The Impact of ventilation systems on controlling the Spread of Covid-19

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A research into the effectiveness of ventilation systems in relation to the reduction of Covid-19 spread inside educational environments while not being to the detriment of the comfort of the occupants.

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Sincerely,
Xiao Guang Pan

Executive summary

The closure of educational institutions during the COVID-19 pandemic had significant negative impacts, emphasizing the need to keep schools open while ensuring safety. It is crucial to find ways to keep educational institutions open while ensuring the safety of students and staff. While measures such as mask-wearing and social distancing have been implemented. This thesis focuses on decentralized, SMART, and personal ventilation systems to understand their effects and develop effective strategies. Consequently, a central research question has been formulated, supported by four sub-questions. The main question is then as follows:

How can smart, personal or decentralised ventilation improve the ventilation system design to make it more COVID-19-proof while not negatively impacting the comfort of the occupants in an educational environment and being both practical and cost-efficient?

The report begins with a comprehensive literature study to establish a theoretical foundation and identify research gaps. It then proceeds to design and experimentation, which include testing four distinct situations: baseline, decentralized, SMART, and personal ventilation. Each situation aims to test the location under different conditions and gather data about how utilisation of the ventilation system and different parameters could affect the infection risk. First, the baseline is established, which serves as the reference point for comparison. Which is then followed by the other designs of the decentralised-, SMART- and personal ventilation. Simulations are primarily used, supported by measurements and surveys when possible. This was then followed by a discussion, where the results are examined, their implications and significance are compared to the literature.

In conclusion, the results from the simulations and measurements indicate that certain systems demonstrate more potential in mitigating infection risks and improving indoor conditions during airborne pandemics, specifically the SMART and PV systems when their design are optimally utilised. In contrast, the decentral ventilation unit proved to be less effective overall. Additionally, the findings underscore the importance of increasing ventilation rates and optimizing the location and distance of supply and exhaust units to minimize the spread of airborne viruses. Therefore, it can be concluded that while ventilation rate and strategic component placement are crucial in ventilation system design, a nuanced approach is necessary to strike a balance between reducing infection risks, meeting comfort requirements, and considering practical and economic factors.

Contents

1 Introduction

1.1 Context regarding the situation

The world has been impacted by Coronavirus Disease 2019 (COVID-19), a highly contagious viral sickness brought on by SARS-CoV-2, the coronavirus that causes severe acute respiratory syndrome. SARS-CoV-2 continues to wreak havoc around the world, with many countries experiencing multiple outbreaks of this viral illness that are primarily attributed to the emergence of mutant variants of the virus. Despite significant advancements in clinical research that have improved understanding of SARS-CoV-2 and the management of COVID-19, limiting the ongoing spread of this virus and its variations has become a matter of increasing concern. Similar to other RNA viruses, SARS-CoV-2 is susceptible to genetic evolution with the development of mutations over time, leading to mutant forms that may differ from its initial strains (Cascella M, et al., 2022).
In order to slow down the spread of the virus, governments have made the decision to lock down public places. For instance, the Dutch government has made the decision to temporary close establishments as restaurants, offices, schools, and other public gathering places (Tijdlijn van coronamaatregelen, 2022). However the lockdown did come with drawbacks for the economy and the people. The initial lockdown resulted in an 8.4% drop in the economy (Centraal Bureau voor de Statistiek, 2022).

Many schools around the world switched from in-person classroom teaching to online classes when the lockdown measures were put in place. Students around the world were severely disrupted by this change. In light of this Responses to Education Disruption Survey (REDS) was launched in August 2020 by Unesco in collaboration with the International Association for Evaluation of Educational Achievement (IEA) and the European Commission as part of the Global Education Coalition effort (Responses to Educational Disruption Survey [REDS], 2022).
According to a report by the Unesco, students have trouble understanding how well they are performing in their studies when they switch from traditional classroom instruction to online learning environments. The majority of teachers reported taking more time to modify and organise courses than they had before the disruption, and they were able to provide pupils with enough material to satisfy the curriculum's requirements. During the period of interruption, many teachers from several nations noted a decline in student learning and engagement (Meinck, etal., 2022).

