) bands	Classification	CO_2 concentrations (ppm)
At or marginally above outdoor Levels	A	400–600
Target for enhanced aerosol(Sport activities, singing)	B	600–800
CO_2 standards level design standard for office work/workplaces	C	800–1000
Medium air quality (CO_2 concentration)	D	1000–1200
Pre-COVID design standards for classroom/Schools	E	1200–1500
Priority for improvements	F	1500–2000
Low ventilation rate/High occupancy/actions need to be taken to improve	G	> 2000

both the Scientific Advisory Group for Emergencies (SAGE) and the Chartered Institution of Building Services Engineers (CIBSE) recommended CO_2 levels should be below 800 ppm and indicated that indoor environments, spaces and workplaces that often exceed CO_2 levels above 1500 ppm were poorly ventilated and should be prioritized for improvement [56,57]. In Europe COVID-19 guidance from REHVA also indicated that CO_2 levels should be below 800 ppm and recommended a setpoint of 550 ppm for recirculating mechanical ventilation systems [58]. Guidance from the World Health Organization (WHO) focuses on ventilation rates rather than CO_2 and recommended a minimum outdoor airflow rate of 10 L/s-person for non-healthcare facilities [59], reinforcing the crucial role that adequate ventilation plays in mitigating aerosol disease transmission. ASHRAE Standard 241 [60], published in 2023 as a direct response to the pandemic, specifically addresses inadequate ventilation rates in non-healthcare settings and outlines precise directives for ventilation that set equivalent higher ventilation rates compared to previous standards such as ASHRAE 62.1 [61]. Additionally, ASHRAE has also developed additional standards and guidance documents, which emphasize using CO_2 monitors for assessing indoor ventilation to mitigate the risk of airborne infections [62]. These measures aim to improve Indoor Air Quality (IAQ), enhance occupant health, and optimize energy efficiency concurrently.

In recognizing that airborne transmission risk is also influenced by activity of occupants, a set of IAQ classification bands based on CO_2 were developed by [54] to enable detailed analysis of various types of spaces used for different purposes. Table 1 shows that the IAQ classification bands range from A to G, with A being the equivalent of outdoor air, B indicating very good air quality, C, D, and E relating to medium air quality for different conditions, and F and G, with CO_2 concentrations above 1500 ppm, indicating low ventilation rates that should be prioritized for improvement. It is important to note that these classifications only consider the adequacy of outdoor ventilation rates and do not consider other IAQ parameters such as particulate matter.

The spread of the SARS-CoV-2 virus has brought the importance of alleviating transmission indoors into sharp relief. Despite improving ventilation being an obvious mechanism for improving IAQ, the invisibility of airborne transmission and lack of feedback on effects makes encouraging effective ventilation difficult and results variable and suboptimal [63]. IAQ in nursing homes is not generally monitored [30], and few studies have been able to conduct in situ measurements of CO_2 concentration to assess ventilation.

2.3. Modelling risks of airborne transmission

Mathematical models or quantitative risk assessments of indoor spaces can be a useful tool to better understand the link between indoor air quality, ventilation and infection risk. Several studies have used single zone models to evaluate factors that influence airborne transmission under steady state conditions [14,64] or with CO_2 data to reflect transient airflows [65,66]. While these models are useful for exposure for a group of people in a single space over a defined time period, such as in some super-spreading outbreaks, they have limitations for multi-room environments. Steady-state multi-zone models developed pre-pandemic [67,68] demonstrated the importance of inter-zonal airflows for understanding infection risks in hospital wards.

A more realistic understanding can be developed using airflow simulation tools such as CONTAM [69], which allow for both simulation of the indoor airflow and the ability to model contaminant transport including exhaled CO_2 or airborne infections such as COVID-19. Such models have the ability to include time varying weather conditions as well as changes in occupancy and ventilation conditions. We see CONTAM used to model both airflow and airborne contaminants in a range of settings including large mechanically ventilated prototype office buildings [70], five prototype commercial buildings [71], a virtual office [72], assessing mitigation strategies in multi-zone hospitals [73], and simulating airborne transmission on a cruise ship [74]. Although CONTAM can successfully model the transport of an airborne contaminant, it is common for CONTAM simulations to be coupled with another quantitative tool to assess infection risk and exposure [2,70,71,74].

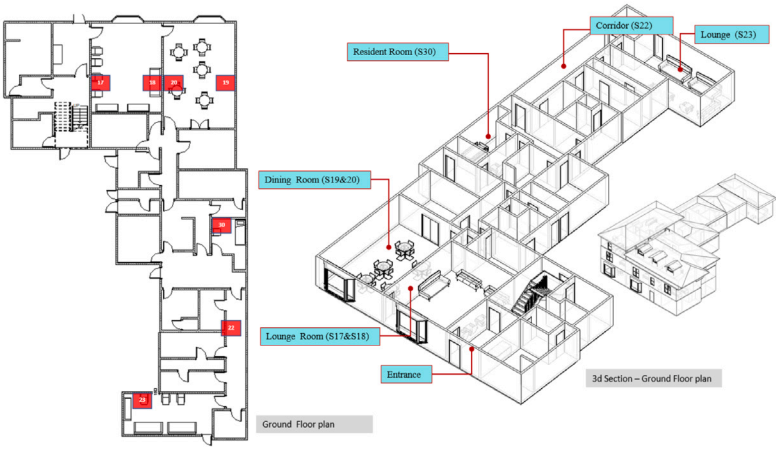
3. Measurement methodology

We deployed LoRaWAN sensors to monitor IAQ in two care homes with nursing. The Explore CO_2 senseair are non-dispersive infrared (NDIR) sensors and were set at 5-min intervals, with accuracy = ±30 ppm ±3% and range 400 to 5000 ppm. The recorded data were retrieved and accessed from an online database and simultaneously monitored in real-time on a dashboard. The primary indicator we used to evaluate ventilation was CO_2 concentration [75] since changes in its concentration may be utilized as an indicator of ventilation rate in an indoor setting. We do not use data to calculate ventilation rates, and focus on an indicator relative to suggested guidelines in the UK. Alongside CO_2 we also measured temperature and relative humidity.

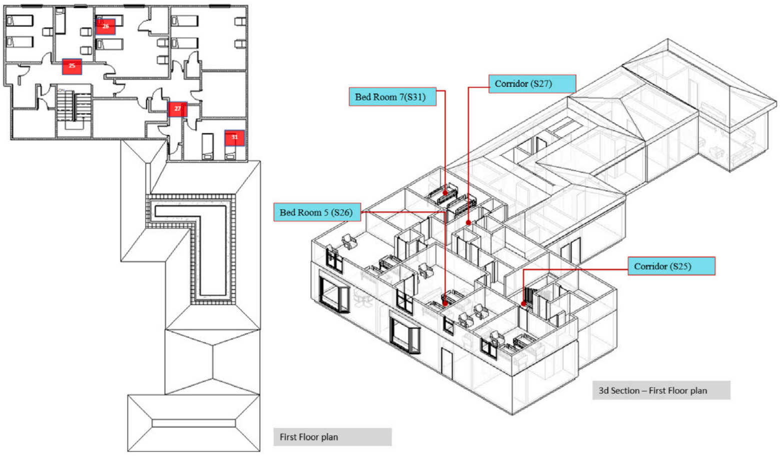
Application of a Wireless sensor network (WSN) was key to the measurement, enabling monitoring and storing environmental conditions before sending the data to a central location. WSNs are used in most monitoring applications because of lower production, operation and maintenance costs, dynamic network topologies and scalability. To effectively and reliably transmit data sensors need proper placement, gateway functionality, data assembly for further processing and a means of saving data to a database and/or cloud servers. System gateways have a high level of dependence and are limited by high memory and power requirements. Memory restrictions can be solved if sensor functionality is restricted to data collection and transmission to edge nodes; with other operations being performed on the edge node. Limiting sensor functions also reduces power demands.

