CHALMERS
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Ventilation Against Disease Transmission in Hospitals

Evaluation of risk levels and energy consequences

Master's thesis in Structural Engineering and Building Technology

RASHA ALASMI

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
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RASHA ALASMI

Supervisor: Professor Lars Ekberg, Department of Architecture and Civil Engineering

Supervisor: Daniel Olsson, CIT Renergy

Examiner: Professor Lars Ekberg, Department of Architecture and Civil Engineering

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Department of Architecture and Civil Engineering
Division of Building Technology
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone: + 46 (0)31-772 1000

Cover: A patient room in Kungälv hospital (Skanska, 2024).

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ABSTRACT

Ventilation plays a critical role in controlling indoor air quality and reducing infection risks, particularly in healthcare settings where vulnerable populations are present. This study examines the effect of different airflow rates on infection control and highlights the differences between guidelines as well as specific national and international guidelines. Using field data from Kungälv Hospital in Sweden, along with simulations from the REHVA COVID-19 Ventilation Calculator and IDA ICE software, the study compares the impact of ventilation on high-risk diseases like measles and moderate-risk illnesses such as seasonal influenza. There are notable differences between the strictest and least stringent guidelines, with some recommending as low as 2 air changes per hour (ACH), while others suggest up to 12 ACH for isolation rooms. Results reveal that as the airflow rate increases, the infection risk decreases, but energy consumption also increases, raising concerns about sustainable building practices. Doubling the ventilation rate from 25 l/s to 50 l/s led to a substantial reduction in infection risk (37% relative reduction), but it also increased energy consumption, highlighting a critical trade-off. Furthermore, the findings show the impact of air cleaners on reducing airborne particles and the potential of integrating them into ventilation systems to enhance infection control. Alongside adequate ventilation, other measures such as utilizing UV lighting, promoting face masks, and reducing occupancy time are essential strategies to improve air quality in healthcare environments. These measures are particularly crucial post-COVID-19 pandemic, where preventing airborne transmission has become a major concern.

Key words: Ventilation, airborne transmission, airflow rates, infection risk, air quality, air cleaners, healthcare guidelines, energy consumption, IDA ICE, REHVA calculator tool, Wells-Riley equation, Kungälv Hospital, COVID-19.

Ventilation mot Sjukdomsspridning på Sjukhus
Utvärdering av risknivåer och energikonsekvenser
Examensarbete inom Konstruktionsteknik och Byggnadsteknologi

RASHA ALASMI

Institutionen för arkitektur och samhällsbyggnadsteknik
Avdelningen för Byggnadsteknologi
Chalmers tekniska högskola

SAMMANFATTNING

Ventilation spelar en avgörande roll i att kontrollera luftkvaliteten inomhus och minska infektionsrisker, särskilt i vårdmiljöer där känsliga grupper vistas. Denna studie undersöker effekten av olika luftflöden på infektionskontroll och lyfter fram skillnaderna mellan riktlinjer samt de specifika nationella och internationella riktlinjerna. Med hjälp av fältdata från Kungälv Sjukhus i Sverige, tillsammans med simuleringar från REHVAs COVID-19 ventilationskalkylator verktyg och IDA ICE-programmet, jämför studien ventilationens påverkan på hög-risk sjukdomar som mässling och medel-risk sjukdomar som säsongsinfluensa. Det finns betydande skillnader mellan de strängaste och minst stränga riktlinjerna, där vissa rekommenderar så lågt luftflöde som 2 luftväxlingar per timme (ACH), medan andra föreslår upp till 12 ACH för isoleringsrum. Resultaten visar att ju högre luftflödet är, desto lägre blir infektionsrisken, men energiförbrukningen ökar också, vilket väcker frågor om hållbarheten. Att fördubbla luftflödet från 25 l/s till 50 l/s resulterade i en betydande minskning av infektionsrisken (37 % relativ minskning), men ökade även energiförbrukningen, vilket belyser en viktig avvägning. Vidare visar resultaten på effekten av luftrenare för att minska luftburna partiklar och möjligheten att integrera dessa i ventilationssystem för att förbättra infektionskontrollen. Tillsammans med adekvat ventilation är andra åtgärder såsom användning av UV-ljus, främjande av ansiktsmasker och minskad vistelsetid viktiga strategier för att förbättra luftkvaliteten i vårdmiljöer. Dessa åtgärder är särskilt kritiska efter COVID-19-pandemin, där förebyggande av luftburen smitta har blivit en stor oro.

Nyckelord: Ventilation, luftburen smitta, luftflöden, infektionsrisk, luftkvalitet, luftrenare, vårdriktlinjer, energiförbrukning, IDA ICE, REHVA-kalkylator verktyg, Wells-Riley-ekvationen, Kungälv Sjukhus, COVID-19.

PREFACE

This master’s thesis project was conducted between January and June 2024 at the Division of Building Technology at Chalmers University of Technology, in collaboration with Västfastigheter and CIT Renergy. The work is a part of Chalmers' research within the FORMAS projects "Buildings Post Corona" and "Clean Surge Air."

I would like to express my sincere appreciation to my supervisor and examiner, Lars Ekberg, at Chalmers University. His support throughout this thesis has been invaluable, providing me with insightful advice and encouragement. I am also grateful for his efforts in arranging the study trip to Kungälv Hospital, which greatly enriched this study. I would also like to extend my thanks to Daniel Olsson for his assistance throughout the process.

Finally, I would like to express my deepest gratitude to my family for their unwavering support throughout my years of study and during the process of writing this thesis.

Rasha Alasmi
Gothenburg, September 2024

Notations

Symbols and Units

ACH	Air Change per Hour
°C	Celsius
cm	Centimeter
CO_2	Carbon Dioxide
ED	Exhaust Air Device
Exp	Experiment
hr	Hour
k	Decay Rate Constant
KWh	Kilowatt-hours
l	Liter
m	Meter
min	Minute
MP	Measurement Point
µm	Micrometer
ppm	Parts per Million
R_0	The Basic Reproduction Rate
R_e	The Effective Reproduction Rate
s	Second
SD	Supply Air Device
t	Time

Abbreviations

AC	Air Cleaner
AII	Airborne Infection Isolation
BOV	Byggenskap och Vårdhygien (Construction and Healthcare Hygiene)
CADR	Clean Air Delivery Rate
CDC	The American Center for Disease Control and Prevention
CFUs	Colony Forming Units
COVID-19	Coronavirus Disease Identified Year 2019
DEP	Dielectrophoresis
HIV	Human Immunodeficiency Virus
HVAC	Heating, Ventilation, and Air Conditioning
IDA ICE	IDA Indoor Climate and Energy
NHS	National Health Service
OVK	Obligatorisk Ventilationskontroll (Mandatory Ventilation Inspection)
PMDS	Polydimethylsiloxane
PTS	Program för Teknisk Standard (The Swedish Program for Technical Standards)
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RSV	Respiratory Syncytial Virus
SARS	Severe Acute Respiratory Syndrome
SFP	Specific Fan Power
SFVH	Svensk Förening för Vårdhygien (The Swedish Association for Healthcare Hygiene)
UV Lighting	Ultraviolet Lighting
WHO	World Health Organization

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1
Introduction

1.1 Background

Ventilation is crucial for maintaining healthy, comfortable, and safe indoor environments, such as homes, workplaces, and healthcare facilities. It plays a key role in building design and operation, addressing important functions like air quality, comfort, productivity, and moisture control. Effective ventilation reduces the risk of disease transmission and supports sustainable building practices. This is especially critical in hospitals, where the high presence of vulnerable populations, such as the elderly, children, pregnant women, and those with weakened immune system, makes the risk of infection a major concern. For these groups, even minor illnesses can pose serious health threats.

The importance of ventilation was particularly highlighted during the Coronavirus pandemic (COVID-19), which underscored its role in reducing the spread of airborne diseases. As a result, many healthcare facilities have prioritized enhancing ventilation to minimize infection risks, emphasizing its necessity in maintaining a safe and healthy environment.

Infections can spread from an infected individual to a susceptible one through various transmission routes, influenced by factors like exposure time. Ventilation helps by diluting the concentration of airborne infections, thus lowering infection risks, and reducing the likelihood of airborne transmission. However, research into how ventilation impacts infection risk, considering variables like exposure duration, airflow rates, and types of diseases remains limited, leading to disparity in guidelines and recommendations from different health organizations. Understanding these relationships is crucial for developing energy-efficient ventilation strategies that not only improve indoor air quality but also minimize infection risks. While there is considerable research on controlled environments in hospitals, such as operating rooms and isolation rooms, there are few studies that focus on uncontrolled settings like patient rooms and waiting rooms. These areas are uncontrolled environments where an unpredictable number of infected individuals can be present simultaneously, often with lower hygienic and disinfection measures.

When considering energy efficiency, it is important to examine the life cycle of hospital buildings. In healthcare settings, operational energy use constitutes the largest portion of the life cycle energy consumption. Ventilation and lighting are the most significant energy consumers in hospital buildings, accounting for 38% and 28% of the total energy consumption, respectively according to Statens Energimyndighet (The Swedish Energy Agency) (2008). Therefore, further research in this domain is essential to develop evidence-based, energy-efficient ventilation solutions that prioritize both patient safety and public health.

1.2 Aim

The aim of this study is to conduct a comparative analysis of existing guidelines to reduce airborne disease transmission in indoor environments. The study examines two distinct risk levels of disease transmission risk: one with high transmission risk and another with lower transmission risk. These risk levels are evaluated against the strictest and least strict guidelines to assess the effectiveness of ventilation in reducing infection risk. Additionally, the study examines the impact of ventilation on these risk levels, with a particular focus on the energy consumption of the ventilation system. This analysis provides insights into how different guidelines affect disease transmission risk and the implications for ventilation system design in various settings.

1.3 Limitations

This thesis primarily bases its analysis on both national and international guidelines provided by both healthcare and real estate organizations. However, the measurements and analyses are conducted within the context of a typical Nordic climate, such as that of Sweden. The main emphasis of the thesis is on the transmission of airborne diseases within a patient room. Other types of healthcare facilities are not included in the scope of this study.

1.4 Problem Identification

The ventilation systems in medical care facilities are critical for the health of both patients and medical staff. Various guidelines from healthcare and real estate organizations address ventilation and indoor environments in hospitals. There is a pressing need in the medical field to compare these different guidelines to pinpoint their similarities and differences. While all guidelines agree that diluting the concentration of airborne infections through ventilation reduces the risk of infection transmission and enhances air quality, there is disagreement regarding the adequate airflow required. Moreover, the COVID-19 pandemic has heightened the importance of ventilation due to the fear of future outbreaks and new pandemics. This increased awareness has led to a greater emphasis to optimize ventilation strategies to minimize airborne infection transmission.

1.5 Method

The method used in this study involves a qualitative approach followed by a quantitative research approach. The qualitative approach is theoretical and based on literature reviews from various health organizations, such as the World Health Organization (WHO), the Centers for Disease Control and Prevention (CDC), and the British National Health Service (NHS), among others, as provided by trusted sources. The quantitative approach is performed using the REHVA calculation guide tool based on the Wells-Riley equation (REHVA, 2022b), and the IDA ICE simulation program (EQUA, 2024). REHVA is used to calculate the relationship between

ventilation and the infection risk, while the IDA ICE program is used to simulate the relationship between the ventilation system and energy use.

This study is based on field measurements conducted at Kungälv Hospital, located north of Gothenburg. Following these field measurements, calculations are performed using REHVA to replicate the conditions present in Kungälv Hospital. The calculated results obtained from the REHVA are then compared against the field measurements to validate the REHVA tool's accuracy and reliability.

The experimental part of the study is carried out in cooperation with Västfastigheter (the real estate owner/facility manager of healthcare buildings in the Västra Götaland Region) and CIT Renergy AB (a subsidiary of Chalmers Industriteknik). Field measurements at Kungälv Hospital are conducted in collaboration with personnel from CIT Renergy AB. Additionally, the study contributes to the ongoing research of the correlation between indoor climate conditions and energy consumption in healthcare settings. It is related to Chalmers' research within the FORMAS projects "Buildings Post Corona" and "Clean Surge Air."

2
Theory

2.1 Particles

Particles are defined as a very small part of matter, such as atoms, molecules, and electrons. Particles are floating all around us. They can greatly vary in size, ranging from microscopic to visible sizes. In the context of indoor air quality, these particles can include dust, pollen, smoke, and various other substances. They can naturally be found in the environment or generated by human activities such as combustion, industrial processes, and vehicle emissions.

2.1.1 Particle Classification

Particles are classified by their aerodynamic diameter, in regard to their size. Aerodynamic diameter is a measure used to characterize particles behavior in a fluid flow, particularly air. The aerodynamic diameter of a certain particle is defined as the diameter of a sphere with the same density as water (1 g/cm^3), which settles in still air at the same velocity as the particle in question (Norén, 2016).

Particle sizes can be classified into different categories based on their diameter. Large particles have a size larger than 100 micrometers (µm). Examples of such particles are sand and hair. Large particles are heavy particles that fall quickly on horizontal surfaces due to gravitational force, by a velocity greater than 0.5 m/s. Coarse particles have a size that varies between 1 µm and 100 µm. Examples of such particles are dust, mold spores, and pollen. Coarse particles fall on horizontal surfaces due to gravitational force, by a velocity ranging from 0 m/s to 0.5 m/s. Fine particles have a size less than 1 µm. Examples of such particles are viruses and gas molecules. Fine particles require a long time to fall on the ground or settle down on a surface, they are assumed to be constantly floating in the atmosphere. Almost 99.9 % of the particles in the atmosphere is made up of fine particles (Norén, 2016). A terminology of particle size ranges is shown in Figure 2.1.

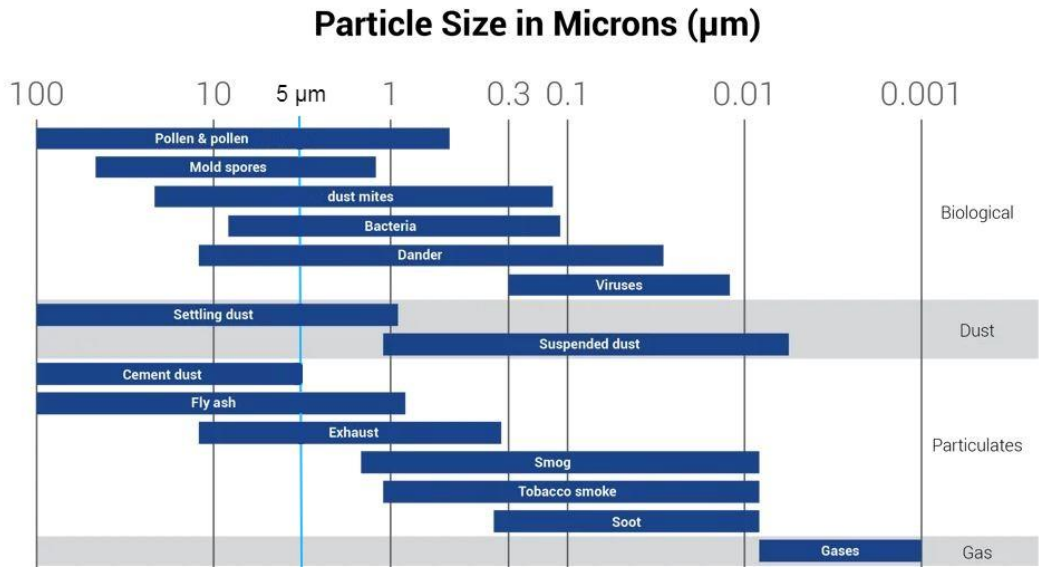

Figure 2.1*: A terminology of particle size ranges (Kelley, 2019).*

When discussing particles suspended in the air, they are commonly referred to as airborne particles, typically smaller than 5 µm. These particles are of primary concern in ventilation discussions due to their ability to remain airborne and travel long distances (Fennelly, 2020).

In the context of healthcare facilities, the terms "droplets" and "droplet nuclei" are often used when discussing infectious disease transmission, particularly respiratory illnesses. Droplets are small liquid particles released when a person talks, coughs, sneezes, or breathes. These particles are generally larger than 5 µm and typically travel less than one meter. In contrast, droplet nuclei are smaller, usually less than 5 µm in diameter. They can remain airborne for long periods and travel more than one meter. A droplet nucleus is the solid residue left after the liquid in a droplet evaporates. Droplets are typically trapped in the upper respiratory tract (nose and throat), while droplet nuclei have the potential to penetrate the respiratory tract, reaching the bronchi and alveoli of the lungs (Alsved, 2020).

2.1.2 Particle Dispersal

Particles are influenced by various driving forces, including gravitational settling, diffusion, and convection. These forces play a significant role in determining the behavior and dispersion of particles. Gravitational settling occurs when particles are pulled down to the ground by gravity. Diffusion involves the movement of particles driven by concentration differences. Convection is the movement of particles driven by temperature differences (Norén, 2016).

In a ventilated room, the movement of airborne particles is influenced by ventilation and other driving forces. Convection is a primary driving force behind effective ventilation in buildings. Gravitational settling, which mainly affects larger droplets, is considered a secondary driving force in the context of ventilation. In a well-mixed,

ventilated environment with evenly distributed particle concentration, diffusion has minimal impact (Norén, 2016).

2.2 Particle Transmission Risk

In healthcare settings, understanding the transmission of particles is crucial for preventing the spread of infectious diseases. Particles, depending on their size and nature, can transmit pathogens through various routes, each with different implications for control and prevention.

2.2.1 Transmission Mechanisms

Healthcare facilities always involve a certain risk of infection for the individuals, including patients, medical staff, and visitors. The infection pathogen can either come from other individuals and/or the environment, known as exogenous infection, or from the individuals' own body, known as endogenous infection. Infection transmission usually leads to actual infection in the susceptible host. However, the transmission can sometimes cause colonization of the infectious agent without showing symptoms of the infection. Colonization does not mean that the individual is infected but rather signifies a high potential of being infected. Therefore, it is necessary to prevent all transmission of infections, including those that only cause colonization (Svensk Förening för Vårdhygien (SFVH), 2016).

To prevent infection transmission, the infection source and routes of transmission must be well identified. Infections can originate from various sources, with humans being the most common carriers. The infected person can either have symptoms or be symptom-free when transmitting infections. Infection can also be transmitted, even when the infected person has left the place because bacteria and viruses can stay in the air for long time. Contact with furnitures and equipments such as humidifiers and incubators can also increase risk of infection transmission (Svensk Förening för Vårdhygien (SFVH), 2016).

There are various routes for infection transmission, the common ones are illustrated in Figure 2.2. Some of these transmission routes include (Svensk Förening för Vårdhygien (SFVH), 2016): contact transmission, droplet transmission, airborne transmission, bloodborne transmission, and insect-borne transmission. A brief description of each route is provided below.

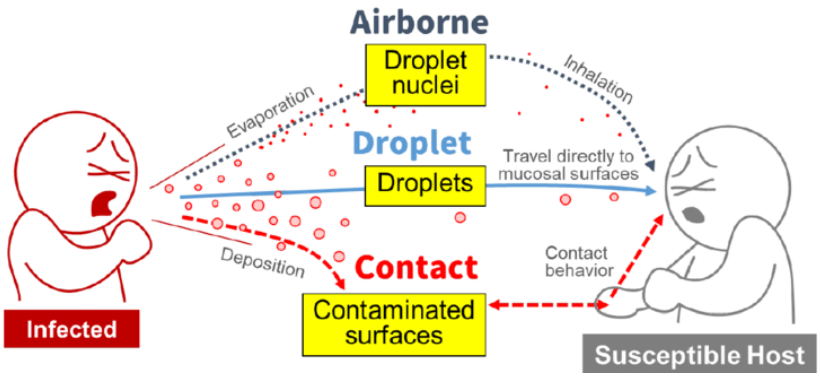

***Figure 2.2**: Transmission routes of particles (Rastogi et al., 2020).*

Contact Transmission

The most common way infections spread in healthcare settings is through direct contact with infected individuals or contaminated surfaces, known as contact transmission. Contact transmission is divided into two transmission ways:

Direct Contact Transmission: Direct contact transmission occurs when a person is infected directly from the source of infection. Examples include touching, kissing, sexual intercourse, and contact with infected bodily fluids such as blood, saliva, urine, feces, or respiratory secretions. Some infections can also be transmitted directly from animals to humans, through physical contact.

Indirect Contact Transmission: Indirect contact transmission occurs when the infection spreads through intermediaries from one individual to another, using hands, clothing, or objects, that are contaminated.

Droplet Transmission

Infectious agents present in droplets are spread when an infected person coughs, sneezes, talks, or breathes. Droplets then quickly fall to the ground within a short distance of about a meter due to their large size, rather than remaining suspended in the air. Droplet transmission is divided into two transmission methods:

Direct Droplet Transmission: Direct droplet transmission occurs when droplets containing infectious agents are inhaled directly by another person or meet their eyes or mucosal membrane.

Indirect Droplet Transmission: Indirect droplet transmission occurs when objects or surfaces become contaminated with droplets containing infectious agents, called fomites.

Airborne Transmission

In some cases, smaller respiratory particles known as droplets nuclei or aerosols can remain suspended in the air for extended periods and may travel farther distances, increasing the risk of airborne transmission. Droplets nuclei can spread in the air and

be inhaled by others. Then, they can penetrate the respiratory tract. Some examples of airborne infections are measles, chickenpox, tuberculosis, and COVID-19.

Bloodborne Transmission

Bloodborne transmission occurs when infectious agents are transmitted through contact with contaminated blood or blood products, such as needlestick, injections, or open wounds. Some examples of bloodborne infections are HIV, hepatitis B and C.

