Reviewing Buildings Management Measures to Curtail Airborne Infections

Abdul-Azeez Adeyemi Isiaka[1], Habiba Iliyasu Atta[2], Erekpitan Omoikhefe Ola-Adisa[3], Yakubu Aminu Dodo[4]

[1]Department of Urban and Regional Planning, Modibbo Adama University, Yola Nigeria
azeezabu@yahoo.com

[2]Department of Microbiology, Ahmadu Bello University, Zaria, Kaduna State, Nigeria.
hiatta@abu.edu.ng

[3]Department of Architecture, Environmental Sciences, University of Jos Nigeria
drarchitecteo@gmail.com

[4]Architectural Engineering Department, College of Engineering, Najran University, Kingdom of Saudi Arabia
yadodo@nu.edu.sa

Abstract: The high mortality and morbidity rates of *the Coronavirus disease 2019 (COVID-19) pandemic led to an explosion of research on studying the dynamics of the survival and transmission of its causative agent, as well as other airborne pathogens. This has resulted in a plethora of information on the role of building design in the spread of microorganisms associated with respiratory diseases. Consequently, it appears that in most settings, the construction and maintenance of residential and commercial buildings did not prioritize the risk posed by airborne pathogens, and thus were ill-prepared for the likely occurrence of a respiratory disease outbreak. For property proprietors and operations managers, upgrading such buildings is a big task. To evaluate the efficacy of the available options, this article examines recent studies and construction operational initiatives for the prevention of indoor respiratory infections from the viewpoint of building managers. After reviewing the background, strategies, techniques, and results covered in these articles, the paper concluded that there are three types of building management (BM) interventions for preventing respiratory viruses from spreading in existing buildings: Hard Services (such as maintenance of Sewage and Heating Ventilation and Air Conditioning systems) to prevent aerosol transmission and Soft Services to prevent droplet transmission. The study also emphasized the necessity of conducting BM intervention studies that consider occupant behaviors in conjunction with unified results of intervention and help inform BM solution decision-making. The review broadens our understanding of BM's role in controlling the spread of airborne diseases and identifies possible areas for future research.*

Keywords: Review, Buildings-Management, Measures, Indoor Air Airborne-Infections

1. Introduction

Global health is under threat worldwide from the respiratory viruses capable of causing pandemics due to the spread of airborne diseases such as Severe Acute Respiratory Syndrome (SARS), influenza, and tuberculosis (Enughwure & Febaide, 2020). It has been determined that non-pharmaceutical interventions (NPIs) are critical and successful in limiting viral propagation before the development and delivery of medical therapies, even though vaccinations as well as medical treatments are organic remedies (Lalmuanawma et al., 2020). The worldwide NPIs against the COVID-19 pandemic, H1N1 in 2009, and end of SARS in 2003 have been led by interventions like collection limitations put in place during the 1918 influenza pandemic one century ago. Several research works have modeled the impact of official non-proliferation orders (NPIs) on the worldwide COVID-19 outbreak and illustrated the resilience of strict regulations such as travel restrictions, stay-at-home directives, suspensions from school, and other event closures (Hoang et al., 2021). Even if lockdowns and severe penalties have been effective, they have come at a high cost and may cause unrecognized psychological effects and social damages (Ferrari et al., 2020). This calls for research on alternate options that might stop the spread of viruses without significantly disrupting people's lives.

However, data about the violation of the COVID-19 pandemic's isolation globally, which involved the virus spreading from travelers housed in isolation centers to the general population, have shown how vulnerable we are to controlling indoor infection in already-existing structures. As of June 2021, for instance, there had been thirty-two (32) COVID-19 "quarantine failures" in New Zealand and Australia, where workers in quarantine hotels, such as security personnel (C. fei Chen et al., 2020), had become infected and had spread the virus to the neighborhood from the quarantine zones (Pinter et al., 2020) with extremely expensive repercussions. Significantly, the isolation hotel leaks linked to all four of Melbourne's first outbreaks resulted in one of the longest shutdowns ever recorded, compelling the usage of quarantine hotels in the city to be phased out by force.

Additionally, while the precise cause of certain pandemics is still unresolved, a lack of knowledge regarding the process of the transmission of SARS-CoV-2 in the early phases of the global epidemic seems like a significant contributing factor. This led to mistakes such as limiting the use of fomite-based controls and choosing unsuitable locations for quarantines, which inadvertently allowed transfers to occur in hotel-managed isolation (CIRT, 2020).

The proper execution of isolation tactics consequently calls for suitable buildings in addition to action options to efficiently eliminate the spread of the virus from infected patients to individuals in quarantine centers, even though immunizing personnel in isolation zones was crucial (Nazir et al., 2021). Controlling indoor infections is essential to stopping the spread of respiratory viruses. Approximately 90% of human existence now takes place in built surroundings (Ferrari et al., 2020), although, during the COVID-19 pandemic, it was discovered that most buildings were unsafe places to stay. In reality, reports that in 2019 (1283 out of 1341), indoor environments accounted for 95.7% of super spreader events globally (Ferrari et al., 2020). Furthermore, the literature currently available regarding the mechanism of respiratory virus transmission has recognized three possible pathways for the virus to spread: aerosols, droplets, and fomite [8]. This suggests that the respiratory virus can spread from pre-existing buildings (Ferrari et al., 2020). Nonetheless, the pandemic's severe interruptions in some buildings highlighted weaknesses and the vital need for health-related elements in non-healthcare situations. Epidemiologists have highlighted the challenges and need for tightening control measures in this regard to reduce the risk of bacteria spreading inside and safeguard patients and the public (Nazir et al., 2021).

2. Building Management and Airborne infection control

Given that the lifespan of a building begins and ends with its maintenance and operation (OM) phase, BM has a major influence on its efficiency, which in turn affects occupant health and interior comfort. In the meantime, occupant behaviors that influence disease transmissions are greatly impacted by BM layout and operations (Nazir et al., 2021). Building Management (BM) has therefore been acknowledged as a crucial part of managing health in the healthcare industry (An et al., 2020). Florence Nightingale developed and put into effect a strong environmental cleaning regimen, indoor air quality management, and ventilation to prevent hospital-acquired infections (HAI) in 1854, which may be considered the beginning of BM practices for infection control (Hoang et al., 2021). Thus, the BM discipline might incorporate all indoor infection control measures. Studies on the indoor setting and its impact on the health of occupants have been a focal point for BM. Before the