3.1. Study design and location:

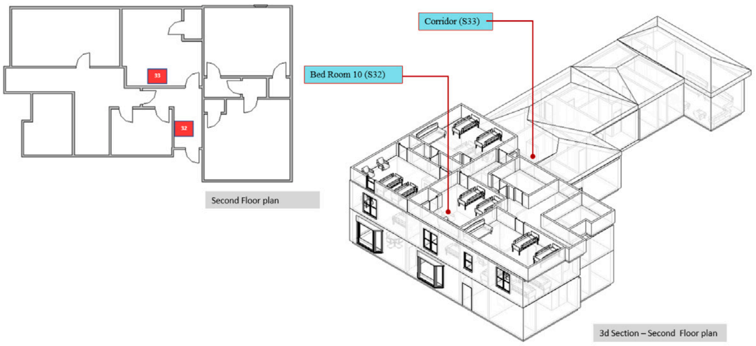
This was a time series survey design of naturally ventilated spaces associated with un-adjusted working and living patterns in care homes. The study focused on two residential care facilities with nursing in Yorkshire, UK, from April 4th to May 31st 2022. Air was sampled from shared areas where residents and staff mixed (lounge, corridor, dining hall, day/staff rooms) in two homes. For comparative purposes, the air was also sampled in bedrooms. Both care homes were predominantly naturally ventilated through windows. Ventilation in



(a) Ground Floor plan



(b) First Floor plan



(c) Second Floor plan

Fig. 1. Care Home-1: Location of rooms and placement of sensors on ground, first and second floors.

bedrooms was provided by opening windows with some mechanical extract ventilation bathrooms.

Care Home-1 had a capacity of 28 residents and had 23 residents and 37 staff members at the time of data recording. Care Home-2 had a total of 102 residents and had 87 residents and 120 staff members at the time of data recording. Both homes included resident bedrooms and communal lounge/dining areas. Care Home-2 also includes a more extensive range of facilities including a pharmacy, bars, and cinema within the building.

Sampling was carried out as part of a wider study where ethical approval was given by the research ethics committees at the Universities of Strathclyde and Leeds. Researchers complied with infection control procedures within the care homes; before each visit, researchers were tested for COVID-19, and during visits personal protective equipment (PPE) was worn. The researchers did not attempt to alter working patterns, make any changes to the environment or increase ventilation beyond what was observed.

- **Outdoor conditions**: A range of 4 to 18 °C was observed except the first two weeks of April where the outdoor temperature was lower at −2 to 9 °C (Avg. 4-13 °C), 79(% rh).

- **Sensor Type:** Duomo ExploraCO2 sensor [76] is a battery-powered LoRaWAN sensor for data collected via cloud servers. The sensor is wall-mounted and with no visual display. The measuring range of the sensor is 400 to 5000 ppm (extended up to 10000 ppm), -20–60 °C, 0%–100% with the accuracy value for CO_2, temperature and humidity value is ±30 ppm ±3% of reading, ±0.2 °C, ±2%RH.
- **Placement of Sensors:** In both care homes, 40 sensors were placed in shared areas, stairs, corridors and in a few bedrooms. The position of all the deployed sensors was around standing head height (1.5–1.8 m high), and sensors were all located on walls and away from doors, windows and heaters.

4. IAQ data visualization and analysis

4.1. Care Home-1 data visualization

In Care Home-1, 17 smart sensors were deployed in the communal and bedroom areas. Nine sensors (named 17 to 24 and 30) were installed on the ground floor, six sensors (#25 to 29, and 30) were on the first floor and two sensors were on the second floor, as shown in Fig. 1.

For each location, plots were generated to show weekly variations using the recorded data of each sensor separately against CO_2, temperature, and humidity. All plots were rendered using MATLAB scripts, and some were generated using Origin. The 3-D floor plans were created using Revit. In each box-plot from Fig. 2 to A.15, the red notch represents daytime (7am to 8pm) while the black notch represents nighttime data (8pm to 7am) for each week.

4.1.1. Lounge and dining halls

The weekly box plots of monitored data for CO_2, temperature and humidity from two lounges and a dining hall are presented in Fig. 2 for the whole monitoring period. Two sensors (17 and 18) were installed in the main lounge, two (19 and 20) in the dining hall and one (23) in another lounge/staff room used mostly for staff meetings and professional visiting staff such as doctors/psychiatrists. Resident areas tend to be slightly warmer and dryer than the staff room with temperatures typically in the range 21 to 24 °C. From the seventh week, the staff-room data shows an abrupt increase in temperature and humidity. During this period decoration work was carried out in the room which is likely to explain the unusual conditions. Due to windows opening and mechanical ventilation in the adjacent kitchen, which was attached to the dining hall via a glass wall and windows for serving in the dining hall, we noticed slightly lower temperature and humidity values in the dining hall compared to the lounge. A normal range of CO_2 was observed at all sensors with the majority of values below 800 ppm and similar mean values in all three rooms. However, there are higher peaks regularly above 1000 ppm and occasionally above 1500 ppm due to changes in the number of occupants.

The daily time-series graphs for the first week of April (Fig. 3) show the variation in values of CO_2, temperature and humidity in the lounge and dining hall. The peaks in CO_2 value are evident for the dining hall and indicate the increase in occupancy, with lower values present when residents move to bedrooms. Since residents follow a daily meal schedules there is some regularity in the peak readings. Support workers, visiting professionals and care home staff also help residents to do extra activities or regular appointments which can be carried out in the lounge area, which also shows some higher values.

In Care Home-1, most rooms were for single occupants, but a few rooms were designated as shared spaces between two occupants. Six bedrooms had sensors installed from the ground to the second floor as shown in Fig. 1. During data logging, sensor 26 (bedroom 5) was noticed as faulty as it logged erratic CO_2 values and therefore we discarded the observed data from this sensor. Fig. 4 presents CO_2, temperature and relative humidity measured in five bedrooms in sub-figures (a), (b) and (c) respectively. We observed a range of CO_2 between 400 to 1600 ppm. Bedroom 7 was shared between two persons and hence had a higher CO_2 level. As expected nighttime CO_2 values tend to be higher than during the day, however the presence of high peaks in both day and night data indicates the presence of additional people such as staff/visiting nurses in the same room. Bedroom temperatures are generally between 21 and 25 °C and are slightly cooler at night, however there are some occasional higher peak values to almost 30 °C.

To meet the regulated requirements in care home environments, corridors are the areas where effective smoke evacuation in the event of a fire is considered wisely. Additionally, providing comfortable ventilation for occupants and preventing overheating is another challenge in such an environment. To assess the ventilation in corridors, six sensors were placed in all corridors from the ground to the second floor. Plots showing the CO_2, temperature and relative humidity are included in the supplementary information.

We observed the normal range of CO_2 between 400 to 1200 ppm in each week and 22 to 26 °C temperature, except in week 1 and week 2, where a peak of 1400 ppm and 28 °C was noticed. During the first and second weeks of April 2022, the outdoor temperature was between −2 to 11 °C. Due to this reason, closed windows and greater use of the heating system may be one of the reasons for higher values. A slightly higher CO_2 level was observed in the long corridor on the ground floor than on the floor above. A similar trend for temperature was also observed between the floors. The trend of relative humidity is opposite to the temperature as expected.