Furthermore Students in REDS also discussed the detrimental effects on their emotional health. The majority of students missed interacting with their classmates, which made many feel more isolated. Many students were concerned about how the disruption might affect their study and future educational opportunities. The instructors also discussed the detrimental impacts on their health, their opinions on the policies put in place at the school, and their capacity to adapt to the changes. Numerous educators worldwide admitted they were worried about contracting COVID-19 at work. They frequently felt exhausted, their sleep patterns were disturbed, and they felt lonely while working from home. As one of society's fundamental pillars. As a result, when schools are closed, many students worldwide are affected. UNISEF estimates that since 2020, at least 463 million students were unable to participate in online learning (COVID-19 and children, 2022). Therefore, it is essential that the schools open as soon as possible.

1.2 Problem statement

The virus's mode of transmission was not fully understood in 2020, when Covid had only recently been discovered and was spreading rapidly. At the time, it was believed that airborne transmission was the predominant method of virus transmission. In order to reduce the spread through the air, the government and schools looked for solutions. Solutions proposed include mouth masks, lowering room occupancy limits, handwashing and vaccinations. Furthermore, research has been conducted on the transmission of infectious diseases through air. It has been established that the best method for usually controlling respiratory infectious diseases, such as COVID-19, is indoor ventilation (Morawska, et al., 2020; Chen, et al., 2021).

Despite the fact that ventilation was being lauded as the best method to combat COVID-19, current research offers no guidance on how to set up a ventilation system to apply it correctly. The most common types of ventilation systems found in classrooms are fully natural systems and systems that are a combination of natural and mechanical ventilation. These ventilation systems fall short of reducing the possibility of contagious diseases spreading through the air. This is because respiratory aerosols have distinct characteristics that set them apart from other indoor air pollutants, particularly in the way they are produced and dispersed by the human respiratory systems. Pathogen-laden aerosols are typically tiny droplets less than 100 micrometres in size. As a result, they can directly enter an exposed person's breathing zone within two metres or less. Furthermore these suspended aerosols also have the potential to travel large distances inside rooms (Ding, et al., 2022).

Another issue is that the existing standards and guidelines for ventilation in classrooms place an importance on perceived air quality and energy demand of the ventilation system. As a result, it's possible that the current standards and guidelines won't be able to provide designers with enough information to create classroom settings where the risk of airborne transmission is tolerably low. As a result, there is an urgent need to develop new or revise existing ventilation and indoor air quality (IAQ) standards for classrooms in schools. These standards and guidelines must consider respiratory droplets to be a significant indoor air pollutant that must be managed through adequate ventilation (McNeill, et al., 2022).

The final issue is that there are numerous types of ventilation systems and products available today. Including decentralised ventilation, smart ventilation, and personalised ventilation. A great deal of research is conducted on these products to determine how they work and how they influence the indoor climate. However, concrete research on how they perform in the face of a pandemic such as Covid-19 is currently lacking.

To conclude the problem statement, it has been made evident that there are many issues on the topic of ventilation and COVID-19. The common thread between the issues is the lack of information. Therefore the research conducted in this project will focus on bridging the information gap between the theoretical knowledge of the various areas and the practical application in the field.

1.3 Report Outline

Chapter 2 encompasses a comprehensive literature study, where relevant information related to various topics are gathered to lay the foundation for the research at hand. In Chapter 3, the primary research gap and research question are defined and formulated. Additionally, this chapter discusses the methodology and setup for both the measurements and simulations conducted in the study.

Chapters 4 and 5 serves as the core of this report, presenting the primary research findings. chapter 4 starts with setup of the baseline situation for the design in chapter 5 to compare to. Research is conducted in the form of measurement, simulation and surveys. In Chapter 5 the designs for each of the systems under investigation are presented and described with a discussion of the parameters taken into account. This chapter is organized around three distinct situations, that each present a design utilising a different ventilation system. The results obtained from simulations, measurements and the calculation of the risk of infection are presented in detail. Each situation is concluded with an assessment of its performance.

Chapter 6 comprises the discussion section, which encompasses several aspects. It explores the implications of the research findings in relation to the existing literature, identifies the limitations encountered during the study, and provides recommendations based on these limitations. Furthermore, insights for policy-makers are discussed, along with the contributions of this thesis and its suitability within the Building Technology Master's program.

Lastly, in Chapter 7, the thesis concludes by summarizing the key findings and outcomes of the research conducted.

2 Literature research

The first step in addressing the research problem is to conduct a comprehensive literature study. This will help to identify the gaps in knowledge and determine what research has already been conducted to develop potential solutions. Additionally, it will provide a solid foundation of knowledge for the research to build upon. By conducting a thorough literature study, we can gain valuable insights and ensure that the research is relevant, innovative and well-informed.