Insect-borne infection

Certain infections are transmitted to humans through the bites of infected insects such as mosquitoes, ticks, fleas, or flies. These insects serve as carriers of infectious agents and can introduce them into the human bloodstream. Insect-borne infection is not a significant concern in the health facilities today, especially in developed countries.

2.2.2 Transmission Risk Levels

Transmission risk levels refer to the probability of a disease spreading from one individual to another within a specific population or setting. The risk levels can vary based on the infectiousness of the disease and the mode of transmission. In epidemiology, the basic reproduction rate, often denoted as R_0, is used to quantify the transmissibility of a contagious disease within a susceptible population. R_0 represents the average number of secondary infections generated by a single infectious individual in a population where everyone is susceptible, and no measures are taken to control the spread of the disease. For instance, an R_0 value of 12 means that one infected person can potentially infect up to 12 others during the infectious period. If R_0 is greater than one, the disease is likely to spread within the population. Conversely, if R_0 is less than one, the disease is expected to eventually die out, as each case results in fewer than one additional infection, leading to a decline in transmission (Knobel et al., 2020).

The R_0 measure is a useful metric for understanding the potential spread of infectious diseases, but it is important to recognize that it is not a fixed value and can vary based on several factors. The R_0 value can differ significantly depending on the specific context of the outbreak and the population being studied. It can also be affected dramatically by the implementation of control measures and precautions. The R_0 calculation is based on the assumption of a homogeneous population, meaning that everyone has the same susceptibility to infection. However, populations are heterogeneous, with variations in immunity, age distribution, and underlying health conditions. For example, the disease Respiratory Syncytial Virus (RSV) primarily affects infants and young children aged up to four years, suggesting that the R_0 value may not accurately represent the transmission probability for RSV. Furthermore, some diseases are dynamic, changing with seasons and across different geographical locations. Given these complexities, R_0 should be interpreted cautiously and in conjunction with other epidemiological measures to provide a more comprehensive understanding of disease transmission dynamics (Delamater et al., 2019).

Since R_0 can only give us a rough idea of a disease's transmissibility, other epidemiological measures can be used, such as the effective reproduction number (R_e), which considers interventions and changes in population immunity over time. The R_e value takes into account a heterogeneous population, unlike the R_0 measure (Delamater et al., 2019).

However, the R_0 value can still give a rough estimate of the most and least contagious diseases found in history. It is also a useful measure for comparing the relative transmissibility of different infectious diseases. Some examples of major infectious diseases are presented in Table 2.1. It is challenging to find an estimate average of R_0 for each disease; hence, a range of R_0 is provided, reflecting variations observed across different outbreaks.

***Table 2.1**: The transmission route and basic reproduction rate R_0 of the major infectious diseases considered in this analysis.*

Disease	Virus	R_0
Measles [1]	Measles virus	12-18
Chickenpox [2]	Varicella-zoster virus	10-12
Smallpox [3]	Variola virus	3.5-6
Seasonal Influenza [4]	Influenza virus	1.4-4
Ebola [5]	Ebola virus	1.8
SARS [6]	SARS-CoV	2-4
COVID-19 (different variants) [7]	SARS-CoV-2	2-6

Note: Data from (Folkhälsomyndigheten, 2023)[1], (The National Immunisation Advisory Committee (NIAC), 2022)[2], (Gani & Leach, 2001)[3] , (Folkhälsomyndigheten, 2023)[4], (Wong et al., 2017)[5], (World Health Organization (WHO), 2003a)[6], (Folkhälsomyndigheten, 2023)[7].

Based on information from the World Health Organization (WHO), a brief description of the previously mentioned diseases is provided below, including details on their characteristics, symptoms, and modes of transmission.

Measles

Measles is a highly contagious viral disease, that can stay in the air for up to two hours. It typically starts with fever, runny nose, cough, red eyes, and sore throat, followed by a rash that spreads over the body. Incubation time is from 10 to 14 days. Measles can be serious, particularly in young children, pregnant women, and people with weakened immune system. Complications can include pneumonia, encephalitis (inflammation of the brain), and in severe cases, death. Measles can be prevented through vaccination. About 2.6 million deaths occurred annually prior to the introduction of measles vaccine in 1963. International effort successfully prevented 56 million deaths during 2000–2021 (World Health Organization (WHO), 2024).

Chickenpox

Varicella, also known as chickenpox, is a contagious disease caused by the varicella-zoster virus. The virus spreads easily through aerosols, particularly affecting individuals who have not been previously infected or vaccinated. People usually get infected with chickenpox at a young age, typically in nurseries and schools. Adults that can get infected tend to suffer more severe consequences than children. Chickenpox is characterized by an itchy rash that typically starts on the upper body, accompanied by fever and overall discomfort. In some cases, complications such as pneumonia or encephalitis (inflammation of the brain) may arise, leading to death. Chickenpox vaccine exist but is not common as measles vaccine (World Health Organization (WHO), 2016a).

Smallpox

Smallpox is a contagious disease that spreads through respiratory droplets during close contact with infected individuals showing symptoms of the disease. It can also be transmitted through touching contaminated surfaces. Incubation time is from seven to 17 days. It typically starts with high fever, fatigue, severe back pain, and occasionally abdominal pain and vomiting, followed by a rash filled with clear liquid. 30% of smallpox cases leads to death. In 1980, smallpox was completely eradicated thanks to vaccines (World Health Organization (WHO), 2016b).

Seasonal Influenza

Seasonal influenza is an acute respiratory infection that spreads through respiratory droplets or aerosol and often comes in seasonal outbreaks, typically during winter. Tropical countries can have influenza all year-round. Typically, individuals recover from fever and associated symptoms within a week without any medical care. Incubation time is only two days. Nonetheless, seasonal influenza can sometimes become a severe illness and even lead to death, especially to vulnerable populations such as infants, the elderly, pregnant women, and those with weakened immune system. Seasonal influenza can be prevented through vaccination, that must be taken every year (World Health Organization (WHO), 2023c).

Ebola

Ebola virus disease is an uncommon but serious disease in humans, that is originally from animals. The disease transmits through contact with body fluids, contaminated surfaces, or contact with infected animals. Incubation time is from two to 21 days. Ebola symptoms include fever, fatigue, and headache. The disease is fatal but can sometimes be prevented by vaccines (World Health Organization (WHO), 2023a).

SARS

Severe Acute Respiratory Syndrome, known as SARS, is a viral respiratory disease caused by the SARS coronavirus (SARS-CoV). SARS is an airborne disease that spreads through small droplets in the air. It firstly emerged during early 2003 in China and then spread to other countries. SARS symptoms are high fever, cough, shortness of breath, and difficulty breathing. Incubation time is from two to 10 days. SARS can

sometimes lead to respiratory failure and subsequently to death, particularly in older adults and individuals with weakened immune system. Public health measures have controlled the disease outbreak and prevented its spread (World Health Organization (WHO), 2003b).

COVID-19

Coronavirus disease, known as COVID-19, is a viral respiratory disease caused by the SARS-CoV-2. COVID-19 primarily spreads through respiratory droplets when an infected person coughs, sneezes, or talks, and can also spread by touching contaminated surfaces. It is also identified as an airborne disease that can spread in the air for long distances. COVID-19 symptoms are fever, cough, fatigue, shortness of breath, loss of taste or smell. Incubation time is from five to 14 days. COVID-19 can sometime develop causing severe respiratory distress, particularly in older adults and those with weakened immune systems. Vaccines for COVID-19 were developed to prevent the disease and reduce symptoms (World Health Organization (WHO), 2023b).

Summary of the risk assessment

Based on different transmission modes and R_0 values provided in Table 2.1, a risk assessment with respect to airborne transmission can be made for the major infectious diseases as the following:

Low-risk: Low-risk implies a low probability of disease transmission. A low-risk disease needs close distance contact to be transmitted. It can be transmitted through physical contact, body fluids, respiratory droplets, or fecal-oral route.

Moderate-risk: Moderate-risk implies a moderate probability of disease transmission. A moderate-risk disease is a disease transmitted through respiratory droplets transmission.

High-risk: High-risk implies a high probability of disease transmission. A high-risk disease is a disease transmitted through airborne transmission.

A risk assessment for the major infectious diseases: measles, chickenpox, smallpox, seasonal influenza, Ebola, SARS, and COVID-19 is presented in Table 2.2.

***Table 2.2**: Risk assessment with respect to airborne transmission of the major infectious diseases considered in this analysis.*

Disease	Transmission	Risk level
Measles	Aerosol	High
Chickenpox	Aerosol	High
COVID-19	Respiratory droplets and aerosol	High
SARS	Respiratory droplets	Moderate
Seasonal Influenza	Primarily respiratory droplets but also aerosol	Moderate
Smallpox	Respiratory droplets and body fluids	Low
Ebola	Body fluids	Low

This study focuses on the influence of ventilation for diluting airborne disease pathogens. With this in mind, airborne diseases are the main concern due to the high potential to reduce the transmission risk by adequate ventilation. Airborne diseases tend to be more contagious than those transmitted via respiratory droplets, since they can remain suspended in the air for longer periods and can be transmitted over longer distances, increasing their probability of infection.

In contrast, diseases transmitted through respiratory droplets and other routes are generally less prone to wide transmission. For example, smallpox, despite its relatively high R_0 value, is considered a low-risk disease because its transmission typically requires close, face-to-face contact. Similarly, while seasonal influenza can sometimes be an aerosol, it is primarily transmitted through respiratory droplets, classifying it as a moderate-risk disease.

Conversely, diseases like COVID-19 may not have very high R_0 value but still pose a significant risk due to ongoing uncertainties in their modes of transmission and control, especially since it is a relatively new disease. Therefore, it's essential to carefully classify diseases based on both factors, transmission mode and R_0 value.

2.3 Airborne Particles: Classification and Measurement

Airborne particles or aerosols refer to particles that carry biological agents such as bacteria, mold, and viruses. These particles remain suspended in the air for extended periods and can travel long distances. Airborne particles may cluster together, either as a single type or a combination of different types, to form viruses. Consequently, virus carrying particles usually have a size range larger than 0.3 µm, ranging from 0.3 µm to 10 µm (Chang et al., 2023).

To classify and count particles by size, a particle counter is often used. This device helps detect particles of specific sizes, assisting in the assessment of viral load, which refers to the concentration of viruses in the air. Viral load is quantified through

sampling techniques that involve detecting genetic material from specific viruses, as described by Alsved (2020) in her study on the transmission of infectious bioaerosols, which addresses sources, transport, and prevention strategies for airborne viruses and bacteria.

Viruses are microscopic infectious agents that can only replicate within living cells. They are smaller than bacteria and can infect a wide range of life forms, including animals, plants, fungi, bacteria, and even other viruses. Viruses are responsible for many diseases across these different types of organisms (Norén, 2016).

In addition to virus detection, air sampling can be used to measure the presence of microorganisms, such as bacteria and mold. Bacteria are single-celled microorganisms that can only be seen under a microscope, with sizes ranging from 0.25 to 100 µm. They can be found everywhere in every habitat, including soil, water, air, and within other organisms. Bacteria come in various shapes, with the most common being cocci (spherical), bacilli (rod-shaped), and spirilla (spiral-shaped). Depending on the type, bacteria can be beneficial, harmful, or neutral to other organisms, including humans (Norén, 2016).

Air sampling to detect microorganisms often uses a measurement called colony-forming units (CFUs), which quantifies viable bacteria or mold in the air. CFU represent the number of microorganisms capable of forming colonies on a growth medium like agar. In healthcare settings, controlling bacterial and fungal levels is critical for infection prevention. Air samples are exposed to agar plates, where bacteria form visible colonies. Each colony represents one CFU, and results are expressed as CFU per cubic meter of air (CFU/m^3) (Norén, 2016).

While CFU measurements are useful for determining microbial contamination, they do not directly correlate with the concentration of airborne particles. CFU quantifies viable microorganisms but does not measure the number of viral particles, which are often responsible for airborne infections. However, CFU values still provide insights into the overall microbial load, cleanliness, and infection risk in a space. Rooms with higher CFU values typically have a greater number of airborne particles, which may indicate poorer air quality (Norén, 2016).

2.4 Ventilation Principles

Understanding ventilation principles is essential for designing effective systems in healthcare facilities. Ventilation in these settings involves delivering fresh, clean air to indoor spaces while removing contaminated, polluted air, thereby maintaining indoor air quality, and creating a comfortable and healthy environment for patients, medical staff, and visitors. Within the health sector, the ventilation system must be carefully designed to protect the patient against airborne particles and maintain an adequate ventilation that meets the requirements and guidelines (Norén, 2016).

The three fundamental principles that describe how ventilation works are given in the WHO report, authored by Atkinson and others (2009).

- *Airflow rate*: the air exchange rates, which involve replacing a certain volume of indoor air with fresh outdoor air within a specified time. The rate of air exchange is typically measured in air changes per hour (ACH) or liter per second (l/s per person or area) (Atkinson et al., 2009).

- *Airflow distribution within zones*: the movement of air from the inlet to the outlet, which should ensure a proper, uniform air distribution. Air distribution patterns have three types: mixed airflow, displaced airflow, and parallel (unidirectional) airflow (Atkinson et al., 2009).

- *Airflow direction between zones*: the direction of air movement, typically from clean to dirty zones to carry out airborne particles (Atkinson et al., 2009).

2.4.1 Ventilation Methods

Proper and adequate ventilation can be achieved in different methods, depending on several factors such as climate, building design, occupancy patterns, and specific ventilation requirements. The ventilation methods can be categorized into natural ventilation, mechanical ventilation, and hybrid ventilation. The following descriptions are given in the WHO report, authored by Atkinson and others (2009).

1. *Natural ventilation system*: This system relies on passive airflow driven by natural forces such as wind, buoyancy, and temperature differences. In hospitals, natural ventilation can be beneficial in areas like waiting rooms, corridors, and non-sensitive patient areas. Since natural ventilation operates without mechanical systems, it is energy-efficient, relying instead on openings, architectural design, human behavior, and climatic conditions. It is particularly effective in mild climates and low-income countries, as its operational and maintenance cost is low. It can sometimes be unsuitable to use natural ventilation because it is difficult to control and predict (Atkinson et al., 2009).

2. *Mechanical ventilation system*: This system relies on mechanical systems, such as air handling unit, fans, and ducts to maintain adequate airflow. Hospitals typically use mechanical ventilation in critical areas such as surgical rooms, intensive care units, and isolation rooms where controlling the air exchange rates, temperature, and humidity is essential. Mechanical ventilation is easier to control and suitable for all climates but can be expensive to install. Mechanical ventilation can be categorized into three main types: exhaust-only systems, supply and exhaust systems, and supply and exhaust systems with heat recovery (Atkinson et al., 2009).

3. *Hybrid ventilation system*: This system combines elements of both natural and mechanical ventilation to optimize energy efficiency and indoor air quality. The hybrid ventilation operates by using sensors, that activate mechanical systems when the natural ventilation is not enough. The hybrid ventilation approach is especially useful when energy-effectiveness and flexibility is needed (Atkinson et al., 2009).

Natural ventilation is not a common practice in hospitals located in cold countries like the Nordic region, including Sweden. Instead, Swedish healthcare facilities rely entirely on mechanical ventilation systems, in order to ensure predictable operation, stable conditions and the possibility for energy recovery. However, there might be a potential for this to change in the future. As technology advances and the climate in Nordic countries becomes more temperate, there may be a shift towards incorporating natural ventilation methods in hospital settings. This possibility is supported by the report "Byggenskap och Vårdhygien (BOV)," authored by Svensk Förening för Vårdhygien (SFVH), which translates to The Swedish Association for Healthcare Hygiene (2016). The report cites the WHO publication "Natural Ventilation for Infection Control in Health-Care Settings" (2009), suggesting a growing interest in exploring natural ventilation solutions for healthcare facilities in Sweden.

2.4.2 Airflow Distribution Principles

Airflow distribution principles are essential for understanding how air is delivered and circulated within a space. Mixed, displaced, and parallel airflow are terms commonly used in the context of Heating, Ventilation, and Air Conditioning systems (HVAC) to describe different methods of air distribution within a space. The following descriptions are given by Norén report on operating theaters (2016).

1. *Mixed airflow*: The supply air is mixed with the room air before it reaches the occupied zone, resulting in a uniform temperature distribution. Mixed airflow systems are commonly used in spaces where thermal comfort and air quality are important, such as offices, classrooms, and commercial buildings (Norén, 2016).

2. *Displaced airflow*: The supply air is provided at a low level, allowing it to rise and displace the existing room air upwards. As the warm air rises, it gradually mixes with the room air, creating a vertical temperature gradient with cooler air at the lower levels and warmer air at the higher levels of the room. Displaced airflow systems are often used in high-ceiling spaces such as auditoriums and conference rooms (Norén, 2016).

3. *Parallel airflow*: The supply air is introduced along one side of the room and extracted from the opposite side, creating parallel airflow moving in opposite directions. Parallel airflow is suitable for areas where maintaining a consistent air quality is critical such as laboratories, surgery rooms, and cleanroom facilities (Norén, 2016).

Patient rooms in Sweden typically adhere to the mixed airflow distribution principle, as outlined in the report "Byggenskap och Vårdhygien (BOV)," written by the SFVH (2016).

2.4.3 Airflow Direction Principles

Airflow direction, the direction of air movement, is an important principle to control disease flow between rooms. Therefore, ventilation systems in healthcare facilities are designed in relation to other rooms using positive, negative, and balanced pressure

ventilation systems. The following descriptions are given by Norén report on operating theaters (2016) and the WHO report by Atkinson and others (2009).

1. *Positive pressure ventilation*: Positive pressure ventilation is typically used in surgeries and laboratories. It works by maintaining a higher supply airflow compared to the exhaust airflow, ensuring that air flows out of the critical areas rather than allowing air from adjacent rooms to enter. This helps prevent the transfer of contaminants into these sensitive spaces (Norén, 2016).

2. *Negative pressure ventilation:* Negative pressure ventilation is typically used in isolation rooms. It works by maintaining a higher exhaust airflow compared to the supply airflow, ensuring that air is drawn into the room rather than escaping into adjacent spaces. This helps prevent the spread of airborne pathogens to neighboring areas (Atkinson et al., 2009).

3. *Balanced ventilation*: Balanced pressure ventilation is typically used in general rooms, administrative offices, and other non-critical zones within healthcare facilities. It works by maintaining a neutral pressure while ensuring adequate air change rates (Atkinson et al., 2009).

Each of the positive, negative, and balanced ventilation systems serves a specific purpose in maintaining air quality, controlling airborne contaminants, and ensuring the safety and comfort of patients, medical staff, and visitors. Normal single patient rooms typically maintain balanced pressure relative to adjacent rooms, while maintaining positive pressure relative to the restroom found within the room. Conversely, isolation rooms typically maintain negative pressure relative to adjacent rooms to prevent infections transmission (Svensk Förening för Vårdhygien (SFVH), 2016).

2.4.4 Ventilation Assessment

The ventilation design in hospitals is a complex work that requires interdisciplinary collaboration among architects, engineers, infection control specialists, and healthcare professionals to create efficient and healthy indoor environments for occupants, particularly patients, medical staff, and visitors. The design must meet specific requirements to effectively prevent the transmission of infections and create a healthy indoor environment defined by appropriate air quality, temperature, humidity, and noise level. Additionally, it should address sustainability, energy efficiency, operational cost, and space required for the ventilation system (Kari Solem et al., 2023.

Given the sensitivity of hospitals, it is crucial to conduct a thorough ventilation assessment after construction completion to ensure that the ventilation system meets the requirements and to plan for future maintenance. This assessment typically involves reviewing documentation, inspecting the building, and conducting measurements. Some of the commonly taken measurements that can be done are air velocity test, room pressure test, airflow rate test, and functional control test. In Sweden, a mandatory ventilation inspection (OVK) is typically required at regular

intervals for certain types of buildings. Typically, Swedish hospitals undergo an initial inspection immediately after the construction completion, followed by recurrent OVK inspections every three years (Nyberg, 2024). By conducting a thorough ventilation assessment, healthcare facilities can identify and address potential risks to indoor air quality and create a healthier environment for all occupants.

2.5 Guidelines and Recommendations

Guidelines and recommendations for requirements regarding hospital ventilation and air quality are essential for maintaining a healthy environment, particularly in healthcare settings where the risk of infectious disease transmission is high. However, these guidelines can vary between various health organizations and experts, reflecting differences in healthcare practices, climate, economic conditions, and local epidemiological factors across countries and regions. For instance, standards that are acceptable in one country may not meet those in another. This study examines guidelines from a range of sources, including The Swedish Program for Technical Standards (PTS), The Swedish Association for Healthcare Hygiene (SFVH), The World Health Organization (WHO), The American Centers for Disease Control and Prevention (CDC), The British National Health Service (NHS), and The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA). The parameters explored in this section include guidelines for airflow rate, CO_2 concentration and CFU concentration. It is important to note that there is currently no available guideline limit for the permissible number of particles in the air.

2.5.1 Airflow Rate

Guidelines for the required airflow in hospitals all emphasize that the dilution of particle concentration through ventilation decreases the risk of airborne infection transmission. However, identifying these guidelines can be challenging due to variations in specificity among different organizations such as the CDC and WHO. The WHO provides general recommendations on ventilation standards that apply internationally, offering broad guidelines applicable across various healthcare settings. In contrast, the CDC offers more detailed and specific airflow requirements for different room types within healthcare facilities. This disparity in specificity between the CDC and WHO guidelines complicates the comparison and interpretation of airflow requirements.