COVID-19 outbreak, respiratory pathogen-related infections have reduced staff productivity, which has led to financial losses. For instance, respiratory conditions like the seasonal flu accounted for the majority of office workers' short-term absences (Codjoe & Nabie, 2014). Furthermore, since many organizations realized that fewer absences from work due to illness associated with interior settings would greatly boost the organization's general efficiency, environmentally friendly construction certifications like LEED and WELL have drawn greater interest in the past few years throughout the building phase of operations (Wang et al., 2020). However, research on BM activities' ability to reduce respiratory infections is still lacking, so it's critical now more than ever to reassess how we design our current buildings.
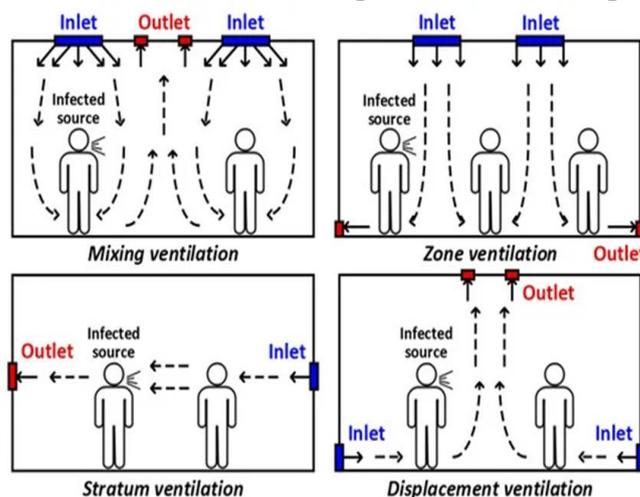

Figure 1: Illustration of various methods of ventilation based on pattern of airflow.
Source: (Ren et al., 2022)

3. Building Management Interventions as a Tool in the Prevention of Infectious Airborne Disease

Microorganisms capable of causing airborne infections comprise various species of bacteria, viruses, and fungi. However, viruses have been implicated in most outbreaks of public health significance due to their low infective dose, and unique morphology. Heating, Ventilation, and Air-Conditioning (HVAC) systems in buildings can play a potential role in the survival of suspended microorganisms in indoor air. Indeed, it is a key factor in the spread of the disease, legionellosis caused by the bacterium, *Legionella pneumophila* (Atta, 2020). Thus there is a possibility of HVAC affecting the spread of other diseases caused by microorganisms suspended as bioaerosols. To prevent the spread of airborne viruses in buildings, HVAC interventions and recommendations for HVAC operations were released. It was acknowledged that there was a need to boost ventilation, but there is still a study gap, as evidenced by the notable differences in HVAC maintenance specifications, such as ventilation rates (Ferrari et al., 2020). Furthermore, there are no regulations governing

the regular monitoring of a building's interior air quality (Ishii et al., 2015). Studies discussing airborne transmission and evaluating HVAC solutions were included in this review. Current research demonstrates the spatial distribution of HVAC system interventions. However, it should be noted by that several studies compare the impact of various HVAC intervention techniques on the spread of airborne viruses, encompassing multiple intervention measures. Ventilation rate has been regarded as an index of air dilution crucial for pathogen elimination in all ventilation experiments. Importantly, the empirical connections between the risk of indoor airborne transfer and airflow rate have been determined via the commonly applied Wells-Riley equation. Nevertheless, since various study procedures and settings are used in different research, the quantitative results vary.
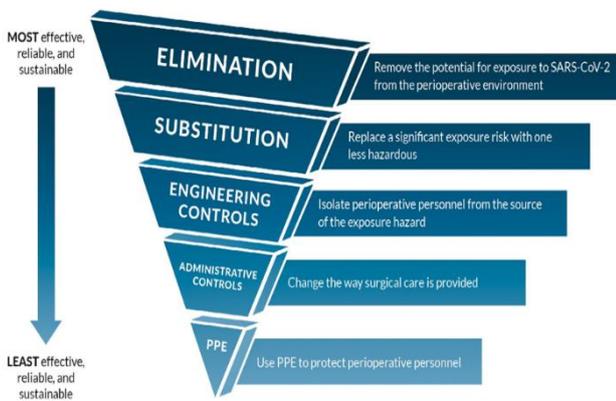

Figure 2: Hierarchy of control strategies of infection pyramid adapted from the US Centers for Disease Control (Adapted from Hierarchy of Controls. Centers for Disease Control and Prevention.
Source**:** (Centers for Disease Control and Prevention, 2015)

For example, a study by Nabie, (2014) demonstrated that residential rooms and schools with air change rates greater than 5ACH might minimize influenza spread at a neighborhood level and postpone the epidemic growth sloped with any respiratory virus]. The increasing source of airflow rate might reduce the chance of contracting COVID-19 infection by an average of 37%, while 100% outside air could cut the risk by 27% (Jones et al., 2008).
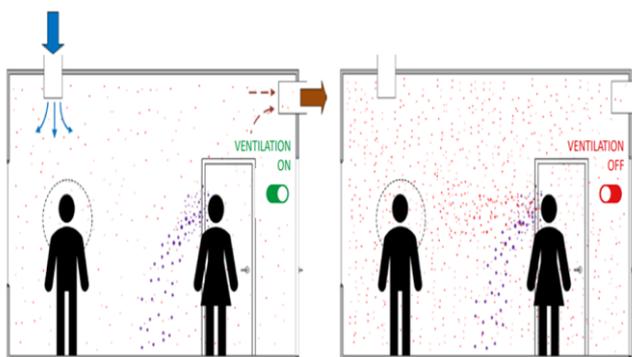

Figure 3: The ventilation system's crucial role in reducing

aerosol exposure in the breathing zone of an infected person, with red spikes indicating the presence of virus-laden particles. Source**:** (Nicas et al., 2005)

The present air circulation standard, which includes the bare essential fresh airflow necessities in different building codes, has been shown through many studies to be inadequate for minimizing airborne transmission, especially in high-occupancy residences like educational institutions, gyms, eateries, medical centers, and hotels (Yates et al., 2021). CO2 level was used as a parameter in eight publications to assess the possibility of airborne infection with various airflow configurations. According to the thoroughly combined air presumption, carbon dioxide content is recognized as an indication for predicting the result of air dilution. The Wells-Riley equation was altered by (Yates et al., 2021), who also created the mathematical connection between CO_2 concentration and the probability of transmission by air (CIRT, 2020). CO_2 levels and airborne viruses do not usually correlate, because particles can be removed from the air using ultraviolet lamps or filters without lowering the quantity of CO_2 in the atmosphere. However, installing CO_2 sensors in government buildings will assist with evaluating the risk for infections and keeping a close watch on the general quality of the air for the health and comfort of building occupants (Naik et al., 2021).
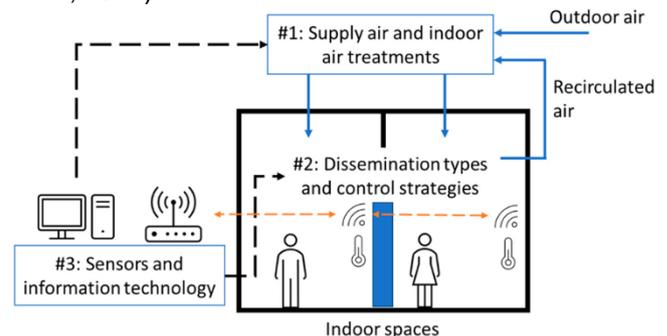