2.1 The setup of the literature research

In this chapter, we outline the setup of our literature research and the approach taken to investigate the various topics of interest. In total there 7 subsections to this chapter that tries to lay down a comprehensive theoretical foundation for the research. The 7 subsections are:

1. 2.2 Ventilation
2. 2.3 The literature
3. 2.4 Guidelines, standards and regulations
4. 2.5 Comfort
5. 2.6 Economics and practicality
6. 2.7 Products and systems
7. 2.8 The research parameters

The first subsection is dedicated to ventilation, which provides an overview of the importance of adequate ventilation in any indoor environment. This subsection includes the different types of ventilation systems and the impact of ventilation on Indoor Air Quality (IAQ).
The second subsection covers the literature, which is a critical component of any research. This section explores the existing literature relevant to the research topic, identifying gaps in the current knowledge and presenting an overview of the latest findings.
The third subsection examines the guidelines, standards, and regulations related to the research topic. This section provides an overview of the relevant regulations, standards, and guidelines. Which in turn are also analysed to find out if they were adequate in dealing with problems relating to airborne pandemics.
The fourth subsection focuses on the economic and practical aspects of the research topic. This section explores the practicality of implementing different ventilation systems, taking into account the costs and benefits associated with each.
In the fifth section the most important factors concerning the comfort of occupants are explained
The sixth subsection provides an overview of the different ventilation systems and products available on the market.
Finally, the seventh subsection covers the research parameters, which defines the parameters that are going to be used in the research and prepares the values that to be used for the parameters. Additionally, the parameters will be arranged in order of significance. By doing so the study will gain a clear understanding of the priorities and values that will inform the research. By covering all of these areas, the chapter on literature research lays down a comprehensive theoretical foundation for the research, providing a solid basis for the rest of the report.

2.2 Ventilation

The importance of ventilation in indoor environments cannot be overstated. Proper ventilation plays a critical role in maintaining indoor air quality, and is essential for ensuring the health and well-being of the occupants. Therefore this chapter aims to provide into the general aspects of ventilation to inform why it is important, including its history, applications, and the different types of ventilation systems available. In today's technology-based culture, people spend a majority of their time in artificial indoor settings such as buildings, cars, or other indoor environments. As such, it is crucial to create a suitable microclimate in these environments. The term microclimate here refers to both the thermal environment and indoor air quality, as these two elements are interconnected. Over-ventilating a room can lead to excessive heat loss, thereby affecting the comfort of people. In contrast, under-ventilating a room can cause unwanted pollutants and odours to linger, negatively impacting the indoor environment (Awbi, 2003). Therefore, when designing a ventilation system for a space these two elements must be taken into account as they are essential to the wellbeing and comfort of people who are using the space.

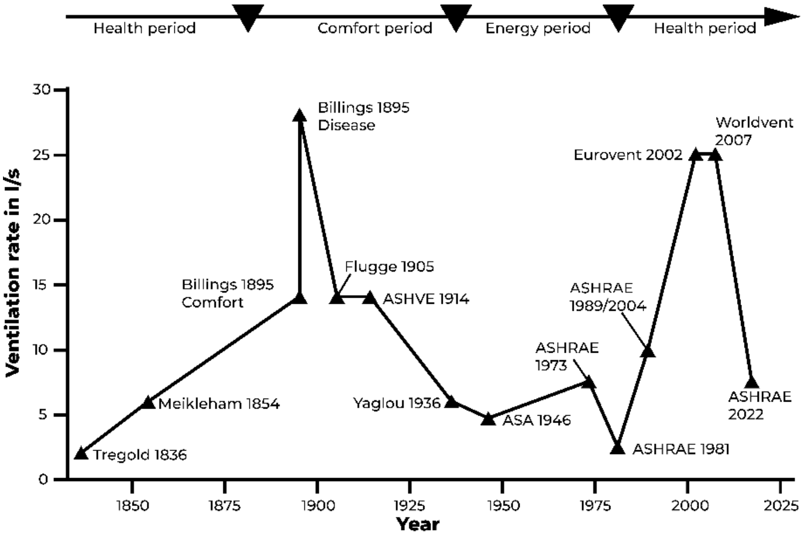


Figure 1 Timeline of ventilation rate per person; Adapted from Nielsen, P., & Li, Y. (2019). Ventilation. In Elsevier eBooks (pg. 346)