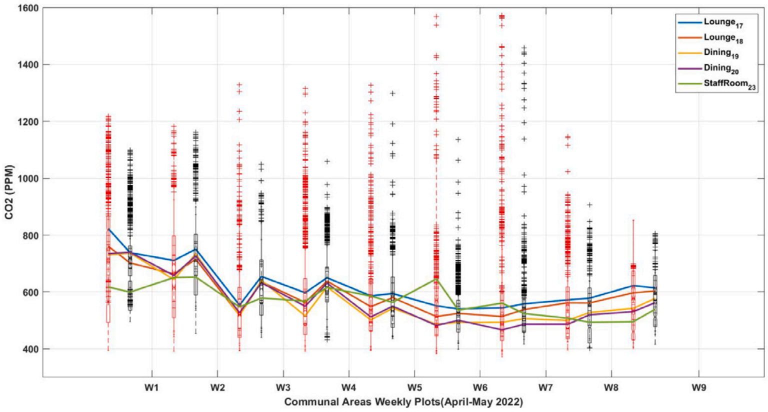
Comparison between measurements in corridors and the immediately adjacent bedrooms (see figures in supplementary information) showed that for both the ground floor and second floor the average CO_2 in the corridor is very similar to that in the neighbouring bedrooms, while on the first floor, the bedroom is consistently higher than the corridor by around 100 ppm. The reason for the difference is not known but may reflect different preferences for window opening by residents on the first-floor room compared to in the other locations. There are some small differences in temperature, with the range on the ground floor (22 to 25 °C) smaller than on the first and second floors (20 to 27 °C).

4.2. Care Home-2 data visualization

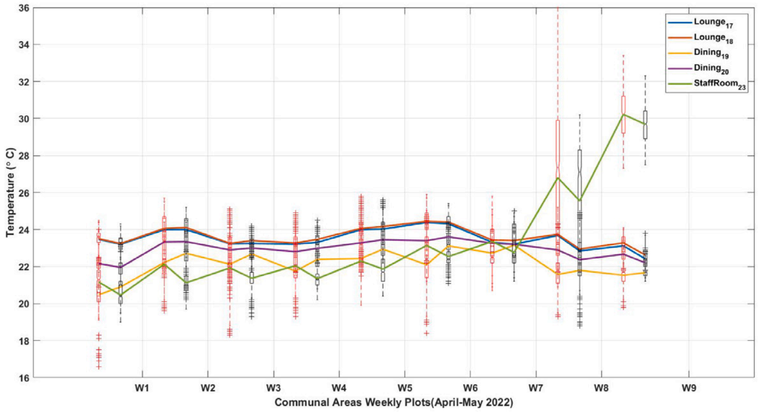
In Care Home-2, the total number of deployed monitoring Sensors was 23 across communal, non-communal and bedroom areas. A two-digit number is assigned to each deployed sensor in the home. Seven sensors (49 to 56) were on the ground floor, eight (34 to 41) were on the first floor, and eight (42 to 48) were on the second floor. The location of sensors can be visualized in Fig. 5 for all three floors. The locations presented are slightly different to Care Home-1, reflecting the different layouts and facilities in Care Home-2.

4.2.1. Atrium and lounge

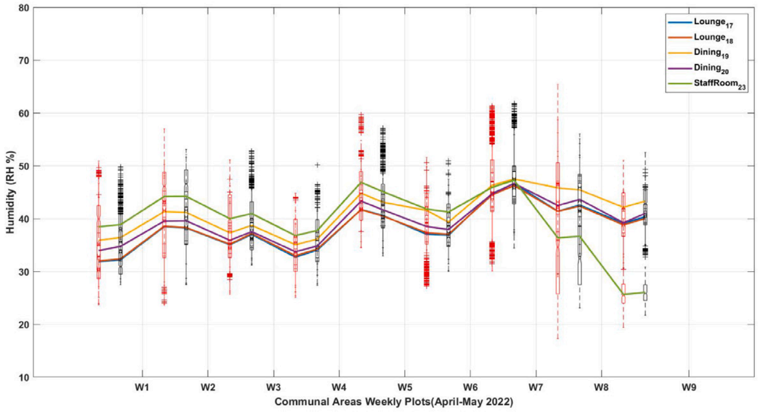
Fig. 6 presents the weekly box plots of the IAQ monitored data of CO_2, temperature and humidity from the largest spaces in Care Home-2, the atrium on the ground floor (sensors 50–53) and the residents' lounge on the first floor (sensor 34). The graphs indicate a narrow range of CO_2 with values almost always below 700 ppm in both locations, and the highest peak concentrations only reaching 900 ppm. This is likely to reflect good ventilation in the area as well as being spacious. A noticeable difference in temperature and humidity was observed between the atrium and lounge, with the lounge consistently up to 2 °C warmer than all of the sensors in the atrium. The lounge on the first floor was well-ventilated but it was a smaller space than the atrium with a higher occupancy density. Conditions across both of these spaces show quite small variations over the time period measured.



(a) CO_2



(b) Temperature



(c) Relative humidity

Fig. 2. Care Home-1: Weekly box-plots of CO_2, Temperature and Relative Humidity showing mean value of monitored data from sensors installed in the Lounge and Dining Hall. Red boxes indicate daytime values and black boxes indicate nighttime values.

4.2.2. Day and staff-rooms

In contrast to the atrium and lounge, data in Fig. 7 from a number of staff and day rooms shows much greater range and variability. These rooms include staff-only spaces such as offices and restrooms, smaller sitting areas, and a cinema where residents may be present. Data is from sensors on the ground (sensors 55,56), first (sensors 36,38,39) and second (sensors 45–47) floor. Mean values of CO_2 generally remain below 800 ppm, however there some very high peak values of over 2000 ppm suggesting that there are occasions when the ventilation rate is not adequate for the occupancy. Similarly there are some greater extremes of temperature, for example values measured by sensor 46 (small dining area) are regularly over 26 °C.

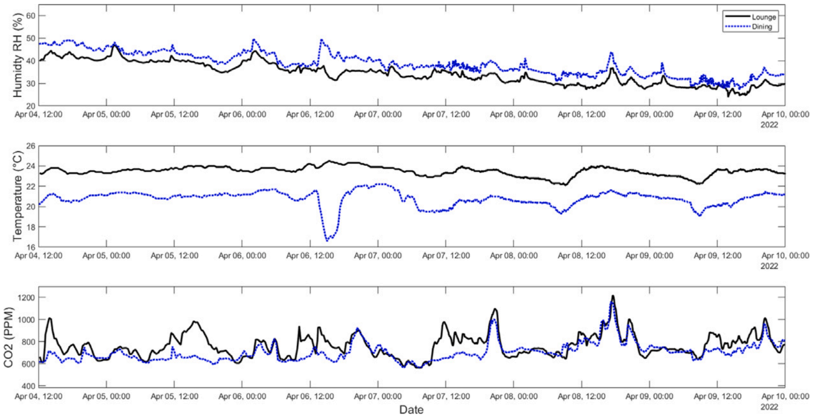


Fig. 3. Time series plots of CO_2, temperature and humidity of first week of April(4–10 April 2022) recorded in the lounge and dining hall.

