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Resilient Building Design in the Age of COVID-19

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MEMS 500 (MEMS 5420) HVAC 1 Independent Study

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I hereby certify that this report herein is my original academic work, completed in accordance with the McKelvey School of Engineering and Undergraduate Student academic integrity policies, and submitted to fulfill the requirements of this course:

Allie Periman

This report is submitted in partial fulfillment of MEMS 500 (MEMS 5420), an independent study course in Heating, Ventilating, and Air-Conditioning I

Contents

1 Executive Summary

MEMS 500 (MEMS 5420) was an independent study course using the text “Heating, Ventilating, and Air-Conditioning” authored by McQuiston, Parker, and Spitler, Sixth Edition. The course included the material up to and including the Space Heating Load. The Cooling Load material was covered during the use of the TRACE 700 software developed by the Trane Company. The report presented herein was an additional requirement of the course.

This report explores resilient building design in the face of a pandemic as an essential consideration for researchers and building designers alike. Understanding how aerosols flow within rooms can influence building design strategies to reduce the transmission of diseases. While building standards were sufficient before the COVID-19 pandemic, we must reconsider the minimum ventilation standards to comply with occupant safety in a pandemic. Existing standards do not have sufficient CFM or air filter ratings to combat aerosol transmitted viruses. In implementing future occupant health design strategies it is important to also consider sustainability as many strategies will inherently increase energy usage. In a practical application based on expert recommendations and CFD airflow research, a set of building design strategies is compiled and demonstrated using a Revit architecture model. Based on the entire findings of the report, making buildings more resilient is no longer an option, but rather a necessity in an era of potential pandemics.

2 Introduction

Nearly two years into the COVID-19 pandemic and it’s becoming ever clearer that life will not return to "normal". The modern pandemic has changed our living, working, and playing habits. Why has this particular virus changed our lives so drastically? What is this new normal and what are we doing to coexist in the age of the pandemic? Do we see a future where it is safe to be indoors without a mask? Through research and technical studies, this paper attempts to answer these questions and provide a framework of strategies to mitigate the indoor spread of viruses. We will examine how viruses have been spread throughout history as well as why COVID-19 spreads so much faster indoors. We will see what the existing commercial building standards are and why the air systems and schedules aren’t well equipped to prevent the spread of the virus. Finally, based on expert opinions and research, a set of design strategies will be compiled and applied to a building model in Revit.

3 How Virus's Spread

3.1 What the historical spread of viruses can teach us about COVID-19.

It is now commonly known that COVID-19 is a respiratory virus meaning it can be carried on droplets expelled through the nose and mouth. What we have realized is unique about this virus is that it not only is carried on large droplets but is also carried on small droplets (aerosols) and particles that can remain in the air for hours [1]. Viruses that are carried via droplets are easier to combat in indoor spaces than viruses that are spread through aerosols. Past outbreaks of viruses that are spread through droplets have allowed health experts to develop vaccines and hygienic strategies to reduce their infection rate.

Transmission of sickness through droplets is well studied so when COVID-19 broke out and didn't follow the same behavior it became all the more dangerous. In an interview with Dr. Kimberly Prather, an expert in Atmospheric Chemistry at UC San Diego, she discusses the indicators that lead us to believe the COVID-19 can be spread via aerosols. The difference between aerosols and droplets is that droplets settle at around six feet whereas aerosols remain in the air for hours. Unlike droplets which are usually sprayed from sneezing or coughing, aerosols can be emitted by simply talking. For aerosols, six feet of distance is not enough to prevent transmission. Inhaling COVID-19 aerosols bypasses your immune system, which is why you may not show signs or symptoms until five days after exposure making it all the more dangerous. Dr. Prather also notes that modern technology was not sufficient to measure aerosols for past pandemics [2]. With advancements in technology, researchers can now measure and track aerosols to inform strategies for reducing transmission.

The viral attachment to aerosols is evident from the fact that high rates of transmission have occurred in large rooms of people and that countries wearing masks have experienced much lower rates of transmission. There is a reduced risk of spread outdoors because the air streams dilute much faster than indoors. Dr. Prather believes there is no scenario where you are 100% protected but there are procedure that can help decrease the risk of infection. In her paper by Science magazine titled *Reducing Transmission of Sars-CoV-2*, Dr. Prather discusses the indoor transmission of COVID-19. She compares the radius of infection to someone smoking a cigarette, the distance at which you can smell the cigarette smoke you may be a risk of infection. In general, infection is highly dependent on the time duration of exposure. Indoors, infection risk is dependent on the ventilation rate, the number of infected people, duration, and airflow [3].

The SARS-Cov-2 has challenged researchers, health experts, and even building designers to develop new strategies for reducing the infection rate. Knowing how the virus is transmitted is simply the first step. Understanding how to reduce transmission in education and workplaces is essential for working professionals and students to get back to ’normal’.

3.2 How aerosols flow in office and educational spaces.

In the spring of 2021 with the vaccine role out and the prospect of students returning to a classroom setting, a major concern was outbreaks. To get a better idea of how the virus spreads indoors we must understand the dynamics of airflow systems in buildings. Ducted systems are the most common if not the only air-side system design for commercial buildings including offices and educational spaces. In this configuration, air flows from the air handling unit (AHU) through ducts and into rooms. The AHU takes in a percentage of air from the outside and mixes it with a percentage of air existing inside the building (called return air). Some of the return air is exhausted (i.e dumped outside of the building) and replaced by the incoming fresh air. During peak load conditions AHU’s may recirculate up to 80%-90% of the return air [1]. Here is where airflow systems can promote viral spread rather than prevent it. The basic principles of building science show that airflow and filtration may vary, depending on scheduling practices and air filter MERV ratings. If there are low air changes per hour and the air is not filtered adequately, classrooms can function as mixing chambers resulting in a higher risk of outbreaks.