As illustrated in Figure 1, the focus of indoor ventilation has undergone multiple shifts over time. Historically, people have always prioritised living in safe, comfortable, and healthy environments. In 1836, Tregold made the first quantitative ventilation recommendation, which primarily focused on carbon dioxide dilution. Following that, in the 19th and 20th centuries, advancements in hygiene reduced the need for high ventilation rates. In the later half of the 20th century, the focus shifted towards energy-saving. However, these changes were not without consequences. Some were beneficial, such as improvements in thermal insulation, advanced air-conditioning and heating system designs. Negatively as a result the indoor air quality has deteriorated, especially in air-conditioned buildings. In fact, the term "sick building syndrome" has become synonymous to the energy-saving age (Robertson et al, 1985). With the advancements in building technology and ventilation systems, there have been significant changes in ventilation rates for buildings. These rates have varied widely over time, from an all-time low of 2,5 l/s per person to an all-time high of around 30 l/s per person. However, the focus has shifted back towards health, wellbeing, and sustainability. Currently, the recommended ventilation rate is around the 6,5 – 8,5 l/s per person, as per the guidelines set forth by organizations such as ASHRAE. It is important to note that this recommended rate may vary based on factors such as the type of building, its occupancy, and its use (ASHRAE, 2022).

When it comes to designing ventilation systems, there are three basic elements to consider: ventilation rate, airflow direction, and distribution pattern. Of these three, the ventilation rate is arguably the most important one. It's the primary element of ventilation that determines the amount of fresh air supplied to a space. Airflow direction and distribution pattern are also crucial elements, but they come after the ventilation rate in terms of importance (Nielsen et al., 2019). The effectiveness of air distribution plays a vital role in the efficient utilization of the supplied ventilation rate. Even if the air distribution is perfect, if the driving force is weak or some part of the system is not functioning correctly, the ventilation rate will be low, and the ventilation will not be effective. This is why most building ventilation standards focus on minimum ventilation rates (Nielsen et al., 2019). While these three make up the basic elements of ventilation, there are other various factors of the indoor environment to consider that these three influence. Such as temperature; humidity; CO2 concentrations; particle amount in the air and the type of ventilation system.

In terms of ventilation system types there are four main types of ventilation(Awbi, 2003):

1. Natural inlet and outlet: This type of ventilation system relies solely on natural forces such as wind and thermal buoyancy to supply fresh air and expel stale air. Fresh air enters the building through openings like windows and doors while stale air exits through outlets like chimneys or vents. This is the most basic and low-cost type of ventilation system, but it is highly dependent on external weather conditions.

2. Natural inlet, mechanical outlet: In this type of ventilation system, fresh air enters the building naturally through openings while stale air is mechanically expelled using exhaust fans or similar devices. This system is more reliable than natural inlet and outlet, but it still relies on natural forces for air supply.

3. Mechanical inlet, natural outlet: In this system, fresh air is mechanically supplied using fans or similar devices while stale air exits the building naturally through openings. This type of ventilation system is often used in industrial settings where air quality is a major concern and mechanical ventilation is needed to meet the required air change rate.

4. Mechanical inlet and outlet: This is the most advanced type of ventilation system, where both fresh and stale air are mechanically supplied and expelled using fans or similar devices. This type of system can provide consistent and reliable air quality regardless of external weather conditions. This type of system is the base within a centralized ventilation system. This type of ventilation system is commonly found in commercial buildings, large residential buildings, and public facilities such as hospitals and schools.

Additionally, mechanical ventilation systems have an easier time reaching steady state conditions inside rooms compared to natural ventilation systems. This is because mechanical systems are designed to deliver a specific airflow rate consistently, while natural systems are also designed to deliver a certain amount of fresh air to a room, due to the unpredictable outdoor conditions such as wind and temperature this less consistent(Awbi, 2003).

In summary, the analysis of ventilation has underlined the persistent challenge faced by designers of such systems - the lack of a universal solution for an optimal design. Each case requires careful consideration of its unique factors, rendering a one-size-fits-all approach unfeasible. However, it has become evident that specific factors hold a pivotal role in determining the design of a ventilation system. Chief among these is the ventilation rate, which constitutes the most influential basic element, shaping the feasibility and scope of the entire system. Moreover, mechanical systems offer greater capability to establish steady-state ventilation conditions compared to natural ventilation, as they are less reliant on unpredictable airflows. Ultimately, this study's defined parameters will inform the development of future ventilation designs.