4.2.3. *Corridors and bedrooms*

Measured data for bedrooms and corridors is presented in the supplementary information. Mean CO_2 values in bedrooms are normally less than 800 ppm, however, as in Care Home-1, there are occasional higher peaks with values up to 1200 ppm due to short duration increased occupancy. Temperatures were similar to Care Home-1 with a range of 22-25 °C on the first floor and a marginally higher range of 22 to 26 °C on the 2nd floor. The corridor areas were well-ventilated and we observed a normal range of CO_2 between 400-800 ppm (daytime) and 400-700 ppm (nighttime) in each week with the mean value normally between 450-550 ppm. A slight difference in temperature and humidity was observed with the increase in elevation.

5. Modelling of airflow and infection risk

5.1. *Overview of the model*

To understand the inter-connectedness of airflow and the potential for airborne infection transmission in a naturally ventilated care home we applied the modelling approach developed in [2]. Ventilation flows were simulated using CONTAM 3.4.0.3 [69] which is a multi-zone indoor air modelling tool. This software can model building ventilation rates in response to wind and thermal conditions, simulate airflow distribution and contaminants within a building, and estimate the impact of envelope air tightening efforts on permeability and associated energy impacts. We first use a CONTAM model to predict the ventilation flows and CO_2 concentrations for typical occupancy schedules as seen in the measurement study. This is used as a comparison method to ensure that the ventilation model is realistic for the care home. Then the ventilation rates and inter-zonal flow values, are extracted from the CONTAM model and used within the multi-zone transmission model presented in [2]. This model considers the emission rate of pathogens into the air by an infectious person, expressed in terms of a quanta generation rate [67,77], which is used to assess the concentration of virus over time, and models the potential exposure to other susceptible individuals. The coupling of CONTAM airflow results with the transmission model better considers the influence of transient behaviour and weather when applying the inter-zonal flow rates to the transmission model, providing a more accurate assessment of the risk.

We modelled a first-floor section based on Care Home-1 with six bedrooms, one corridor, two stairs areas, a store, an office, one shower room and four toilets. The residential area is divided into 17 zones within the section of the home considered. All the bedrooms are located along the long corridor and are of different sizes. The larger rooms were shared by two residents while the small rooms were occupied by a single resident. The model geometry is determined using the floor plan of the care home. A plan view of the geometry is presented in Fig. 8, showing selected zones, air flow elements and the direction of the flow. Table A.2 in the supplementary information shows the details of each zone number with a description of its area, volume and assumed occupancy.

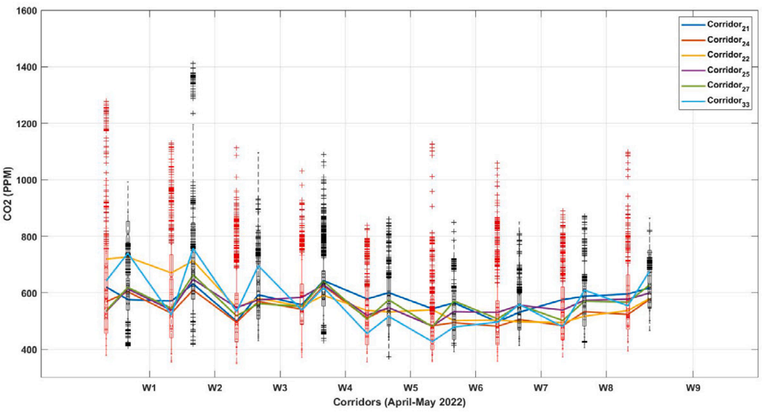
Each bedroom has one large sash window, therefore, windows in the rooms are set on the boundary wall with a width of $1\ \mathrm{m}$, height of $0.05\ \mathrm{m}$, discharge coefficient of 0.6 and exponent of 0.5 (large opening). To ensure air circulation in the toilets, ventilation extract fans are installed; in the model, these are represented using a simple air-handling system with the minimum outdoor air (OA) flow set to $90\ \mathrm{sm^3/h}$ to ensure sufficient air is present in the system. If the OA parameter is too high for the required volume of air then CONTAM will exhaust the surplus air without consequence. The converse is true if OA is too high, additional outdoor air will be supplied to meet the air-handling system requirements [78]. A supply and a return system are added to the toilet to simulate the suction effect of the extraction fan. The CO_2 generation rate for an adult is specified as $0.0052\ \mathrm{L/s}$ [15] along with a molar mass of $44\ \mathrm{kg/kmol}$ and a default (outdoor) concentration of 400 ppm. Due to the lack of data surrounding occupancy and window/door opening schedules, it was difficult to calibrate the parameters used within the CONTAM model. The CONTAM model outlined here is therefore intended as an approximation of the space for comparison purposes, and not as an exact replica.

The outdoor conditions were based on conditions in April and modelled for 10 days of data. Simulations used a weather file for Leeds, West Yorkshire, UK in the model for the same period to see the outdoor effect on the indoor environment. Although this is not the exact location of the care home, it is within the same geographic region so was considered representative of typical weather conditions over the period.

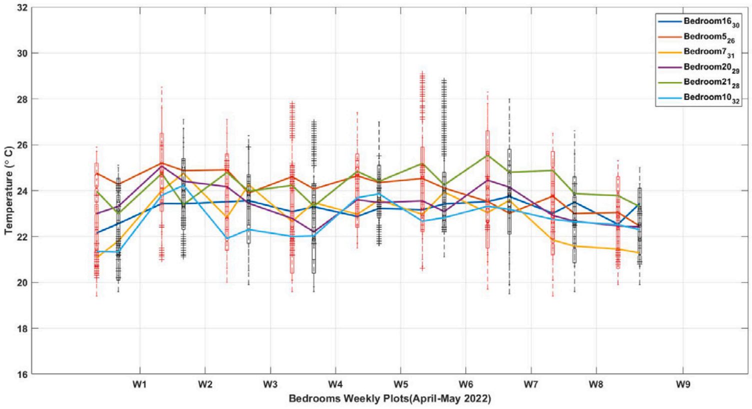
5.2. *Comparison results*

Fig. 9(a) presents the data from the CONTAM model considering the transient flow and weather conditions, along with scheduled windows opening (3 h) during the day and closed doors at night. Bedroom 7 has been modelled as having two residents, and two support workers are scheduled to visit rooms in the morning to help residents get ready for breakfast, lunch, and dinner time and at night to prepare them for sleep. Fig. 9(b) presents the monitored data from the care home-1 environment using IAQ monitoring sensors over a comparable period.