4 Existing Code Compliance Design Configurations and Scheduling Practices

Commercial building codes may vary from state to state, but the primary authority is ASHRAE or the American Society for Heating, Refrigeration, and Air-Conditioning Engineers. ASHRAE outputs standards widely used by building contractors to comply with state regulations. They function as the experts in the industry and will output guides and best practices as well as requirements for building owners and contractors to implement. When it comes to indoor air quality (IAQ), ASHRAE Standard 62.1 and 62.2 are the recognized standards for ventilation system design and acceptable (IAQ).

As a small-scale example, we will assess the ventilation and IAQ requirements of a typical single-zone classroom per 62.1-2019 requirements. The outdoor air rate requirements are 10 cfm/person or 0.12 cfm/ft^2 [4] and the configuration as variable air volume single-zone system ceiling mounted distribution system from ASHRAE 62.1-2019 is below.

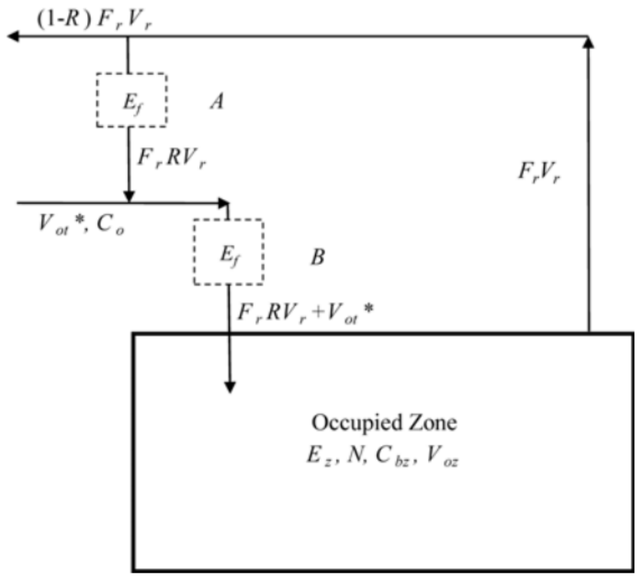

Figure 1 Ventilation system schematic for a single-zone variable air volume system [4]

In addition to outdoor air rate requirements, there are space breathing zone contaminant concentration requirements depending on recirculation and filtration setup. If the classroom has a filter location at B in Fig. 1 then the contaminant concentration is given by Eq.1

$$C_{bz} = \frac{N + E_z F_r V_{oz}(1 - E_f)C_o}{E_z F_r V_{oz}} \tag{1}$$

Where C_{bz} is breathing zone contaminant concentration, V_{oz} is the required zone outdoor airflow rate, N is the contaminate generation rate, E_z is the zone air distribution effectiveness, F_r is the design flow reduction fraction factor, E_f is the filter efficiency, and C_o is the outdoor contaminant consecration[4]. This equation applies to all potential contaminants and it provides key relationships between factors affecting clean air within a building. There are many more nuances to ASHRAE 62.1 that affect indoor air quality. Fortunately, rather than hand calculating these elements, they are programmed into building design software like Revit and TRACE in practice.

The typical ventilation design for a school, hospital, or other commercial building is a ceiling-mounted supply and return as analyzed above [1]. In this arrangement, researchers discovered the dangers of this design in a classroom setting through CFD analysis. Their findings indicate that a single person in a typical classroom setting not wearing a mask can contaminate 80%-90% of the room. At the breathing zone of other occupants, the contamination is anywhere between 80-100 ppm. The study assumes no abrupt movements, so if students were moving about the classroom the contamination levels may be higher [1]. Simulations are an excellent way to determine which system to install, or best practices in managing air flow rate; however, true airflow is difficult to model so should be taken with a grain of salt.

With the outbreak of COVID-19, it is clear that the minimum requirements per ASHRAE standards are not sufficient for infection control. The current minimum for out air changes per hour for large commercial buildings is 3.5 ACH but there is talk of increasing that to closer to 4 to 6 ACH [5]. Additionally, current air-filtration measures and standards are not effective against the virus which, when coupled with existing outdoor air minimums can be catastrophic. A term commonly used to determine filter effectiveness is clean air delivery rate or CADR[5]. Increasing the CADR to a space can be a powerful tool in minimizing viral concentration without dramatically increasing the airside system operation (and thus energy usage and cost). Optimizing a space in this manner may look like adding high-grade filters on the terminal or AHU level and increasing the outdoor ACH.

5 The Intersection of Building Health and Sustainability

According to the global alliance for building and construction 2021 report, the building and construction industry consistently accounts for around 40% of the worlds carbon emissions.

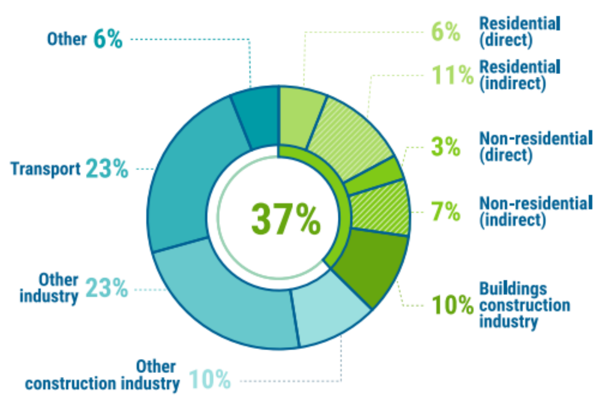

Figure 2 Energy related CO_2 emissions by building sector of the building and construction industries 37% share in 2020 [6]

Energy-driven retro-commissioning, LEED certifications, and other better building best practices have been increasingly popular as building owners have become concerned with their environmental footprint. Many of these strategies don't only lower the building's carbon footprint, they also lower the energy-related costs. When minimizing the energy consumption through retro-commissioning, the focus is on the air-side systems and thus greatly impacts indoor air quality. For example, decreasing the active hours of the equipment from constantly running, to operating only when people are in the building can have an impact on the energy used. Other energy-reducing measures have an overall objective of minimizing the operating time of major HVAC equipment while still maintaining code compliance.