Figure 4: Installed CO_2 sensors to assist in evaluating the risk of infection.
Source: (S. Li, 2023)

3.1   Air Filtration Approaches

Filtration has been used in controlling the spread of pathogenic microorganisms suspended in air, with emphasis placed on high-priority areas such as isolation centers, hospitals, and laboratory facilities. Air filtration reduces the level of average particulate matter (PM) in indoor environments, it is thought to offer long-term health advantages for occupants of such buildings (Hänninen et al., 2017). This study examined a total of twenty-four (24) publications that investigated the use of high-efficiency particle air (HEPA) filters to prevent the spread of viruses inside by filtering out virus-laden particles. These papers focused on cases where filters were placed in central HVAC systems as well as independent HEPA machines, namely portable air cleaners (PAC). The consequences of placing HEPA filters above ventilation vents, however, were only

examined in one paper (Salamone, Belussi, et al., 2017) other studies either assessed the results of using PACs in natural environments or examined the impacts of HEPA filters in laboratory settings. These assessments showed that the indoor air could be drawn toward HEPA-filtered PAC purifiers, which could then be strategically placed and equipped to remove pollutants from the air.

A direct intervention experiment using surface and air samples from 29 homes with COVID-19 patients, contrasting the outcomes of COVID-19 testing. Following the use of portable air cleaner, they discovered that only one sample showed the presence of the SARS-CoV-2 virus, as opposed to 75% positive samples before the intervention, indicating an 80% success rate (Salamone, Danza, et al., 2017). This conclusion is noteworthy despite the small sample size since it is solely a direct solution. It was discovered that PACs may be used to augment central circulation systems in buildings; nevertheless, the combined effects are not entirely favorable. A study based on indoor a gym examined the effects of airflow and portable air cleaners both individually and used in combination. The findings showed that the combination of ventilation and PAC could reduce pollutant density by 80%, which was 20% more than the reduction of 60% achieved by airflow or PAC used singly (Alves et al., 2019).

On the other hand, other studies contend that due to the increased turbulence in the air caused by ventilation systems in the areas, the efficacy of PACs decreases (Hu et al., 2019). Conversely, since PACs can quickly lower the atmospheric burden in a limited area, regardless of airflow when doors are maintained closed, they offer a useful and affordable way to limit contaminants for buildings with physical HVAC systems (Salamone, Belussi, et al., 2017). By analyzing the results of placing PAC in various locations across space, several studies have attempted to determine the ideal placement for PAC. For example, it was demonstrated by (Karmann et al., 2017) that the optimal position for PAC in an isolation setting is next to the patient's bed. Furthermore, Blocken has shown that ground-level PAC is more efficient than other vertical locations in a gym (Schwee et al., 2019).

Similarly, (Viegas et al., 2017) found that the airflow patterns and dust removal effects of PACs varied noticeably depending on where they were placed inside a classroom (Nagy et al., 2023). Moreover, (Viegas et al., 2017) showed that the air purifier's impact on the dispersion of respiratory droplets in a dentistry room is highly dependent on the proximity between it and the nebulizer (Sharmin et al., 2014). HEPA filtration is just as effective as its reliability and upkeep, particularly when it comes to routine substitution of filters and inspection. First, as demonstrated by the experiment conducted in a dental clinic (Jiang et al., 2016), particles may escape from filters that are not adequately sealed and eventually get disseminated by the fan. Furthermore, over time, filters progressively become full and congested, which reduces airflow across the filter and, therefore, the amount of particles filtered in the room. For this reason, filters need to be changed

regularly (Ciabattoni et al., 2016). Filter change frequency varies between various types of machinery. As demonstrated by (Trivedi & Badarla, 2019). However, the majority of studies infer that installing HEPA was an affordable intervention strategy. Yeo and colleagues, for example, claimed that covering the ventilation grills with a HEPA filter is an inexpensive and simple way to address the issue (Sharmin et al., 2014), but they made no mention of the possibility that the filters may result in a decrease in the rate of airflow. However, the early financial gains and energy savings have to be balanced against the cost of frequent filter replacements and the harmful environmental effects of filter disposal.

Concerns regarding the use of PAC in quiet locations are raised by the fact that how it operates will increase indoor ambient sound levels, which differ depending on the kind of device together with its settings (Revel et al., 2014). For example, (Jamaludin et al., 2014) demonstrated that noise levels in dentistry rooms rose by 14 dB when PAC was set to its maximum setting (Ciabattoni et al., 2016). There is disagreement in the evaluation of the stakeholders' reaction to the noise, nevertheless. For instance, (D. Li et al., 2017) discovered that based on user input and Dutch school rules, which need an underlying noise quantity of less than 35 dB, the decibel levels produced by the mobile HEPA filtering system are unsuitable for classroom utilization. (Salamone, Belussi, et al., 2017).

3.2   Air Pressure

Indoor airflow patterns have a major influence on the spread of airborne viruses in buildings consequently, priority healthcare settings have made extensive use of the air pressure produced by HVAC systems to lessen the spread of viruses from contaminated places to other locations. Furthermore, because there was a greater demand for isolation facilities during the COVID-19 pandemic mechanical air pressure intervention techniques were used to convert nonclinical spaces into isolation rooms. For instance, Miller et al. showed how, as a last-minute and emergency measure, conventional air conditioning systems at nursing buildings in the United States might be modified to create a low-pressure isolation space (Enughwure & Febaide, 2020). However, several aspects, such as air leakage systems need to be further optimized to prevent unfavorable air leaks that reduce efficacy, and may also have an impact on how effective air pressure controls are. The build-up of pathogenic particles within the ionizer and its neighboring surfaces, which requires frequent cleaning, is another significant disadvantage of negative air ionization (CIRT, 2020).

3.3   Disinfection   by   Ultraviolet   Germicidal Irradiation

Ultraviolet Germicidal Irradiation (UVGI) sterilization rating systems like the WELL criteria (Ferrari et al., 2020) take into account the importance of sunlight in

59

healthcare facilities. This review assesses the effectiveness of artificial sunshine in mitigating the survival of the SARS-CoV-2 virus in air, based on two recent trials. Initially, an impact of artificial daylight on the viability of SARS-CoV-2 in aerosols was examine by (Nazir et al., 2021). After being exposed to artificial sunshine for less than 20 minutes, 90% of the virus was determined to have become inactive. They also found that exposure to high-intensity sunshine resulted in a significantly lower increase in decay rate, suggesting that the UV index is an important factor (An et al., 2020; Nazir et al., 2021). It was also demonstrated that the extensive use of ultraviolet germicidal irradiation (UVGI). Wells et al. performed the first examination of its capacity to disinfect the air against microorganisms in 1942. The first investigative cluster took place throughout the 1980s and 1990s when the upper-room UVGI system was used for several clinical investigations on tuberculosis (TB) (Lalmuanawma et al., 2020). UVGI study was rekindled during the 2003 SARS pandemic and earlier influenza pandemics (Ishii et al., 2015). Before the COVID-19 pandemic, the efficacy of UV radiation with a 254nm wavelength in destroying respiratory transmissible aerosols in medical environments had been firmly entrenched (Schwee et al., 2019). Eleven studies evaluated the efficiency of the UVGI method, and their focus was on four modeling studies (Serra et al., 2014).