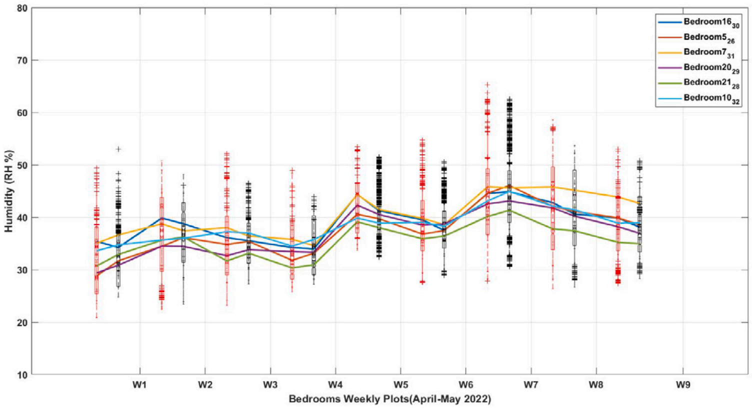
The results of both cases indicate a higher concentration of CO_2 in bedroom 7 and a lower concentration in the corridor. While there are several differences in the modelled and measured results, and the simulation cannot be treated as a validated model, both show similar values of CO_2 and show that the model captures trends such as morning and evening peaks in the bedroom data when a care worker is in



(a) CO_2



(b) Temperature

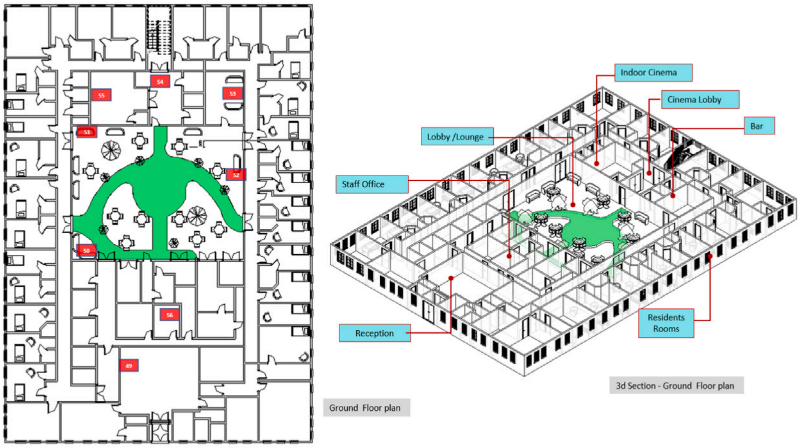


(c) Relative Humidity

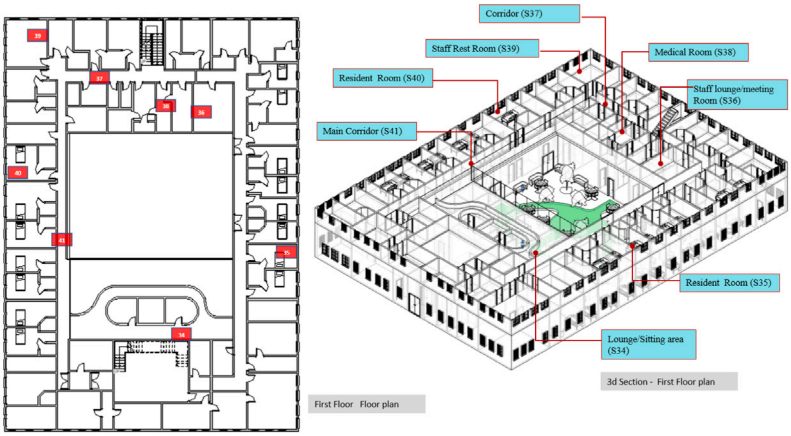
Fig. 4. Care Home-1: Weekly-plots of CO_2, Temperature and Relative Humidity showing mean value of monitored data from sensors installed in Bedrooms. Red boxes indicate daytime values and black boxes indicate nighttime values.

the room with a resident. The measured data shows higher values of CO_2 than the modelling for a few days, especially on 9 April 2022. There could be several reasons behind this including additional visitors in the home with residents, variations in window opening schedules, or differences in ventilation due to variable weather conditions.

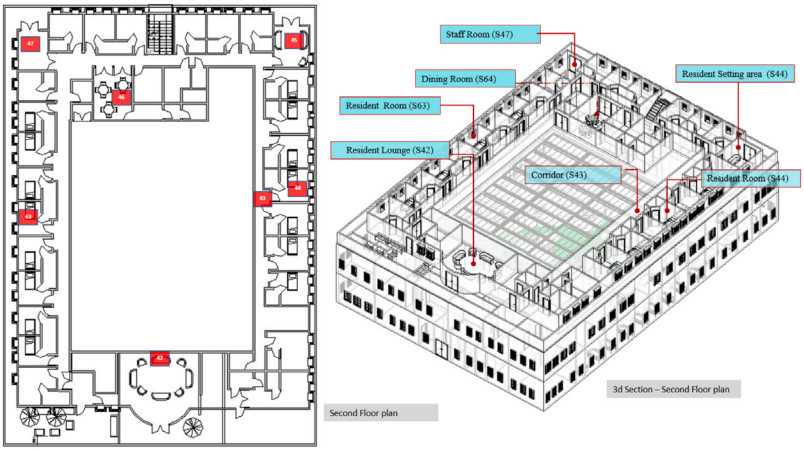
The CONTAM airflow model for Care Home-1 and measured data have similar values and trends of CO_2 concentrations data, which indicate that the model is able to give a representation of realistic airflows and occupancy in the care home. The model cannot exactly replicate the care home scenario, but the similar conditions compared



(a) Ground Floor Plan



(b) First Floor Plan



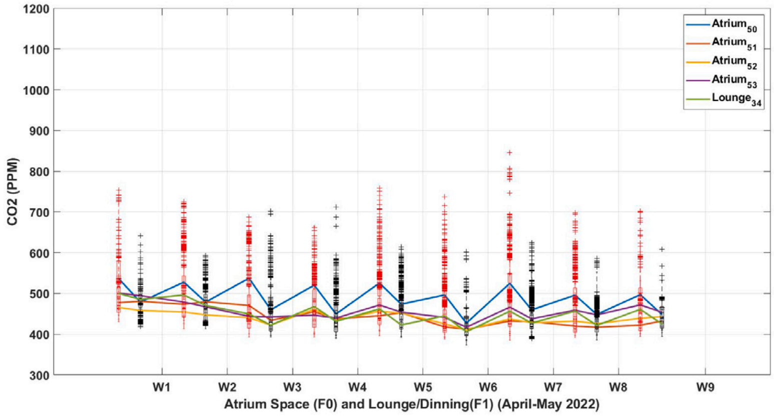
(c) Second Floor plan

Fig. 5. Care Home-2: Location of rooms and placement of sensors on ground, first and second floors.

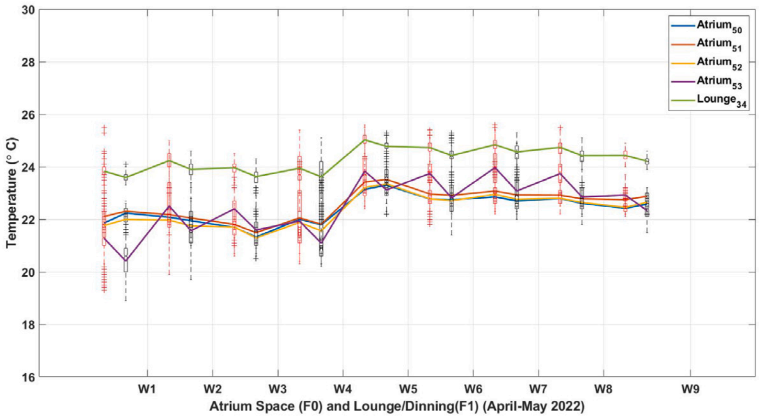
to the measured data give confidence that the model can be used to evaluate typical ventilation scenarios and infection risks for a care home of this type.