With the emergence of COVID-19, energy-conscious building owners and operators were faced with a new problem; how to reduce energy usage while maintaining the high exchange rates required for stopping the spread of the virus. It was and continues to be a catch 22 situation. An owner can reduce the operating time of the HVAC equipment to save energy, but at what cost to occupant health? The SARS-Cov-2 has challenged building owners to develop smart HVAC operation and sustainability practices.

6 Strategies for Mitigating Viral Spread

6.1 The Importance of Building Health in and Epidemic.

Fear of more outbreaks brought building health to the forefront of conversations within the building research and design industry. Building science and airflow experts as well as design engineers, architects, and owners realize the critical role building wellness plays amid a pandemic. Listening to the insights of professionals is crucial to discover and implement effective strategies for reducing the spread of new and existing viruses.

As a building expert with Tetra Tech High-Performance Building Group, Nicole Isle comments on the shift from "good practice" to "necessity" of building wellness. The author outlines several strategies for preventing the spread of the virus. A number of these strategies have previously been developed, but are not frequently employed by building owners. Ventilation effectiveness, air filtration, and humidity control are the three main areas of opportunity which all affect indoor environmental air quality (IEQ). The most effective way to control IEQ and reduce virus particles in a room is to design ventilation systems appropriately, monitor air quality, and improve ventilation. The same is true for air filtration. Building codes and standards require air filters in HVAC systems with varying degrees of filtration depending on the building type. HVAC systems filter out particulates from the supply air according to their maximum efficiency reporting value (MERV). As an example, hospitals use MERV 17 or higher HEPA filters in their HVAC systems that can filter up to 95% of bacteria and viruses. According to Isle, COVID-19 is a virus that is small enough to pass through most industry filters but is often attached to larger particles and gets caught in the filters anyway [7]. Isle recommends replacing filters regularly and installing at least a MERV 13 filter (which captures 75 percent of viruses and bacteria) in all buildings. Further, she recommends that UV lighting be installed in spaces to kill viruses that have gotten past the air filter [7]. Finally, she notes the importance of humidity control in reducing viral transmission. It is recommended by Isle to maintain a relative humidity of 40-60% in spaces to prevent bacteria and viruses from growing. Humidity levels in this range are high enough for virus particles to fall on surfaces very quickly; however, it does not create an environment where they will flourish [7][8].

These strategies work well for viruses spread through droplets, but we have learned that COVID-19 is spread through aerosols. Indoor environments have the highest transmission rate due to the behavior of aerosols [3]. There are a few strategies that building owners can implement for infections spread through aerosols, like increasing a room outdoor exchange rate to dilute the air particles. This can be costly and use a lot of energy, so how do building owners make their facilities safe for occupation without spending a fortune on wasted energy and maintaining occupant comfort? A strategy could be adding filters to individual VAV boxes that serve an occupied zone so that air recirculated in that room it will not contain viral loads. Another strategy could be promoting vertical ventilation with diffusers. Finally, though high exchange rates are favorable, they could induce turbulent air streams that could carry the virus across the room. To mitigate this, attempting to promote laminar airflow entering a room will reduce this risk.

6.2 CFD Simulated Airflow to Guide Design Strategies.

We can model how the COVID-19 virus is transmitted using modern technology and an understanding of room airflow. The virus will cling to airborne particles, increasing the chances of individuals inhaling them and getting the virus. A study conducted by MIT using computational fluid dynamics, found that promoting vertical flow and reducing horizontal flow is ideal for mitigating viral transmission [9]. The MIT researchers identified a handful of problematic scenarios in classroom ventilation. In winter, the windows are cold causing the air near them to sink, disrupting the general upward flow of air. In this case, infected students sitting by windows are likely to spread the virus but adding space heating near windows may help. A second scenario is open windows, though may increase air changes, promote horizontal flow. Introducing baffles that deflect the air down may help prevent aerosol spread. Because turbulent fluid flow is difficult to predict even with advanced software, it's impossible to create the ideal scenario of air circulation and have 0% transmission in the classroom[9]. Regardless, researchers have used what we know about air circulation and fluid dynamics to provide strategies like these for reducing this risk.

A more recent study published by Engineering Systems, conducted by Haigang Brian Li P.E. and Kourosh Nemati Ph.D., sought to minimize the spread of COVID-19 in a classroom setting. Their setup was of a typical classroom with students and the teacher spaced six feet apart. They assumed the room was receiving a supply airflow rate of 1080 CFM and that the room is receiving 100% fresh uncontaminated air. There is one sick student in the classroom not wearing a mask and all occupants are relatively stationary. The researchers modeled several configurations of air supply to the classroom and discovered optimal classroom designs as well as a handful of dangerous ones. The results indicated that an inexpensive strategy for new buildings is displacement ventilation with low-velocity, low-supply, and ceiling-mounted returns. Another finding showed enhancing the displacement ventilation with larger surface diffusers has similar results and is compatible with higher velocity flows. Finally, cleanroom-type ventilation with laminar flow supply ceiling diffusers and low wall returns is the most costly but can be implemented for the lowest transmission rate. The researchers also recommend maximizing outdoor air supply to the room [1].