Additionally, there exists variability among different guidelines for the recommended airflow rates to maintain low infection risk. To achieve harmonization among these diverse guidelines and recommendations, it is essential to first identify their similarities and differences to determine the least and most stringent guidelines among them. In other words, to establish a reasonable minimum and maximum airflow threshold to consider. Some of the national and international guidelines and recommendations for a patient room are presented in Table 2.3.

***Table 2.3**: The recommended air change rate for a typical patient room.*

Source	Organization name	Recommended air change rate [ACH]	Additional notes
PTS[1]	The Swedish Program for Technical Standards	Nearly 2	Equivalent to 25 l/s for 49 m^3 room volume
SFVH[2]	The Swedish Association for Healthcare Hygiene	6	-
WHO[3]	The World Health Organization	6	Equivalent to 40 l/s for 24 m^3 room volume
CDC[4]	The American Centers for Disease Control and Prevention	4-6	4 ACH when supplemental heating and/or cooling systems are used, 6 ACH otherwise
NHS[5]	The British National Health Service	6	Natural ventilation is sometimes used in patient rooms
REHVA[6]	Federation of European HVAC Associations	4	-

Note: Data from (Program för Teknisk Standard (PTS), 2023)[1], (Svensk Förening för Vårdhygien (SFVH), 2016)[2], (World Health Organization (WHO), 2021)[3], (Sehulster et al., 2019)[4], (National Health Service (NHS), 2021)[5], and (REHVA, 2020)[6].

The recommended air change rates provided in Table 2.3 may originate from guidelines specifying different room sizes and units. To ensure comparability, the airflow values from various guidelines are interpreted and converted into the unit of air changes per hour (ACH). For instance, the PTS recommends an airflow rate of 25 l/s for a room size 18 square meters (m^2) with a height of 2.7 meters (m), while the CDC recommends an airflow rate of 40 l/s for a room size of 4 m by 2 m with a height of 3 m. These values are transformed into air changes per hour using Equation 2.1. Equation 2.2 can be used to transform the unit air changes per hour to liters per second.

$$\text{Air change rate (ACH)} = \text{Ventilation rate } \left(\frac{\text{l}}{\text{s}}\right) \times 3600\left(\frac{\text{s}}{\text{hr}}\right) \times \frac{0.001\left(\frac{\text{m}^3}{\text{s}}\right)}{\text{Room volume}(\text{m}^3)} \quad (2.1)$$

***Equation 2.1**: The equation for calculating the air change rate per hour (ACH) based on the ventilation rate (l/s).*

Or,

$$\text{Ventilation rate } \left(\frac{\text{l}}{\text{s}}\right) = \text{Air change rate (ACH)} \times \text{Room volume}(\text{m}^3) \times \frac{1000\left(\frac{1}{\text{m}^3}\right)}{3600\left(\frac{\text{s}}{\text{hr}}\right)} \quad (2.2)$$

Equation 2.2*: The equation for calculating the ventilation rate (l/s) based on the air change rate per hour (ACH).*

It is important to note that the PTS recommendation of 25 l/s is intended for patient rooms accommodating one to two patients. If there are more patients in the room, a higher airflow rate is required, specifically 10 l/s for each patient. For example, a patient room with three patients would need an airflow rate of 30 l/s (Västerbottens Läns Landsting, 2014). In contrast, the CDC recommendation of 6 ACH is designed for a single patient room, accommodating only one patient (Sehulster et al., 2019).

The less strict guideline among those presented in Table 2.3 is the PTS guideline, recommending 2 ACH, while the strictest ones suggest 6 ACH. PTS stands for Program för Teknisk Standard (Program for Technical Standard), functions both as an IT system and a network for sharing experiences related to healthcare construction in Sweden. In the Swedish context, PTS represents the real estate sector, and hospitals in Sweden typically adhere to PTS recommendations when designing their facilities. Conversely, SFVH, which stands for Svensk Förening för Vårdhygien (The Swedish Association for Healthcare Hygiene), represents the perspective of healthcare experts. SFVH argues that the recommended air change rate 2 ACH is inadequate and suggests approximately an air change rate of 6 ACH. This indicates that the current guideline of 2 ACH may not be sufficient to prevent airborne transmission, especially in the wake of the COVID-19 pandemic that occurred between 2019 and 2021, where the importance of preventing airborne transmission became even more critical. Furthermore, it is important to consider that air change rates lower than 2 ACH increase the risk of airborne disease transmission, as indicated in the WHO report "Natural ventilation for infection control in health-care settings" (2009).

Given the knowledge of healthcare experts in healthcare risks and the role of ventilation, as well as the proficiency of real estate in designing energy-efficient ventilation systems within space constraints, it is crucial to strike a balance between these perspectives for effective implementation of guidelines.

Airborne precaution room, as described by WHO, or airborne infection isolation room, as described by the CDC, is a room for patients who require airborne isolation precautions. This type of room is typically used in healthcare settings to prevent the spread of infectious diseases or to protect patients who have weakened immune system (Atkinson et al., 2009). The recommended air change rates for an isolation room are presented in Table 2.4, providing a reference for the maximum air change rate applicable to all patient rooms in general. The air change rate for isolation rooms is provided to indicate the upper limit of airflow rates recommended for these rooms.

***Table 2.4**: The recommended air change rate for a typical isolation room.*

Source	Organization name	Recommended air change rate [ACH]	Additional notes
SFVH[1]	The Swedish Association for Healthcare Hygiene	12	-
WHO[2]	The World Health Organization	12	Equivalent to 80 l/s for 24 m^3 room volume
CDC[3]	The American Centers for Disease Control and Prevention	6-12	12 ACH for new construction and 6 ACH for existing construction
NHS[4]	The British National Health Service	10	-
REHVA[5]	Federation of European HVAC Associations	6-12	-

Note: Data from (Svensk Förening för Vårdhygien (SFVH), 2016)[1], (World Health Organization (WHO), 2021)[2], (Sehulster et al., 2019)[3], (National Health Service (NHS), 2021)[4], and (REHVA, 2020)[5].

Most of the guidelines recommend an air change rate of 12 ACH for an isolation room. These guidelines offer an insight into an estimate of the maximum air change rate suitable for a typical patient room, in general. A higher air change rate than 12 ACH is not recommended by the SFVH, as further increases have minimal impact on reducing airborne disease transmission (Svensk Förening för Vårdhygien (SFVH), 2016).

2.5.2 Carbon Dioxide Concentration

Carbon dioxide (CO_2) concentration in indoor environments is a typical used indicator of air quality, particularly because it reflects the adequacy of ventilation. CO_2 levels are measured in parts per million (ppm). High levels of CO_2 indicate poor ventilation, which can lead to decreased cognitive function, decreased productivity, and in extreme cases, more serious health effects.

In the atmosphere, CO_2 naturally exists at a concentration around 400 ppm. However, in indoor environments, CO_2 levels increase due to human respiration, activities, and rate of ventilation. Although CO_2 is not toxic at concentration found in most indoor environments, high levels can lead to health risks (Cabovská et al., 2022).

As per guidelines from Folkhälsomyndigheten (The Swedish Public Health Agency) (2014), CO_2 concentration should ideally not exceed 1000 ppm under normal conditions. Comparing the average CO_2 concentration in a room to this threshold allows for the assessment of indoor air quality and potential health risks.

2.5.3 Colony-Forming Units (CFUs)

It is crucial to establish CFU concentration limit. as a high CFU value indicates a high number of microbial airborne particles present in the air, as discussed in Section 2.3. However, no specific limit value for CFU concentration is clearly identified; CFU values may vary depending on the type of area within the hospital and local regulations or guidelines. Currently, specific guidelines are available only for surgical rooms. Below are some general guidelines for CFU concentration, obtained from different sources:

1- For infectively sensitive surgery, the CFU limit should be less than 10 CFU/m^3 of air. Furthermore, a mean value of less than 5 CFU/m^3 is recommended to ensure that the limit value 10 CFU/m^3 is achieved (Norén, 2016).

2- For non-infectively sensitive surgery, the CFU limit should be less than 100 CFU/m^3 of air (Norén, 2016).

3- For facility rooms outside surgical areas, such as corridors, the CFU limit should be less than 200 CFU/m^3 of air (Joelsson, 2015).

4- The recommended CFU values for non-industrial indoor environments can be classified according to a study about biological particles in indoor environments (Wanner et al., 1993), as shown in Table 2.5:

Table 2.5*: Classification of CFU range limit values.*

Classification	**CFU/m^3**
Very low	0-25
Low	25-100
Intermediate	100-500
High	500-2000
Very high	>2000

Given the guidelines and recommendations regarding CFU limit values presented earlier, establishing a definitive CFU limit value for patient rooms is challenging. Patient rooms fall under hygiene class 2 classification, with hygiene class 1 being the least stringent and class 3 the most stringent (Joelsson, 2015). Therefore, aiming for a value within the intermediate range is advisable for patient rooms.

3
Methodology

3.1 Input Data

To accurately assess the airflow requirements, it is essential to consider diseases with different levels of risk and transmission potential. For this study, measles, a high-risk disease, and seasonal influenza, a moderate-risk disease, have been selected to represent different risk levels when determining the adequate airflow rate in a hospital's patient room.

The measles disease has been selected due to its high contagious probability. Since measles can remain airborne for several hours, even after an infected person has left the room, significantly increasing the risk of transmission in enclosed spaces with inadequate ventilation. Although measles vaccines have significantly reduced the incidence of the disease, it has not been fully eradicated, and outbreaks can still occur, particularly in areas with lower vaccination rates or among unvaccinated individuals. According to Folkhälsomyndigheten (2024b), measles remains a common infection in low-income countries such as Africa and Asia. In Sweden, where measles is considered eradicated, a few cases are still imported annually often through internation travels.

Folkhälsomyndigheten (2018) reported a measles outbreak in Gothenburg during 2017-2018, where 28 people were infected. These outbreaks are not only a thing of the past but continue to happen. There is an ongoing warning in Sweden about the importance of measles vaccination, especially for small children before traveling in Europe. This is due to the recent increase in measles cases in some European countries, particularly the United Kingdom, during 2023 and 2024 (Folkhälsomyndigheten, 2024a). This demonstrates that even if measles is completely eradicated in one country, cases can still occur due to international travel. Given these factors, investigating measles transmission and its implications for healthcare settings is of significant interest within the medical field.

In addition to that, the COVID-19 pandemic resulted in setbacks for immunization and vaccination plan held by WHO. Due to the setbacks, millions of children were not vaccinated enough to reach immunization against measles. Therefore, there is an ongoing plan to regain progress and eradicate measles globally. Until then, there will always be a risk of measles outbreak everywhere in the world (Minta et al., 2023).

The seasonal influenza disease has been selected for this study for several reasons. Seasonal influenza can be unpredictable in terms of its severity and variability. Although it is usually considered a mild disease, it can become severe and even fatal for some vulnerable individuals. Since seasonal influenza occurs annually with different strains and variants, predicting the severity of each season and the effectiveness of vaccines is challenging. This unpredictability can lead to seasonal

epidemics that place considerable pressure on medical staff and hospitals (World Health Organization (WHO), 2023c).

Globally, seasonal influenza affects about a billion people each year. Of these, approximately three to five million cases become severe, requiring medical intervention, and resulting in 290,000 to 650,000 deaths annually. A vaccine for seasonal influenza is available and recommended for vulnerable populations, such as the elderly, children, pregnant women, and those with weakened immune system. Despite the availability of the vaccine, the number of cases remains alarmingly high, suggesting issues with either vaccine efficacy or vaccination coverage (World Health Organization (WHO), 2023c).

Regarding the transmission mode, seasonal influenza spreads easily among people in crowded places through respiratory droplets. When an infected person coughs or sneezes, droplets are released into the air, potentially reaching other people or surfaces (World Health Organization (WHO), 2023c).

Seasonal influenza is compared with measles in this study to evaluate ventilation airflow conditions. By contrasting a moderate-risk disease like seasonal influenza with a high-risk disease like measles, the study offers valuable insights into how ventilation influences the transmission of these diseases.

This study examines a range of airflow rates with a focus on ventilation. Since the study involves both field measurements and modeling, various airflow rates are examined in each method. However, the field measurements are limited to three specific airflow rates, 15 l/s, 30 l/s, and 45 l/s due to technical adjustment constraints. In the modeling, a broader range of airflow rates, from 0 l/s to 80 l/s (0 to 6 ACH), is used. This extended range is included to demonstrate the effects of ventilation at both extremely low and high airflow rates. Additionally, it aims to include all guidelines and recommendations regarding required airflow rates for a normal patient room, as discussed earlier in Section 2.5.1. Modeling for higher airflow rates up to 12 ACH, which are relevant for isolation rooms, is not necessary, as the focus is on normal patient rooms.

3.2 Field Measurement

This study involves a comprehensive investigation into the effectiveness of various ventilation rates on air quality within a hospital setting. The research focuses on examining the impact of different airflow rates on particle and CO_2 concentration decay, using both field measurements and modeling approaches. While CO_2 concentration is not directly linked to particle concentration or viral load in the air, it serves as an indirect indicator of air quality and the accumulation of airborne particles. The following subsections provide detailed descriptions of the field measurement site, the experimental procedures, and the equipment and instruments used for measurements.

3.2.1 Kungälv Hospital

The field measurements were conducted at Kungälv Hospital, located in Kungälv, north of Gothenburg, Sweden. Established in 1964, Kungälv Hospital is a part of the Västra Götaland Region's healthcare system that provides various medical services to the residents of Kungälv municipality and surrounding areas. Due to the growing population in Gothenburg and the increasing proportion of elderly individuals, the demand for healthcare has significantly increased. As a result, between 2016 and 2020, two entirely new care buildings were constructed to replace the hospital's old patient wards. Completed in 2020, the new buildings accommodate patient rooms for various medical disciplines including surgery, orthopedics, urology, medicine, and geriatrics. The patient room examined in this study is one of the 280 single patient rooms designed specifically for somatic care (Skanska, 2024).

The building is built with high quality and designed down to the smallest detail. Following many inspections, it has attained preliminary certification at the gold level under the Miljöbyggnad certification system, representing the highest standard of sustainability. Miljöbyggnad is a certification system for sustainable buildings that assesses them across sixteen different indicators including energy use, indoor environment, and material quality, ensuring that the building promotes both human well-being and environmental health. To meet these high standards, all rooms are tightly sealed to minimize air leakage and feature an optimal ventilation system, enhancing both energy efficiency and indoor air quality (Skanska, 2024).

3.2.2 Experimental Procedure

The measurements were conducted in patient room 18, located on the fifth floor of the emergency department. Despite the department being non-operational since its construction due to staff shortages, the rooms are fully equipped, with the ventilation system fully operational as if the room were in active use. The patient room used for the measurements occupies a total area of 23 m^2 with a height of 2.7 m, including the bathroom area. Excluding the bathroom area of 5.5 m^2, the room’s volume considered is 47 cubic meters (m^3). A drawing of the patient room and adjacent areas are illustrated in Figure 3.1.

Figure 3.1*: A schematic birds-eye view of the patient room relative to the corridor and bathroom.*

The ventilation system used in the patient room is a controlled mechanical system based on mixed air ventilation principle. The supply air device is positioned centrally in the ceiling, while the exhaust air device is in the bathroom ceiling above the toilet. To facilitate airflow transfer to the exhaust device, a ventilation grill is installed in the door separating the room from the bathroom. Additionally, the room maintains a balanced air pressure differential relative to the corridor and a positive air pressure differential relative to the bathroom.

The measurements for this study were conducted on March 14 and 15, 2024, during a typical rainy winter day in Gothenburg. Measurements were carried out under different conditions: on March 14, airflow rates of 15 l/s and 45 l/s were examined, and on March 15, the airflow rate of 30 l/s was examined. The number of people present in the room also varied, with two individuals on the first day and three on the second.

The primary aim of the measurements is to assess the decay of particle and CO_2 concentration resulting from air ventilation at two different locations within the room: adjacent to the patient's bed and at the room's center. These locations were selected to mirror areas where staff and visitors might typically be present. Accordingly, two particle counters and two CO_2 monitors were strategically placed within the room. Each respective device was positioned at both measurement point 1 (MP1), next to the patient's bed, and measurement point 2 (MP2), in the center of the room, as illustrated in Figure 3.2.

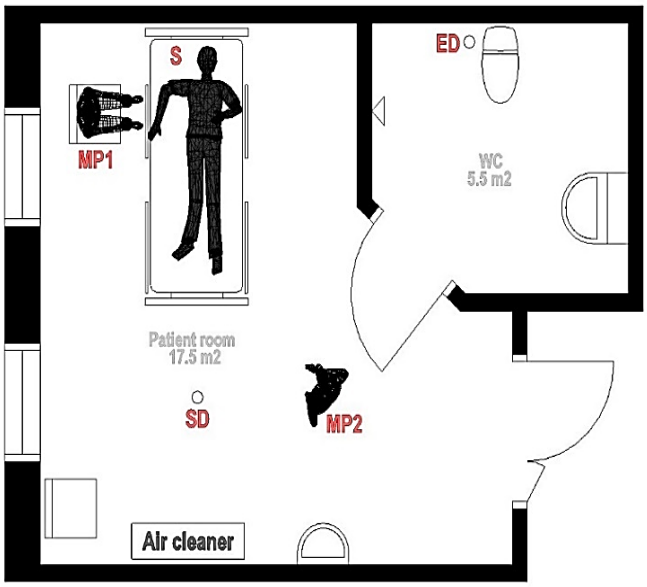

***Figure 3.2**: A schematic birds-eye view of the measurement point locations.*

At position MP1, an air sampling device was installed to measure the concentration of CFU in the air. The device operated at an airflow rate of 101 l/min for ten minutes. This air sampling procedure was repeated across multiple experiments, after which the agar plates were incubated for several days to allow bacterial colonies to develop. On the opposite side of the room, an air cleaner was introduced, as shown in Figure 3.2, to assess its impact on the reduction of airborne concentration. The supply air device (SD) and the exhaust air device (ED) are also depicted in Figure 3.2.

Since the experiment was conducted in an environment without actual patients and staff, it was necessary to simulate the release of particles and CO_2. To simulate a cough/sneeze event by an infected patient, particles were released directly above the patient's head at point S, using powder smoke (Björnax Smoke Products). Additionally, a CO_2 releaser was used at the same location to mimic patient breathing and allow for the monitoring of CO_2 concentration decay.

The patient room serves as a vital space within the healthcare facilities, where patients receive medical care, treatment, and rest during their stay. Given that the patient room used for the experiment is designated for the emergency department, it typically accommodates patients for short durations. Although the room does not adhere to strict regulations regarding Airborne Infection Isolation (AII), they are still standard protocols to follow for cleaning and disinfection to prevent the spread of contamination.

Patients admitted to the emergency department often present with burns, skeletal injuries, or have undergone accidents, placing them at a heightened risk of infection. Consequently, it's necessary to protect such patients, as they may be particularly susceptible to further infection. The patient room used in this study, presented in Figure 3.3, is designed to allow airflow adjustments, with settings ranging from 15 l/s to 45 l/s. In accordance with Swedish healthcare standards that adhere to PTS

guidelines, the room is typically set to an airflow rate of 25 l/s to meet the minimum ventilation requirement for patient rooms accommodating one to two patients.

***Figure 3.3**: A picture of the patient room used for the field measurements (2024).*

This study involved testing at three different airflow rates: 15 l/s, 30 l/s, and 45 l/s. For each airflow rate, three separate experiments were conducted, labeled as Exp1, Exp2, and Exp3, resulting in a total of nine experiments. However, considering the presence of measurement instruments at two distinct locations (MP1 and MP2), the total number of data-sets expanded to 18. A detailed description of the experiments is provided in Table 3.1, which outlines the use of a mixing fan and an air cleaner during each experiment.

***Table 3.1**: The description of the experiments.*

Experiment (Exp)	Mixing fan	Air cleaner
1	on	off
2	off	off
3	off	on

In each experiment, a consistent amount of CO_2 gas and powder smoke was released into the air. In Experiment 1, two mixing fans were used to ensure thorough air mixing before releasing the CO_2 gas and powder smoke. In Experiment 2, the mixing fans were not used to observe the present airflow conditions. In Experiment 3, an air cleaner was activated before introducing the CO_2 gas and powder smoke to facilitate comparison with the other experiments.

After completing the third experiment for each specific airflow rate, an Impactor device was activated, and agar plates were set up to assess the CFU in the air. Two separate tests were conducted with the Impactor: one while the air cleaner was in operation and another without it. This approach aimed to evaluate the effectiveness of

the air cleaner in reducing particle concentration and to assess how different airflow rates impact the reduction of these particles.

Prior to each experiment, the air was neutralized by opening the door to allow the particle and CO_2 concentration to return to normal levels. This step ensured a consistent starting point for each experiment and minimized any residual effects from previous tests.

3.2.3 Measurement Equipment

For the field measurements, five measuring equipment of three different types were used: two TSI AeroTrak Handheld Particle Counters, two Rotronic CP11 handheld monitors, and a Klotz Impactor FH6. Additionally, an air cleaner prototype developed within the Clean Surge Air project was used to assess the effect of increased airflow on particle concentration decay. The following subsections provide a brief overview of these tools.

3.2.3.1 TSI AeroTrak® Handheld Particle Counter

The TSI AeroTrak® Handheld Particle Counter Model 9303, as shown in Figure 3.4, is a device designed for the quantification of airborne particles, categorizing them into various size ranges, from 0.3 µm to 25 µm. The device generates a flow rate of 2.83 liters/minute (l/min) and can store up to 1,500 sample records of particle count data. Subsequently, the data can then be downloaded using a USB port and analyzed using dedicated software tailored for interpretation. Additionally, if necessary, the data can be printed for documentation purposes (TSI, 2024).

