in which windows could not be opened and ventilation was only provided by the air-conditioning system. Their tables were more than one metre apart. The index case was pre-symptomatic and developed a fever and cough the same evening after leaving the restaurant. The secondary cases were sitting along the line of airflow generated by the air-conditioning system, while diners sitting elsewhere in the restaurant were not infected. The authors of the report attributed transmission to the spread of respiratory droplets carrying SARS-CoV-2 via the airflow generated by the air-conditioning.

The investigation of two other outbreaks from China in January 2020 considered air-conditioning systems using a re-circulating mode as a probable aid to transmission [30,31].

The first outbreak was associated with a 150-minute event at a temple [30]. The index case, who had previously visited Wuhan, was pre-symptomatic until the evening after the event. The attack rates in the outbreak were the highest among those who shared a 100-minute bus ride with the index case (23 out of 67 passengers; 34%). Passengers sitting closer to the index case did not have a statistically higher risk of COVID-19 than those sitting further away. However, all passengers sitting close to a window remained healthy, with the exception of the passenger sitting next to the index case. This supports the hypothesis that the airflow along the bus facilitated the spread of SARS-CoV-2. In contrast, there were seven COVID-19 cases among 172 other people who attended the same 150-minute temple event, all of whom described having had close contact with the index case.

The second outbreak was associated with a training workshop that took place between 12 and 14 January 2020 in Hangzhou city, Zhejiang province [30]. It had 30 attendees from different cities, who booked hotels individually and did not eat together at the workshop facility. The workshop had four group sessions lasting four hours each, which were in two closed rooms of 49 square metres and 75 square metres, respectively. An automatic timer on the central air-conditioners circulated the air in each room for 10 minutes every four hours, using 'an indoor re-circulating mode'. No trainees were known to be symptomatic during the workshop. Between 16 and 22 January 2020, 15 of the trainees were diagnosed with COVID-19.

Several outbreaks have also occurred among workers in meat-processing facilities [7,9]. Poor ventilation has been one factor implicated in such outbreaks.

Adaptations of HVAC systems to reduce the risk of SARS-CoV-2 transmission in closed spaces

Ventilation with outdoor air is deemed to dilute contaminants in closed spaces and increase the time required for exposure to an infectious dose. This process is energy-consuming, but automatically controlled HVAC systems usually lower the air exchange just before and after the use of closed spaces depending on room occupation and can even be switched off during certain periods, e.g. overnight.

A 2006-2007 study in crowded dormitories for students at Tianjin University in China showed an inverse association between common cold infection rates and mean air exchanges in winter [32]. Baseline numbers of required air exchanges during customary use are proposed by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) as 7-10 L/s per person [33]. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) recommends ensuring the minimum number of air exchanges per hour, following the applicable building regulations[2].

In addition to the ventilation itself, air filtration could be another way of reducing the risk of transmission of SARS-CoV-2 compared to only increasing the air exchange rate in closed spaces. A study using a case study of airborne transmission of influenza for modelled estimates of relative influenza risk reduction showed, for a hypothetical office, a positive association between risk reductions and the use of higher filter quality according to the MERV (Minimum Efficiency Reporting Value) filter classifications of ASHRAE. The greatest risk reduction at the lowest costs was shown for MERV 13 filters [34].

The filters commonly used in HVAC systems (see Table A3 in the Annex) are capable of retaining large droplets but not aerosols (small droplets and droplet nuclei). High Efficiency Particulate Air (HEPA) filters have demonstrated good performance with particles of the size of SARS-Cov-2 (approximately 70–120 nm) and are used in aeroplanes and in healthcare settings [15]. The role of HEPA filters in buildings outside of healthcare settings in preventing the transmission of infectious diseases is unclear. For SARS-CoV, the virus causing SARS ,a modelling study of how the infection risk was modified by three types of ventilation systems in relatively large commercial aeroplanes showed that, among the three systems, the mixing ventilation system had the highest risk and the conventional displacement system had the lowest risk.

A relative humidity of 40–60% may help to limit the spread and survival of SARS-CoV-2 within a closed space [24,33]. Humidity levels in this range could therefore be considered for HVAC systems. However, even new buildings with state-of the art HVAC systems cannot usually exceed more than 40% relative humidity, especially in winter, and older systems often cannot exceed much lower relative humidity levels because of the risk of damaging the HVAC system as well as room structures due to the risks of condensation and mould development [2,33].

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