Remedial Adaptations in Building Services Engineering to Reduce COVID-19 Transmission

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Abstract

The work presented in this paper is aimed at assessing the various remedial building services engineering measures that can be applied to enable safer building occupation during the ongoing (at the time of writing) COVID-19 pandemic, as well as additional resilience in the event of similar events in the future.

Due to the rapid development of research into the SARS-CoV-2 virus and COVID-19, new data is becoming available on an ongoing basis. The available information at the time of writing has been appraised and conclusions have made based on the most prevalent scientific theories.

Guidance from various building services engineering bodies have been assessed for the UK (CIBSE), Europe (RHEVA) and the USA (ASHRAE) as well as governmental guidance/mandates in the UK and abroad.

This paper assesses the potential effectiveness of each measure at reducing the transmission of COVID-19; the ease of application within existing building services systems; the negative connotations for energy-usage, utility costs, carbon emissions and system maintenance/lifespan; and any adverse implications for the comfort of occupants. The investigated measures will then be appraised for their effectiveness at combatting the spread of COVID-19 compared with the ease of which they can be implemented (in terms of practicality and financial viability).

Keywords COVID-19 airborne transmission, building air conditioning systems, ventilation, building services engineering measures, HVAC systems, system capacity.

1 Introduction

The COVID-19 pandemic has led to the government encouraging, and at times mandating, people/businesses to avoid close-proximity interaction to mitigate the risk of transmission. This work reviews various guidance issued by building services associations (CIBSE, RHEVA, ASHRAE), as well as guidance/mandates issued by governmental bodies of UK and abroad, for the reoccupation of office buildings.

Research is ongoing and new data is emerging on a regular basis. This report has reviewed the currently available scientific research and made suggestions based on prevalent theories. Although vaccination is likely to play a significant role in allowing people to return to regular occupation of office buildings, amendments to building services systems will be key in facilitating this return, whilst helping to reduce rates of transmission.

1.1 An Overview of the COVID-19 Virus (SARS-CoV-2)

The COVID-19 virus is a respiratory infection and, as such, transmission can occur in several ways: Respiratory droplet transmission (droplets >5-10μm in diameter), Droplet nuclei transmission (droplets that are <5μm in diameter), Airborne transmission (droplets <5μm in diameter) and Contact transmission (spreads of virus through physical surfaces). **Figure 1** illustrates person-to-person transmission through the above modes, as well as faecal-oral transmission (which although identified as possible, there are (as yet) no documented cases of transmission).

For many months into the pandemic, scientific opinion on virus transmission was conflicting. The World Health Organization (WHO) (WHO, 2020) suggested that transmission occurs almost entirely (if not entirely) through respiratory/nuclei droplets and contact transmission only, while the Center for Disease Control and Prevention (CDC) (CDC, 2020) in the USA stated that the majority of virus transmission occurs through contact/droplet transmission, with some evidence that airborne transmission of SARS-CoV-2 is possible in special circumstances.

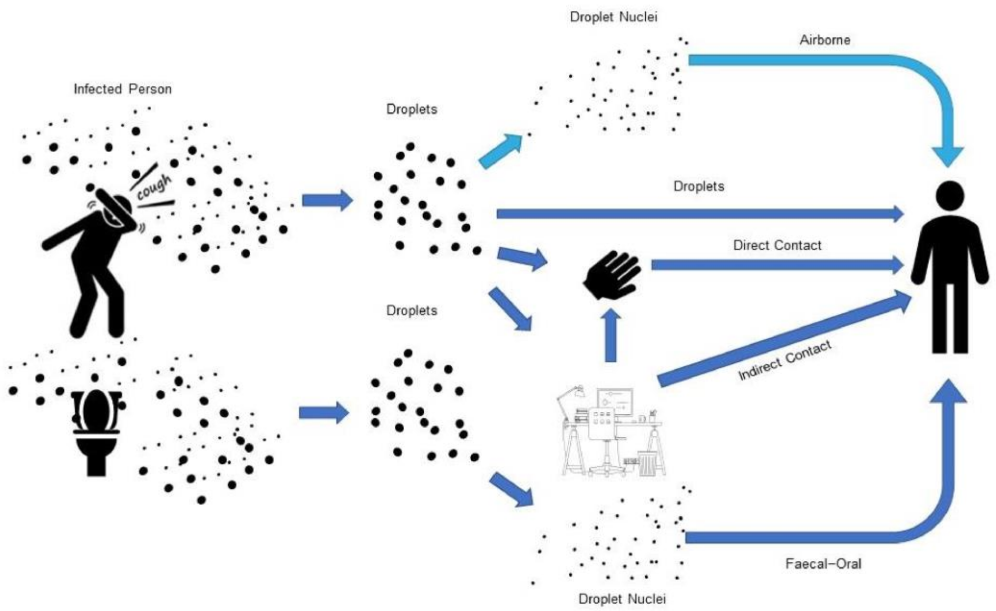

Figure 1 – SARS-CoV-2 (COVID-19) transmission methods (REHVA, 2020)

1.2 Measures to Prevent the Spread of the COVID-19/SARS-CoV-2

Measures have been implemented with specific impetus on curbing what are thought to be the most common forms of transmission: contact transmission and transmission through respiratory/nuclei droplets. Measures implemented by the Governments have varied at different stages of the pandemic, however, most of these included: Social-distancing (physical separation of 2m between people – with appropriate PPE), business-opening restrictions, reduced capacity, reduced operating hours, remote working, increased hand-hygiene, limitation of group gatherings, wearing of face coverings, self-quarantine people with COVID-19, self-isolation for people in close contact with COVID-19-infected individuals, self-isolation for people who enter the UK from countries where travel has been deemed to be high-risk for contracting COVID-19 and assessment of working conditions prior to people coming back into offices.

1.3 The Role of Building Services for People Returning to Office Spaces

The UK Government (and other governments internationally) have issued stipulations and guidance notes to facilitate the reoccupation of office buildings. Throughout the pandemic, avoidance of working in office buildings has been encouraged. This was implemented at the start of the initial UK Government 'Lockdown' implemented in March 2020 (UK Government, 2020) and has been sustained by many businesses that are able to operate in a largely remote-working capacity (The Guardian, 2020).

Guidance has been issued by the WHO in their document *Getting your workplace ready for COVID-19* (WHO, 2020); in the UK Government's *Working safely during COVID-19 in offices and contact centres* (UK Government, 2020); in *CIBSE COVID-19 Ventilation Guidance* (CIBSE, 2020); as well as by the Federation of European Heating, Ventilation and Air-Conditioning Associations (REHVA, 2020) and from CDC of USA (CDC, 2020) on how building services systems should be adapted prior to building re-occupation. There are differences in guidelines from the by UK Government, WHO, REHVA, CDC, CIBSE and ASHRAE due to numerous reasons, including: the time at which guidance was issued, difference in scientific opinion and socio-economic/political reasons.