Figure 3.4*: The TSI AeroTrak® Handheld Particle Counter Model 9303 (TSI, 2024).*

Characterized by its user-friendly interface and small screen display, the device offers ease of operation and readability. While similar instruments exist, the model 9303 distinguishes itself by being lightweight and cost-effective without compromising on accuracy. The device is usually used to trace particle contamination sources,

distinguish between clean and contaminated areas, identify filter leaks, and evaluate air quality. This instrument serves as a valuable tool for various applications related to environmental monitoring and quality control (TSI, 2024).

3.2.3.2 Rotronic CP11 Handheld monitor

The Rotronic CP11 handheld monitor, as shown in Figure 3.5, is a device designed for measuring temperature, humidity, and CO_2 concentration. In addition to these primary functions, it has the capability to calculate the dew point and wet bulb temperature autonomously. Similar to the AeroTrak device, the Rotronic device can record measurements, with its memory capable of storing up to 18,000 data records. This data can then be downloaded using specialized software for further analysis (Rotronic, 2024).

Figure 3.5*: The Rotronic CP11 handheld monitor (Rotronic, 2024).*

Moreover, the Rotronic device offers additional analysis functions, including identifying maximum, minimum, and average values. All this data is conveniently displayed on a compact screen. Despite its seemingly simple design, the device is highly capable and can assist in assessing indoor air quality and monitoring for potential leakage issues. Its multifunctionality makes it a valuable tool for various applications related to environmental monitoring and quality control (Rotronic, 2024).

3.2.3.3 Klotz Impactor FH6

The Klotz Impactor FH6, as shown in Figure 3.6, is a device designed for air sampling and microbiological testing to assess microbial growth in the air. The process begins by carefully placing agar plates, which are small dishes filled with a gel-like nutrient substance derived from seaweed, inside the device and setting the appropriate airflow and recording time parameters. Agar serves as a nutrient source for the growth of microorganisms such as bacteria, mold, and yeast. To ensure accurate results, it's essential to handle the agar plates with care, working on disinfected surfaces and using disinfected hands. The measurement process involves

drawing air into the device through a circular fan located at the top, using a specified airflow. Microorganisms present in the air are then deposited onto the agar plates, where they begin to grow. After sampling, the agar plates are transferred to a suitable environment in the laboratory to allow the bacteria to grow and form visible colonies. These colonies are then counted and expressed in units of CFU/m^3. The Klotz Impactor FH6 finds widespread use across various settings, including hospitals, laboratories, and industrial facilities, for assessing the cleanliness level of the air and monitoring microbial contamination (KLOTZ, 2024).

***Figure 3.6**: The Klotz Impactor FH6 (KLOTZ, 2024).*

3.2.3.4 Air Cleaner

The air cleaner, shown in Figure 3.7, is a device designed as a prototype for research and experiments within the Clean Surge Air project at Chalmers University in Gothenburg, Sweden. However, a similar model, by the brand Light Air, is available commercially for sale to improve indoor air quality by effectively removing contaminants such as dust, pollen, and other airborne particles.

***Figure 3.7**: The air cleaner prototype with CellFlow DEP technology (2024).*

The air cleaner uses CellFlow DEP technology, an advanced air purification method that combines traditional filtration with electrostatic precipitation and dielectric

polarization. As air enters the purifier, it passes through an ionizer that negatively charges airborne particles like dust, pollen, smoke, and microorganisms. These charged particles then encounter the positively charged EcoPrecision filter, which effectively traps both large and ultrafine particles, ensuring thorough air cleaning. By combining these advanced technologies, CellFlow DEP air purifiers provide superior performance, capturing a wide range of pollutants more efficiently while maintaining energy efficiency and low noise levels (LightAir, 2024).

The CADR (Clean Air Delivery Rate) value is a standard measure of an air cleaner's capacity, indicating the volume of clean air delivered per hour in cubic meters (m^3/hr). The air cleaner used in this study was operated at a high CADR value of 1400 m^3/h (approximately 30% of maximum setting).

3.3 REHVA Tool Calculations

Model calculations are performed to mirror the baseline conditions observed during field measurements at Kungälv Hospital. These calculations utilize the REHVA COVID-19 Ventilation Calculator V2.1, developed in 2020 by Prof. Jarek Kurnitski and REHVA. The calculator tool is designed to address the potential spread of COVID-19 through HVAC systems in buildings. Over recent years, this calculator tool has undergone multiple updates to assist building managers, engineers, and health professionals in estimating infection risks based on various HVAC parameters and operational conditions. Moreover, the REHVA calculator tool can be adapted to estimate the probability of infection for other diseases by adjusting relevant parameters within the Wells-Riley equation, upon which it is based. Key parameters for consideration include the quanta emission rate, inactivation rate, deposition rate, and breathing rate (REHVA, 2022b).

3.3.1 Introduction to Wells-Riley Equation

The concept of airborne transmission was initially described by William F. Wells in 1934, followed by Riley and O'Grady in 1961. The Wells-Riley equation, however, was not formally presented until 1978 (Atkinson et al., 2009). The equation was introduced to study measles outbreaks in schools and was developed to quantify the risk of airborne transmission of infectious diseases. It considers factors such as ventilation rate, infectiousness of the source, duration of exposure, and susceptibility of individuals (Park & Song, 2023).

The Wells-Riley equation is challenging to use because it depends on specific assumptions and complex mathematical calculations. It is primarily based on the quanta emission rate, which refers to the number of infectious airborne particles needed to infect an individual. However, determining the quanta emission rate involves considerable uncertainty since the values can vary widely across different disease outbreaks (REHVA, 2022b). Despite this complexity, the Wells-Riley equation is a valuable tool for estimating relative infection risks, rather than exact risks. This estimation helps in comparing the likelihood of airborne disease transmission and the efficiency of public health measures (Shen et al., 2021). The equation is detailed in Equation 3.1.

$$P = 1 - e^{-\frac{Iqpt}{Q}} \quad (3.1)$$

Equation 3.1*: The basic form of Wells-Riley equation.*

Where,

- P is the probability of infection for a susceptible individual [-],
- I is the number of infectious individuals [-],
- q is the quanta emission rate [quanta/hr],
- p is the breathing rate of a susceptible person [m^3/hr],
- t is the duration of exposure [hr], and
- Q is the room ventilation rate [m^3/hr].

Equation 3.1 represents the basic version of the Wells-Riley equation. In practice, additional factors such as the use of mask usage, filtration efficiency, and air cleaning devices can be included to refine the estimation of infection risk (Shen et al., 2021). In this study, a modified version of the Wells-Riley equation, which includes a detailed calculation for the room ventilation rate, denoted as Q, is presented in Equation 3.2. The modified equation also includes additional removal mechanisms beyond ventilation, such as deposition rate, inactivation rate, and the efficacy of air cleaners.

$$Q = V\left(\lambda_{vent} + k_{deposition} + k_{inactivation}\right) + CADR \quad (3.2)$$

Equation 3.2*: The modified form of Wells-Riley equation including additional removal mechanisms.*

Where,

- V is the volume of the room [m^3],
- λ_{vent} is the fresh air supply rate [1/hr],
- $K_{deposition}$ is the deposition rate of particles to surfaces [1/hr] ,
- $K_{inactivation}$ is the inactivation rate of the virus [1/hr], and
- CADR is the clean air delivery rate from air cleaning devices [m^3/hr].

The Wells-Riley equation is based on several critical assumptions. First, while there is no direct evidence that increasing ventilation reduces the infection risk, the equation assumes that improved ventilation will reduce the concentration of pathogens in the air, thereby reducing the potential for infection. Second, the presence of pathogens in the air does not necessarily lead to infection, as people vary in their susceptibility to diseases, the Wells-Riley equation assumes uniform susceptibility among all individuals. Nonetheless, the equation incorporates additional factors, such as the virulence of the pathogen and the dose required to cause infection (Atkinson et al., 2009).

Similarly, the REHVA tool simplifies its approach with key assumptions. It assumes that the air in a room is well-mixed, ensuring a uniform concentration of particles throughout the room (Mikszewski et al., 2022). It also assumes that the risk of infection is directly proportional to the amount of virus inhaled, following a linear relationship (D. Müller et al., 2021). These assumptions are designed to reduce the tool's complexity.

3.3.2 Key Parameters

In the default case of the REHVA tool, which uses the REHVA calculator tool, the room dimensions are set at 17.4 m² in area and 2.7 m in height, resulting in a total volume of 47 m³. Two scenarios are considered, involving two individuals: the first scenario includes one infected person and a visitor, while the second scenario involves one infected person and a medical staff member. The exposure duration is eight hours for the visitor and one hour for the medical staff member. During these periods, the infected individual is actively speaking for 10% of the time and is silent for the rest. The tool does not include any infection prevention or control measures such as masks or vaccines, and all the air supplied to the room is drawn directly from outside without any recirculation Additionally, for the purpose of the present project, an air cleaner with a CADR value of 1400 m^3/hr is included in the REHVA tool, similar to the setup in the field measurements.

A key variable in the Wells-Riley equation is the quanta emission rate, noted earlier in Section 3.3.1. This rate is represented by q and is measured in quanta per hour (quanta/hr). By definition, one quantum is the dose of airborne disease carrying particles that is required to infect 63% of susceptible individuals. The specific value of q varies depending on both the type of disease and the activities being performed (REHVA, 2022b), as detailed in Table 3.2. The values listed in Table 3.2 are based on the 50th percentile from a probability distribution, reflecting average conditions.

***Table 3.2**: The quanta emission rate values for measles and seasonal influenza for different activity types.*

Activity type	Measles [quanta/hr]	Seasonal Influenza [quanta/hr]
Resting, oral breathing	3.1	0.035
Light activity, speaking	15	0.17
Light activity, singing (or loudly speaking)	260	3

Note: Data from (Mikszewski et al., 2022).

The breathing rate, denoted as p, is the rate at which a susceptible person breathes in air, typically measured in m^3/hr. Similar to the quanta emission rate, the breathing rate varies depending on the type of activity being performed by the individual (REHVA, 2022b). This variation is detailed in Table 3.3.

***Table 3.3**: The breathing rate values for different activity types.*

Activity type	Breathing rate [m^3/hr]
Resting, oral breathing	0.54
Light activity, speaking	1.1
Light activity, singing (or loudly speaking)	1.38

Note: Data from (REHVA, 2022b).

The particle deposition rate on surfaces, denoted as $k_{deposition}$, is estimated at 0.3 per hour for both measles and seasonal influenza (Diapouli et al., 2013; Thatcher et al., 2002). The inactivation rate, represented as $k_{inactivation}$, refers to the natural decay rate of the virus and is estimated at 0.63 per hour for measles and 0.8 per hour for seasonal influenza (REHVA, 2022a).

A summary of all the parameters used in the REHVA tool is provided in Table 3.4. All values are adjusted to reflect a baseline condition that includes 10% speaking activity. The ventilation rates examined are the same as those used for the field measurement: 15, 30, and 45 l/s, which correspond to 1.2, 2.3, and 3.5 air changes per hour (ACH), respectively.

***Table 3.4**: Summary of all the parameters used in the REHVA tool.*

Parameter	Unit	Measles	Seasonal Influenza
Room volume	m^3	47	
Exposure time	hr	1/8	
Number of infected people	-	1	
Number of susceptible people	-	1	
Breathing rate (p)	m^3/hr	0.6	
Deposition on surfaces ($k_{deposition}$)	1/hr	0.3	
Inactivation rate ($k_{inactivation}$)	1/hr	0.63	0.8
Quanta emission rate (q)	quanta/hr	4.29	0.0485

3.4 IDA ICE Energy Calculations

The IDA ICE program, a dynamic simulation software developed for building performance analysis, is used for the energy calculations in this study. A model of a patient room with a volume of 47 m^3 is created using IDA ICE to calculate the energy consumption for the supply and exhaust air systems, including fan electricity, as well

as heating and cooling coil energy use. The weather conditions are set to those of Gothenburg, Landvetter. The heating controller setpoint is 23°C, and the cooling controller setpoint is 26°C. The room occupancy is adjusted for two people. An air handling unit with supply air, exhaust air, and a heat exchanger are used, operating with a controlled system. Default construction elements and triple-pane window glass are used, with appropriate thermal bridge values. For infiltration, air tightness is set at 0.8 ACH.

The air handling unit has a constant supply temperature of 16°C, with the heat exchanger efficiency set at 80%. The effectiveness of both the heating and cooling coils is set at 1. The specific fan power (SFP) is set at 1.5 kW/(m³/s) for both supply and exhaust fans, with an efficiency of 60%. The rated airflow is set at the maximum tested rate of 80 l/s. The fan SFP value, efficiency, and rated flow are kept constant for both supply and exhaust air across all airflow rates. The model is then prepared for energy simulation, with each simulation adjusting the supply and exhaust air to different airflow rates, ranging from 0 l/s to 80 l/s.

4
Results

4.1 Field Measurement

The field measurement results provide critical insights into the effectiveness of different airflow rates in reducing particle and CO_2 concentration in a hospital setting. These measurements were conducted using AeroTrak particle counters, Rotronic CO_2 monitors, and an Impactor device. The data collected from these devices are highlighted in the following subsections, along with the impact of using an air cleaner.

4.1.1 Particle Concentration

The results from the two AeroTrak devices at positions MP1 and MP2 are shown in Figures 4.1 and 4.2, respectively. The figures illustrate particle concentration over time, measured in particles per liter (pt/l), based on the data collected every minute by the AeroTrak device. The x-axis represents time in minutes (min), ranging from 0 to 360 minutes, while the y-axis shows the particle concentration scaled by 10,000. There are three lines representing different particle sizes: blue for particles larger than 0.3 µm, orange for particles larger than 1 µm, and green for particles larger than 5 µm.

Three experiments (labeled Exp1, Exp2, and Exp3) are marked on the graph, with clear peaks in particle concentration observed during these experiments. The graph is also divided into three distinct sectors, each representing different airflow rates: 15 l/s, 30 l/s, and 45 l/s.

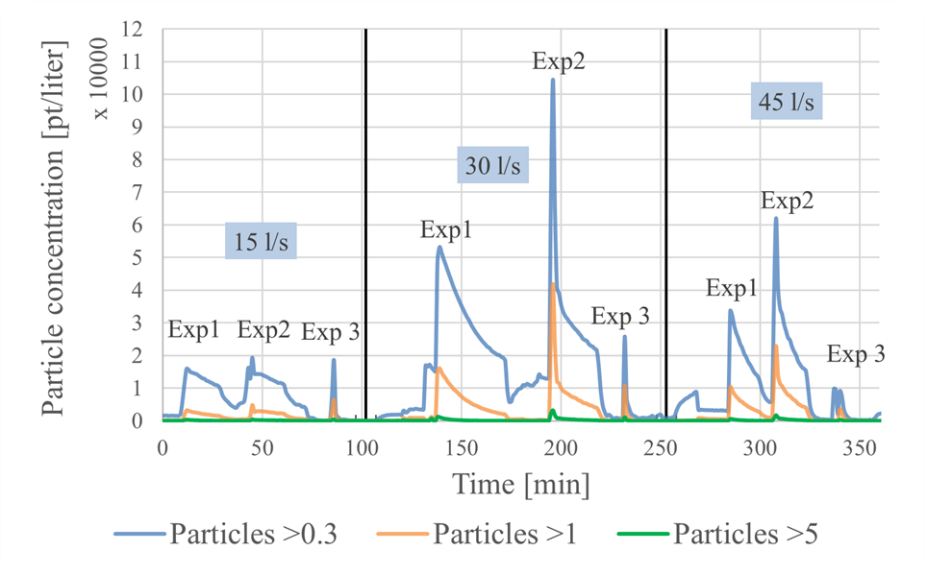

***Figure 4.1**: This figure shows results from the AeroTrak device at position MP1 for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

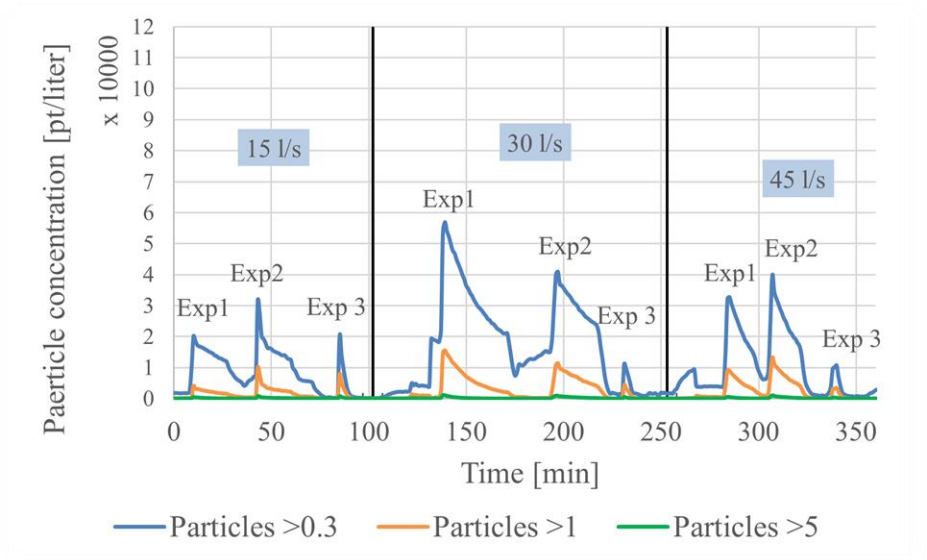

***Figure 4.2**: This figure shows results from the AeroTrak device at position MP2 for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

The detailed results for each experiment conducted at positions MP1 and MP2 can be found in Appendix A, with a total of 18 figures. The results include a series of data points for each experiment and particle size, each accompanied by a regression equation that shows the decay of particle concentration over time. These graphs track particles of various sizes: particles larger than 0.3 µm, larger than 1 µm, and larger than 5 µm. The plotted data represents the particle concentration adjusted by subtracting a background value. The background value represents the ambient level of particles and is used as a baseline for subsequent measurements. By subtracting this background concentration from the measured values during the experiments, the data is normalized, and the removal rate is accurately depicted. This approach is essential

because particle concentration does not decay to zero; they rather return to the normal (background) level. The time intervals chosen for plotting are those with the highest R^2 values, which quantify how well the data fits the regression line, indicating the accuracy of the measurements.

4.1.2 Carbon Dioxide Concentration

The results from the two Rotronic devices at positions MP1 and MP2 are shown in Figures 4.3 and 4.4, respectively. The figures illustrate the CO_2 concentrations over time, measured in ppm based on the data collected every minute by the Rotronic device. The x-axis represents time in minutes, ranging from 0 to 360 minutes, while the y-axis shows the CO_2 concentration scaled by 1,000.
Three experiments (labeled Exp1, Exp2, and Exp3) are marked on the graph, with clear peaks in CO_2 concentrations observed during these experiments. The graph is also divided into three distinct sectors, each representing different airflow rates: 15 l/s, 30 l/s, and 45 l/s.

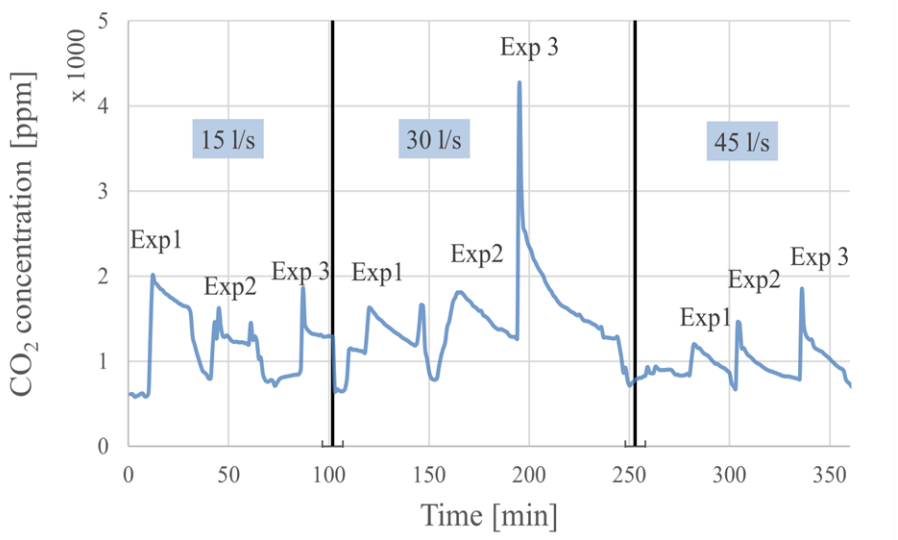

***Figure 4.3**: This figure shows results from the Rotronic device at position MP1 for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

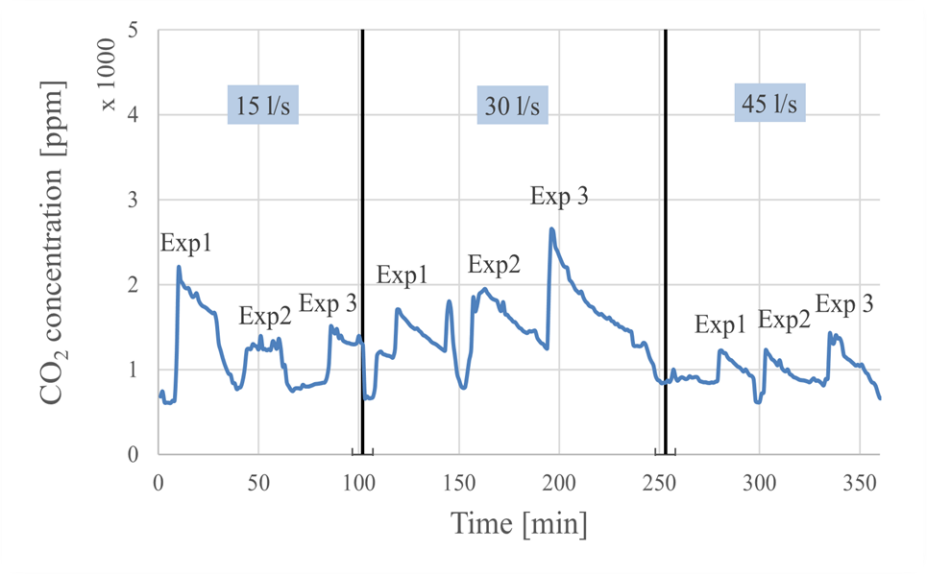

***Figure 4.4**: This figure shows results from the Rotronic device at position MP2 for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

The detailed results for each experiment conducted at positions MP1 and MP2 can be found in Appendix B, which includes a total of nine figures. The results include a series of data points for each experiment, accompanied by a regression equation that shows the decay of CO_2 concentration over time. The methodology for plotting the CO_2 concentration results follows the same approach used previously with the AeroTrak data, ensuring consistency in the analysis.