3.4 Heating system

The vapor from heating systems in buildings could play a significant role in affecting the status of microorganisms suspended in the air. Thus, the type of heating system was addressed in three publications analyzed in this study. The studies focused on ways to lower the spread of viruses through building mechanical changes. First, Yu et al. showed that throughout wintertime, viral-laden droplets and aerosols may use air that comes through electrical heat pump (EHP) systems as a route of virus transmission. As a result, they suggested adjusting the warming air angles and lowering the wind velocity of the EHP heater (Ishii et al., 2015). Furthermore, novel heating techniques were suggested to mitigate the danger of airborne transmission and lower the energy usage of conventional HVAC systems.
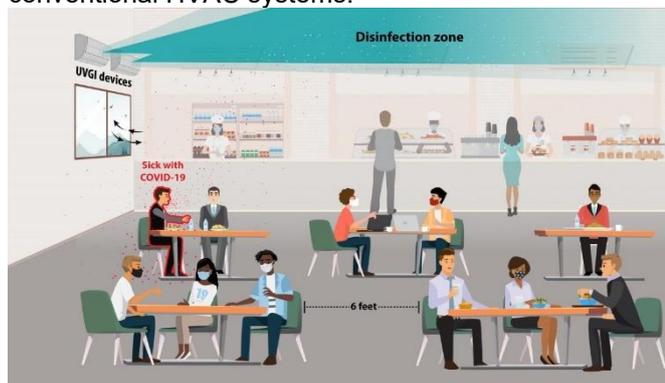
Figure 5: An indoor setting receiving ultraviolet germicidal infection. **Source:**
(***Https://Www.Uvhealsafeair.Com/Blog/Are-Uv-Disinfection-Systems-Effective/ - Search Images***, **2024**)

In one of the studies, the use of conventional HVAC systems was explored to minimize the risk of airborne transmission, for instance, a radiator for the panel heating system connected to horizontally ground-sourced heat pumps to provide more hygienic heating in confined spaces. (Kotopouleas & Nikolopoulou, 2016).
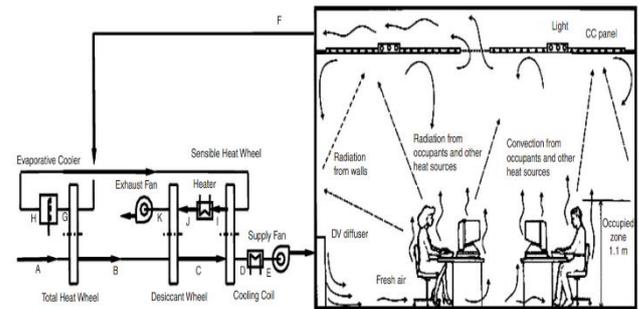
Figure 1: A diagram of a combined heating and cooling system to mitigate the danger of airborne transmission. Source**:** (Liu et al., 2017)

3.4   Drainage system

Drainage infrastructure; the drainage system's interventions were covered in twelve studies. After the SARS epidemic of 2003, when 42 deaths were linked to the SARS virus spreading through the residence's drainage system in Hong Kong Amoy Gardens, the initial drainage systems and infection control research center were established (Alves et al., 2019). Six articles in our review case investigations(Kotopouleas & Nikolopoulou, 2016), original research papers (Kotopouleas & Nikolopoulou, 2016; Qurat-Ul-Ain et al., 2018), and simulations confirmed that viral aerosols in the indoor air of Amoy Gardens gained access through floor drains into the bathrooms, thus intensifying the outbreak. Not unexpectedly, a second study cluster using similar analytical methods (Sharmin et al., 2014), case studies (Salamone, Belussi, et al., 2017; Sharmin et al., 2014), and experimental models (Schwee et al., 2019) emerged during the COVID-19 pandemic. Nonetheless, studies on the presence of the SARS-CoV-2 virus in drainage or sewer systems were expanded to include ordinary condominiums and healthcare buildings. Based on the findings of those studies, it was observed that defective plumbing and flushing of toilets could promote the transfer of airborne pathogens through the sewage system of the building. For example, Huang and colleagues (2017) proposed that the positive pressure inside the drainage stack affects the upward airflow within the vertical drainage stack (Ishii et al., 2015). Additionally, Jack and colleagues showed how an insignificant amount of sucking pressure could generate

60

a large quantity of air movement, which in turn caused the opposite airflow to enter the occupied region. A sewage system that is poorly constructed or maintained may likely cause an unpleasant odor thus presenting a possibly fatal threat in the event of a pandemic caused by an airborne virus. Conversely, a well-engineered trap seal maintenance system is crucial in limiting the movement of airborne microorganisms from the drain into the air (Schwee et al., 2019). Given appropriate maintenance of the indoor drainage system, historical data indicates that the danger of transmission of respiratory viruses via the building drainage system is comparatively low (Nagy et al., 2023). Therefore, maintaining and operating the current drainage facilities effectively was the major goal of the drainage system intervention. The investigation by Wong et al. brought to light the difficulties in keeping hospital wastewater systems operational during the COVID-19 epidemic and the need to precisely map the drains to respond quickly to leaks, particularly in older architectural designs (Huang & Long, 2015). However, there is a dearth of comprehensive guidelines about maintaining and using drainage systems to prevent infection.
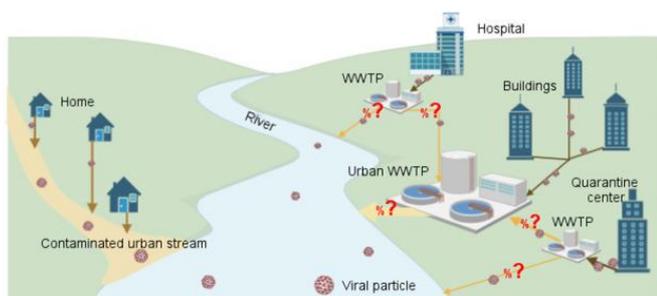

Figure 7: Schematic illustration of main channels of movement of SARS-CoV-2 viral particles to a surface water source
Source: (Giacobbo et al., 2021)