5.3. Extension to transmission model

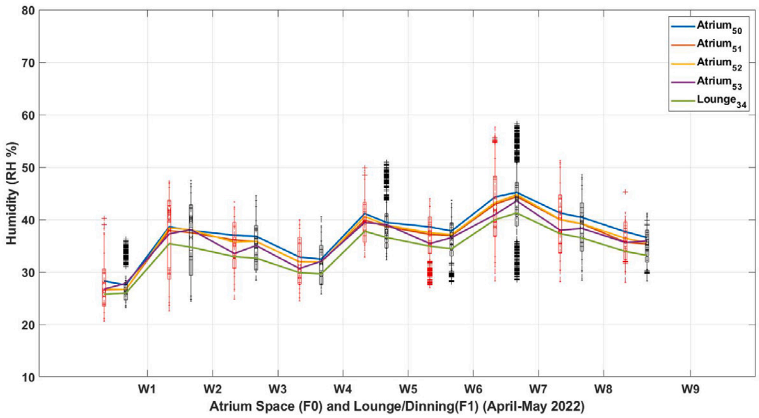
We extracted the airflow results from the above CONTAM model and used these together with the transmission model outlined in [2] to investigate the transient concentration of airborne pathogens if there were to be an infectious support worker present, who is moving between the connected zones in a care home. The transmission model was adapted appropriately to suit the scenario modelled in this study. The ventilation rates for each zone in the transmission model were informed by the simulated airflow through windows and leakage in the CONTAM Model, representing natural ventilation. The natural ventilation in the rooms and corridors ranged from 0.38–3.14 ACH, with much higher



(a) CO_2



(b) Temperature

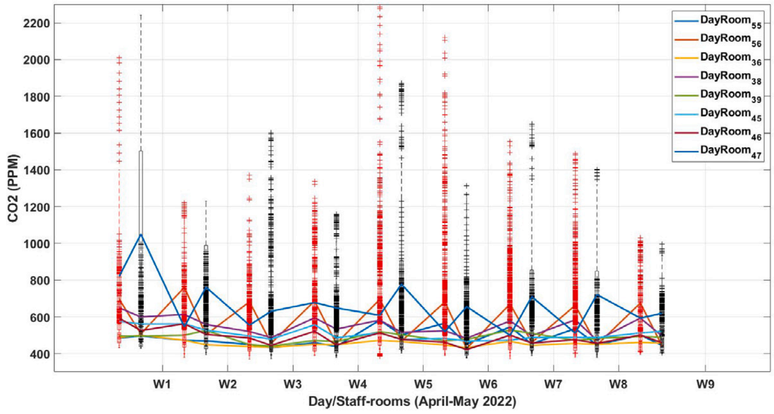


(c) Relative Humidity

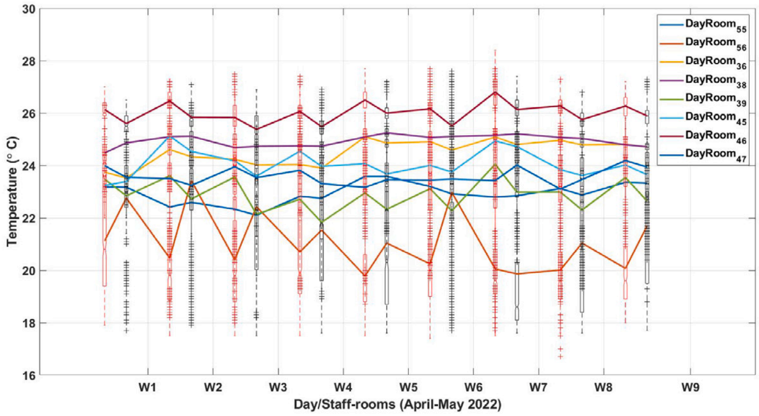
Fig. 6. Care home-2: Weekly plots of CO_2, Temperature and Relative Humidity showing mean values from data measured in the atrium and dining hall. Red boxes indicate daytime values and black boxes indicate nighttime values.

rates up to 30 ACH observed in the bathrooms with extract ventilation fans. The residents were modelled as susceptible people, with bedrooms 2, 3 and 6 as single-occupant rooms while bedrooms 7 and 8 were shared between 2 people, totalling 7 initially susceptible individuals. The infected care worker is assumed to spend two hours in each of the resident's room over two visits (10-hour total duration), with the mobility pattern as follows:

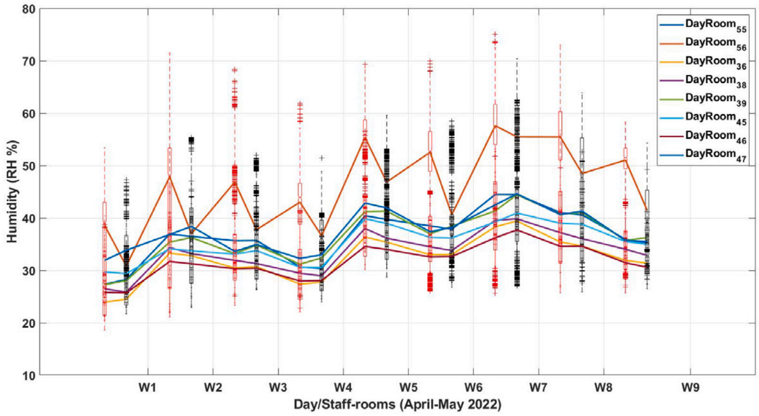
- 8:00-9:00, visited bedroom 3 (zone 2)
- 9:00-10:00, visited bedroom 4 (zone3)
- 10:00-11:00, visited bedroom 6 (zone 6)
- 11:00-12:00, visited bedroom 8 (zone 14)
- 12:00-13:00, visited bedroom 7 (zone 16)



(a) CO_2



(b) Temperature



(c) Relative Humidity

Fig. 7. Care Home-2: Weekly plots of CO_2, Temperature and Humidity measured in staff and day rooms. Red boxes indicate daytime values and black boxes indicate nighttime values.

The same mobility pattern was then repeated from 13:00 to 18:00. The support worker was assumed to exhale infectious virus at a rate of 0.5 quanta/min, which represents a more infectious case of for example COVID-19 or influenza [64,77]. Within the transmission model, viral inactivation and viral decay were not considered since we wanted to focus solely on the effects of ventilation as a mitigation tool to reduce risk. In reality, although we would expect to see some viral decay, with the outbreak period being relatively short at only 10 h, it seemed reasonable to assume that ventilation would be the dominant removal mechanism over viral decay [79].

Fig. 10 presents the predicted concentration of infectious quanta in the room air when the infector visited Zones 2, 3, 4, 14 and 16. The change in airborne pathogen concentration with the infectious staff member moving from zone-to-zone, illustrates the growth curve of