2.3 The literature

2.3.1 Information about the COVID-19 virus

The coronavirus responsible for the COVID-19 belongs to the Coronaviridae family of viruses. Additionally, it was discovered that this virus's genetic makeup was remarkably similar to that of the SARS coronavirus (SARS-CoV), which was responsible for the pandemic in the years 2002–2003. Leading to the virus being named as the severe acute respiratory syndrome coronavirus-2 [SARS-CoV-2] (Gorbalenya et al., 2020).

Figure 2 depicts the four main structural proteins that the virus is composed of: the spike (S), membrane (M), envelop (E), and nucleocapsid (N) proteins. As depicted in figure 2 The spike protein (S) extrudes from the surface of the virus and allow the virus to bind to human cells and enter them. Thereby initiating the infection process (Knowlton, 2019).

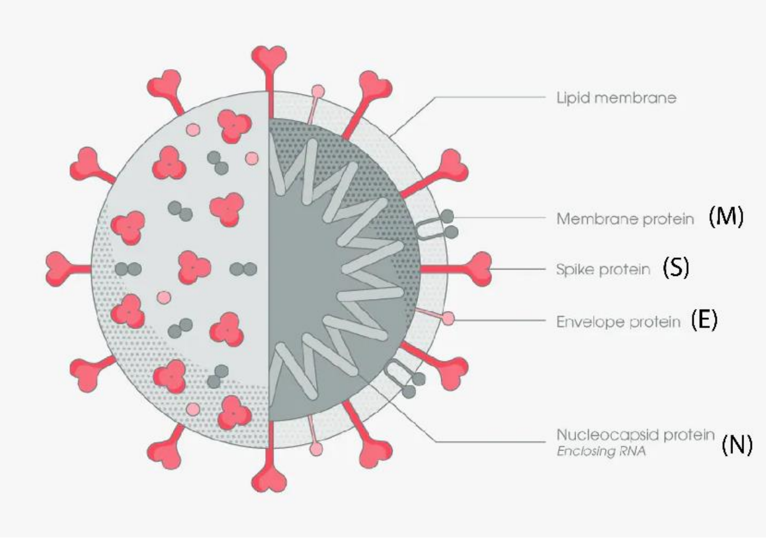


Figure 2 Structure of COVID-19 virus; Adapted from Celticdiagnostics. (n.d.). COVID-19 Research tools. celticdiagnostics.com.

The virus enters the body through respiratory aerosols and binds to nasal epithelial cells in the upper respiratory tract. The Angiotensin-converting enzyme 2 (ACE-2) is the primary host receptor for the COVID-19 virus entering cells. This enzyme is found in abundance in adult nasal epithelial cells. The virus will then reproduce locally before moving to other locations, most notably the lungs. During this replication of the virus, the body’s immune response is minimal. Furthermore, despite having a low viral load at this phase, the infected person is already contagious (Parasher 2021).

As it is shown in figure 3, while the size of the virus remains the same, the particle carrying it can vary in size. This phenomenon was demonstrated through an experiment using the Malvern Spraytech spray droplet measurement system, which was employed to determine the size distribution of respiratory droplets produced by coughing and speaking. Analysis of the data showed that coughing produced two types of droplets: large droplets measuring between 100 and 1000 µm in diameter, and small droplets measuring between 1 and 100 µm in diameter, with the latter being more prevalent. Conversely, the small droplets were detected during speech (Somsen et al., 2020; Dhand et.al., 2020).

Figure 3 The relative size of particles; From Ang, C. (2020, October 10). The Relative Size of Particles. Visual Capitalist.

The resulting size differences in the particles that can carry the virus itself, also has an effect on the duration which the virus can stay airborne. Three studies by Somsen et.al; Ng et.al; Van Doremalen et.al, have found that the particles depending on the size can stay in the air ranging from 9 minutes to 9 hours. Visible large drops around 100 to 500 µm do not travel far before their trajectory bends down due to gravity to rapidly fall onto the ground within 1 s. While the smaller aerosolised particles with the size of 1 µm and less stay longer in the air. Figure 4, on the next page, shows the relative sizes of the particles where the virus can travel on(Somsen et.al; Ng et.al; Van Doremalen).