3.5 Cleaning and disinfection of surfaces in the indoor environment

Droplets have been implicated in several respiratory infectious diseases and are much larger than aerosols. Thus, they are more likely to succumb to gravity and deposit on surfaces. These surfaces could include door knobs, furniture, and any other item within a building. Such contaminated inanimate surfaces are called fomites and are viable means of transmission of infectious diseases through contact. Droplets could be released into the air during the cough, sneeze, or speech from a person carrying a respiratory pathogen. Susceptible hosts touching surfaces contaminated by respiratory viruses (for instance, Influenza, Common cold) can get infected with these pathogens when they touch their mouths or noses (Atta, 2023). Housekeeping and cleaning when human saliva from sick individuals comes into touch with common interior surfaces like doorknobs and furniture, respiratory viruses can be disseminated to other persons who subsequently come in contact with such contaminated surfaces (Hu et al., 2019). Hand hygiene and surface disinfection have therefore been considered the primary methods for eliminating infections from interior surroundings surfaces, and the literature frequently describes their combined use. Furthermore, how often an occupant's hand makes touch with a surface, which is contingent upon occupant engagement with buildings, is strongly linked to the risk of respiratory virus transmission via interior surfaces. Limiting the number of surfaces in a location that is available to people and managing the occupancy rate are two strategies to stop the spread of fomite. For example, the creation of a model of fomite-mediated transmission to predict pollution hazards in the built environment and the extraction of building utilization and readily available surface information using BIM-based simulations. It was concluded that the two best methods for lowering the danger of an outbreak through the fomite pathway are to lower the number of surfaces exposed in rooms and to restrict the number of people who can occupy a space (De Sario et al., 2013). Consequently, surfaces in medical wards are frequently cleaned. For instance, (Wei et al., 2018) showed how to properly clean surfaces in a COVID-19 containment building in China by doing so every eight hours in conventional wards and every four hours in intensive care units using an antibiotic that included 1000 mg/L of chlorine (Salamone et al., 2016). Alcohols have been reported to be the most effective cleaning and disinfecting agents against respiratory viral pathogens, including Influenza virus, severe acute respiratory syndrome (SARS) virus, and SARS-CoV-2 (Schwee et al., 2019).

3.6 Building and occupancy management

To help the Building Management team monitor real-time space occupancy and maintain adherence to socially acceptable distances, some studies have shown that BIM and IoT-based apps might be used to display space occupancy (Aftab et al., 2017). Additionally, sensor data can be utilized to provide useful information for infection management. Moreover, Fazio et al. created an interior navigator based on BIM that supports users in traversing intelligent structures by monitoring their position over time and advising the most effective path to their goal (Meinke et al., 2016). Furthermore, (Meinke et al., 2017). Similarly, (Z. Chen et al., 2017) showed how an aerosol detection system operating in real-time could accurately measure aerosol transmission in healthcare environments, offering data to support treatment decision-making (Becker et al., 2018). These developments demonstrated how adopting new technology may help BM change the handling of space for controlling infections. There is a paucity of research on the economic viability and other consequences of space management, with the

exception being a comparison of the expenses associated with renovation operations, and maintenance of an office complex with the benefits of lower employee absenteeism and increased efficiency (Masood et al., 2018). Furthermore, Mokhtari and Jahangir looked at how population distribution affected energy use and found that its effect on the surroundings changed with the season and type of HVAC system operation.

4. Future Research Directions

a. Integrated intervention outcomes

The complexities involved in studying the survival and fate of respiratory pathogens in the air require a multidisciplinary approach with input from experts in the fields of Built Environment, Mathematical Modelling, Microbiology, Aerosol Science, and others. This review demonstrates that the patterns of respiratory virus spread to building-related factors are intricate because they are impacted by many different determinants, including the layout and maintenance of lighting facilities, HVAC, and sewage systems; sanitation and hygiene procedures; furniture arrangement; occupant density; and occupant behavior. Only a few researchers take into consideration all three modes of transmission: fomite, droplets, and aerosol. Thus, this might lead to an underestimation of the amount of virus exposure that occupants may experience, even though there exists a multitude of methods designed to evaluate the risk of infection in diverse indoor environments. Therefore, to regulate occupancy rate and other BM efforts, integrated risk evaluations are necessary to assess the likelihood of viruses gaining entry through every contact channel and to compute the decreased risk attained by technical safeguards, conservation techniques, and other BM activities. Additionally, even though the studies included in this review examined a variety of BM treatment methods, the majority of them do not significantly improve the process of making choices for executives and administrators regarding interventions. To make a wise choice, regulators as well as building supervisors must first understand the integrated impacts of solutions, such as if certain initiatives have additive, multiplicative, or discordant consequences. A comprehensive examination of the combined impacts of treatments is necessary, even though much research has taken into account several actions, such as occupant density controls and ventilation.

b. Occupant behavior

This analysis demonstrates how building inhabitants have a significant influence on indoor air quality by impacting levels of CO_2, heat, aerosol particles, and all the pathways via which transmissible diseases are transmitted in buildings. In the first place, building residents' appearance and activities, such as breathing, talking, and singing, as well as their bodily actions, such as walking, strenuous exercise, and resting, directly impact indoor environments and the efficacy of BM measures (Duan et al., 2018). However, actions taken by building occupants such as face masking, hand sanitization, coughing/sneezing hygiene, and HVAC system operations like opening and closing windows and doors and adjusting thermostats (Salamone, Belussi, et al., 2017) can also impact the spread of viruses in buildings. The strong influence of occupant behaviors on viral load from inhaled aerosol has led to the inclusion of several renter-specific parameters in various infection risk modeling studies. For example, Stabile evaluated the viral load in different retail situations according to occupant population and activity (Z. Chen et al., 2017). However, further research on occupant behaviors for each infection pathway is required to develop strong metrics for evaluating the threat of infection at the building level. For example, it's important to consider how often people interact with surfaces within the built environment and how often they practice hand hygiene in different circumstances. The associated behavioral variables in many contexts are yet unclear.

c. Hard infection control

According to the literature, the primary focus of present building systems is to sustain particular moisture and temperature levels; nevertheless, the risk posed by respiratory viruses within buildings may appear to be disregarded (Enughwure & Febaide, 2020). To understand the combined effects of surroundings and possible conflicts between occupant comfort, occupant health, and building environmental performance, a quantitative assessment of each of these variables is required. There is consensus that the minimum fresh airflow criteria and other HVAC operation guidelines do not go far enough in diluting interior air to stop the spread of airborne pathogens in high-occupancy buildings. To dilute, filter, and purify indoor air, the ideal ventilation rate in conjunction with other IAQ management methods is yet unclear. Furthermore, because interior airflows are so reliant on fleeting occurrences and changes in external circumstances, there remain important unexplored regions in indoor airflow that require additional research despite modeling and experimentation. Furthermore, it appears that UVGI systems are a powerful addition to other HVAC initiatives in existing buildings. Further research is needed to give quantitative proof of UVGI system costs and advantages for BM decision-making.