6.3 ASHRAE Recommendations.

ASHRAE developed a general set of guidelines meant to provide insight into building operations and operational checks to prepare for a future pandemic. The guidelines not only discuss operations that reduce transmission but also consider energy savings with an overarching theme of whole building health. A key main building readiness measure is epidemic operating and scheduling procedures. Optimizing scheduling practices can make a building increasingly resilient to future pandemics and natural disasters. When lock-downs were implemented across the U.S., buildings that were once occupied continued normal operation. HVAC systems had no plan or schedule in place if the building were to suddenly change normal operation in the face of a pandemic. Any HVAC system will have an "occupied" and "unoccupied" mode, but an epidemic situation requires this white and black scheduling to have varying levels of occupancy. Following the pandemic, ASHRAE released a set of operating modes to increase building resiliency. The Epidemic Operating Conditions in Place (ECiP) outlines updated modes of operation for any HVAC system. The ECiP modes are "occupied at pre-epidemic capacity", "occupied at reduced capacity", "unoccupied temporarily", and "operation during building closure for indefinite periods". Each mode will control the HVAC system accordingly decreasing unnecessary energy use. ASHRAE goes a step further and states modes for Post-Epidemic Conditions in Place (PECiP) before occupying and operational considerations once occupied. Additionally, ASHRAE's best practices include equipment checks, upgrades, and integration into the building automation system. [10]. The remaining guidelines pertain to building health and resilience including practical and analytical approaches to increasing filters MERV ratings, new sanitizing technologies including Bipolar Ionization, and additional equipment specific considerations [10]. These measures are indicators of shifts in building design practices[8].

6.4 A Summary of Strategies.

Table 1 is a summary of strategies compiled from the research presented in this report and inspired by ASHRAE's COVID-19 response guidelines. These strategies are by no means all-encompassing but are initial steps that building owners can take toward resiliency and contagion prevention. The solutions were developed by observing commonalities between opinions of experts in building science as well as studies of airflow dynamics and airside system design that produce results for the most effective transmission reduction design strategies.

Table 1 A summary of commercial building COVID-19 transmission prevention guidelines

#	Targeted Building Element	Strategy Description	Implementation
1	People	Masks	All occupants wear masks
2	Space design	Six foot furniture buffer	Desks and Chairs 6-feet apart
3	Space design	UVC Light	Add UVC lights to spaces to kill viruses
4	Space design	Open windows	Though there is controversy around lateral air movement, opening windows will increase ACH and reduce viral concentration
5	Space design	Reverse ceiling fans	Reversing fans to pull air upward promotes lateral movement and pulls the air towards ceiling mounted return ducts
6	Space design	Portable HEPA filters	Introduce portable HEPA filters to the space
7	Space design	Cleaning and Maintenance	Implement a cleaning and maintenance plan for spaces and air systems
8	HVAC	High grade filters	Replace air distribution filters with higher grade filters (MERV 15-18)
9	HVAC	Increase ACH and CADR	Increase the ACH (minimum 4) for each zone (introduce more outside air when feasible)
10	Building Automation System	Smart systems	Deliver air to a space only when occupied
11	Building Automation System	Epidemic mode	Program a mode that switches to 100% outdoor air when activated
12	Building Automation System	40%-60% RH	Monitor the indoor humidity and set it to remain between 40%-60% RH
13	Building Automation System	IAQ monitoring	Monitor the IAQ and set alarms to trigger when the concentration gets too high
14	Ventilation	Displacement ventilation	Large wall supply diffusers with ceiling returns to promote lateral airflow
15	Ventilation	Cleanroom-type ventilation	Laminar flow supply ceiling diffusers and low wall returns to promote lateral airflow

7 A Theoretical Design in Revit

To implement the findings presented in table 1 Revit was used to design a sample ducted commercial HVAC system. The following section presents the preliminary calculations for essential parameters that will ensure compliance with a handful of the 15 strategies. Following, a sample zone system serving two rooms designed per the calculations and other strategies is examined. The Revit design was made with the assistance of the LinkedIn learning course "Revit 2021: Essential Training for MEP". The design looks at a single zone serving two rooms in a standard commercial building. The floor plan for the case design is depicted in 3 and has a standard eight-foot ceiling height.