4.1.3 Colony-Forming Units (CFUs)

The results from the Impactor device located at position MP1 are detailed in Table 4.1. This table presents the concentration of CFU per m^3, comparing different airflow rates of 15 l/s, 30 l/s, and 45 l/s. Additionally, it compares the CFU counts during two conditions: with the air cleaner (AC) turned off and with the air cleaner turned on.

***Table 4.1**: Results from the Impactor device for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

Airflow [l/s]	No. of people	AC off [CFU/m^3]	AC on [CFU/m^3]	Reduction by AC [%]
15	2 still people	312	27	91
30	3 still people	344	37	89
45	2 still people	197	15	92

It is important to note that the Impactor device also removes a portion of the particles from the air during its operation, The Impactor device generates an airflow rate of 101 l/min or 10 minutes, which is equivalent to 1.68 liters per second. This airflow rate accounts for 10% of the 15 l/s airflow, 5% of the 30 l/s airflow, and 3.5% of the 45 l/s airflow. Despite this contribution, the Impactor device has a minimal effect on the overall particle removal rate at different airflow rates. Since the primary focus of this study is to compare removal rates at various airflow rates, rather than focus on the precise value of the removal rate, the minor influence of the Impactor device can be considered negligible in the analysis.

4.2 REHVA Tool Calculations

The results from the REHVA tool are summarized in Table 4.2, showing the infection risks for measles and seasonal influenza at different airflow rates of 15 l/s, 30 l/s, and 45 l/s , as well as with the use of an air cleaner. It also shows the infection risk at two different exposure times, one hour and eight hours. For an eight-hour exposure, the measles infection risk ranges from 18% to 9.3%, while the seasonal influenza infection risk ranges from 0.2% to 0.1%, depending on the airflow rate. The table also highlights the reduction in infection risk when activating the air cleaner. Detailed results for the REHVA tool calculations can be found in Appendix C.

***Table 4.2**: Results from the REHVA tool, demonstrating the infection risks for measles and seasonal influenza diseases at various airflow rates and exposure times.*

Airflow rate [l/s]	**Infection risk [%]**			
	Measles, 8-hour exposure	Seasonal Influenza, 8-hour exposure	Measles, 1-hour exposure	Seasonal Influenza, 1-hour exposure
	AC off / AC on	AC off / AC on	AC off / AC on	AC off / AC on
15	18.0/ 1.4	0.2 / 0.0	1.5/0.2	0/0
30	12.2 / 1.3	0.1 / 0.0	1.2/0.2	0/0
45	9.3 / 1.3	0.1 / 0.0	1/0.2	0/0

The REHVA tool represents the infection risk as a growth rate curve, illustrating particle dispersion over time with continuous emission. Figure 4.5 shows the infection risk percentages for measles over an eight-hour exposure period at different airflow rates of 15 l/s, 30 l/s, and 45 l/s. The graph also shows the effect of using an air cleaner. Since the air cleaner's impact on infection risk is almost the same at all airflow rates, showing just one airflow rate is sufficient. The infection risk for the medical staff, with an exposure time of one hour, is too low to be further investigated. Therefore, the analysis focuses on an eight-hour exposure time, involving a scenario with one infected patient and one visitor. Additionally, the infection risk for seasonal influenza is negligible and is not included in the figure.

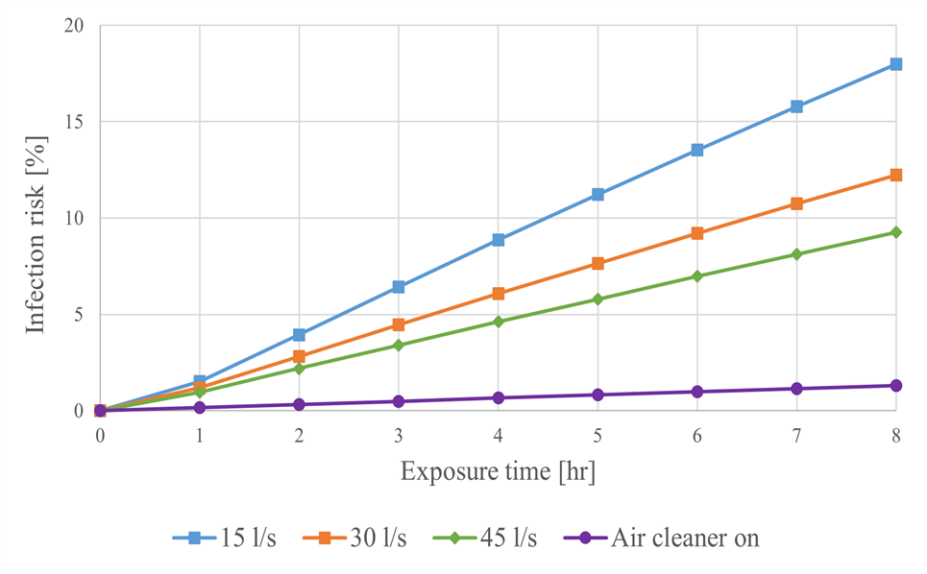

***Figure 4.5**: This figure shows results from the REHVA tool for the relationship between exposure time and the infection risk for measles at airflow rates of 15 l/s, 30 l/s, 45 l/s, and with the use of an air cleaner.*

The four curves represent different scenarios: airflow rates of 15 l/s, 30 l/s, 45 l/s, and the use of an air cleaner. As exposure time increases, the infection risk also increases for all scenarios. The highest infection risk, 18%, is observed at 15 l/s. The infection risk decreases with higher airflow rates of 30 l/s and 45 l/s. The lowest infection risk is achieved when the air cleaner is used, maintaining a significantly lower risk throughout the exposure period.

5
Analysis

5.1 Field Measurement

The results of the field measurements conducted in this study provide critical data on how different airflow rates reduce particle and CO_2 concentration in a hospital setting. This section presents a detailed analysis of the findings, utilizing data from AeroTrak particle counters, Rotronic CO_2 monitors, and the Impactor device. The following subsections will further investigate the specifics of particle concentration, CO_2 concentration, and microbial contamination, highlighting key findings and their implications for improving ventilation strategies in healthcare environments.

5.1.1 Particle Concentration

As observed in the AeroTrak results in Section 4.1.1, particularly in Figures 4.1 and 4.2, an overall common trend is observed regarding the removal of particles at various airflow rates and positions. To thoroughly analyze the experiments, the focus will be on several parameters, including location, particle size distribution, airflow rate, and the presence of a mixing fan and air cleaner.

5.1.1.1 Location

Although the graphs in Figures 4.1 and 4.2 show a common trend across positions MP1 and MP2 in experiment 1, there is a noticeable difference between these positions in experiment 2. In experiment 1, the room's air was well-mixed due to the use of a mixing fan, resulting in similar particle concentration and removal rates at both positions. However, in experiment 2, where no mixing fan was used, the graph reveals distinct differences in particle concentration between positions MP1 and MP2.

This difference is clearly illustrated in Figure 5.1, which depicts the particle concentration in experiment 2 at positions MP1 and MP2, specifically with an airflow rate of 30 l/s for particles larger than 0.3 µm. Both graphs show a peak in particle concentration followed by a decay. However, at position MP1, where the AeroTrak device is placed next to the patient, the peak is higher and sharper compared to position MP2, where the device is positioned in the center of the room.

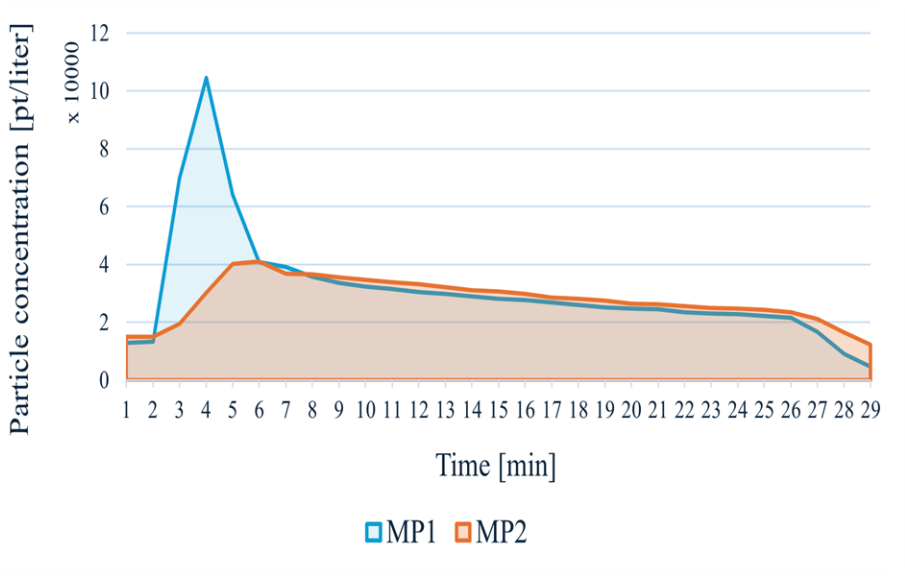

***Figure 5.1**: This area graph shows the particle concentration per time in experiment 2 at positions MP1 and MP2, with an airflow rate of 30 l/s for particles larger than 0.3 µm.*

At position MP2, the peak is lower and occurs about two minutes later than at position MP1. The graph at position MP2 also demonstrates a prolonged and slower decay compared to position MP1, which shows a faster decay. Additionally, particle accumulation is much higher at position MP1 than at position MP2, which is naturally explained by the higher exposure of the person sitting next to the patient to the particles.

The lower and delayed peak at position MP2 can be attributed to the absence of a mixing fan. Without the mixing fan, it takes longer for air to move from the patient to position MP2, causing a delayed and lower peak in particle concentration. Consequently, the concentration at position MP2 rises more slowly initially and then decays more gradually as particles continue to diffuse throughout the room.

The difference between the graphs for positions MP1 and MP2 indicates that the air in the room is not well mixed. Therefore, a mixing fan may be necessary, as the ventilation system functions best in a well-mixed air room. Implementing such measures not only enhances the efficiency of the ventilation system but may also reduce the infection risk for individuals sitting near the patient.

5.1.1.2 Particle Size Distribution

The powder smoke used in the experiments for this study is manufactured by Björnax and primarily consists of limestone mixed with polydimethylsiloxane (PMDS). It is non-toxic and safe for health and the environment, typically used for visualization of air movements indoors. The powder smoke, representing a cough/sneeze event, is analyzed in Figure 5.2 based on the average particle size distribution as measured by the AeroTrak devices.

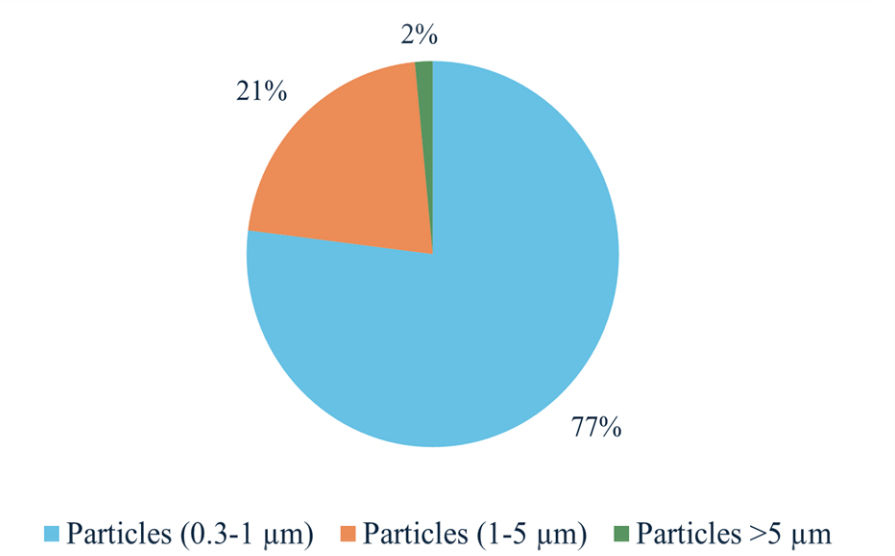

***Figure 5.2**: This pie chart shows the average particle size distribution of the powder smoke at airflow rates of 15 l/s and 45 l/s at position MP1.*

At airflow rates of 15 l/s and 45 l/s at position MP1, the particle size distribution is as follows: 77% for particles sized 0.3-1 µm, 21% for 1-5 µm, and 2% for particles larger than 5 µm. These values closely align with real cough/sneeze data regarding particle size. Research conducted in 2019 found that 70% of particles fall within the 0.3-1 µm range, 28% are in the 1-5 µm range, and 2% are larger than 5 µm (Lee et al., 2019). These values represent the average particle size distribution of an ill person at different stages of the disease. The close match between the AeroTrak device data and the research findings validates the AeroTrak data and the use of the powder smoke for stimulating the cough/sneeze event.

5.1.1.3 Airflow Rate

As discussed earlier, the presence of ventilation leads to a decrease in particle concentration over time. This decline becomes more significant with higher airflow rates, as illustrated in Figure 5.3. Each curve in Figure 5.3 represents a distinct airflow, with each modeled by a regression equation depicting the decline in particle concentration over time.

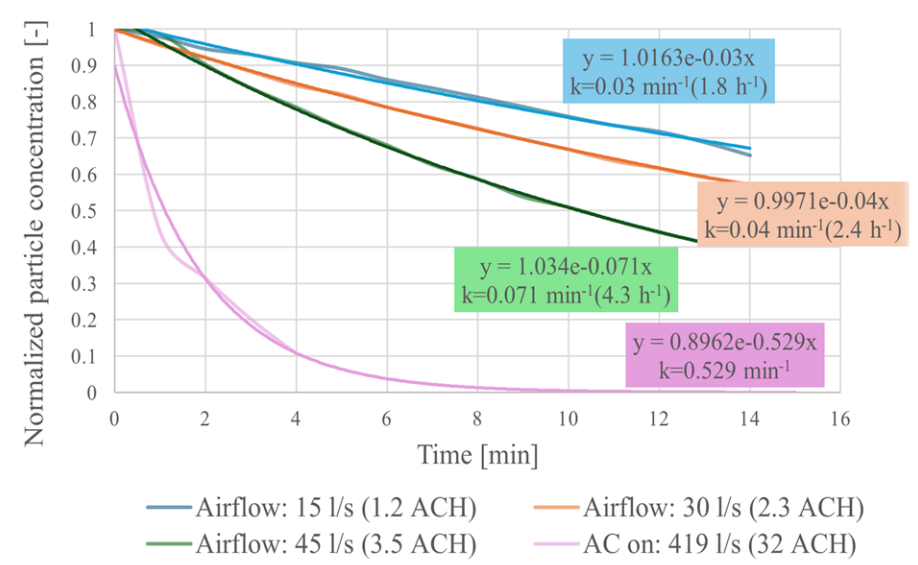

***Figure 5.3**: This figure shows the normalized particle concentration (particles>0.3 µm) per minute for airflow rates of 15 l/s, 30 l/s, 45 l/s, and with the use of an air cleaner.*

The total decay rates of particle concentration, denoted as k, represent the rate at which particle concentration decrease over time. The decay rates for airflow rates of 15 l/s, 30 l/s, and 45 l/s are 0.03 min^{-1}, 0.04 min^{-1}, and 0.071 min^{-1}, respectively. With the addition of an air cleaner, the decay significantly increases to 0.529 min^{-1}. When converting the total decay rates and ventilation rates to a unified unit of air changes per hour (ACH), the total decay rates correspond to 1.8 ACH, 2.4 ACH, and 4.3 ACH for ventilation rates of 1.2 ACH, 2.3 ACH, and 3.5 ACH, respectively. The difference between the total decay rates and the ventilation rates is the decay rate due to particle deposition on surfaces.

To ensure accurate evaluation and comparison of the decay rates across varying airflow rates, the concentration data are normalized to account for fluctuations in background concentration. The decay curves are modeled using the equation $y=ae^{-bx}$, where a is close to 1, representing the initial concentration, and b is the decay rate constant. It is important to note that Figure 5.3 is based on average values from positions MP1 and MP2 for particles larger than 0.3 µm. Specifically, the curve for the air cleaner reflects the decay rate under an airflow rate of 30 l/s with the air cleaner activated.

The airflow rates chosen for the experiments, namely 15 l/s, 30 l/s, and 45 l/s, were selected based on the available settings in the hospital, as testing at other rates was not possible. Figure 5.4 illustrates the decay rates for particles larger than 0.3 µm, 1 µm, and 5 µm across these airflow rates. The figure represents the average for measurements taken at positions MP1 and MP2.

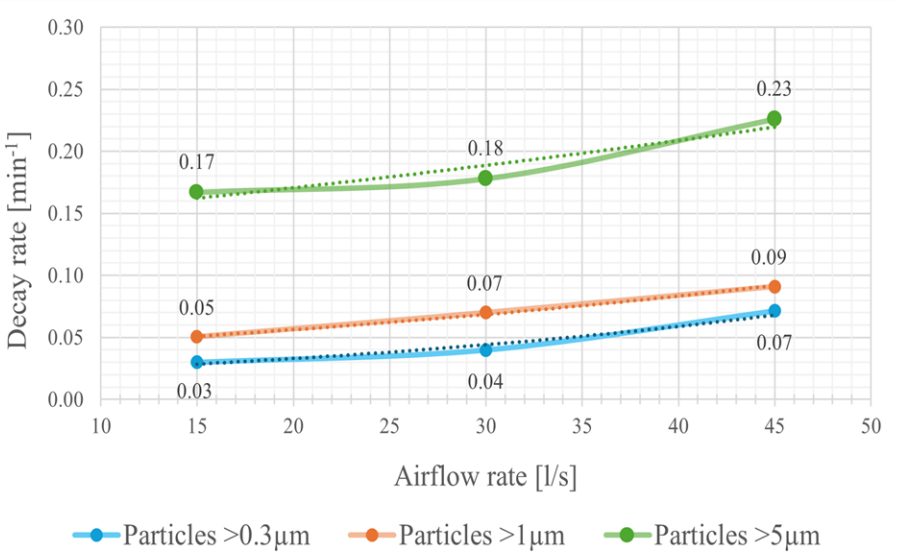

***Figure 5.4**: This figure illustrates the decay rates at different airflow rates for particles larger than 0.3 µm, larger than 1 µm, and larger than 5 µm.*

It is evident from the data that decay rates increase with larger particle sizes. This occurs because larger particles settle more quickly and are more easily trapped by the exhaust system compared to smaller particles. Additionally, the same methodology is applied to examine whether the results would be consistent for particle size ranges of 0.3–1 µm, 1–5 µm, and greater than 5 µm, yielding similar decay rates. This additional analysis is conducted to validate the accuracy of the methodology used.

The concept of recovery time, often used in cleanroom assessments, indicates how effectively the ventilation system removes airborne contamination. It is a valuable measure of how long airborne infections may persist in the air, helping determine appropriate occupancy limits. Recovery time refers to the duration required for a specific airflow to achieve a certain level of contamination removal. For example, at an airflow rate of 15 l/s, it takes 23 minutes to remove 50% of the contamination in the air, whereas removing 99% of the contamination requires 154 minutes. The corresponding recovery times for airflow rates of 15 l/s, 30 l/s, 45 l/s, and with an air cleaner are presented in Table 5.1.

***Table 5.1**: The recovery time, expressed in minutes, for airflow rates of 15 l/s, 30 l/s, 45 l/s, and with the use of an air cleaner.*

Airflow [l/s]	**Time [min] required for removal, 50% efficiency**	**Time [min] required for removal, 99% efficiency**
15	23	154
30	17	115
45	10	66
419 (AC)	1	8

The equation used to calculate the recovery time is shown in Equation 5.1. This equation is derived from solving the basic exponential decay equation:

$$C2 = C1 \times e^{-kt} \tag{5.1}$$

Equation 5.1*: The basic equation for calculating the recovery time.*

Where,

- C2 is the final concentration [pt],
- C1 is the initial concentration [pt],
- k is the removal rate constant [min^{-1}], and
- t is the time [min].