It is well acknowledged that the minimal fresh airflow regulations and other HVAC operation guidelines do not appear to cover the dilution of indoor air as a means of preventing the spread of airborne pathogens in high-occupancy buildings. To dilute, filter, and purify indoor air, the ideal ventilation rate in conjunction with other IAQ management methods is yet unclear. Furthermore, since internal airflows are so reliant on fleeting occurrences and changes in external circumstances,

there remain important unexplored regions in indoor airflow that require additional research despite prevailing modeling and experimentation studies. Furthermore, it would appear that UVGI systems are a powerful addition to other HVAC initiatives in buildings that exist. Further research is needed to give quantitative proof of UVGI system costs and advantages for BM decision-making.

d. Soft infection control

Soft infection control measures have not been fully explored in the control of airborne disease transmission in the built environment. While several studies have noted significant limits and issues, the application of UV systems and robots for disinfection in diverse public contexts is an emerging practice. Therefore, further study is needed to determine whether disinfection robots are safer, more effective, and more affordable than conventional manual cleaning methods. However, additional soft service activities can potentially contribute to the transmission of viruses. Proper infection control measures are necessary because, for example, domestic waste as well as hospital waste may include virus-laden moisture and nutrients that are transmitted to humans through a variety of bacteria from environmental sources [46]. In a similar vein, hospital laundry services will probably be standardized for infection control reasons, but how hotels would manage laundry while in a pandemic to prevent soiled linen from transmitting the virus appears to be unknown.

e. Use of Information Technology

The 4th industrial revolution, sometimes known as Industry 4.0, has accelerated due to the COVID-19 pandemic. Pandemic control has seen a huge surge in fascination with emerging technologies including blockchain, Big Data, the Internet of Things (IoT), cloud computing, AI, and simulators [160]. Industry 4.0 possesses the capability to revolutionize the management of building operations, according to this study. For example, ICT-based technologies are primarily used to enable actions related to space and occupancy administration. This review's focus on numerous studies illustrated how building management system (BMI) could be built with sophisticated sensors, surveillance footage, and technologies based on AI to support prevention measures like holder motion tracking (Ferrari et al., 2020), resident measurement, distance from society and face hiding surveillance, and the identification of high occupants (D. Li et al., 2017). Furthermore, machine learning approaches can monitor and regulate indoor air quality in buildings using a learning model, therefore revolutionizing current building operations through predictive management of the HVAC system (Jiang et al., 2016; Lalmuanawma et al., 2020). But far from producing the perfect answer, the BM sector is still in the early stages of adopting these IT-driven technologies. The present Building Automation System (BAS) is dependent on sensors to collect data regarding pressure, temperature, humidity, CO_2 concentrations, and particle presence. However, the high expense of placing multiple sensors in buildings has made their practical application difficult (Jones et al., 2008). Moreover, applications for Smart Buildings heavily depend on algorithms created pre-COVID-19 pandemic; nevertheless, the records from the past could not be relevant in the period post-pandemic and necessitate additional research (Alves et al., 2019).

5. Conclusion

The analysis of the content led to the conclusion that all three groups of measures for the prevention of respiratory infectious diseases in existing buildings beneath the fields of facilities management are: cleaning/disinfection techniques to stop the spread of viruses via the fomite route, maintenance of HVAC facilities, and elimination measures to stop the spread of viruses through airborne route. Others include space and occupancy management techniques to stop the spread of viruses via the droplet route. Generally speaking, a combined approach is needed to minimize the spread of respiratory viruses in the indoor environment, since a single architectural or ambient solution is inadequate. This paper highlights the lapses in the extent in which health elements of building systems were disregarded during their construction phase and eventual occupancy behavior, thus putting residents' well-being at risk during a global pandemic. This should be a rallying point for all building contractors. On the other hand, this also presents a chance to reconsider how we utilize our building infrastructure thus leading to the reinvention of facilities management. Building specialists believe that the health of tenants is a persistent global concern and that the COVID-19 outbreak may not be the last one yet. Because the respiratory virus's transmission patterns are affected by a wide range of elements like construction layout and upkeep, maintenance of HVAC and sewer systems, sanitation procedures, interior arrangement, furnishing designs, occupancy rates, and behaviors, this review demonstrates that there are still gaps requiring more research shortly. Thus, to better understand these complexities, more interdisciplinary research including experts in a variety of research areas including Built environment, Mathematical Modeling, Microbiology, Aerosol Science and Engineering, and Epidemiology is required. Building experts think that there will likely be more outbreaks of the COVID-19 disease and that tenant health is a constant worldwide worry. This review has shown that the transmission pattern of airborne viruses is affected by a multitude of interrelated factors.

References

Atta, H.I. (2020). "Why studying microorganisms in the air is vital" on the American Society for Microbiology website.

https://asm.org/Articles/2020/December/Why-Studying-Microorganisms-in-the-Air-Is-Vital

Atta, H.I. (2023). Aerosolisation and Bioaerosols In Aeromicrobiology. https://doi.org/10.1016/B978-0-323-96122-6.00008-6

Aftab, M., Chen, C., Chau, C. K., & Rahwan, T. (2017). Automatic HVAC control with real-time occupancy recognition and simulation-guided model predictive control in low-cost embedded system. Energy and Buildings, 154, 141–156. https://doi.org/10.1016/J.ENBUILD.2017.07.077

Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the Co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. Journal of Environmental Management, 239, 244–254. https://doi.org/10.1016/J.JENVMAN.2019.03.036

An, C., Lim, H., Kim, D. W., Chang, J. H., Choi, Y. J., & Kim, S. W. (2020). Machine learning prediction for mortality of patients diagnosed with COVID-19: a nationwide Korean cohort study. Scientific Reports 2020 10:1, 10(1), 1–11. https://doi.org/10.1038/s41598-020-75767-2

Atta, H.I. (2020). "Why studying microorganisms in the air is vital" on the American Society for Microbiology website. https://asm.org/Articles/2020/December/Why-Studying-Microorganisms-in-the-Air-Is-Vital

Atta, H.I. (2023). Aerosolisation and Bioaerosols In Aeromicrobiology. https://doi.org/10.1016/B978-0-323-96122-6.00008-6

Becker, V., Kleiminger, W., Coroamă, V. C., & Mattern, F. (2018). Estimating the savings potential of occupancy-based heating strategies. Energy Informatics, 1(1), 35–54. https://doi.org/10.1186/S42162-018-0022-6/FIGURES/9

Centers for Disease Control and Prevention. (2015). Hierarchy of Controls. The National Institute for Occupational Safety and Health (NIOSH)Https://Www.Cdc.Gov/Niosh/Topics/Hierarchy/Default.Html.

Chen, C. fei, Zarazua de Rubens, G., Xu, X., & Li, J. (2020). Coronavirus comes home? Energy use, home energy management, and the social-psychological factors of COVID-19. Energy Research & Social Science, 68. https://doi.org/10.1016/J.ERSS.2020.101688

Chen, Z., Zhu, Q., Masood, M. K., & Soh, Y. C. (2017). Environmental Sensors-Based Occupancy Estimation in Buildings via IHMM-MLR. IEEE Transactions on Industrial Informatics, 13(5), 2184–2193. https://doi.org/10.1109/TII.2017.2668444

Ciabattoni, L., Ferracuti, F., Ippoliti, G., Longhi, S., & Turri, G. (2016). IoT-based indoor personal comfort levels monitoring. IEEE International Conference on Consumer Electronics, 125–126. https://doi.org/10.1109/ICCE.2016.7430548

CIRT. (2020). Impact of COVID-19 on Construction Projects.