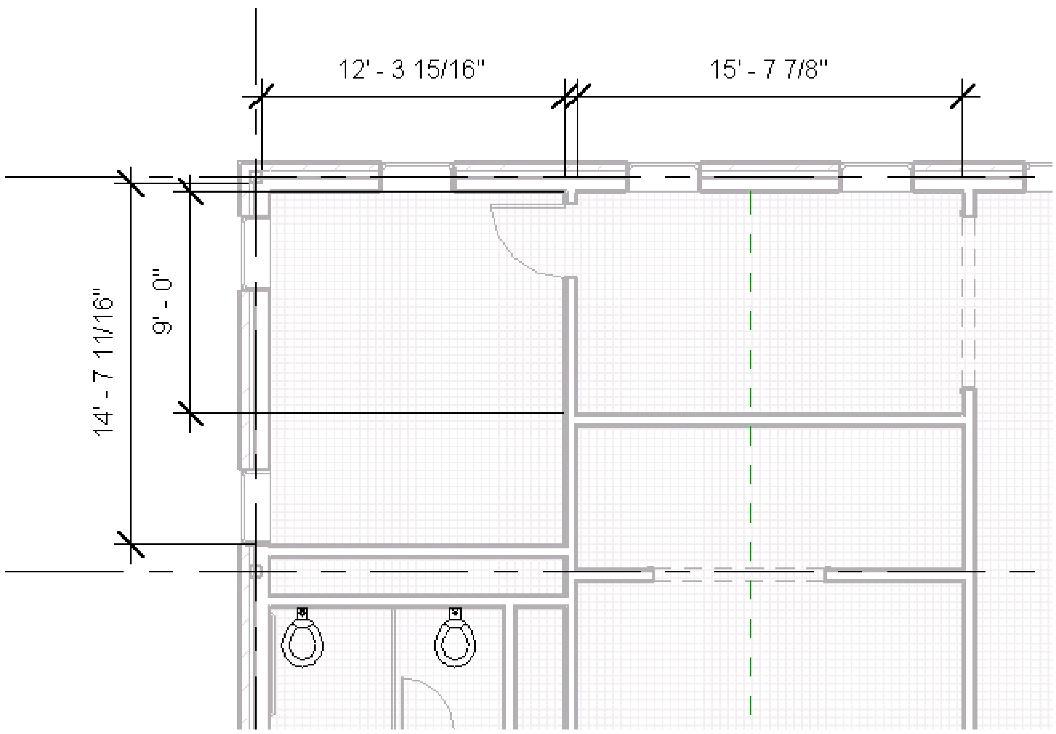

Figure 3 The floor plan for the case design model with dimensions

The optimal configuration to promote lateral laminar airflow per strategy 15 is shown in Fig. 4. It is important to recognize that this is not the standard configuration for commercial buildings which generally have supply and return diffusers in the ceiling. Though implementing a ceiling-mounted supply and return may be structurally simpler, but it promotes air mixing and turbulence in the room as depicted in Fig. 5.

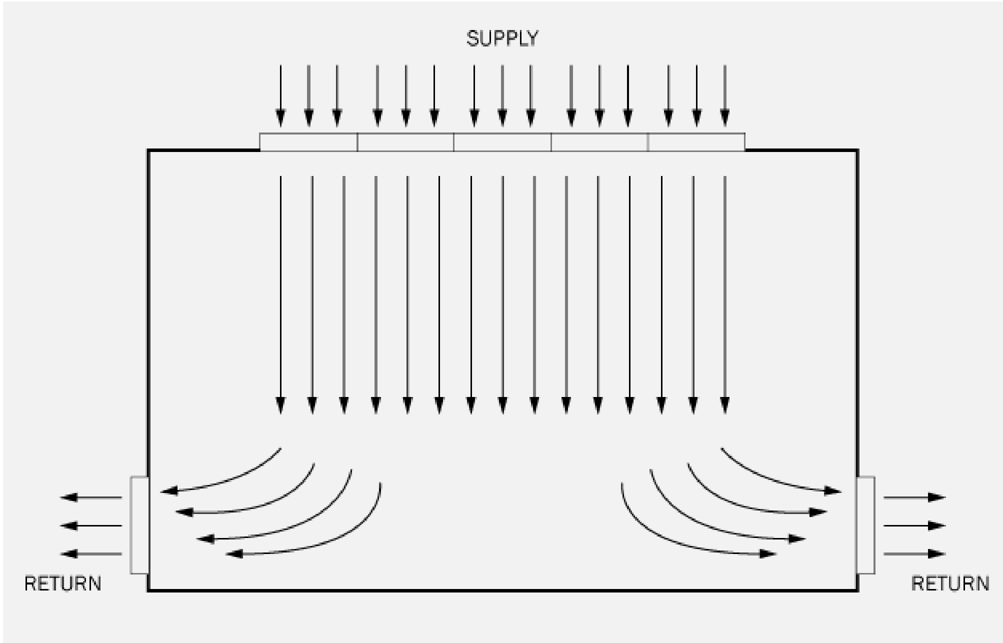

Figure 4 Lateral laminar flow of the desired cleanroom-type ventilation [11]

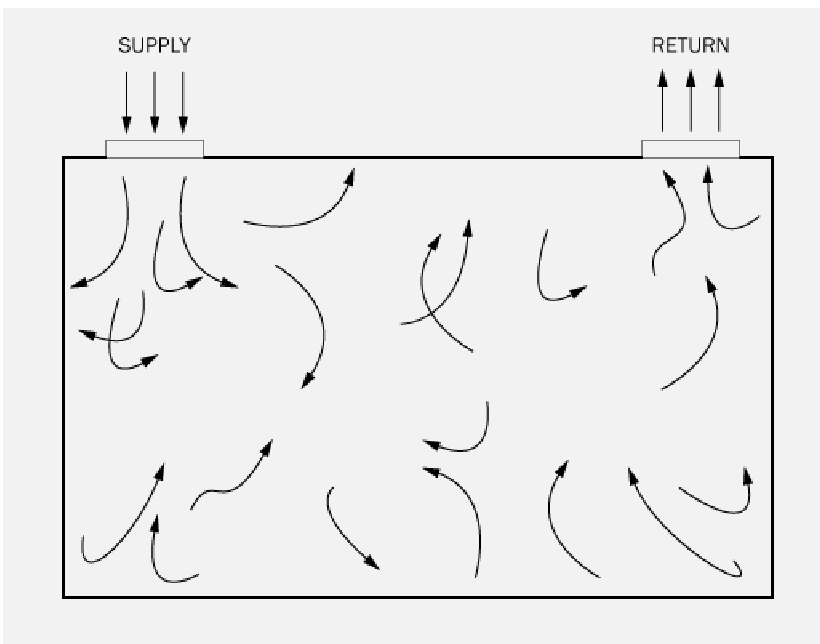

Figure 5 Standard ceiling mounted supply and return configuration [11]

7.1 Set up and preliminary calculations. To ensure appropriate air changes per hour and CADR to comply with strategy nine, the CFM is initially set to 250 per differ for the zone. There are three supply and three return diffusers modeled for the zone meaning there is 750 cubic feet per minute of air entering the space and the same leaving the space.