However, since we do not have the exact initial and final concentrations, we can assume values. For instance, if the initial concentration is assumed to be 800 particles (pt), and we aim to achieve a removal efficiency of 99%, the final concentration would be 8 pt (1% of 800). The equation is then reformulated to solve for time, as shown in Equation 5.2

$$t = \frac{-ln(C2/C1)}{k} \tag{5.2}$$

Equation 5.2*: The reformulated equation for calculating recovery time based on assumed concentrations (Sehulster et al., 2019).*

Based on the decay rates obtained from the field measurements and using Equation 5.2, the recovery time for each airflow rate is calculated, as shown in Table 5.1.

5.1.1.4 Mixing Fan

In experiment 1, a mixing fan was used to create a well-mixed air environment in the patient room. While the ventilation system operates on a mixed airflow principle and is expected to achieve uniform mixing without additional air mixing, this was not the case in the experiments. In experiment 2, where no mixing fan was used, significant differences in particle concentration and decay rates are observed between positions MP1 and MP2.

A well-mixed air environment is crucial for ensuring a homogeneous and evenly distributed air supply throughout the room. This prevents the formation of areas with high or low particle concentration, allowing particles to spread equally and reducing the overall particle concentration. Additionally, it influences the decay rate of particle concentration in the room. Experiment 1, which uses a mixing fan, has a higher decay

rate compared to experiment 2, without a mixing fan. This trend is observed for all particle sizes and positions but is particularly noticeable for larger particle sizes. Detailed results supporting this observation can be found in Appendix A.

5.1.1.5 Air Cleaner

The addition of an air cleaner to experiment 3 has significantly impacted the reduction of particle concentration. An air cleaner with a CADR value of 1400 m^3/hr was added into experiment 3 at three distinct airflow rates to assess the effect of an extremely high airflow rate scenario. The decline in particle concentration with the use of the air cleaner across various airflow rates and particle sizes is illustrated in Figure 5.5. The values presented in Figure 5.5 represent the average for measurements taken at positions MP1 and MP2.

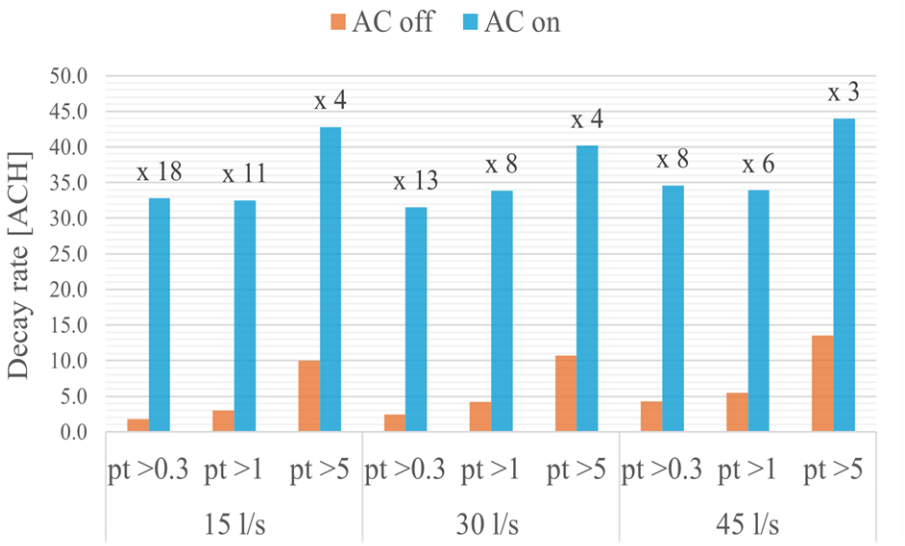

Figure 5.5*: This figure shows the differences in particle concentration decay rates with the air cleaner on versus off at various airflow rates and for different particle sizes: particles larger than 0.3 µm, larger than 1 µm, and larger than 5 µm.*

Figure 5.5 illustrates the differences in particle concentration decay rates with the air cleaner device on and off. The air cleaner results in significantly higher decay rates compared to when it is not in operation. This difference is quantified by the term "change factor," which characterizes the air cleaner's impact on particle concentration removal. The change factor is calculated by dividing the removal rate with the air cleaner on by the removal rate with the air cleaner off. For instance, at an airflow rate of 15 l/s, the change factors are 18, 11, and 4 for particles larger than 0.3 µm, larger than 1 µm, and larger than 5 µm, respectively. Additional change factor values for different airflow rates are clearly presented in the same figure.

From the observations in Figure 5.5, two key conclusions can be drawn:

- *Change Factor and Airflow Rate*: The change factor is higher at lower airflow rates. This phenomenon can be attributed to the air cleaner having a more significant effect when ventilation airflow is inadequate. In contrast, at higher airflow rates, the air cleaner's impact diminishes, as adequate ventilation alone can effectively reduce particle concentration.

- *Change Factor and Particle Size*: The change factor is smaller for larger particles. Larger particles tend to settle out of the air more quickly due to the influence of gravity, while smaller particles remain airborne for longer periods and are therefore more likely to be captured by the air cleaner.

As previously mentioned, the air cleaner used in this study operates with a CADR value of 1400 m^3/hr, as determined in laboratory measurements. During the experiments, the CADR value was also calculated by subtracting the removal rate with the air cleaner on from the removal rate with the air cleaner off, then multiplied by the room's volume. However, during the hospital experiments, the air cleaner operated at varying levels ranging from 1300 m^3/hr to 1568 m^3/hr, with an average value of 1414 m^3/hr. This close match suggests that the air cleaner used is functioning almost as expected. Fluctuations in the air cleaner's effectiveness can be influenced by factors such as the level of airborne contaminants, ventilation effectiveness, and occupancy levels.

5.1.2 Carbon Dioxide Concentration

As observed in the Rotronic results in Section 4.1.2, particularly in Figures 4.3 and 4.4, an overall common trend is observed regarding the removal of CO_2 concentration at various airflow rates and positions. Thorough analysis of the data reveals that CO_2 concentration decreases as the airflow rate increases, mirroring a similar trend observed in particle concentration, as shown in Figure 5.6. Each curve in Figure 5.6 represents a distinct airflow, with each modeled by a regression equation depicting the decline in CO_2 concentration over time.

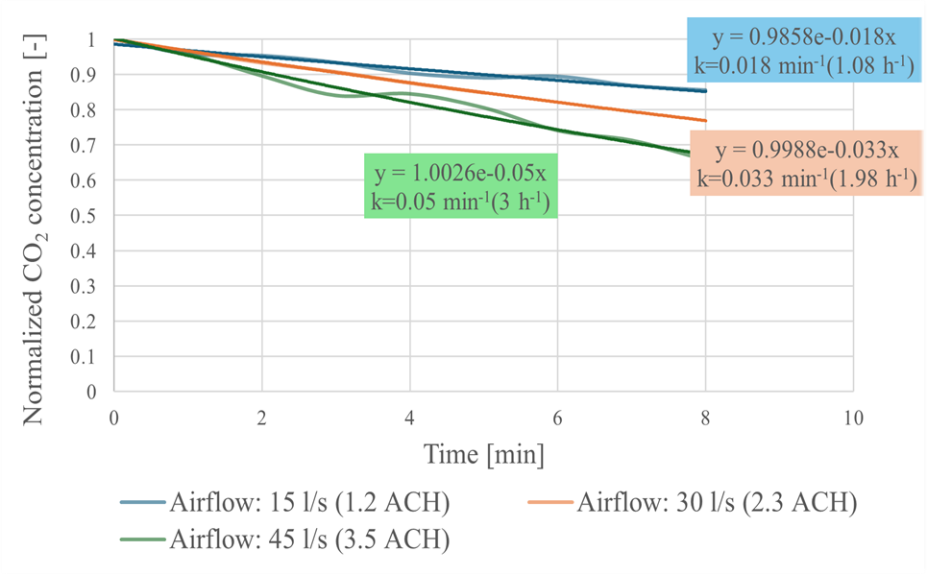

***Figure 5.6**: This figure shows the normalized CO_2 concentration per minute for airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

The decay rates of CO_2 concentration, denoted as k, are 0.018 min^{-1}, 0.033 min^{-1}, and 0.05 min^{-1} for airflow rates of 15 l/s, 30 l/s, and 45 l/s, respectively. When converting the decay rates and ventilation rates to a unified unit of air changes per hour (ACH), the total decay rates correspond to 1.08 ACH, 1.98 ACH, and 3 ACH for ventilation rates 1.2 ACH, 2.3 ACH, and 3.5 ACH, respectively. Since gravity does not influence the CO_2 concentration and there is no deposition on surfaces as with particle concentration, the CO_2 decay rate closely mirrors the decay rate of ventilation. There is a strong correlation between the CO_2 decay rate and ventilation rate in nearly all cases, indicating that the ventilation system is functioning as expected and providing the intended airflow rate.

The impact of the air cleaner on CO_2 removal is not analyzed, as it has no effect on the CO_2 concentration in the air. The same approach used to normalize particle concentration is applied to normalize CO_2 concentration. Similarly, the data presented in Figure 5.6 is based on the average of measurements taken at positions MP1 and MP2.

When comparing the CO_2 concentrations to the guidelines outlined in Section 2.5.2, it is evident that high airflow rates are necessary to meet the requirements, as shown in Table 5.2. The average CO_2 concentration is calculated for the duration of the experiment at each airflow rate. However, for 30 l/s airflow rate, the concentration value is adjusted based on two occupants instead of three in the room, for comparison purpose. At an airflow rate of 45 l/s, the CO_2 concentration meets the requirement, remaining below 1000 ppm. At an adjusted airflow rate of 30 l/s, the concentration is close to the requirement, while it falls short at 15 l/s.

***Table 5.2**: The average CO_2 concentration at airflow rates of 15 l/s, 30 l/s, and 45 l/s.*

Airflow rate [l/s]	CO_2 concentration [ppm]
15	1130
30	1002
45	918

5.1.3 Colony-Forming Units (CFUs)

The CFU results presented in Section 4.1.3 demonstrate the air cleaner's effectiveness in reducing airborne contamination. These results, which align with the data from the Aerotrak device as shown in Table 5.3, indicate a significant reduction in contamination levels. The reduction observed by the AeroTrak device represents the average reduction measured at positions MP1 and MP2 for particles larger than 0.3 µm.

***Table 5.3**: The reduction percentage of contamination by the AC, based on measurements from the Impactor and AeroTrak devices.*

Airflow rate [l/s]	Reduction by AC [%] (from Impactor)	Average reduction by AC [%] (from AeroTrak)
15	91	95
30	89	92
45	92	88

Although there are no strict limits for CFU levels, the observed CFU concentrations can be compared to the guidelines mentioned in Section 2.5.3. Based on Table 4.1, all CFU levels at airflow rates of 15 l/s, 30 l/s, and 45 l/s fall within the intermediate classification (100-500 CFU/m^3), which is considered acceptable. However, to meet the stricter limit of CFU value less than 200 CFU/m^3, only the airflow rate of 45 l/s meets this requirement. It's also important to note that at an airflow rate of 30 l/s, there were three people in the room instead of two. Even after adjusting the CFU count for two people, it would still exceed the 200 CFU/m^3 threshold.

5.2 REHVA Tool Calculations

The model calculations performed using the REHVA tool can be extended to include a wider range of airflow rates, both higher and lower rates. This extension is shown in Figure 5.7, which illustrates the relationship between airflow rate and the infection risk for measles. The infection risk for seasonal influenza is not further investigated,

as it is negligible compared to measles, based on the results from Table 4.2. In Figure 5.7, the x-axis represents the airflow rate in liters per second (l/s), while the y-axis represents the infection risk in percentage (%). The graph shows an exponential decay trend, indicating that as airflow rate increases, infection risk decreases.

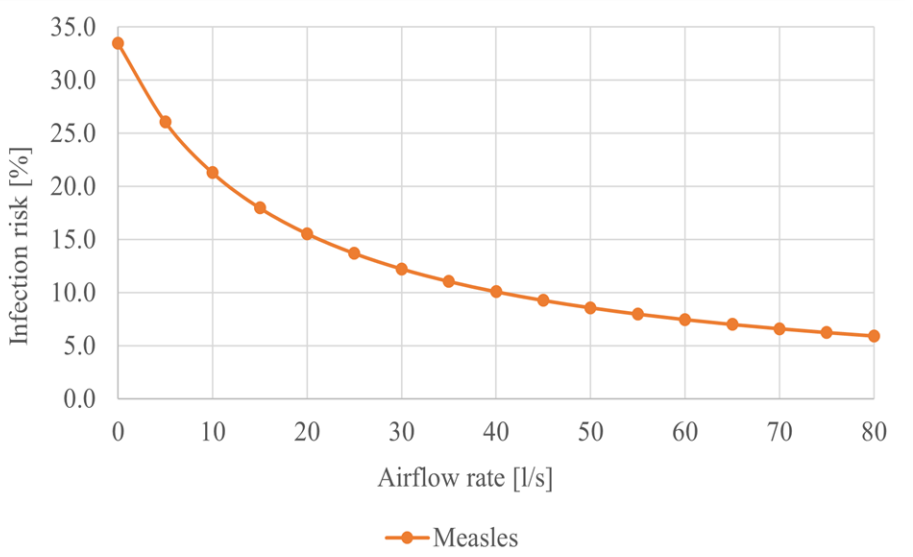

***Figure 5.7**: This figure shows the relationship between airflow rate and infection risk for measles, calculated using the REHVA tool.*

The graph in Figure 5.7 demonstrates a significant reduction in measles infection risk as the airflow rate increases, with the data starting from 0 l/s. Initially, there is a noticeable decline in infection risk from about 34% at airflow rate 0 l/s to approximately 12% at airflow rate 30 l/s. This decline suggests that increasing the airflow rate in this range is particularly effective at reducing the infection risk.

As the airflow rate increases from 30 l/s to about 50 l/s, the rate of reduction in infection risk slows but remains significant. The curve flattens with increasing airflow rate, providing minimal further reduction in infection risk, indicating a threshold or saturation point where additional airflow has little effect.

In conclusion, while the ideal range for reducing measles infection risk appears to be between 30 l/s and 60 l/s, airflow rates above 60 l/s do not significantly impact the infection risk.

5.3 IDA ICE Energy Calculations

The energy calculations performed using the IDA ICE program is illustrated in Figure 5.8, where the x-axis represents the airflow rate in liters per second (l/s), and the y-axis represents the total HVAC energy use in kilowatt-hours per square meter (kWh/m²). The data points represent the HVAC energy use at different airflow rates,

ranging from 0 l/s to 80 l/s. The total HVAC energy use includes the energy consumption for the fan, heat exchange unit, heating coil, and cooling coil. The graph shows a power trend, indicating that as the airflow rate increases, the energy use increases.

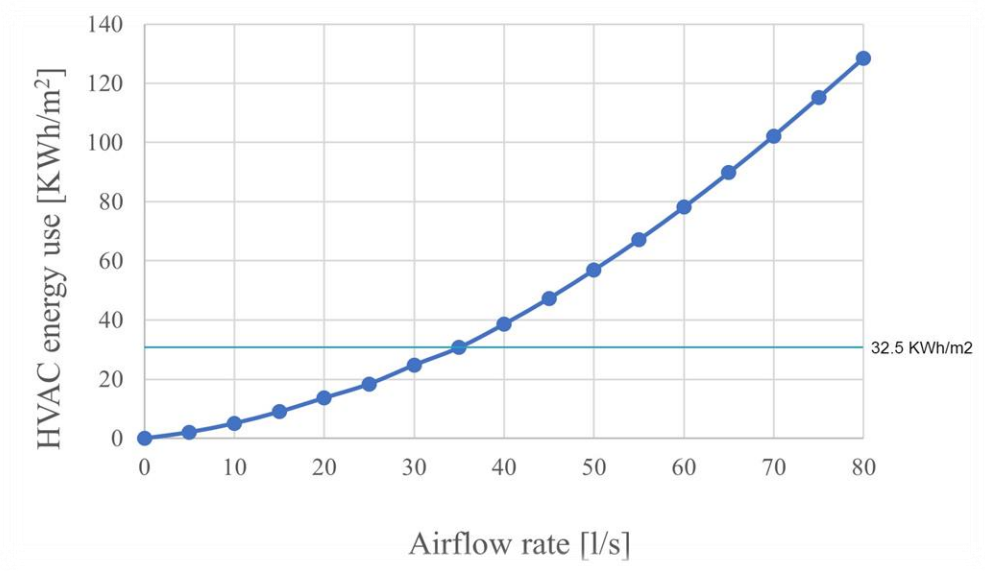

***Figure 5.8**: This figure shows the relationship between airflow rate and HVAC energy use, calculated using the IDA ICE.*

The graph in Figure 5.8 demonstrates a significant increase in the total HVAC energy use as the airflow rate increases, with the data starting from 0 l/s. Low airflow rates result in low HVAC energy use, while high airflow rates lead to a non-linear increase in energy use. To understand the magnitude of the energy use shown in the graph, a reference value is considered. According to the Swedish Energy Agency, the average energy use for ventilation in Swedish hospitals is 32.5 kWh/m² per year (Baltzar, 2011). This value is important to consider when designing energy-efficient ventilation systems, particularly in spaces like patient rooms where requirements are lower compared to areas such as operating rooms.

6
Discussion

6.1 Validation of the REHVA Tool with the Field Measurements

The comparison between the experimental results and the REHVA tool calculations shows a strong correlation, validating the effectiveness of the REHVA tool in predicting particle concentration changes under varying airflow conditions. In Figure 6.1, the graph illustrates the correspondence between experimental measurements of particle concentration decay and REHVA tool's predictions of particle concentration dispersion.

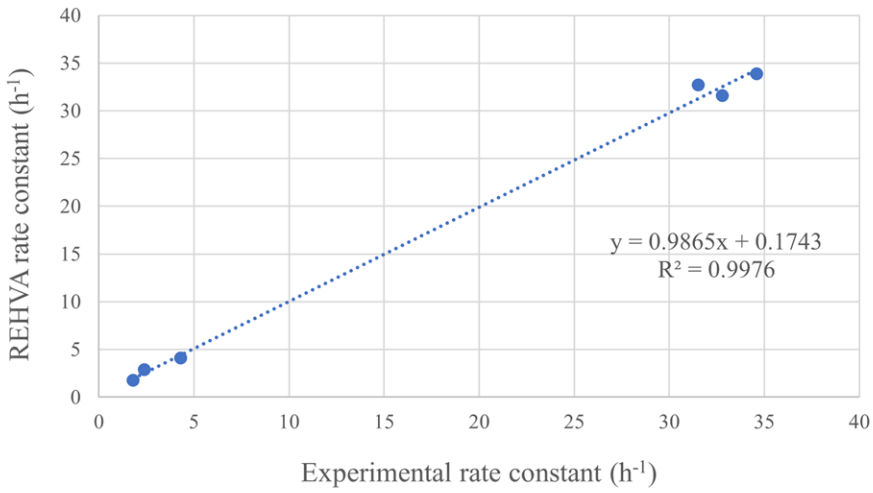

***Figure 6.1**: This figure shows the correspondence between the experimental measurements and the REHVA tool calculations.*

In the experiments, particle concentration decreases over time and is modeled as a decay curve. In contrast, the REHVA tool shows that particle concentration increases over time, represented as a growth curve. While the field measurements focus on the removal of particles from the air, the REHVA tool highlights the dispersion of particles within the air.

The decay rate constants in the experiments account for ventilation removal, deposition removal, and air cleaner removal, excluding inactivation rates since only particle concentration is measured, not viral load. Conversely, the growth rate constant in the REHVA tool includes these removal mechanisms in addition to the inactivation rate. To make the experiments comparable to the REHVA tool, the growth rate constant is adjusted by subtracting the inactivation rate, thereby aligning it with the same removal factors used in the decay curve.

The data points in Figure 6.1, plotted with decay rate constants against growth rate constants, show a strong linear correspondence, as evidenced by the regression with a high R^2 value. Each point on the graph corresponds to a pair of decay and growth rate constants under the same airflow rate, totaling six data points. The low points represent the decay and growth rate constants at airflow rates of 15 l/s, 30 l/s, and 45 l/s without an air cleaner. In contrast, the high points represent the decay and growth rate constants for the same airflow rates of 15 l/s, 30 l/s, and 45 l/s specifically when an air cleaner is used.

The high R^2 value and the slope being close to 1 indicate an excellent fit, demonstrating that the REHVA tool's predictions align closely with the experimental data. This confirms the tool's accuracy in predicting particle concentration changes under similar conditions. The graph also shows the distinction between points with and without an air cleaner, highlighting the significant impact of air cleaners on particle removal. A more detailed correspondence for airflow rates of 15 l/s, 30 l/s, and 45 l/s is shown in Figure 6.2.