Codjoe, S. N. A., & Nabie, V. A. (2014). Climate Change and Cerebrospinal Meningitis in the Ghanaian Meningitis Belt. International Journal of Environmental Research and Public Health 2014, Vol. 11, Pages 6923-6939, 11(7), 6923–6939. https://doi.org/10.3390/IJERPH110706923

De Sario, M., Katsouyanni, K., & Michelozzi, P. (2013). Climate change, extreme weather events, air pollution and respiratory health in Europe. European Respiratory Journal, 42(3), 826–843. https://doi.org/10.1183/09031936.00074712

Duan, K., Fong, S., Zhuang, Y., & Song, W. (2018). Carbon Oxides Gases for Occupancy Counting and Emergency Control in Fog Environment. Symmetry 2018, Vol. 10, Page 66, 10(3), 66. https://doi.org/10.3390/SYM10030066

Enughwure, A. A., & Febaide, I. C. (2020). Applications of Artificial Intelligence in Combating Covid-19: A Systematic Review. OALib, 07(08), 1–12. https://doi.org/10.4236/OALIB.1106628

Ferrari, D., Milic, J., Tonelli, R., Ghinelli, F., Meschiari, M., Volpi, S., Faltoni, M., Franceschi, G., Iadisernia, V., Yaacoub, D., Ciusa, G., Bacca, E., Rogati, C., Tutone, M., Burastero, G., Raimondi, A., Menozzi, M., Franceschini, E., Cuomo, G., Guaraldi, G. (2020). Machine learning in predicting respiratory failure in patients with COVID-19 pneumonia-Challenges, strengths, and opportunities in a global health emergency. PloS One, 15(11). https://doi.org/10.1371/JOURNAL.PONE.0239172

Giacobbo, A., Rodrigues, M. A. S., Zoppas Ferreira, J., Bernardes, A. M., & de Pinho, M. N. (2021). A critical review on SARS-CoV-2 infectivity in water and wastewater. What do we know? Science of the Total Environment, 774, 145721. https://doi.org/10.1016/j.scitotenv.2021.145721

Hänninen, O., Canha, N., Kulinkina, A. V., Dume, I., Deliu, A., Mataj, E., Lusati, A., Krzyzanowski, M., & Egorov, A. I. (2017). Analysis of CO2 monitoring data demonstrates poor ventilation rates in Albanian schools during the cold season. Air Quality, Atmosphere and Health, 10(6), 773–782.

https://doi.org/10.1007/S11869-017-0469-9/FIGURES/4

Hoang, M. L., Carratù, M., Paciello, V., & Pietrosanto, A. (2021). Body Temperature-Indoor Condition Monitor and Activity Recognition by MEMS Accelerometer Based on IoT-Alert System for People in Quarantine Due to COVID-19. Sensors (Basel, Switzerland), 21(7). https://doi.org/10.3390/S21072313

https://www.uvhealsafeair.com/blog/are-uv-disinfection-systems-effective/ - Search Images. (2024). https://www.bing.com/images/search?q=https%3A%2F%2Fwww.uvhealsafeair.com%2Fblog%2Fare-uv-disinfection-systems-effective%2F&qs=n&form=QBIDMH&sp=-1&lq=0&pq=https%3A%2F%2Fwww.uvhealsafeair.com%2Fblog%2Fare-uv-disinfection-systems-effective%2F&sc=0-73&cvid=F358B81D25A840E584E828D5DF8FBC67&ghsh=0&ghacc=0&first=1

Hu, M., Xiao, F., Jørgensen, J. B., & Wang, S. (2019). Frequency control of air conditioners in response to real-time dynamic electricity prices in smart grids. Applied Energy, 242, 92–106. https://doi.org/10.1016/J.APENERGY.2019.03.127

Huang, L., & Long, E. (2015). Architecture and Planning Design Strategy of Post-disaster Temporary Settlement with High Building Density——Analysis Based on the Questionnaire in Dujiangyan after Wenchuan Earthquake. Procedia Engineering, 121, 101–106. https://doi.org/10.1016/J.PROENG.2015.08.1028

Ishii, T., Ochi, S., Tsubokura, M., Kato, S., Tetsuda, T., Kato, J., Nishikawa, Y., Morita, T., Kami, M., Iwamoto, Y., & Tachiya, H. (2015). Physical performance deterioration of temporary housing residents after the Great East Japan Earthquake. Preventive Medicine Reports, 2, 916–919. https://doi.org/10.1016/J.PMEDR.2015.10.009

Jamaludin, A. A., Keumala, N., Ariffin, A. R. M., & Hussein, H. (2014). Satisfaction and perception of residents towards bioclimatic design strategies: Residential college buildings. Indoor and Built Environment, 23(7), 933–945. https://doi.org/10.1177/1420326X13481614

Jiang, C., Masood, M. K., Soh, Y. C., & Li, H. (2016). Indoor occupancy estimation from carbon dioxide concentration. Energy and Buildings, 131, 132–141. https://doi.org/10.1016/J.ENBUILD.2016.09.002

Jones, K. E., Patel, N. G., Levy, M. A., Storeygard, A., Balk, D., Gittleman, J. L., & Daszak, P. (2008). Global trends in emerging infectious diseases. Nature 2008 451:7181, 451(7181), 990–993. https://doi.org/10.1038/nature06536

Karmann, C., Schiavon, S., Graham, L. T., Raftery, P., & Bauman, F. (2017). Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings. Building and Environment, 126, 431–441. https://doi.org/10.1016/J.BUILDENV.2017.10.024

Kotopouleas, A., & Nikolopoulou, M. (2016). Thermal comfort conditions in airport terminals: Indoor or transition spaces? Building and Environment, 99, 184–199. https://doi.org/10.1016/J.BUILDENV.2016.01.021

Lalmuanawma, S., Hussain, J., & Chhakchhuak, L. (2020). Applications of machine learning and artificial intelligence for Covid-19 (SARS-CoV-2) pandemic: A review. Chaos, Solitons & Fractals, 139, 110059. https://doi.org/10.1016/J.CHAOS.2020.110059

Li, D., Menassa, C. C., & Kamat, V. R. (2017). Personalized human comfort in indoor building environments under diverse conditioning modes. Building and Environment, 126, 304–317. https://doi.org/10.1016/J.BUILDENV.2017.10.004

Li, S. (2023). Review of Engineering Controls for Indoor Air Quality: A Systems Design Perspective. Sustainability, 15(19), 14232. https://doi.org/10.3390/su151914232

Liu, G., Xiao, M., Zhang, X., Gal, C., Chen, X., Liu, L., Pan, S., Wu, J., Tang, L., & Clements-Croome, D. (2017). A review of air filtration technologies for sustainable and healthy building ventilation. Sustainable Cities and Society, 32, 375–396. https://doi.org/10.1016/j.scs.2017.04.011