To calculate the air changes per hour the following equation is used.

$$ACH = \frac{CFM * 60[min]}{V_z} \tag{2}$$

Where ACH is the air changes per hour, CFM is the net airflow $[ft^3/min]$ and V_z is the volume of the area served $[ft^3]$. The volume of the zone per Fig. 3 is approximately 2575 ft^3. Plugging in for CFM and V_z the ACH is thus 17.47 which is well above the recommended threshold of 4 ACH. The next part of the analysis will examine the velocity required to create a laminar flow supply per strategy eight. The velocity will affect the CFM so the initially high ACH calculation gives room to decrease the flow rate.

To determine a laminar (or close to laminar) airflow into the room we must calculate the velocity of the airflow that will induce a laminar Reynolds number. With the velocity known, Revit can then size the supply duct system appropriately. To do this we implement a simple fluid flow principle that if the Reynolds number is less than 2000 the flow is laminar. Thus, we estimate the desired velocity using the Reynolds equation given below.

$$Re = \frac{uD_h}{\nu} \tag{3}$$

Where u is the velocity diffuser $[ft/s]$, D_h is the hydraulic diameter of the duct $[ft]$, and ν is the kinematic viscosity of air $[ft^2/s]$. Assuming standard air at sea level, the kinematic viscosity is $1.57 * 10^-4 ft^2/s$. With the relation in equation 3, to maintain a Re of 2000 we know the velocity should enter the space at around 0.314 ft/s or 18.84 FPM. For such a low airflow the ducts must be very large (per the relation above) which can be difficult to implement in commercial buildings with limited ceiling space. We instead induce semi-laminar flow with a Re of 10^4. The resultant velocity is approximately 100 FPM. With the desired velocity known, Revit sized the ducts to promote this airflow.

Now, we revisit the ACH calculation, and duct sizing to reassess the design velocity. If the cubic feet per minute of airflow is instead lowered to 150 CFM per diffuser, the ACH is 10.5, still well above the desired minimum. Multiplying the ACH by 60 produces the CADR which is 629 for the zone. An average CADR is 300 [5] so the system is well above the clean air delivery rate.

Lowering the CFM decreases the duct diameter. If we again decrease the design velocity to 50 FPM, the duct sizing is still within a reasonable range. The final Reynolds number is on the order of 5305 which is closer to the laminar regime.

7.2 Implementing the design. With the system appropriately sized, it was modeled in Revit for the space in Fig. 3 with the following design.

Table 2 Design of the mechanical systems serving the sample model

System	Description
AHU	The AHU is a BLANK with 80% outside air intake and an epidemic mode that switches to 100% outside air intake. The AHU has a filter rating of MERV 13
VAV unit	The VAV unit is a parallel fan powered box with 10 inch inlet. There is a MERV 17 filter in the unit. There is an evaporator coil in the box and is programmed to supply air at 50% RH.
Supply Diffusers	There are three 24 x 24 - 10 inch neck ceiling mounted diffusers supplying 150 CFM
Return Diffusers	There is one 12 x 12, one 6 x 6 and one 12 x 4 wall mounted difusers returning 150 CFM each
Windows	Operable windows

The mechanical system configurations listed above were implemented in a ducted system design. Figure A.3 depicts the top view of the mechanical design.

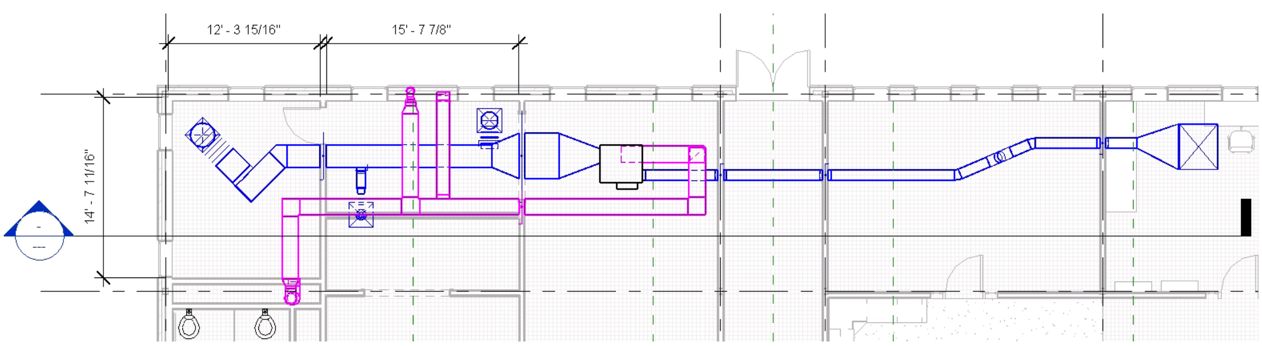

Figure 6 Top view of mechanical design

The blue ducts represent the supply air while the pink ducts represent the return air. The VAV box is the black square in the center of the image. Notice that there is a large bulge (or diffuser) in the ductwork directly after the VAV box. This is a design strategy to decrease the velocity of the airflow exiting the fan to the desired design velocity. The upward-facing arrow on the left of the image indicates the line where a section view has been drawn. That section view is in 7.