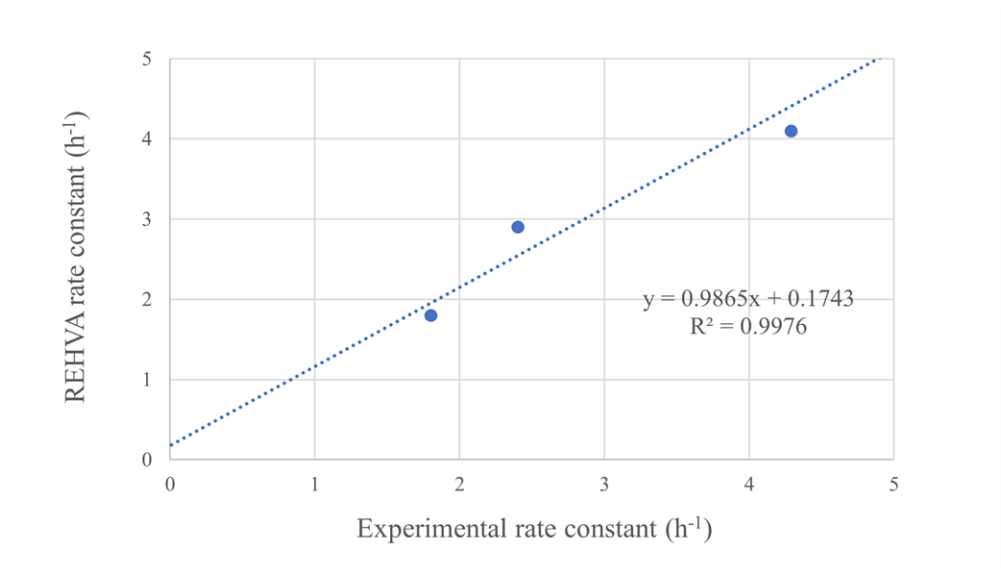

***Figure 6.2**: This figure shows a more detailed correspondence between the experimental measurements and the REHVA tool calculations.*

The correspondence consistency proves the reliability of the REHVA tool and suggests that the assumptions and parameters used, such as the deposition rate, have been accurately selected. It also highlights the tool's effectiveness in calculating infection risks for diseases beyond COVID-19.

6.2 Airflow Rate

The decision not to further investigate the infection risk of seasonal influenza in this study is based on its relatively low quanta emission rate compared to measles. As

shown earlier in Table 3.2, the quanta emission rate for seasonal influenza during light activity, such as speaking, is 0.17 quanta/hr, significantly lower than the 15 quanta/hr for measles during the same activity. This substantial difference indicates that seasonal influenza poses a much lower risk of airborne transmission, as it primarily spreads through droplets. Therefore, it is less relevant to this study, which focuses on optimizing ventilation for airborne diseases.

Determining an appropriate airflow rate for a patient room is a challenging task due to several factors, including infection risk, the consequences of infection in terms of costs, energy consumption, space required for the ventilation system (such as air handling units and ducts), installation and operational costs, climate conditions, and the presence of infected individuals. To visualize the relationship between infection risk and energy use as the airflow rate increases, the curves from Figures 5.7 and 5.8 are overlaid in a single diagram in Figure 6.3.

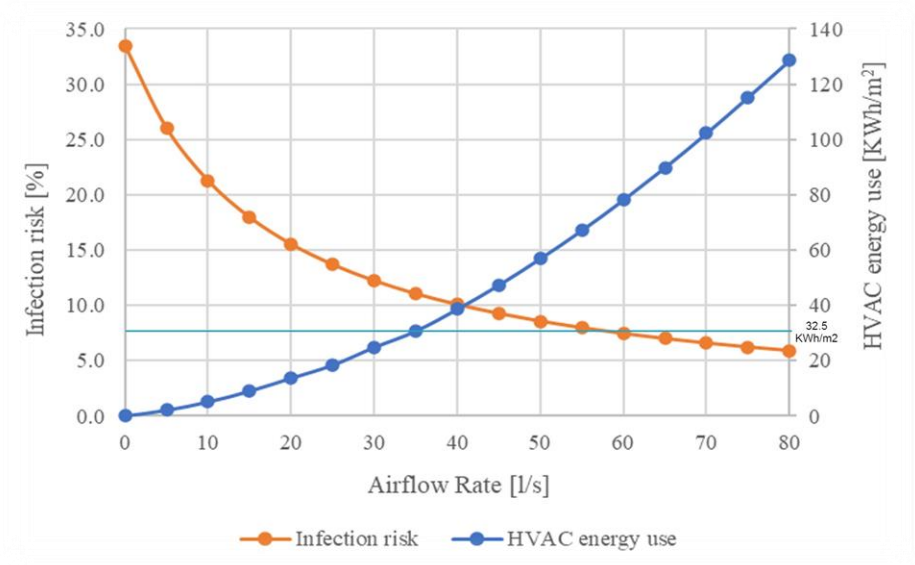

***Figure 6.3**: This figure presents an overlay of the infection risk curve and the energy use curve.*

At first glance, Figure 6.3 suggests that an airflow range of 40-50 l/s offers a balanced trade-off between infection risk and energy use. However, determining the ideal airflow rate is complex and subject to further discussion. Both the infection risk and energy use should be assessed in cost terms for proper comparison. While calculating energy use is straightforward by determining the cost of 1 KWh, assessing the cost of infection risk is more complicated, as it involves additional healthcare costs, loss of productivity, and other factors.

As discussed earlier in Section 5.2, the infection risk decreases substantially between airflow rates of 0 l/s and about 50 l/s. The curve flattens with increasing airflow rate, indicating that further reductions in infection risk become progressively less significant. Therefore, it may be reasonable to recommend doubling the PTS guideline from 25 l/s (2 ACH) to 50 l/s (4 ACH), which could lead to a 37% reduction

in infection risk, bringing it below 10%. However, this would lead to a substantial increase in energy use, exceeding the average value for ventilation in Swedish hospitals.

An airflow rate above 60 l/s (4.5 ACH) is considered excessive and inefficient. Thus, under the conditions studied in the present work, the recommendation of 6 ACH that has been proposed in Sweden and internationally may not be necessary for a typical patient room but could be essential for other specific cases. Given that energy use in healthcare settings is already high (36.7% of total hospital energy use), it is important to balance infection control with energy savings. Strict adherence to the highest ventilation standards may not be necessary for every room or case.

If a lower infection risk is required, alternative measures can be taken without significantly increasing ventilation rates and, consequently, energy consumption. These measures include the use of face masks, UV lighting, reducing occupancy time, and the implementation of room air cleaners

7
Conclusion

The purpose of this study is to compare existing guidelines for minimizing airborne disease transmission in indoor environments and evaluate their effects on energy consumption in healthcare settings. By focusing on the transmission of airborne diseases within patient rooms and evaluating different ventilation conditions, this research provides critical insights into optimizing ventilation systems to enhance patient safety, reduce infection risks, and control energy consumption.

This study successfully evaluated the effectiveness of various ventilation rates in reducing airborne particle and CO_2 concentration, which correlate with lower infection risks for diseases like measles and seasonal influenza. Using AeroTrak particle counters, Rotronic CO_2 monitors, and an Impactor device for microbial contamination assessment, the study offers detailed insights into the effects of ventilation on particle and CO_2 reduction. The findings highlight the importance of factors such as airflow rate, particle size distribution, location, and the use of air cleaners and mixing fans. Both field measurements and REHVA tool calculations confirmed the effectiveness of higher airflow rates and air cleaners in significantly reducing the infection risks. These findings contribute to the broader field of indoor air quality and infection control, emphasizing the importance of adequate ventilation in healthcare settings, especially post the COVID-19 pandemic.

The validation of the REHVA tool with experimental data highlights the tool's reliability in predicting particle concentration changes under varying airflow conditions. This allowed the testing of infection risks over a wider ventilation range and for diseases beyond COVID-19. However, it is not possible to determine an ideal airflow rate that balances infection risk reduction with energy efficiency, as it depends on numerous influencing factors that are complex to evaluate. The study did explore the effects of doubling the ventilation rate, examining its impact on infection risk and energy use. The study also proved the effectiveness of air cleaners and suggested their potential integration with ventilation systems to reduce contamination, particularly in critical care areas Additionally, measures such as UV lighting, disinfection protocols, face masks and hygiene routines should be incorporated into a comprehensive infection control strategy.

Rather than only increasing ventilation, another effective approach to reducing infection risk is to minimize occupancy time. For example, a one-hour exposure for medical staff resulted in significantly lower infection risk than an eight-hour exposure for visitors. Reducing the time individuals spend in shared spaces was successfully implemented during the COVID-19 pandemic. Therefore, both increased ventilation rate and reduced occupancy time should be considered in healthcare facility design and operation to ensure effective infection control.

The experimental measurements in this study could have been improved by releasing the same amount of particles and CO_2 for each experiment and conducting all experiments on the same day rather than on different days. This consistency in the

experimental conditions would have provided more reliable and comparable data, resulting in similar peaks. Additionally, the recording intervals of the particle counters and CO_2 monitors (every minute) may have led to missed peak concentrations. More frequent data recording could capture more accurate results.

While this study provides valuable insights, its focus on patient rooms in Nordic climatic conditions is a limitation. Future research should validate these findings across different healthcare settings, such as waiting rooms, and in various climates. In warmer or low-income countries, for instance, natural ventilation may be more feasible than in Sweden. Further studies should also explore the integration of alternative measures, such as air cleaner systems, to assess their economic viability and practicality. Additionally, research is needed to develop energy-efficient ventilation solutions that consider additional factors, such as operational costs, duct sizes, and noise control.

On an international level, there is a necessity to unify ventilation guidelines for hospitals, as existing guidelines differ among various health organizations. Moreover, the ongoing debate between the Swedish real estate and healthcare experts regarding airflow rates should be resolved through collaboration, combining real estate expertise on costs, energy efficiency, and practicality with healthcare knowledge on infection risk and patient safety.

In conclusion, this study highlights the critical role of effective ventilation in controlling airborne diseases in healthcare settings, considering existing guidelines and recommendations from health organizations. It also underscores the importance of advanced modeling techniques, such as the REHVA tool, in achieving accurate modeling of infection risk. The study has successfully laid the foundation for a methodology that combines measurements and modeling for a specific scenario, such as measles transmission in a patient room.

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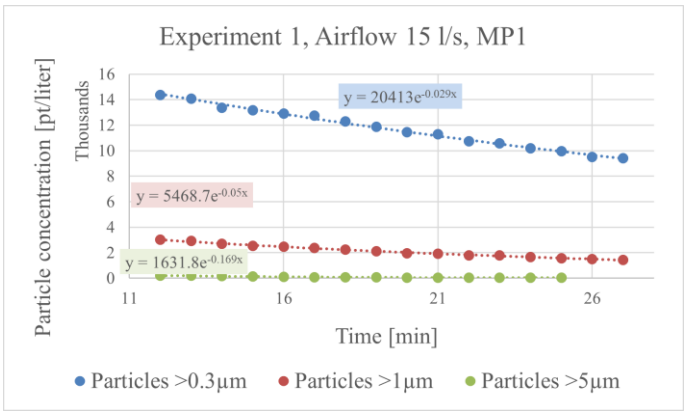
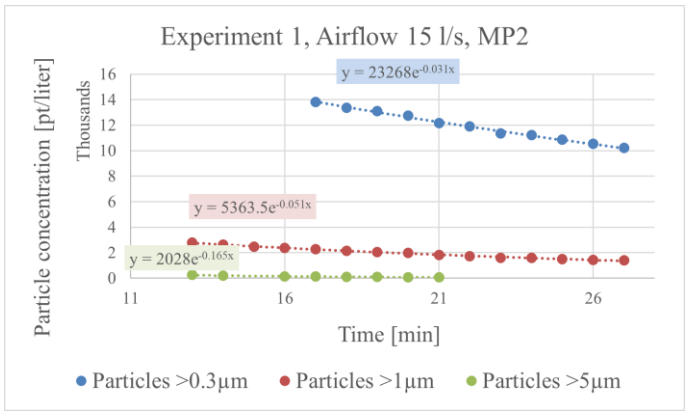
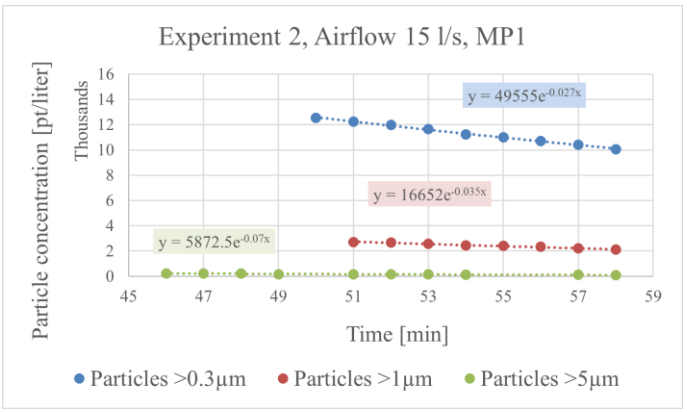
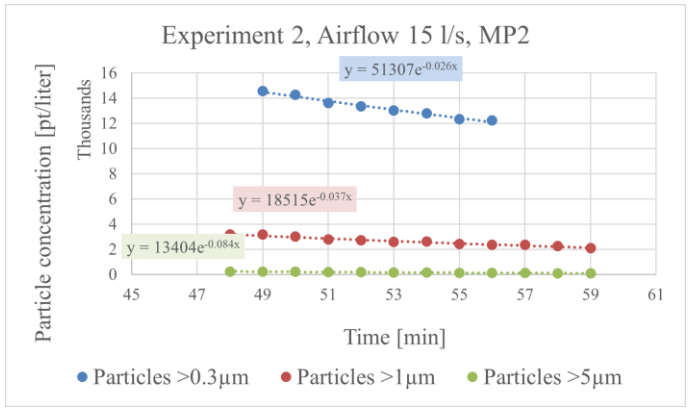
Appendix A

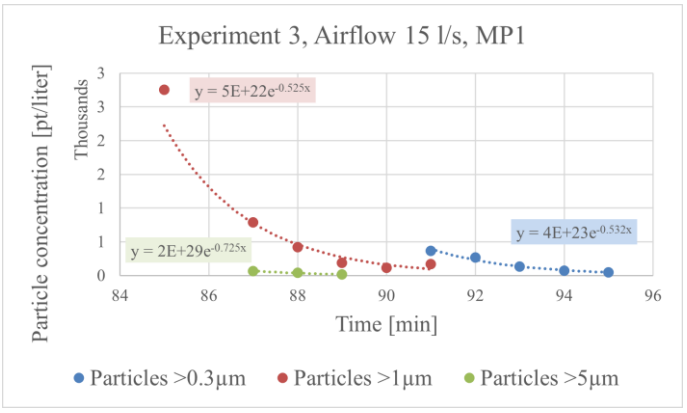
Detailed results from the AeroTrak device for each experiment conducted at positions MP1 and MP2

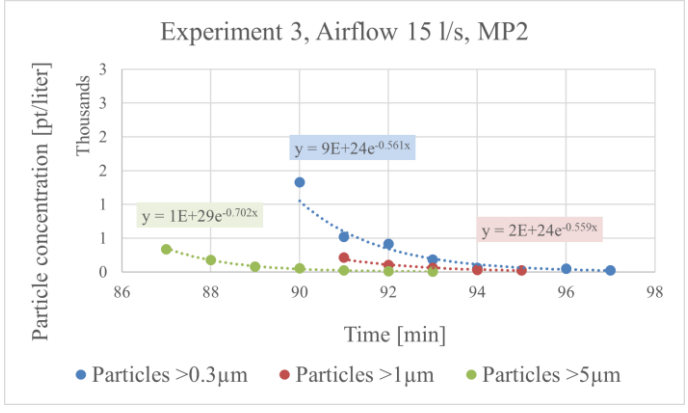


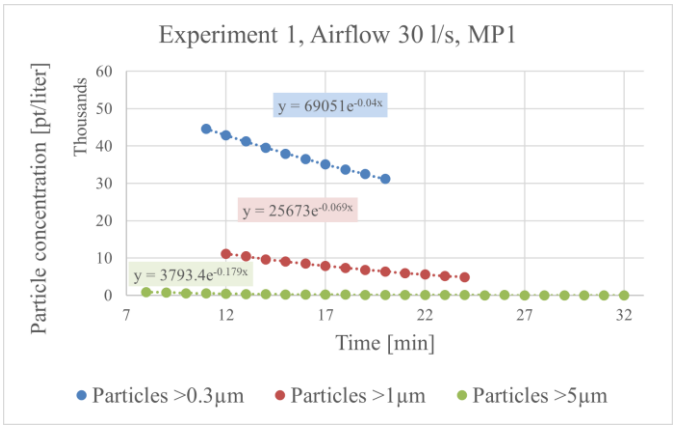


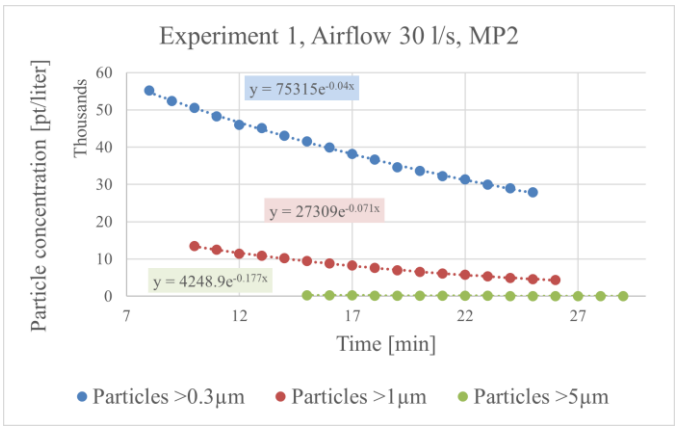


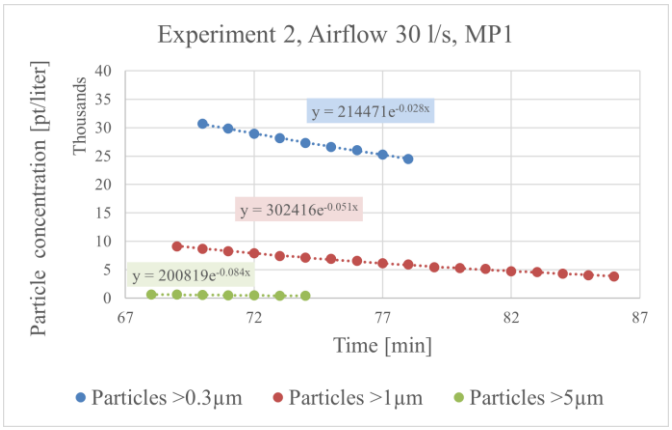


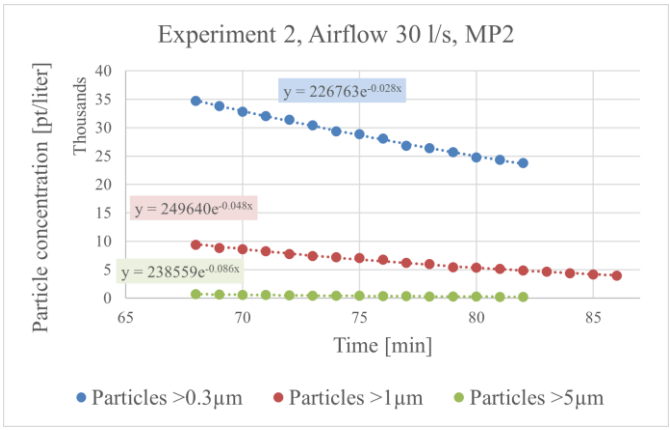


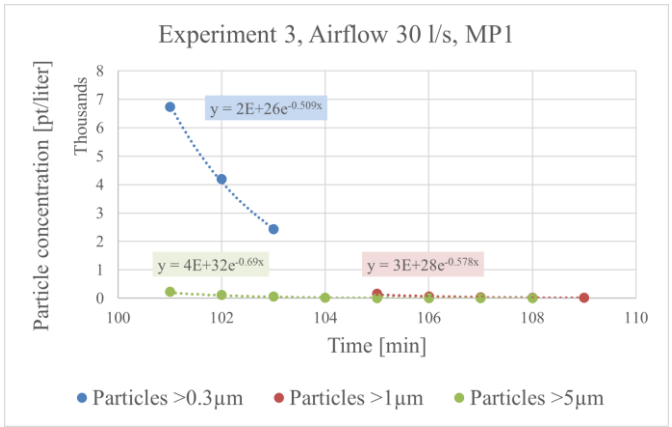


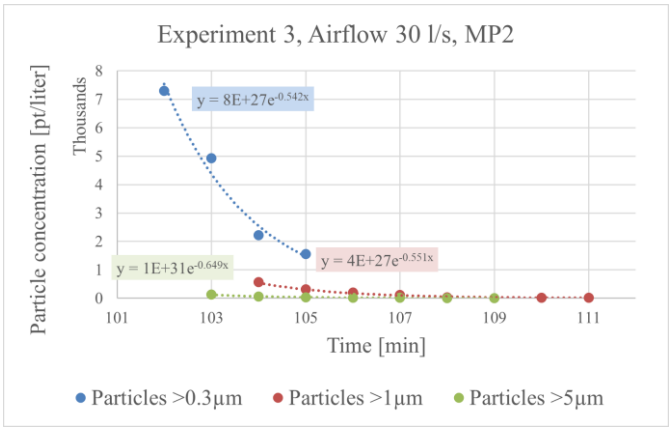

Experiment 1, Airflow 30 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 69051e-0.04x
y = 25673e-0.069x
y = 3793.4e-0.179x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

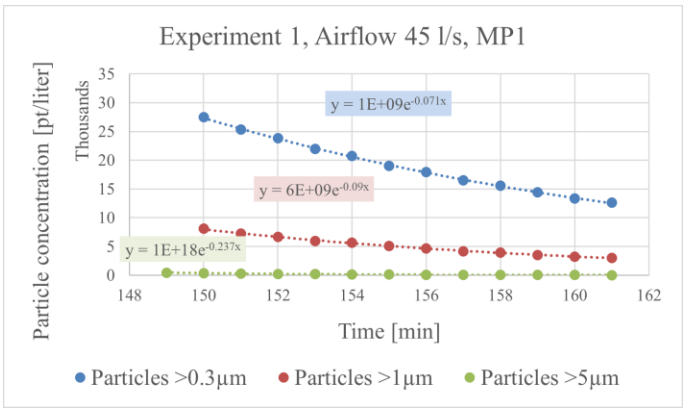

Experiment 1, Airflow 30 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 75315e-0.04x
y = 27309e-0.071x
y = 4248.9e-0.177x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