However, virtually all guidance emphasises:

- Adjusting seating layouts and/ or installing transparent partitions to maintain distance between occupants.
- IAQ monitoring via sensors and reviewing supply and extract diffusers/dampers to ensure the best possible air quality for where occupants are present.
- Encourage natural ventilation by opening doors and windows, where conditions allow.
- Continual and increased operation of ventilation systems to all spaces with 100% fresh outdoor air and disable demand-control ventilation (DCV) controls that reduce air supply based on temperature or occupancy.
- Improve filtration to as high as possible without diminishing design airflow while managing filters for leakage and minimising filter bypass.
- Consider using High Efficiency Particulate Air (HEPA) filtration systems.
- Consider using ultraviolet germicidal irradiation (UVGI) as a supplemental measure to inactivate airborne virus in the upper level of common occupied spaces.
- Maintenance works as per existing maintenance schedule but with PPE (Personal Protective Equipment) as well as respiratory protection.

The following sections of this paper will review building services guidance measures as below:

(i) Increasing the Ventilation Rate by Adjusting the Fan Speed/Operational Hours
(ii) Opening of Windows to Supplement Ventilation
(iii) Ultraviolet (UV) Treatment

and will look at the immediate and long-term effects of these remedial measures.

2 Increasing the Ventilation Rate by Adjusting the Fan Speed/Operational Hours

Various guidance documents (REHVA, 2020) (ASHRAE, 2020) (CDC, 2020) (UK Government, 2020) recommend increasing outdoor air ventilation rates. Utilising fresh air to dilute the air within internal spaces is an effective method of reducing contaminants within spaces as it increases the effective outdoor air dilution rate per person (ASHRAE, 2020). The exact nature of SARS-CoV-2 remains unclear (how long particles remain suspended in the air) so, previous research has been utilised to calculate the efficiency of differing ventilation rates/durations for contaminant removal. Utilising CDC calculation methodology (NIOSH, 2009), for a perfectly mixed room, the particle removal efficiency is calculated as:

$$Particle\ Removal\ Efficiency = 100\ x\ (1 - 0.368^{ACH})$$

The calculation is based on droplet nuclei (this calculation is specifically utilized for the analysis of airborne infectious disease such as tuberculosis) having been released at a single point in time and no more contaminants are introduced throughout the calculation model (the contaminant source is removed). The graph (**Figure 2**) shows the calculation results for different ventilation rates (ACH) over a one, two and three-hour time period.

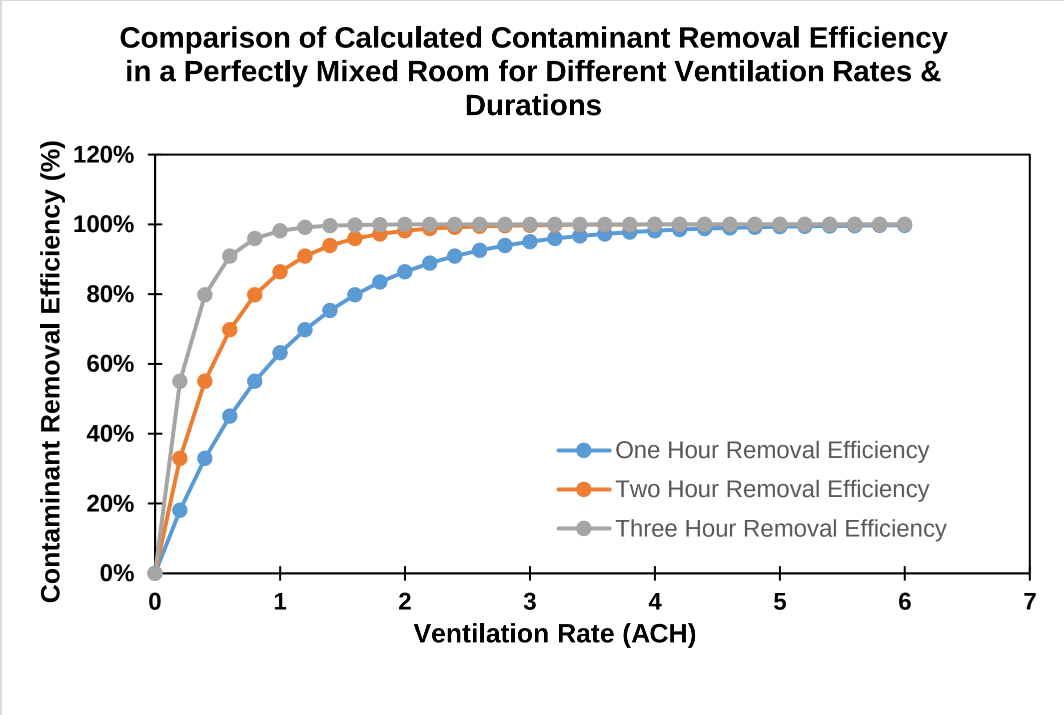

Figure 2 – Comparison of Calculated Contaminant Removal Efficiency in a Perfectly Mixed Room for Different Ventilation Rates & Durations.

From **Figure 2**, the exponential relationship between ventilation rates (ACH) and contaminant removal efficiency (%) is clearly demonstrated. As the ventilation rates approach 6ACH for an hour-long duration, almost 100% of the contaminants have been removed (99.75%) – increasing the ventilation rate beyond this point sees increasingly diminishing returns. This information has been modelled for a variety of ACH ventilation rates and durations (refer to *Remedial Adaptations in Building Services to Reduce COVID-19 Transmission* (Waters, 2021) for full tabulated values).

2.1 Increased Energy-Usage from Increasing Fan Duty

As time progresses, a key consideration for building operators will be whether they will have capacity in their existing ventilation systems to provide additional flow rate without the requirement for the replacement of the system's fan. Because of various design margins that are prescribed, at various points of system design, a fan speed generally used is greater than the actual system requirement. This suggests that many currently operating systems (that have been designed/specified in accordance with applicable regulations and guidance) have capacity to run at an increased speed to provide a greater air supply. To appreciate the effects from any adjustments to an existing fan, it is important to consider this in relation to the applicable ‘fan laws’ (*CIBSE Guide B, 2005*). Therefore, to achieve and increased airflow from existing ventilation systems, fan speed will need to be increased. By using ‘fan laws’ and percentage increase in lieu of actual values, a 20% increase in fan rpm (fan speed) results in a 44% increase in static pressure and in a 72.8% increase in fan power consumption i.e. a relatively small increase in the air volume of a fan can have significant impacts on the static pressure (which needs to be maintained below the overall rated capacity of the fan to ensure that sufficient air distribution is able to occur throughout a ducted system) and fan power consumption (which will affect the cost of running the fan, as well as the environmental impact arising as a result of its use).