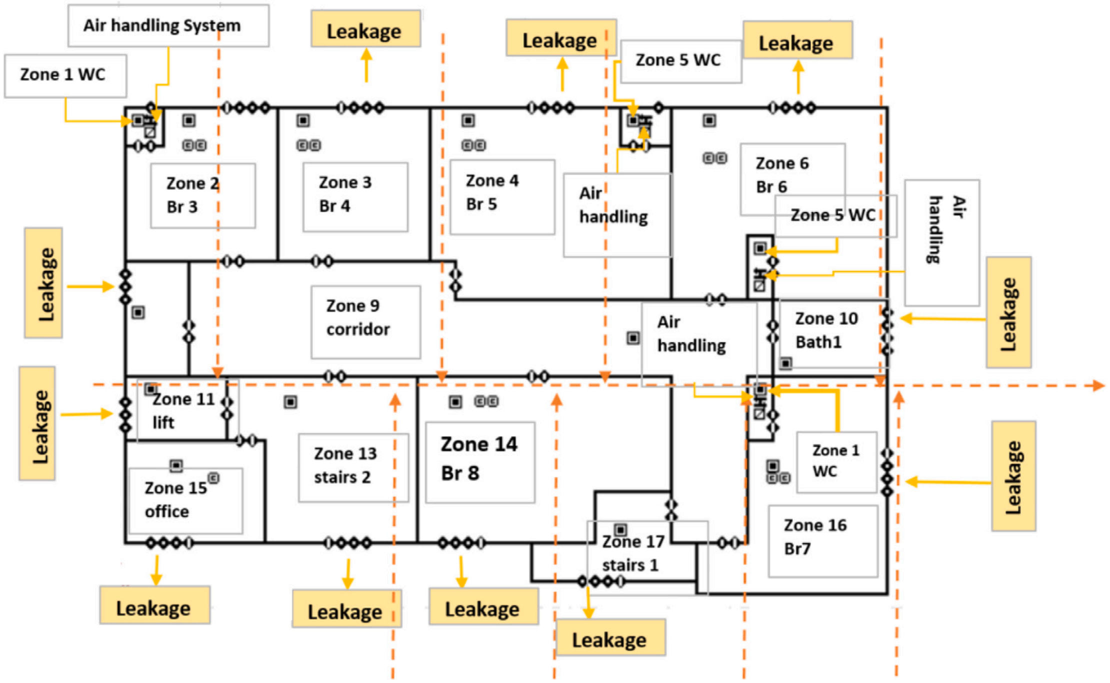
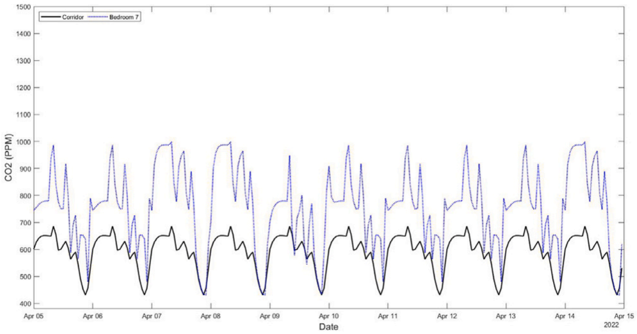
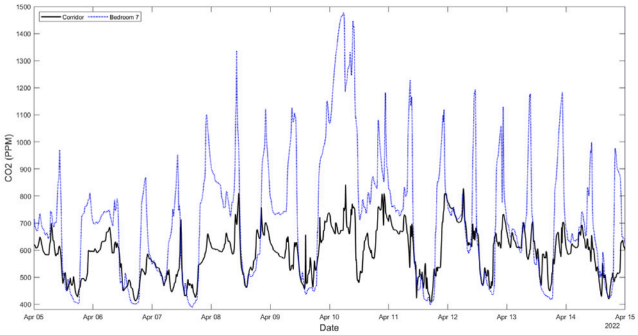


Fig. 8. Selective 17-zone geometry of the care home model along with path flows used in the case study.



(a) Simulated CO_2 data from the CONTAM model for transient weather condition



(b) Monitored CO_2 data comparison in corridor and bedroom 7

Fig. 9. Comparison between monitored CO_2 concentration in Care Home-1 with the modelled data based on an approximation of the care home with the scheduling of windows opening and closed doors. Here the black solid line represents the CO_2 concentration in the corridor while the blue dotted line is used to represent the CO_2 Concentration in bedroom 7.

the infectious quanta concentration once the infectious person enters a room. The variation in the peak values obtained for the quanta concentration, and the corresponding time taken to reach the peak is due to varying room volumes and respective ventilation rates varying across the rooms. We also observe the gradual decay in quanta concentration once the infectious person leaves and moves to another zone. This is

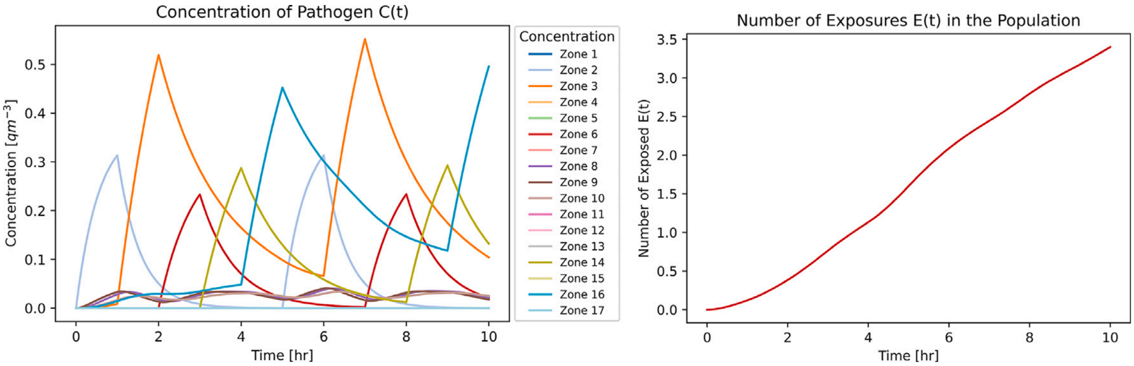


Fig. 10. Extended Transmission Model: Concentration of airborne pathogen when an infected staff member visited zones 2,3, 6, 14 and 16 in the care home model (left), Exposure curve- illustrating the total predicted number of exposed individuals, $E(t)$, when an infector visits residents in the home (right).

useful for better capturing the risk posed to a susceptible resident fixed in one of the zones and shows that despite the infectious individual not being present, the pathogen concentration is non-zero and thus, so is the risk of infection.

In some cases, the decaying quanta concentration never reaches zero, for example, Zone 2 in Fig. 10. In this case, it is possible to observe compounding in the airborne pathogen concentration. When the infector returns for a second time, the quanta concentration then builds on this value and we see the peak reach a higher value in the second visit, increasing the risk further. This compounding effect shows the importance of considering transient behaviour, and efficient air cleaning. Here, natural ventilation is not effective in diluting and removing all of the infectious quanta concentration from the air, leading to an elevated risk on the second visit. As a direct consequence of using the simulated airflow within the model, we also observed slight increases in concentration in connected zones where the infectious individual is not present due to inter-zonal flows.

Within the transmission model, the modelled concentration solution is extended to a compartmental epidemic model, in this case a Susceptible-Exposed (SE) model. The predicted number of exposures in a given zone k is given as

$$\frac{dE_k}{dt} = pC_k S_k,$$

where E_k is the total number of exposed individuals in zone k, S_k is the total number of susceptible individuals in zone k, C_k is the concentration of airborne pathogen in zone k, and p is the pulmonary rate of an individual which is set as $p = 0.01\ \mathrm{m}^3\mathrm{min}^{-1}$ [67]. The number of exposures in each zone are then summed to provide the total number of exposures in the whole population, $E(t)$, as in [2]. The solution for the predicted number of exposures in the given scenario is presented in Fig. 10. The predicted exposure curve is fairly linear in nature due to small time period explored, the small population, and a relatively simple schedule for the infectious individual, although there are slight differences in the curve gradient and shape due to the growth and decay of the transient concentration solution and the varying room volumes. This illustrates the possibility of extending the use of more realistic inter-zonal flow values exported from a CONTAM airflow simulation to a transmission model where we are then able to simulate scenarios with particular ventilation, disease and occupancy schedules in order to assess the transient concentration of pathogen and predict risk through predicted exposure solutions from an epidemic model, providing a better risk assessment.