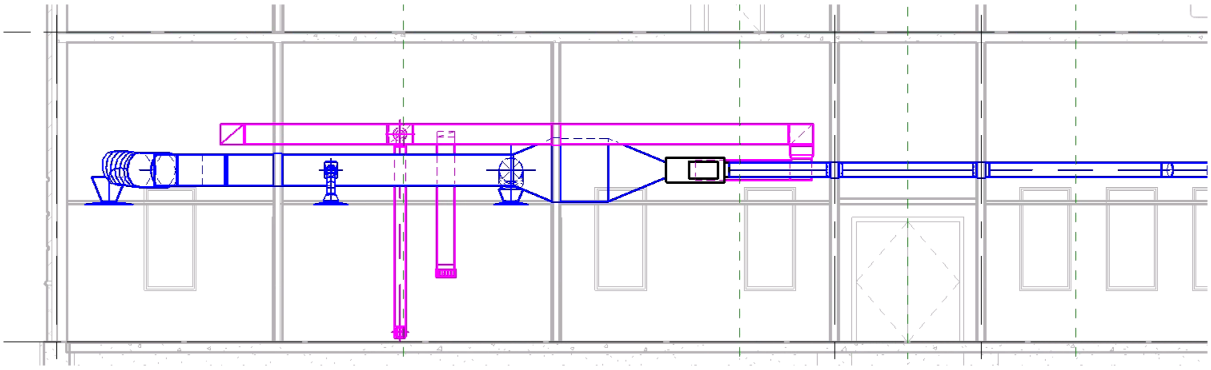

Figure 7 Section view of mechanical design

The section view shows the return ducts are modeled above the supply ducts but drop down through the walls so that they can serve wall-mounted diffusers. Finally, Fig. 8 shows a three-dimensional isometric view of the whole system.

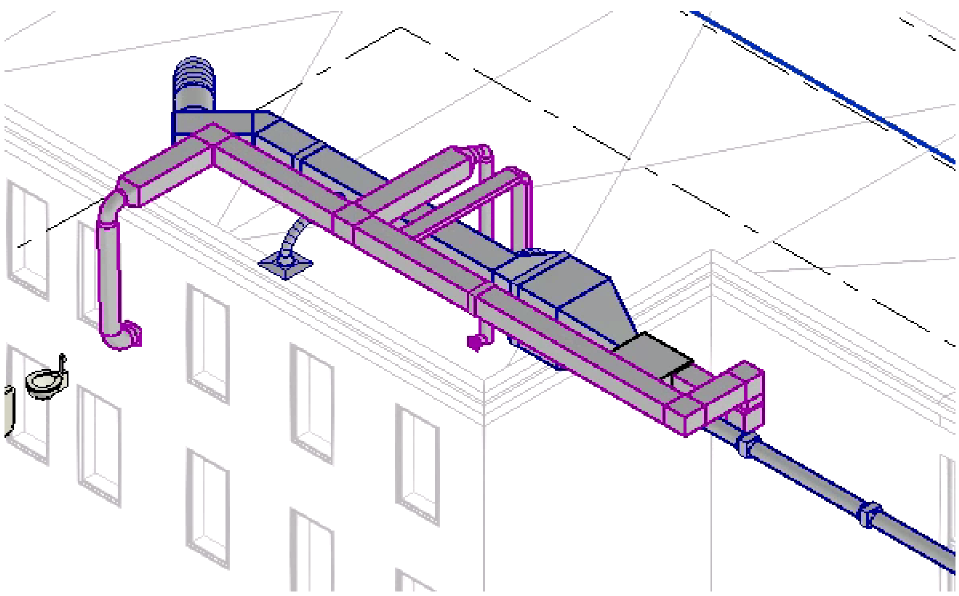

Figure 8 Isometric view of mechanical design

Became this is an isometric view it is not an accurate representation of where the duct system is located in space, but it gives a different perspective on the configuration as a whole. For full isometric, section, and front views of the building depicting the full system see appendix A.

8 Conclusion

By understating what is known about the Coronavirus through expert opinions and research, we can design resilient buildings for the future. Implementing well-studied ventilation and airflow techniques can mitigate the spread of the virus. Common trends in research and expert analysis allow us to determine a set of strategies that can reduce the transmission of airborne diseases. Building science and mechanical design techniques like laminar flow ceiling-mounted supply and wall-mounted return can be standardized for new commercial buildings to increase future resilience. Other key elements include increasing the filter grade on airflow systems, increasing the ACH to a heavily occupied space, and programming an epidemic mode into the building automation system.

A sample model of the presented techniques reviled that though laminar supply flow may be spatially infeasible, minimizing the supply velocity and promoting vertical airflow is recommended. Finally, while the model design is a simple representation of a Revit application, it was not verified structurally. There may need to be further investigation into strategies to drop commercial-grade return ducts through walls to achieve the displacement ventilation desired.

Moving forward building owners and designers must be aware of what building resilience truly means. Imagining future strategies around architectural design, retro-commissioning, and sustainability certifications that reduce environmental impact and improve occupant health are essential.