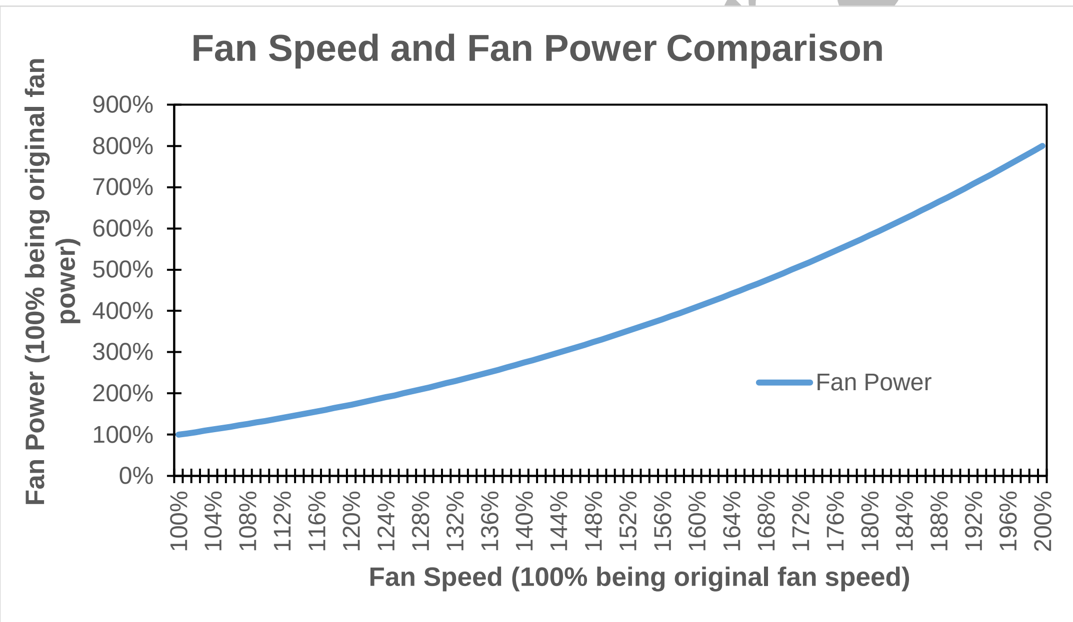

Figure 3 – The relationship between fan speed and fan power.

Figure 3 demonstrates fan power increases exponentially as the fan speed increases. It is highly unlikely that fans installed in existing ventilation systems have enough spare capacity to increase by 200%, however, this illustrates the significant increase in the required fan power (doubling the fan speed required four times the fan power).

Figure 4 shows the increased energy consumption associated with an increase in fan speed based on a 5kW fan with 10 hours of operation a day at a continuous speed – office occupied from 09:00-18:00 with 30 minutes ventilation before and after occupancy. The data in both **Figure 3** and **Figure 4** clearly shows significant increase in energy-usage associated with the increase in fan speed/duty. Increasing the fan speed by 20% translates to a potential increase of 32.76kWh/day (based on 10 hours of operation per day of a 5kW fan).

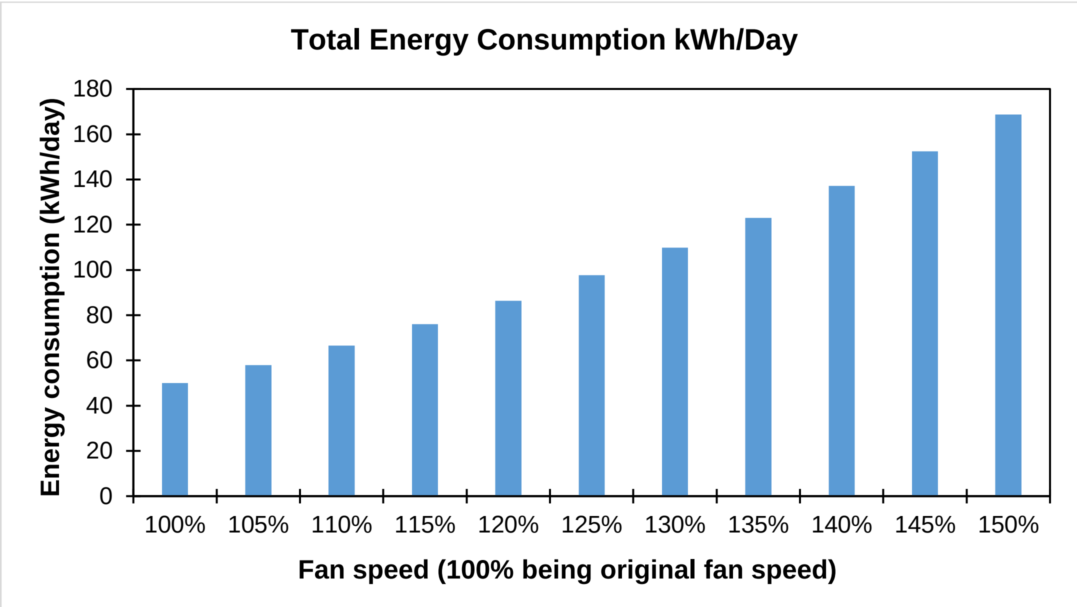

Figure 4 – The relationship between fan speed and energy consumption (based on 9 hours of operation a day).

2.2 Increased Energy-Usage from Increasing Fan Operational Hours

Based REHVA guidance (REHVA, 2020), buildings should: operate for 2 hours before opening; reduce to a lower speed 2 hours after closure; and keep fans running on evenings/weekend. **Figure 5** is a daily-profile developed on percentages of the fan's design duty (which will be operating at a duty greater than its initial design value in accordance with the measures outlined in the preceding section:

- 50% from 21:00-06:00 (overnight)
- 80% from 06:00-08:00 (2 hours prior to building occupancy)
- 100% from 08:00-19:00 (during building occupancy)
- 80% from 19:00-21:00 (2 hours after building occupancy)

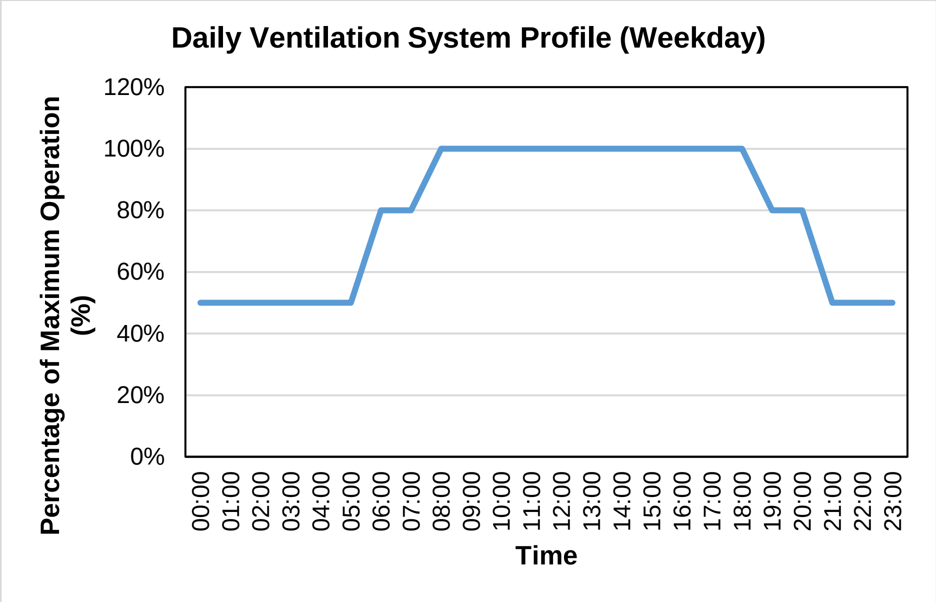

Figure 5 – Daily ventilation system profile (weekday)

The below weekly-operational profile (**Figure 6**) was developed utilising the daily profile (**Figure 5**), as well as a 50% operational value throughout the weekend, in accordance with REHVA guidance.