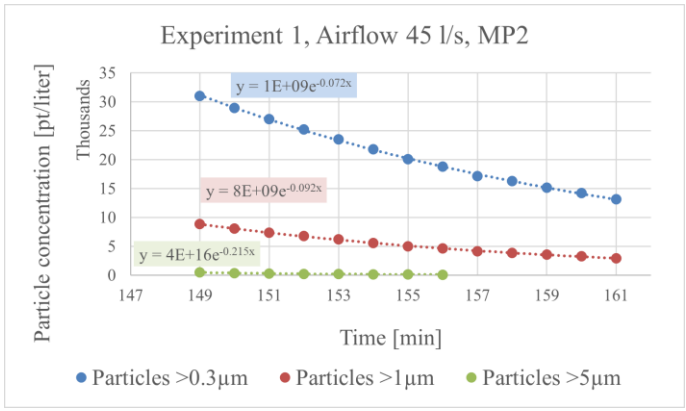

Experiment 2, Airflow 30 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 214471e-0.028x
y = 302416e-0.051x
y = 200819e-0.084x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

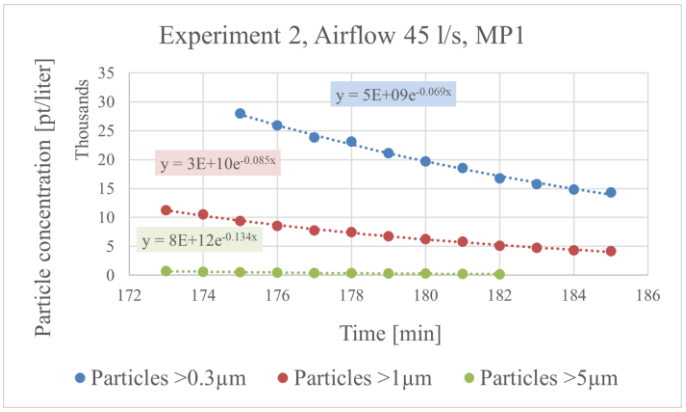

Experiment 2, Airflow 30 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 226763e-0.028x
y = 249640e-0.048x
y = 238559e-0.086x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

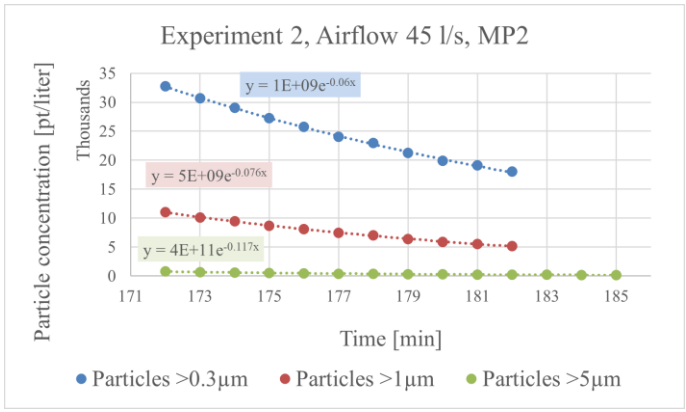

Experiment 3, Airflow 30 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 2E+26e-0.509x
y = 4E+32e-0.69x
y = 3E+28e-0.578x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

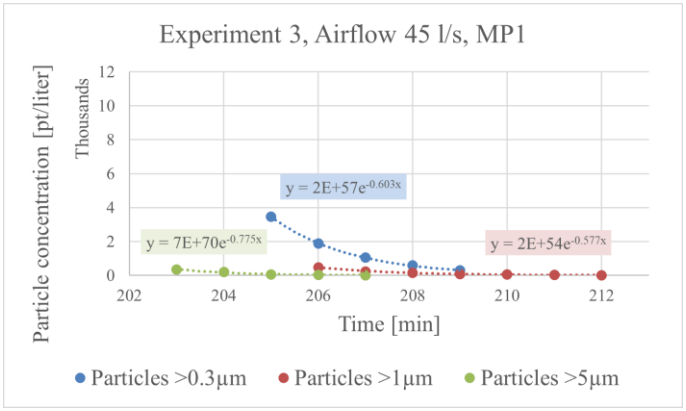

Experiment 3, Airflow 30 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 8E+27e-0.542x
y = 1E+31e-0.649x
y = 4E+27e-0.551x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

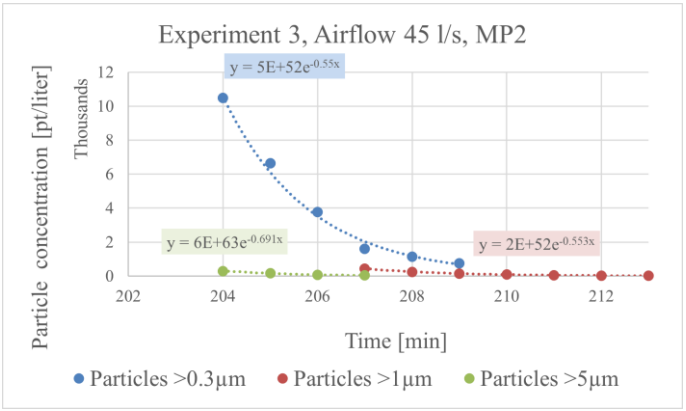

Experiment 1, Airflow 45 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 1E+09e-0.071x
y = 6E+09e-0.09x
y = 1E+18e-0.237x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm


Experiment 1, Airflow 45 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 1E+09e-0.072x
y = 8E+09e-0.092x
y = 4E+16e-0.215x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm


Experiment 2, Airflow 45 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 5E+09e-0.069x
y = 3E+10e-0.085x
y = 8E+12e-0.134x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

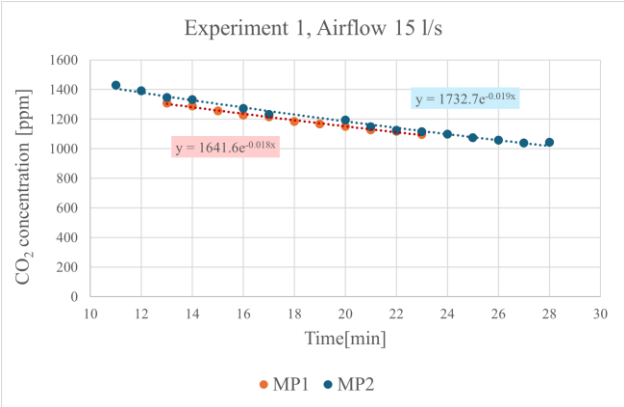

Experiment 2, Airflow 45 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 1E+09e-0.06x
y = 5E+09e-0.076x
y = 4E+11e-0.117x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

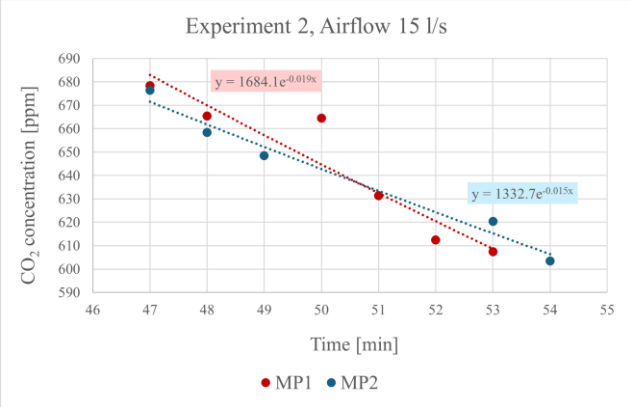

Experiment 3, Airflow 45 l/s, MP1
Particle concentration [pt/liter]
Thousands
y = 2E+57e-0.603x
y = 7E+70e-0.775x
y = 2E+54e-0.577x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

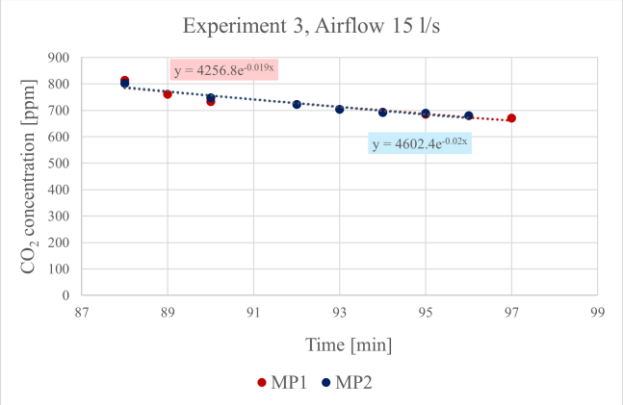

Experiment 3, Airflow 45 l/s, MP2
Particle concentration [pt/liter]
Thousands
y = 5E+52e-0.55x
y = 6E+63e-0.691x
y = 2E+52e-0.553x
Time [min]
Particles >0.3µm
Particles >1µm
Particles >5µm

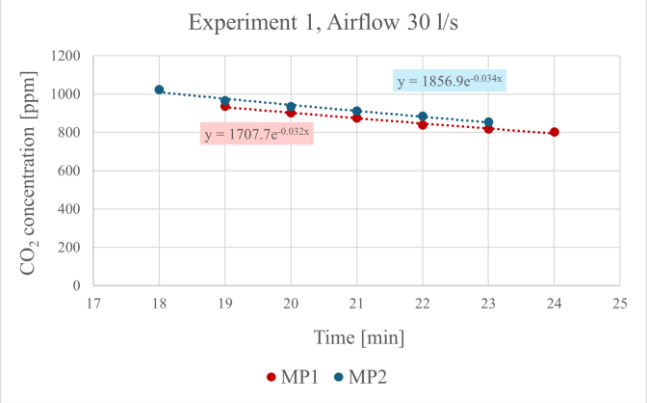
Appendix B

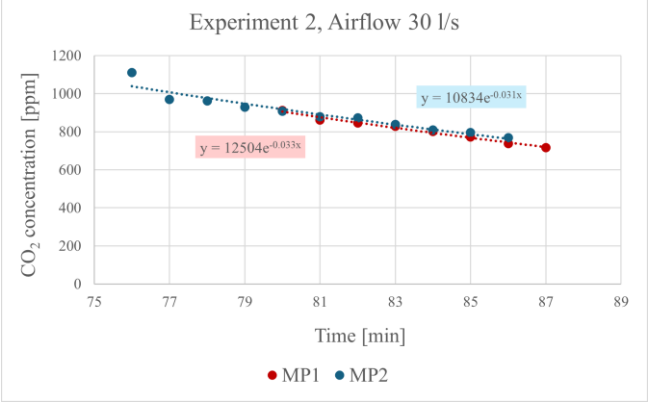
Detailed results from the Rotronic device for each experiment conducted at positions MP1 and MP2

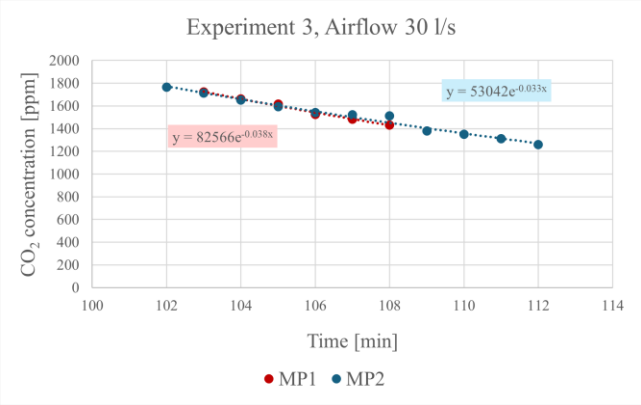


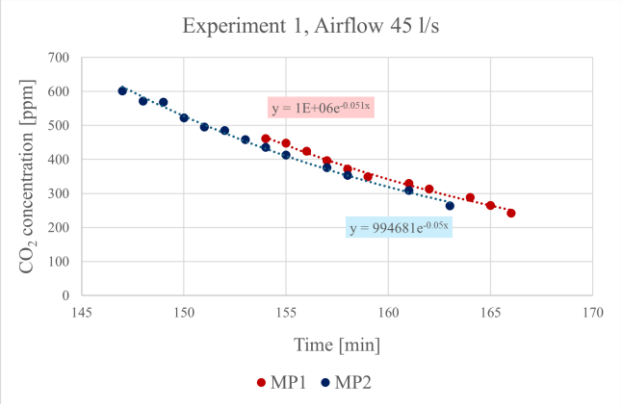


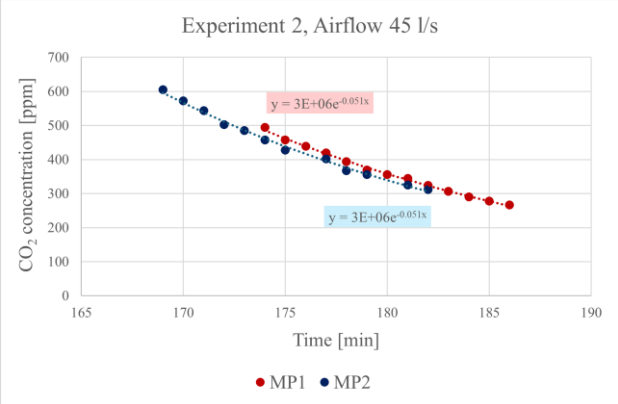


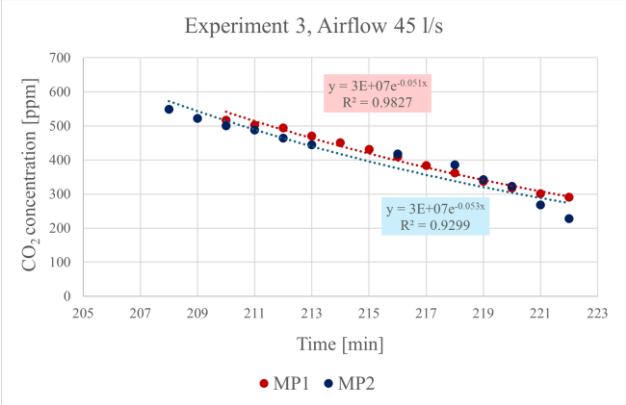





Experiment 3, Airflow 30 l/s
CO_2 concentration [ppm]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
100
102
104
106
108
110
112
114
Time [min]
y = 53042e-0.033x
y = 82566e-0.038x
MP1
MP2


Experiment 1, Airflow 45 l/s
CO_2 concentration [ppm]
700
600
500
400
300
200
100
0
145
150
155
160
165
170
Time [min]
y = 1E+06e-0.051x
y = 994681e-0.05x
MP1
MP2


Experiment 2, Airflow 45 l/s
CO_2 concentration [ppm]
700
600
500
400
300
200
100
0
165
170
175
180
185
190
Time [min]
y = 3E+06e-0.051x
y = 3E+06e-0.051x
MP1
MP2


Experiment 3, Airflow 45 l/s
CO_2 concentration [ppm]
700
600
500
400
300
200
100
0
205
207
209
211
213
215
217
219
221
223
Time [min]
y = 3E+07e-0.051x
R² = 0.9827
y = 3E+07e-0.053x
R² = 0.9299
MP1
MP2

Appendix C

Detailed results from the REHVA tool for both measles and seasonal influenza

Key Parameters

Input Parameters			
	Measles	Seasonal Influenza	
No of infectious persons in the room	1	1	-
Mask efficiency for susceptible persons	0	0	-
Mask efficiency for infectious person	0	0	-
Inactivation rate of the virus	0.63	0.80	h-1
Deposition to surfaces	0.3	0.3	h-1
Additional control measures	0	0	h-1

Measles

Airflow rate	Floor area	Height	Ventilation rate per floor area	Air cleaner CADR	Qunta emission rate	No of susceptible persons	Breathing rate	Occupancy time	Air change rate	Total first order loss rate	x steady state concentration	Average concentration	Quanta inhaled (dose)	Probability of infection	R event
l/s	A (m^2)	h (m)	L/(s m^2)	m^3/h	quanta/h	-	m^3/h	h	λ_v (h^{-1})	λ (h^{-1})	[]	quanta/m^3	quanta	-	-
0	17.4	2.7	0.00	0	4.29	1	0.6	8	0.00	0.9	0.87	0.08	0.41	**0.34**	**0.34**
5	17.4	2.7	0.29	0	4.29	1	0.6	8	0.38	1.3	0.90	0.06	0.30	**0.26**	**0.26**
10	17.4	2.7	0.57	0	4.29	1	0.6	8	0.77	1.7	0.93	0.05	0.24	**0.21**	**0.21**
15	17.4	2.7	0.86	0	4.29	1	0.6	8	1.15	2.1	0.94	0.04	0.20	**0.18**	**0.18**
20	17.4	2.7	1.15	0	4.29	1	0.6	8	1.53	2.5	0.95	0.04	0.17	**0.16**	**0.16**
25	17.4	2.7	1.44	0	4.29	1	0.6	8	1.92	2.8	0.96	0.03	0.15	**0.14**	**0.14**
30	17.4	2.7	1.72	0	4.29	1	0.6	8	2.30	3.2	0.96	0.03	0.13	**0.12**	**0.12**
35	17.4	2.7	2.01	0	4.29	1	0.6	8	2.68	3.6	0.97	0.02	0.12	**0.11**	**0.11**
40	17.4	2.7	2.30	0	4.29	1	0.6	8	3.07	4.0	0.97	0.02	0.11	**0.10**	**0.10**
45	17.4	2.7	2.59	0	4.29	1	0.6	8	3.45	4.4	0.97	0.02	0.10	**0.09**	**0.09**
50	17.4	2.7	2.87	0	4.29	1	0.6	8	3.83	4.8	0.97	0.02	0.09	**0.09**	**0.09**
55	17.4	2.7	3.16	0	4.29	1	0.6	8	4.21	5.1	0.98	0.02	0.08	**0.08**	**0.08**
60	17.4	2.7	3.45	0	4.29	1	0.6	8	4.60	5.5	0.98	0.02	0.08	**0.07**	**0.07**
65	17.4	2.7	3.74	0	4.29	1	0.6	8	4.98	5.9	0.98	0.02	0.07	**0.07**	**0.07**
70	17.4	2.7	4.02	0	4.29	1	0.6	8	5.36	6.3	0.98	0.01	0.07	**0.07**	**0.07**
75	17.4	2.7	4.31	0	4.29	1	0.6	8	5.75	6.7	0.98	0.01	0.06	**0.06**	**0.06**
80	17.4	2.7	4.60	0	4.29	1	0.6	8	6.13	7.1	0.98	0.01	0.06	**0.06**	**0.06**

Seasonal Influenza

Airflow rate	Floor area	Height	Ventilation rate per floor area	Air cleaner CADR	Qunta emission rate	No of susceptible persons	Breathing rate	Occupancy time	Air change rate	Total first order loss rate	x steady state concentration	Average concentration	Quanta inhaled (dose)	Probability of infection	R event
l/s	A (m^2)	h (m)	L/(s m^2)	m^3/h	quanta/h	-	m^3/h	h	λ_v (h^{-1})	λ (h^{-1})	[]	quanta/m^3	quanta	-	-
0	17.4	2.7	0.0	0	0.05	1	0.6	8	0.0	1.1	0.89	0.00	0.00	**0.004**	**0.004**
5	17.4	2.7	0.3	0	0.05	1	0.6	8	0.4	1.5	0.92	0.00	0.00	**0.003**	**0.003**
10	17.4	2.7	0.6	0	0.05	1	0.6	8	0.8	1.9	0.93	0.00	0.00	**0.002**	**0.002**
15	17.4	2.7	0.9	0	0.05	1	0.6	8	1.1	2.2	0.94	0.00	0.00	**0.002**	**0.002**
20	17.4	2.7	1.1	0	0.05	1	0.6	8	1.5	2.6	0.95	0.00	0.00	**0.002**	**0.002**
25	17.4	2.7	1.4	0	0.05	1	0.6	8	1.9	3.0	0.96	0.00	0.00	**0.002**	**0.002**
30	17.4	2.7	1.7	0	0.05	1	0.6	8	2.3	3.4	0.96	0.00	0.00	**0.001**	**0.001**
35	17.4	2.7	2.0	0	0.05	1	0.6	8	2.7	3.8	0.97	0.00	0.00	**0.001**	**0.001**
40	17.4	2.7	2.3	0	0.05	1	0.6	8	3.1	4.2	0.97	0.00	0.00	**0.001**	**0.001**
45	17.4	2.7	2.6	0	0.05	1	0.6	8	3.4	4.5	0.97	0.00	0.00	**0.001**	**0.001**
50	17.4	2.7	2.9	0	0.05	1	0.6	8	3.8	4.9	0.97	0.00	0.00	**0.001**	**0.001**
55	17.4	2.7	3.2	0	0.05	1	0.6	8	4.2	5.3	0.98	0.00	0.00	**0.001**	**0.001**
60	17.4	2.7	3.4	0	0.05	1	0.6	8	4.6	5.7	0.98	0.00	0.00	**0.001**	**0.001**
65	17.4	2.7	3.7	0	0.05	1	0.6	8	5.0	6.1	0.98	0.00	0.00	**0.001**	**0.001**
70	17.4	2.7	4.0	0	0.05	1	0.6	8	5.4	6.5	0.98	0.00	0.00	**0.001**	**0.001**
75	17.4	2.7	4.3	0	0.05	1	0.6	8	5.7	6.8	0.98	0.00	0.00	**0.001**	**0.001**
80	17.4	2.7	4.6	0	0.05	1	0.6	8	6.1	7.2	0.98	0.00	0.00	**0.001**	**0.001**

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

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