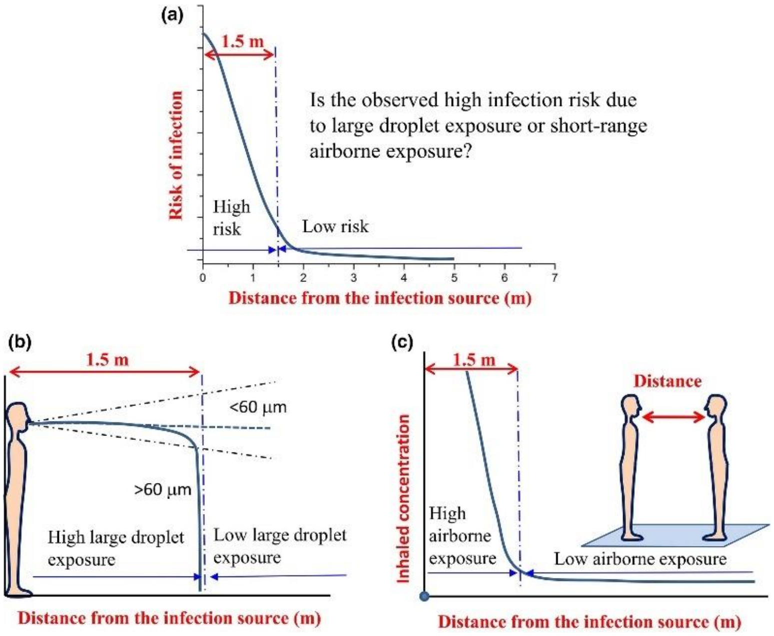


Figure 4 expose risk particle size; From Liu et al., (2017) Airborne transmission of expiratory droplets. Wiley Online Library.

As shown in Figure 4, a study by Liu et al. (2017) also highlights that the highest risk of airborne infection by large droplets occurs within 1.5 meters of the source. Beyond this distance, the risk of infection from larger droplets decreases. Since the outbreak of the COVID-19 pandemic in late 2019, the virus has undergone multiple mutations, resulting in increased infectivity with each variant. At the time of writing this report (28th April 2023), the prevalent strain is the Omicron XBB variant. The level of infectivity of the virus is measured in quanta, which is the number of virus particles that can transmit an infectious disease. A single quanta represents the minimum amount of virus particles required to initiate an infection in a susceptible individual. Dai et al. (2022) conducted a study on the quanta values of three COVID-19 variants, including the Alpha, Delta, and the current Omicron variant. The results showed that the q value are between 89–165 h^{-1} for the Alpha variant,312–935 h^{-1} for the Delta variant and lastly 725–2,345 h^{-1} for the Omicron variant (Dai et al., 2022). These values indicate the pressing need to develop methods to effectively deal with the COVID-19, as with each passing virus mutation the infectivity increases manyfold.

In conclusion, the findings of studies on the novel Coronavirus underscore the potential dangers associated with inadequate ventilation in enclosed spaces, highlighting airborne transmission as the predominant mode of transmission. Furthermore, it has been revealed that infectious particles can linger in the air for extended durations, ranging from 3 minutes to 9 hours depending on their size, emphasizing the pressing need for ventilation designs that effectively reduce the amount of stagnant air pockets. Moreover, it is noteworthy that the quanta, which represents the quantity of virus particles capable of transmitting the disease, has been observed to increase with each new variant. In this study, the infection risk calculation uses these three variants, aiming to provide insights into the potential impact of ventilation systems during different stages of the pandemic.

2.3.2 Covid 19 calculating methods

In 1955 William Firth Wells publicised his book ‘Airborne contagion and air hygiene – An ecological study of droplet infections’. Which laid down the basis of what is now considered airborne transmission research. This book is structured in two main sections. The first section of this book covers the physics, chemistry, and biology of droplets and droplet nuclei, as well as the physics, chemistry, and biology of infection and disinfection. Also highlighted are the physiology and parasitology of droplet nuclei contagion. The second section of the book delves deeper into the principle and methods of airborne infection prevention by explaining the forces responsible for the infection (Wells, W. F., 1955). Which served as the foundation for the Wells-Riley equation, a formula that later on was developed to estimate the risk of airborne infection.