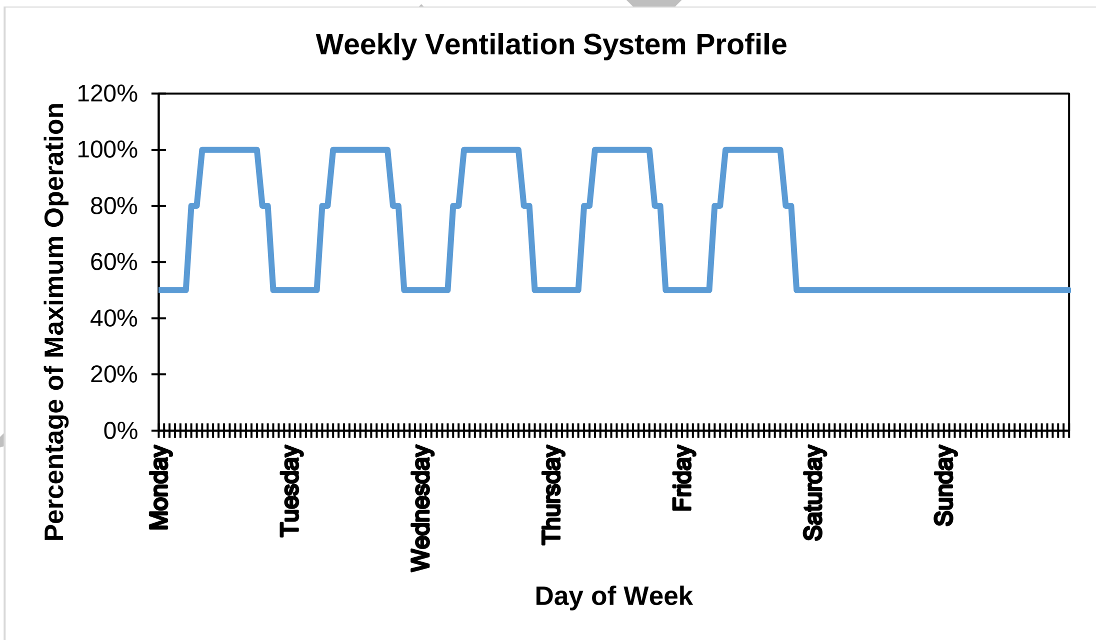

Figure 6 – Weekly ventilation system profile

This weekly-profile (**Figure 6**) was then applied to 5kW fans operating between 100-130% of their initial (design) fan speed (**Figure 7**).

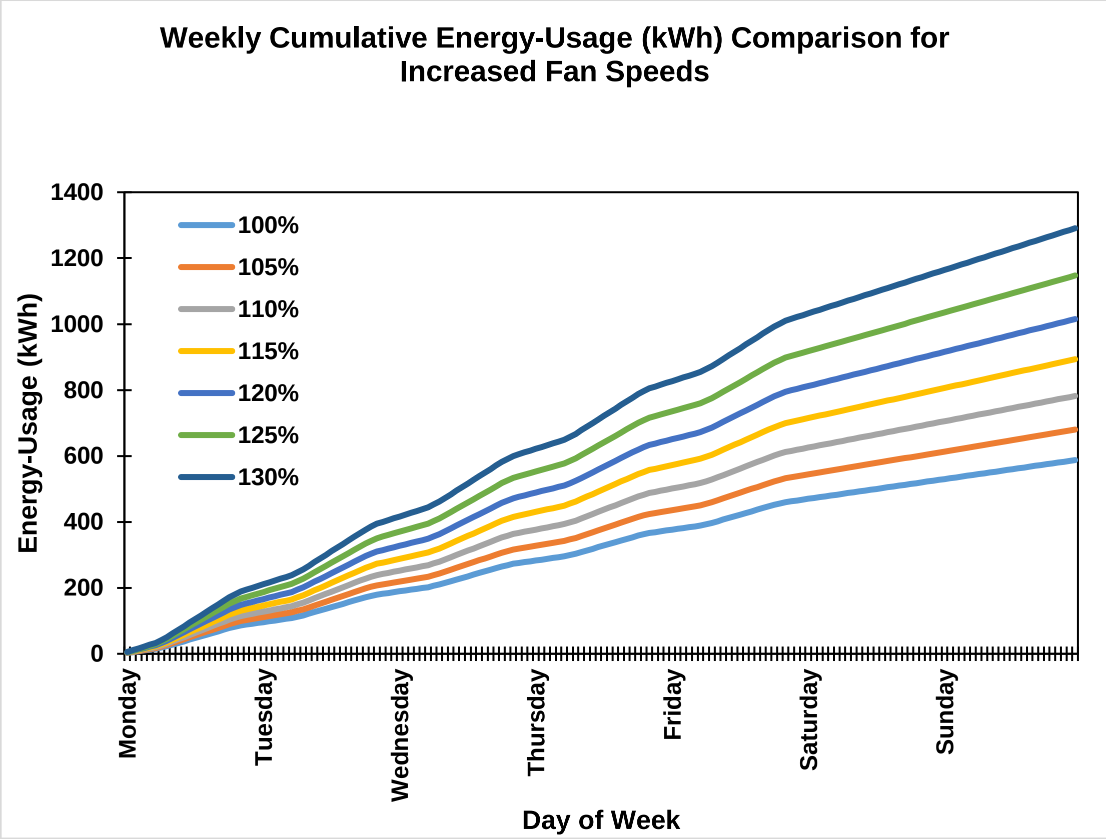

Figure 7 – Weekly cumulative energy-usage (kWh) comparison for increased fan speeds

The data in **Figure 7** shows how the increased fan power/speed results in significant increases in energy-usage. Increasing the original design fan speed by 20% results in a weekly energy usage increase of 703.24kWh, almost twice the original energy-usage at the initial design fan speed.

In lieu of specific direction from engineering bodies, as well as differing opinions in the scientific community as to the nature of transmission for the COVID-19 virus, it is unclear what ventilation levels will prove effective at reducing the spread of the viral transmission. The additional energy-usage (as well as cost/environmental impact which will be discussed in next sections 2.3 and 2.4) could be considered when planning for additional hours of operation.

2.3 Increased Costs from Increasing Fan Speed/Operational Hours

Using the UK average cost of electricity of 14.37p/kWh (UK Power, 2020)) **Table 1** assesses the additional costs associated with running a fan at increased speeds (with an initial designed power consumption of 5kW for 10 hours each working day) when the building is occupied.