Masood, M. K., Jiang, C., & Soh, Y. C. (2018). A novel feature selection framework with Hybrid Feature-Scaled Extreme Learning Machine (HFS-ELM) for indoor occupancy estimation. Energy and Buildings, 158, 1139–1151. https://doi.org/10.1016/J.ENBUILD.2017.08.087

Meinke, A., Hawighorst, M., Wagner, A., Trojan, J., & Schweiker, M. (2016). Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort. Building Research & Information, 45(1–2), 222–238. https://doi.org/10.1080/09613218.2017.1233774

Meinke, A., Hawighorst, M., Wagner, A., Trojan, J., & Schweiker, M. (2017). Comfort-related feedforward information: occupants' choice of cooling strategy and perceived comfort. Building Research & Information, 45(1–2), 222–238. https://doi.org/10.1080/09613218.2017.1233774

65

Mirakhorli, A., & Dong, B. (2016). Occupancy behavior based model predictive control for building indoor climate—A critical review. Energy and Buildings, 129, 499–513. https://doi.org/10.1016/J.ENBUILD.2016.07.036

Nagy, Z., Gunay, B., Miller, C., Hahn, J., Ouf, M. M., Lee, S., Hobson, B. W., Abuimara, T., Bandurski, K., André, M., Lorenz, C. L., Crosby, S., Dong, B., Jiang, Z., Peng, Y., Favero, M., Park, J. Y., Nweye, K., Nojedehi, P., … Vellei, M. (2023). Ten questions concerning occupant-centric control and operations. Building and Environment, 242, 110518. https://doi.org/10.1016/J.BUILDENV.2023.110518

Naik, K., Pandit, T., Naik, N., & Shah, P. (2021). Activity Recognition in Residential Spaces with Internet of Things Devices and Thermal Imaging. Sensors 2021, Vol. 21, Page 988, 21(3), 988. https://doi.org/10.3390/S21030988

Nazir, A., Azhar, A., Nazir, U., Liu, Y. F., Qureshi, W. S., Chen, J. E., & Alanazi, E. (2021). The rise of 3D Printing entangled with smart computer aided design during COVID-19 era. Journal of Manufacturing Systems, 60, 774–786. https://doi.org/10.1016/J.JMSY.2020.10.009

Nicas, M., Nazaroff, W. W., & Hubbard, A. (2005). Toward understanding the risk of secondary airborne infection: Emission of respirable pathogens. Journal of Occupational and Environmental Hygiene, 2(3), 143–154. https://doi.org/10.1080/15459620590918466

Pinter, G., Felde, I., Mosavi, A., Ghamisi, P., & Gloaguen, R. (2020). COVID-19 Pandemic Prediction for Hungary; a Hybrid Machine Learning Approach. https://doi.org/10.1101/2020.05.02.20088427

Qurat-Ul-Ain, Iqbal, S., Khan, S. A., Malik, A. W., Ahmad, I., & Javaid, N. (2018). IoT Operating System Based Fuzzy Inference System for Home Energy Management System in Smart Buildings. Sensors 2018, Vol. 18, Page 2802, 18(9), 2802. https://doi.org/10.3390/S18092802

Ren, C., Zhu, H.-C., & Cao, S.-J. (2022). Ventilation Strategies for Mitigation of Infection Disease Transmission in an Indoor Environment: A Case Study in Office. Buildings, 12(2), 180. https://doi.org/10.3390/buildings12020180

Revel, G. M., Arnesano, M., & Pietroni, F. (2014). Development and validation of a low-cost infrared measurement systemfor real-time monitoring of indoor thermal comfort. Measurement Science and Technology, 25(8). https://doi.org/10.1088/0957-0233/25/8/085101

Salamone, F., Belussi, L., Danza, L., Galanos, T., Ghellere, M., & Meroni, I. (2017). Design and Development of a Nearable Wireless System to Control Indoor Air Quality and Indoor Lighting Quality. Sensors (Basel, Switzerland), 17(5). https://doi.org/10.3390/S17051021

Salamone, F., Belussi, L., Danza, L., Ghellere, M., & Meroni, I. (2016). An Open Source "Smart Lamp" for the Optimization of Plant Systems and Thermal Comfort of Offices. Sensors 2016, Vol. 16, Page 338, 16(3), 338. https://doi.org/10.3390/S16030338

Salamone, F., Danza, L., Meroni, I., & Pollastro, M. (2017). A Low-Cost Environmental Monitoring System: How to Prevent Systematic Errors in the Design Phase through the Combined Use of Additive Manufacturing and Thermographic Techniques. Sensors (Basel, Switzerland), 17(4). https://doi.org/10.3390/S17040828

Schwee, J. H., Johansen, A., Jørgensen, B. N., Kjærgaard, M. B., Mattera, C. G., Sangogboye, F. C., & Veje, C. (2019). Room-level occupant counts and environmental quality from heterogeneous sensing modalities in a smart building. Scientific Data, 6(1). https://doi.org/10.1038/S41597-019-0274-4

Serra, J., Pubill, D., Antonopoulos, A., & Verikoukis, C. (2014). Smart HVAC control in IoT: energy consumption minimization with user comfort constraints. TheScientificWorldJournal, 2014. https://doi.org/10.1155/2014/161874

Sharmin, T., Gül, M., Li, X., Ganev, V., Nikolaidis, I., & Al-Hussein, M. (2014). Monitoring building energy consumption, thermal performance, and indoor air quality in a cold climate region. Sustainable Cities and Society, 13, 57–68. https://doi.org/10.1016/J.SCS.2014.04.009

Trivedi, D., & Badarla, V. (2019). Occupancy detection systems for indoor environments: A survey of approaches and methods. Https://Doi.Org/10.1177/1420326X19875621, 29(8), 1053–1069. https://doi.org/10.1177/1420326X19875621

Viegas, E. K., Santin, A. O., & Oliveira, L. S. (2017). Toward a reliable anomaly-based intrusion detection in real-world environments. Computer Networks, 127, 200–216. https://doi.org/10.1016/J.COMNET.2017.08.013

Wang, P., Zheng, X., Li, J., & Zhu, B. (2020). Prediction of epidemic trends in COVID-19 with logistic model and machine learning technics. Chaos, Solitons & Fractals, 139, 110058. https://doi.org/10.1016/J.CHAOS.2020.110058

Wei, P., Ning, Z., Ye, S., Sun, L., Yang, F., Wong, K. C., Westerdahl, D., & Louie, P. K. K. (2018). Impact Analysis of Temperature and Humidity Conditions on Electrochemical Sensor Response in Ambient Air Quality Monitoring. Sensors 2018, Vol. 18, Page 59, 18(2), 59. https://doi.org/10.3390/S18020059

Yates, T., Zannat, H., Khandaker, N., Porteaud, D., Bouvet, F., & Lantagne, D. (2021). Evidence summary of water, sanitation, and hygiene

(WASH) coordination in humanitarian response. Disasters, 45(4), 913–938. https://doi.org/10.1111/DISA.12463