A Complete front, section and isometric views of model building

Figure A.1 Complete front view of mechanical systems

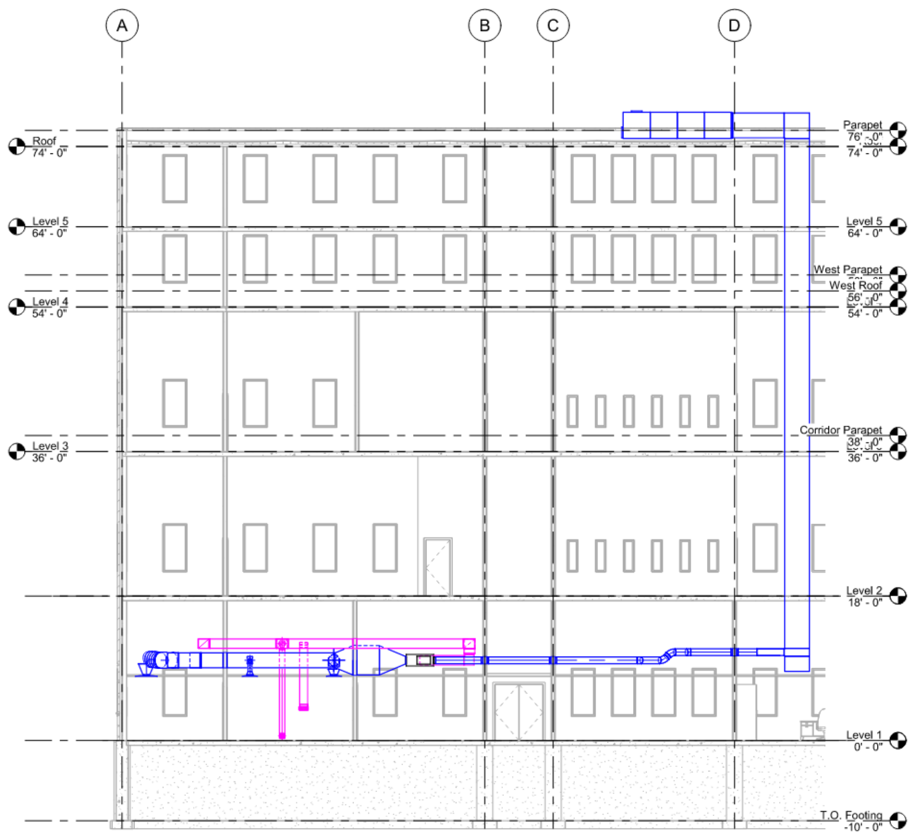

Figure A.2 Complete section view of mechanical systems

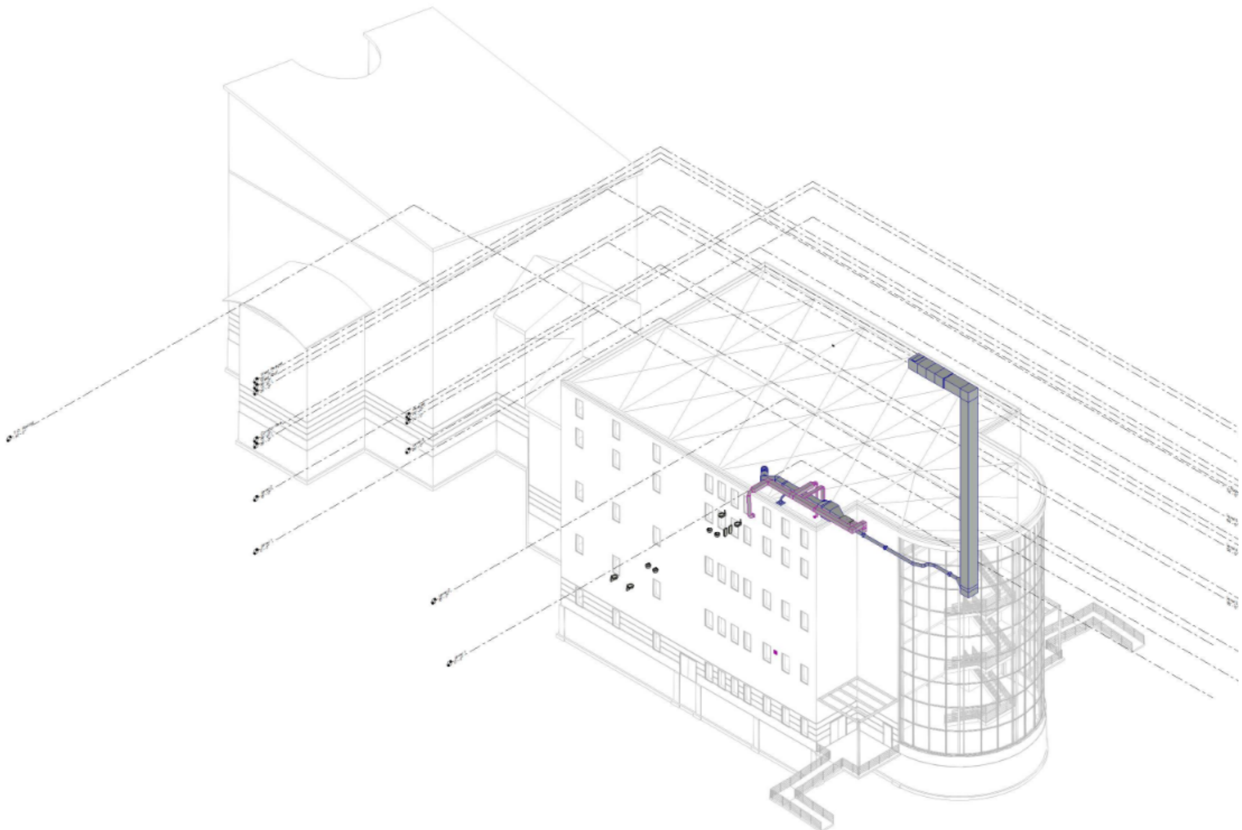

Figure A.3   Full isometric view of mechanical systems

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