Table 1 - Electricity prices for increased fan speed (fan with an initial power consumption of 5kW, running for 10 hrs per working day)

Fan Speed	Total kWh/Day	Increase in kWh/Day	Increase in Electricity Cost per Day	Increase in Electricity Cost per Month (20 Working Days)	Increase in Electricity Cost per Year (260 Working Days)
100%	50	0.00	N/A	N/A	N/A
105%	57.88	7.88	£1.13	£22.65	£294.46
110%	66.55	16.55	£2.38	£47.56	£618.34
115%	76.04	26.04	£3.74	£74.85	£973.05
120%	86.40	36.40	£5.23	£104.61	£1,359.98
125%	97.66	47.66	£6.85	£136.96	£1,780.53
130%	109.85	59.85	£8.60	£172.01	£2,236.12
135%	123.02	73.02	£10.49	£209.86	£2,728.13
140%	137.20	87.20	£12.53	£250.61	£3,257.97
145%	152.43	102.43	£14.72	£294.39	£3,827.04
150%	168.75	118.75	£17.06	£341.29	£4,436.74

Even before considering running ventilation systems for additional hours out of building occupancy, a 20% increase in fan speed (for an initial 5kW fan power consumption running 10 hours a day) would result in additional electricity costs of £104.61 per month. There is also no clear timeline on when ventilation systems should return to their standard operation. Therefore, it also worth considering that, if these measures remain in place for a prolonged period, the additional expenses accumulate. A 6-month period running the same fan (with an initial fan power consumption of 5kW) would result in an additional £679.90. Bearing in mind that a 5kW fan would only serve a relatively small office, it is likely that real-life costs could far exceed this.

2.4 Environmental Impacts of Increasing Fan Speed/Operational Hours

Table 2 compares the carbon emissions associated with increasing the fan speed to achieve an increased ventilation duty (utilising the previous example of a 5kW fan operating for 10 hours a day). In accordance with SAP 10 (BRE, 2018), a carbon factor of 0.233kgCO_2e/kWh has been used to assess carbon emissions associated with electricity use. Increasing the fan speed to 120% results in 30.34kgCO_2e over the course of a single week. The potential carbon emissions further increase when considering additional operating hours outlined in the weekly profile (**Figure 6**) in Section 2.2, as shown in **Table 3**.

Table 2 - Carbon emissions associated with different fan speeds (fan with an initial power consumption of 5kW, running for 10 hrs per working day)

Fan Speed	Total kWh/Day	Increase in kWh/Day	Total Carbon Emissions per Day (kgCO2e)	CO2 Emissions per Day(kg_{CO2e})	Increase in CO2 Emissions per Week (5 Days) (kg_{CO2e})	Increase in CO2 Emissions per Month (20 Days) (kg_{CO2e})	Increase in CO2 Emissions per Year (260 Days) (kg_{CO2e})
100%	50.00	0.00	11.65	0.00	0.00	0.00	0.00
105%	57.88	7.88	13.49	1.84	9.18	36.73	477.45
110%	66.55	16.55	15.51	3.86	19.28	77.12	1002.60
115%	76.04	26.04	17.72	6.07	30.34	121.36	1577.73
120%	86.40	36.40	20.13	8.48	42.41	169.62	2205.11
125%	97.66	47.66	22.75	11.10	55.52	222.08	2887.02
130%	109.85	59.85	25.60	13.95	69.73	278.90	3625.71
135%	123.02	73.02	28.66	17.01	85.07	340.27	4423.48
140%	137.20	87.20	31.97	20.32	101.59	406.35	5282.58
145%	152.43	102.43	35.52	23.87	119.33	477.33	6205.29
150%	168.75	118.75	39.32	27.67	138.34	553.38	7193.88

Table 3 – Weekly carbon emissions associated with increasing fan speed and hours of operation (utilising the weekly profile in Figure 6)

% of Initial (Design Fan Speed)	100%	105%	110%	115%	120%	125%	130%
Energy-Usage (kWh)	587.5	680.1	781.9	893.5	1015.2	1147.4	1290.7
CO2 Emissions (kgCO2e)	136.8	158.4	182.2	208.2	236.5	267.4	300.7

An increase to 120% of the initial fan speed results in total carbon emissions of 100.65$kgCO_2e$ (20.13$kgCO_2e$ per/day x 5 working days); however, this is further increased with the application of the increased operational profile for the fan (**Figure 6**) and increases to 208.19$kgCO_2e$.

Note there are side-effects potentially arising as a result of increased fan speed that need to be considered; negative effects on HVAC system life and increased maintenance requirements, possible noise implications arising from ventilation flow rates greater than design levels, increased energy-usage/costs and increased carbon emissions

Aside from logistical constraints for increasing fan speed, consideration must also be given to the effects on system life; increased maintenance; and increased noise from the fans, ductwork and terminal units.

3 Opening of Windows to Supplement Ventilation

Numerous engineering associations (CIBSE, ASHRAE) stress the need for increased ventilation and use of natural ventilation where possible. Opening windows to supplement mechanical ventilation is an effective method of increasing fresh (outside) air dilution, however, there are issues to be considered:

- Air temperature-conditioning is much harder to achieve when the temperature differential between inside/outside air is large.
- Heating/Cooling systems may operate at increased levels to try and counteract outdoor temperatures entering via open windows – this may result in systems operating at full capacity for prolonged periods.
- Internal air movement (velocity) is difficult to control due to wind from outside entering through open windows.

Ventilation rates achieved through natural ventilation vary significantly with a number of factors, including internal/external temperatures, stack-effect, wind-driven ventilation, size of openings, number and position of openings, however, it is highly likely it will improve the overall ventilation rate in conjunction with a mechanical system.

3.1 IES Simulation

To assess the additional benefit provided by the opening of building windows to provide ventilation, IES simulations were carried out for a generic office building, refer to *Remedial Adaptations in Building Services to Reduce COVID-19 Transmission* (Waters, 2021) for further details.

The IES simulations carried out only consider the effectiveness of natural ventilation to improve air quality in a building that does not have a mechanical ventilation system.