In future work, we plan to evaluate the model for multiple case scenarios by considering a greater range of ventilation rates and quanta emission rates. In the transmission model, it is also possible to replace the ventilation rate with a more general removal rate, allowing for the inclusion of viral inactivation and viral deposition, but this was not considered here. The model focuses on the movement of one person and assumes that others remain fixed in one location. Adding multiple transient occupants into the model is complex but would give insight into the interaction between ventilation and occupancy, allowing for more varied scenarios. The shared areas like the lounge and dining room would also be an interesting scenario to assess infection risk. Future work to compare the effectiveness of different infection control strategies using the model would also be beneficial, and this could include using approaches such as the “equivalent mask efficiency” as applied in [71] to compare the relative impact of ventilation measures to mask wearing.

6. Discussion

Despite care homes being a setting of significant concern for infection risk, both during the COVID-19 pandemic and more widely due to the vulnerability of residents to other pathogens and the effects of poor air quality, there is very little published data on the ventilation within care homes. The current study has measured parameters associated with ventilation and thermal comfort in multiple spaces across two UK care homes. The two homes are different in nature with Care Home-2 considerably larger than Care Home-1, and with a wider range of facilities for residents.

The measured data suggests that both care homes show reasonable ventilation during the measured period, with the average CO_2 around 800 ppm or below in the majority of spaces. This is in line with guidance on ventilation in the UK at the time of the study [53]. However, the data shows that in many spaces there are higher peak values which likely reflect increased occupancy for short periods of time. The highest peaks were observed in the staff and day rooms in care home-2 which reflect both the smaller sizes of these rooms and peaks in occupancy at certain times of day. Through the modelling we saw relatively high levels of quanta concentration and infection risk and the simulated airflow in the CONTAM model suggests some quite low ventilation rates achieved through natural means; rates were rarely above 3 ACH, with some bedroom and corridor spaces considerably lower. This indicates that the low CO_2 values observed in practice may be more likely to be a result of the relatively low occupancy of most rooms rather than good ventilation. This is important to consider when using CO_2 as an indicator of infection risk and the implementation of infection control measures during outbreaks. While the ventilation rates seen in this study are indicative of a comfortable environment, they may not be sufficient for rapidly diluting infectious aerosols in a room during an outbreak scenario. Additional measures such as local air cleaners or face masks for staff may be beneficial to implement during periods of high disease prevalence, and future work should explore the likely performance of these options.

There have been many challenges and limitations were recorded in conducting research in care homes during COVID-19, including:

- Social distancing: In-person visits to homes were limited to essential visits only. Two visits were arranged at the beginning and end of the study to install and retrieve sensors in care homes. Researchers wore personal protective equipment (PPE) during these visits and were tested for COVID-19 before each visit. No changes were made to working patterns or ventilation beyond what was observed. Data collection was done remotely from cloud servers.
- Quality concerns: Though, data were collected remotely, close observation of the site was impossible during the IAQ monitoring period. Researchers could only observe ventilation during the installation/de-installation of the sensors.

In the case of CONTAM modelling, the exact mobility of staff, support workers and resident movement together with aspects such as window opening was not recorded while undertaking measurements and hence assumptions were made in the modelling. In reality, it is likely that the occupancy schedule would be much more complex. However, the schedule used within the CONTAM modelling and transmission model is representative of typical behaviour. The CONTAM model only considers a subset of a care home (the first floor). Ideally, we would model the whole building as transient occupancy and airflow from the rest of the building may influence the airflow across the modelled floor. Calibration of a complex building such as a care home in CONTAM is a very challenging undertaking, and most existing data is limited to simpler residential settings where even with detailed tracer gas experiments comparisons between models and experiments range from 10 to 30% [80,81]. As such it is important to treat the CONTAM and transmission model results presented here as indicative of how building airflows and occupancy schedules could affect transmission risk, rather than as an exact representation of the particular care home.

The transmission model assumes a constant quanta emission rate and we do not include viral decay or deposition. However, the infectiousness amongst individuals can vary significantly [77], and so in future work, it may be more appropriate to allow this to vary with time, or run scenarios with a greater range of emission rates. Similarly, the loss rates due to deposition and decay may be important in some settings and are important to incorporate in future models. The ventilation rate is also assumed to be constant in the transmission model. In our case this was because the transient airflow model indicated very minimal variations in ventilation rate, however, this may not be the case for all naturally ventilated buildings. Our ongoing work is looking to develop a fully transient version of the transmission model.

Within the scope of this paper, we have analysed CO_2 levels and ventilation conditions within care homes in the context of the COVID-19 pandemic, but we have not considered wider air quality aspects in care homes. Future investigations should expand the scope to examine the presence of airborne particles, such as PM2.5 and PM10, alongside ozone (O3) and volatile organic compounds (VOCs). Future studies should aim to both quantify sources and exposures, and provide insights into the potential negative impacts of these air pollutants in the context of care homes.

7. Conclusion

Sufficient ventilation is a prerequisite for a pleasant working or living environment, but good indoor air quality is also essential for health. Very old and often frail care home residents require well-ventilated environments for their quality of life, care experience, and mental and physical health. To the best of our knowledge, our study represents the first detailed analysis of care home ventilation in the context of infection transmission using both measured data and infection risk modelling.

Using LoRaWAN smart sensor-generated data, we have shown that capturing, analysing and visualizing CO_2, humidity and temperature is feasible in care environments. During a UK spring/summer period effective ventilation as measured by CO_2, together with humidity and temperature, is possible in naturally ventilated settings. However, elevated CO_2 and temperature levels were present when outdoor conditions were rainy and cold and whole home heating systems were operational. Higher CO_2 conditions were also noticeable in certain rooms with higher occupancy levels.

The comparison of monitored data from care homes and CONTAM modelling simulation results indicate a similar trend of CO_2 concentration as observed in the IAQ monitoring, and demonstrate the potential to use infection transmission models to assess multi-zone airborne risk in care home settings. However, results suggest that some of the low CO_2 concentrations may be indicative of low occupancy rather than good ventilation and that further measures may be needed during infection outbreaks.

COVID-19 has further demonstrated the need for nursing homes to effectively develop and implement good ventilation and effective IAQ solutions. We believe that increasing systemic attention to these under-studied facilities with vulnerable populations will ultimately improve the health, well-being, and quality of life of nursing home residents and lower their medical expenditures. While our study indicates that adequate ventilation can often be achieved, encouraging positive ventilation behaviours in staff and residents and taking additional precautions during outbreaks and periods of high disease prevalence are likely to be beneficial for resident and staff health.

CRediT authorship contribution statement

Kishwer Abdul Khaliq: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Sara Mohamad:** Writing – original draft, Visualization, Resources. **Alexander J. Edwards:** Writing – review & editing, Visualization, Validation, Software, Formal analysis. **Catherine Noakes:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrew H. Kemp:** Writing – review & editing, Supervision. **Carl Thompson:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Gráinne McGill:** Writing – review & editing. **Tim Sharpe:** Writing – review & editing, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: During the COVID-19 pandemic CN was a participant in the UK Scientific Advisory Group for Emergencies (SAGE), co-chaired the SAGE Environment and Modelling Sub-Group and was a member of the SAGE care home working group.

Data availability

The adaptive Python code used in Section 5.3 can be found at https://github.com/kishibutt/MultiZone_CareHome. The CONTAM model is available at https://github.com/kishibutt/CONTAM_CareHome_Model, while sensors data can be downloaded at https://github.com/kishibutt/sensorsData.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2024.111174.

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