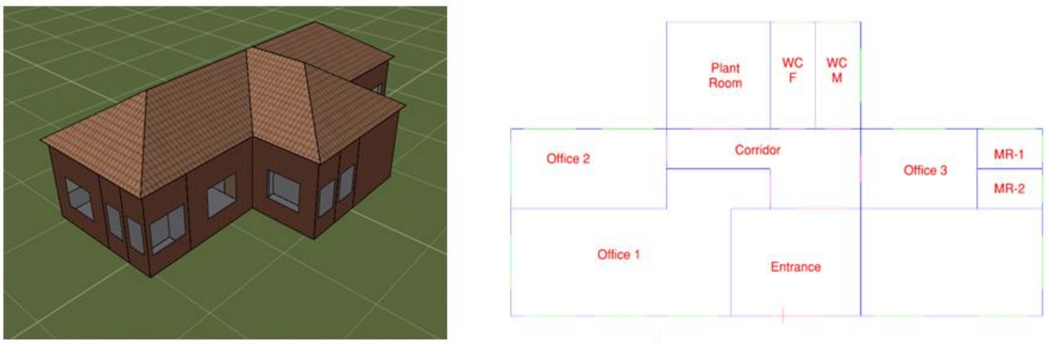

Figure 8 – 3D view and layout view of office building used for IES simulation

Three simulations were run and the room CO_2 concentration (ppm) assessed in each. CO_2 concentration is a good indicator of the concentration of respiratory particles within the space (which could potentially transmit SARS-CoV-2). The simulations carried out are:

1. **Base case model -** with occupancy, internal gains, background infiltration of 0.25ACH, all windows/doors closed, and no mechanical ventilation.
2. **Windows open/internal doors closed model** – as base case with external windows and entrance door opened (internal doors remain closed)
3. **Windows/doors open model** – as base case with external windows, entrance door and internal doors all open

Thermal properties were all applied in accordance with Part L2A, CIBSE/BSRIA (UK Government, 2010); generic internal gains and 0.25ACH was applied across all rooms to replicate infiltration; and constant occupancy was assumed to replicate worst-case scenario for air quality indicators. Different opening profiles were applied within MacroFlo (opening type, exposure level, opening percentage) and were assigned with a continuous operational profile to remain open, as described in *Remedial Adaptations in Building Services to Reduce COVID-19 Transmission* (Waters, 2021). Ambient CO_2 concentration is generally around 400ppm and acceptable air quality within a space is generally deemed to be a CO_2 concentration of <1000ppm (ASHRAE, 2016). Table 4 shows a reduction in CO_2 concentration within each space (other than the plant room which is unoccupied) achieved through the opening of external windows/doors. Further improvement occurs in the corridor when internal doors are also open (and maximum CO_2 concentration remains similar in the other spaces).

Table 4 - IES simulation results for natural ventilation effectiveness

	Room CO2 Concentration (ppm)				
Location	Base Case	Windows Open/Internal Doors Closed		Windows/Doors Open	
	Maximum	Maximum	Difference Between Base Case	Maximum	Difference Between Base Case
Office 4	2548	486	-2062	486	-2062
Office 3	2548	516	-2032	524	-2024
Meeting Room 2	11854	787	-11067	787	-11067
Meeting Room 1	11854	555	-11299	555	-11299
Entrance	2548	527	-2021	491	-2057
Office 1	2548	491	-2057	498	-2050
Male Toilets	6536	532	-6004	538	-5998
Female Toilets	6536	683	-5853	659	-5877
Office 2	2548	462	-2086	471	-2077
Corridor	2548	2299	-249	515	-2033
Plant Room	400	400	0	508	108

The results of the MacroFlo are analysed utilising a wireframe view (**Figure 9**) of the building. The results of the simulations support the hypothesis of natural ventilation significantly contributing to improvements of air quality within internal spaces. It is noteworthy that spaces with identical geometry (such as the toilets and meeting rooms), but different window opening arrangements, are subject to different maximum CO_2 concentrations (due to differences in crossflow ventilation). It is also notable that the internal corridor space without an external adjacency only receives minimal benefit from natural ventilation via window-opening when its doors remain open.

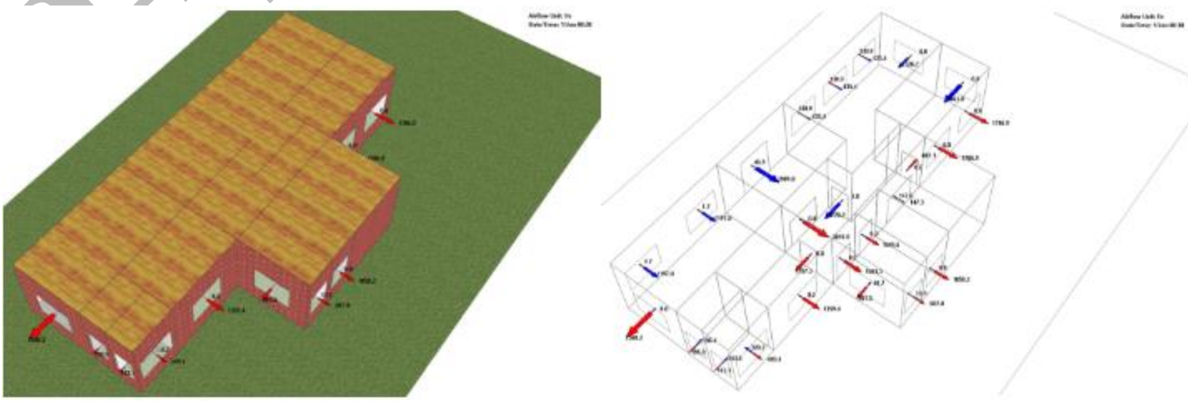

Figure 9 – MacroFlo analysis of typical office building – 3D view

Given the significant improvements in room CO_2 concentration, and the large air flow rates through windows evidenced via MacroFlo, opening windows would provide further benefit in terms air quality. However, this is offset against a reduction in thermal comfort, or a sizeable increase in heating/cooling loads. For the base case simulation (with constant occupancy/gains) a peak cooling load of 10.8kW was calculated. For the simulation with all doors/windows open, a peak cooling load of 62.52kW was calculated (a 620.5% increase).

4 Ultraviolet (UV) Treatment

Although there are uncertainties, there is mounting evidence to suggest the efficacy of UV-C light (ultraviolet light with between 100-400nm) to deactivate the COVID-19 virus (specifically at a wavelength of 254nm) (CIBSE, 2020). However, there remain a number of unknown factors to consider, such as dosage, exposure time and how these factors vary with external factors – such as the outside air ventilation rate (due to the removal of contaminants as demonstrated in **Figure 2**.

4.1 UV Required Dosage to Inactivate SARS-CoV-2

There have been several studies into the effectiveness of UV radiation for the inactivation of SARS-CoV-2, and research data for similar coronaviruses can also be analysed for comparison. **Table 5** shows research data for the inactivation of SARS-CoV-2 and other coronaviruses.

Table 5 – Required doses of UV irradiation to achieve inactivation

Virus Considered (source)	**90% inactivation** (m J/cm²)	**99% inactivation** (m J/cm²)	**99.9% inactivation** (m J/cm²)
SARS-CoV-2 (GMS Hygiene & Infection Control - Upper Limit) (Heßling, et al., 2020)	10.6	21.2	31.8
SARS-CoV-2 (GMS Hygiene & Infection Control - Median) (Heßling, et al., 2020)	3.7	7.4	11.1
SARS-CoV-2 (Buonanno, et al., 2020)	0.56	1.12	1.68
HCoV-229E (Buonanno, et al., 2020)	0.57	1.13	1.70
HCoV-OC43 (Buonanno, et al., 2020)	0.40	0.80	1.20

The data in the **Table 5** has either been provided for each instance of inactivation (90%, 99% & 99.9%) or calculated. There is a logarithmic reduction for each level of increase (i.e. compared to the 90% inactivation dosage (mJ/cm²), twice the dosage is required for 99% inactivation and three times the dosage for 99.9% inactivation). The tabulated data is also shown in **Figure 11**.

Figure 11 illustrates the wide variance in the required UV irradiation dosages required for inactivation. The upper limit of irradiance required to inactivate SARS-CoV-2 in the GMS-published findings is conservative and their median figure is likely more reliable (Heßling, et al., 2020), however, there is still a remarkable difference between their findings and the other findings included for the required inactivation doses (although some of these are for different coronavirus strains). The uncertainty in the data currently available means that it is difficult to assess the effectiveness of UV irradiation with precision. UV light can be applied with varying levels of effective irradiance (µW/cm²), each with their own permissible exposure times. Based on the permissible exposure times for various levels of effective irradiance according to the CDC/NIOSH (NIOSH, 2009) (**Figure 10**), **Figure 12** assesses the calculated effective irradiance for various UV lamp intensities (mJ/cm²) that are typically used in commercial applications. The effective irradiance is calculated for a period of 7,200 seconds (2 hours) for each lamp type (each operating at 254nm).

Permissible exposure time*		Effective irradiance
(Units given)	(Seconds)	(μW/cm^2)
8 h	28,800	0.2
4 h	14,400	0.4
2 h	7,200	0.8
1 h	3,600	1.7
30 min	1,800	3.3
15 min	900	6.7
10 min	600	10
5 min	300	20
1 min	60	100
30 s	30	200
10 s	10	600
1 s	1	6,000
0.5 s	0.5	12,000
0.1 s	0.1	60,000

*At 254 nm, the CDC/NIOSH REL is 6 mJ/cm^2 (6000 μJ/cm^2). Permissible exposure times (PET) for healthcare workers can be calculated for various irradiance levels as follows.

$$\text{PET (seconds)} = \frac{\text{REL (6000 }\mu\text{J/cm}^2\text{ at 254 nm)}}{\text{Measured irradiance level at 254 nm (}\mu\text{W/cm}^2\text{)}}$$

Figure 10 – Permissible UV Exposure Limits (NIOSH 2009)

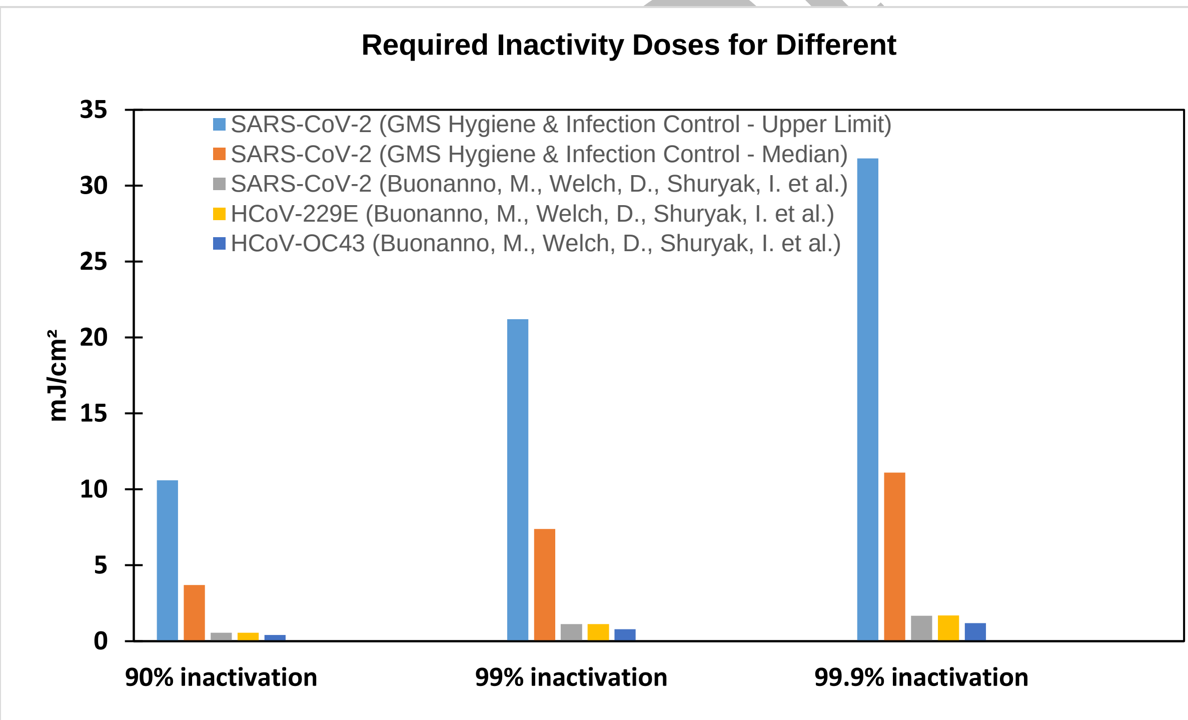

Figure 11 – Required doses of UV irradiation to achieve inactivation

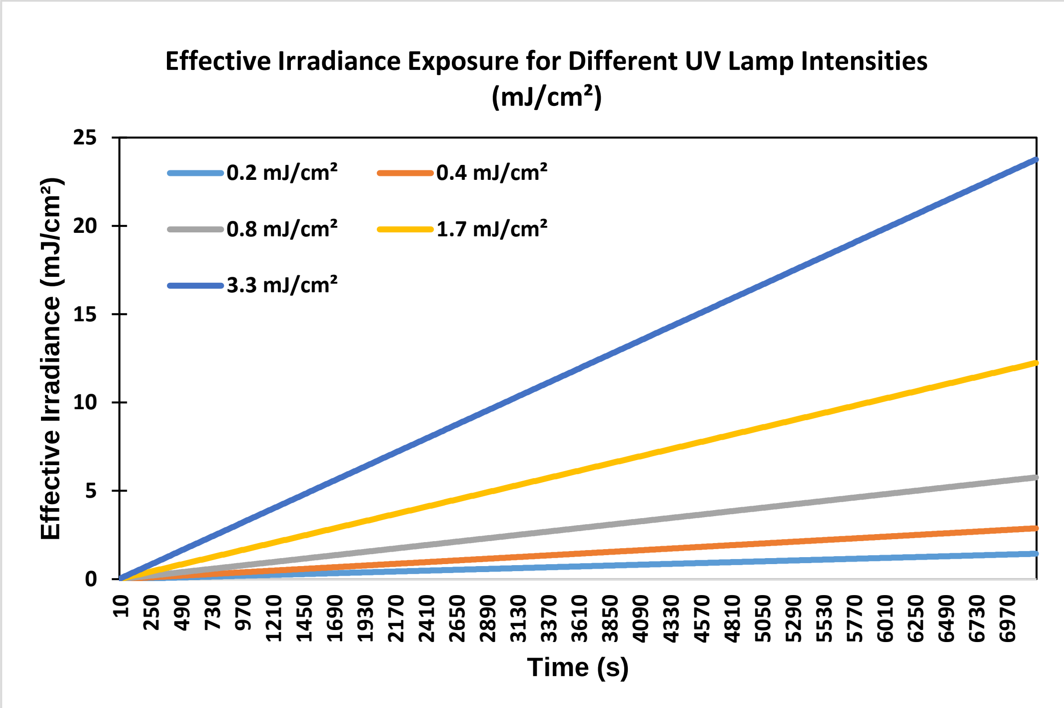

Figure 12 – Calculated effective irradiance over a 2-hour period for different UV lamp intensities.

Only the 0.2mJ/cm² lamp irradiance is acceptable for 8 hours of exposure (typical of an office occupant's potential daily exposure). This results in a total dosage of 1.44mJ/cm² after a 2-hour period (and a 5.76mJ/cm² dosage after 8 hours). The effectiveness of low intensity UV lights to inactivate SARS-CoV-2 is highly dependent on the inactivation dose required. 2 hours of exposure to a 0.2mJ/cm² U lamp would achieve 90% inactivation based on 3 out of the 5 research findings. 8 hours of exposure would achieve 90% inactivation in all but the upper limit of the GMS-published findings.

Utilising higher intensity UV lights where occupants do not remain in the room are likely to be highly effective at inactivating the virus before/after occupation. 2 hour use of a 3.3mJ/cm² would provide an effective US dosage of 23.76mJ/cm² which would achieve 99% inactivation on all the test data listed in **Table 5** (including the upper limit level stated in the GMS-published findings). However, only 30 minutes of human exposure is permissible for this UV lamp intensity, so usage could only occur outside of occupied hours. Although further research is required to establish the precise effective irradiance dosage required to achieve acceptable inactivation, evidence suggests that UV lamps can be effective if used in the correct manner.

Depending on further research findings, low level and higher-level intensity UV lamps could both be instrumental in helping to curb the spread of COVID-19.

4.2 Methods of Application for UV Treatment

There are three forms in which UV systems are typically implemented:

In-duct UV – the installation of a UV lamp within ductwork to disinfect air as it passes through (the rate of disinfection being a produce of lamp size and air velocity through the system). Generally, it is preferable to install UV lamps in return air ductwork to disinfect air before it is re-circulated and to protect internal components from contamination. However, given the suggested HVAC system guidelines for operation during the COVID-19 pandemic (RHEVA, CIBSE, CDC), it is likely that re-circulation on units will be switched off, and units will operate at 100% outside air (see Section 1.3). Higher intensity UV lamps can be used as occupants will not be subject to exposure due to enclosure in ductwork.

Free-standing room filter – installed within a stand-alone air filtration unit (such as the HEPA units). Air is drawn through an irradiated zone within the unit and may be used in conjunction with other filters. Constraints apply with regards to unit positioning and only air that passes through the unit is treated. Higher intensity UV lights can be utilised as direct exposure to room occupants will not occur if the lamp is contained within the unit.

Upper room germicidal systems – installed in the upper areas of a space (above head height) and relying on air mixing to treat a room's entire volume over a period of time. Upper room systems offer a particularly effective solution for spaces that are subject to poor ventilation rates, as they are not dependent on airflow through a duct/room air cleaner. UV-C light can damage human tissues and, as the wavelength is below the visible light spectrum, damage can often be insidious, with the effects unnoticed for some time.

All methods need to be considered alongside the existing HVAC system, as well as any other measures being introduced to combat the spread of the COVID-19 virus. As demonstrated in (Section 2) ventilation may remove the majority of viral contaminants after a period of operation, which would then reduce the number of contaminants a UV system would be able to remove (due to them being removed by other means). Systems should be considered alongside one another to ensure a holistic solution is achieved.

5 Comparison of Proposed Measures

As stated throughout the investigations carried out within this report, research into SARS-CoV-2 and COVID-19 is ongoing and there remains uncertainty on the nature of transmission. However, few methods considered here have each been assessed on their respective likelihood in the reduction of transmission (based on the available scientific data), the capital and ongoing costs, the ease of application and how occupant comfort is affected. **Table 6** is a scoring matrix – with a score of '5' being the best possible score and '1' being the worst (refer to *Remedial Adaptations in Building Services Engineering to reduce COVID-19 Transmission* (Waters, 2021)). Additional weighting has been utilised to place more importance on the '*Potential Reduction in Contaminant Transmission'* score (it has twice the weighting of the other scores) due to its essential importance when considering any of the measures outlined in this report.

Table 6 – Scoring matrix table comparing measures for the reduction of COVID-19 transmission assessed within this report.

Technology	Measure	Potential Reduction in Contaminant Transmission	Capital Cost	Ongoing Cost	Environmental Impact	Ease of Application	Occupant Comfort Impact	Average
Mechanical Ventilation	Increasing Fan Speed	4	4	2	2	3	4	3.29
Natural Ventilation	Opening Windows	5	5	3	3	5	1	3.86
UV Treatment	Free-Standing Room Filter	3	3	4	3	5	5	3.71
	In-Duct UV Lamp	2	2	4	3	3	5	3.00
	Upper Room Germicidal UV	4	4	4	4	5	5	4.29

The scoring in **Table 6** has been selected based on the analyses carried out within the respective sections of this paper. The scoring considers each measure individually, however, in reality, a holistic approach is required to ensure the different measures can work effectively to complement/assist each other. The scoring matrix is a simplification of a complex selection process that needs to be considered for each idiosyncratic existing arrangement, and it is important to keep this in mind when reviewing. For instance, although a '*Free-Standing Room Filter'* scores relatively high, it will not provide the same level of benefits as alterations to the central ventilation system would provide – however, it can be implemented with relatively low cost/impact to occupant comfort and existing systems. The highest scoring measure is the '*Upper Room Germicidal UV*' which, although there remain uncertainties at present on the required dosages for inactivation of SARS-CoV-2 (see Section 4.1), offers an excellent opportunity to reduce the number of contaminants within a building, without the need for alterations to existing systems. However, this needs to be considered alongside other measures, as the effectiveness of UV dramatically decreases when contaminants are being removed by other means, such as ventilation (as evidenced by the contaminant removal by ventilation in **Figure 2**). '*Natural Ventilation*' scores highly because increasing ventilation rates is a highly effective measure to reduce transmission and this can be implemented without significant costs, however, these cost/energy benefits could be offset if additional energy is required for temperature conditioning through alternative means.

6 Conclusion

The findings in this paper exemplify the complex nature of viral transmission and its uncertainties. Further still, the complexities arising between implementing multiple adaptations of building services to mitigate transmission require careful consideration to assess the interface between measures and how they affect each other. The COVID-19 pandemic has come as a surprise to most and, as such, existing systems have not been designed with resilience in mind for such an event. Building designers in the future should recognise the potential possibility of future pandemics and how this may affect building-usage and, for periods of time, remove the impetus from cost/energy efficiency and focus instead on mitigating the transmission of viruses. Retrospective amendments to building services systems can be complex to implement and, as such, making design considerations for similar circumstances in the future would facilitate this process.

Word count: 5,044

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