A measles outbreak in 1974 served as the foundation for the airborne transmission model, that is currently known as the Wells-Riley model. This specific pandemic was significant because it spread quickly through a school where 97% of the students were immunised when they were under 1 years old. It was presumed that the virus was recirculated by the ventilation system (Riley, 1978). Based on the works of Wells, Riley et.al produced a model that could quantify the probability of infection.
This is model shown in equation 1:

$$(1) : \quad \mathrm{P} = 1 - \mathrm{e}^{-\frac{\mathrm{Ipqt}}{\mathrm{Q}}}$$

Where:

- P is the probability of infection for susceptible,
- I is the number of infectors,
- p is the breathing rate per person (m3/s),
- q is the quantum generation rate by an infected person (quanta/s),
- t is the total exposure time (s),
- Q is the outdoor air supply rate (m3/s).

However this model makes a couple of assumptions for it to work. The assumptions made within in this model are:

- Children who have the measles are contagious to others for three days before symptoms appear.
- It is believed that measles is only transmitted through the air and that infection results in lifelong immunity (Wells, W. F., 1955) hence reducing the number of susceptible people exposed to it (Langmuir, A.D., 1951). The droplet nucleus concept, which postulates a random distribution of infectious particles in enclosed space air, was accepted (Riley, R. L. et al., 1961)
- Throughout the course of the school day, a steady-state concentration of airborne illness is assumed (Riley, 1978).
- Finally, it is predicted that the number of children that are susceptible will be depleted. This applies directly to the circumstances surrounding the epidemic under consideration and is not a generalisation that might apply to every measles epidemic. In the entire school, the index case infected no fewer than 28 secondaries. William Firth Wells referred to this ratio as the infectious potential and stated that it must be greater than unity in order for a chain reaction to take place, leading to an epidemic(Wells, W. F., 1955). The ratio C/I in this case was an extremely high 28. As a result, it was anticipated that during the second generation, children's

> exposure to infectious agents would increase by a factor of 28 and the epidemic chain reaction would get off to an incredibly powerful start(Riley, 1978).

While it is not uncommon to make assumptions in mathematical models, not all cases can rely on such assumptions to accurately calculate the risk of infection. In order to make the model more applicable to a wider variety of situations, Rudnick et al. developed the Rudnick & Milton model for airborne infection risk, which is based on the Wells-Riley model. This model eliminates the need to rely on previously made assumptions and shifts it from requiring a steady-state condition to being based on CO2 levels. The Rudnick & Milton model works by determining the fraction of inhaled air that has already been exhaled by someone in the building (rebreathed fraction) and uses CO2 concentrations as a marker for exhaled-breath exposure. This article has therefore proposed an alternate equation that addresses these issues. Additionally, this article derives a non-steady-state variant of the Wells-Riley equation that can be used in poorly ventilated locations where outdoor air supply rates can be assumed to be constant. As a result this led to the following equation (2):

(2) Old (Wells-Riley): $\mathrm{P} = 1 - \mathrm{e}^{-\frac{\mathrm{Ipqt}}{\mathrm{Q}}}$ → New (Rudnick-Milton) : $\mathrm{P} = 1 - \mathrm{e}^{-\frac{\mathrm{fIqt}}{\mathrm{n}}}$

Where:

- P is the probability of infection for susceptible,
- I is the number of infectors,
- f is equivalent to the fraction of indoor air that is exhaled breath
- q is the quantum generation rate by an infected person (quanta/s),
- t is the total exposure time (s),
- n is the amount of people in the room

The main change in this equation is the factor *p* to *f* and the factor *Q* to *n*. Where n is the amount of people in the room and f is equivalent to the fraction of indoor air that is exhaled breath, which is also the rebreathed fraction. This is calculated with:

$$\mathrm{f} = \frac{\mathrm{C} - \mathrm{C}_0}{\mathrm{C}_\mathrm{a}}$$

Where:

- C is the volume fraction of CO2 in indoor air
- Co is the volume fraction of CO2 in outdoor air
- Ca is the volume fraction of CO2 added to exhaled breath during breathing

However, the use of CO2 as a proxy for infectious airborne particles is not certainly valid. Recent studies have debated whether the use of CO2 is an accurate representation of the indoor environment in the context of airborne transmission. Studies advocating for the use of CO2 as a proxy include recent works by Peng et al.(2021) and Di Gilio et al.(2021), While in contrast a study conducted by Zhang et.al concluded that no definitive relation between the indoor particles and CO2 concentration was observed. The study by Peng et al. analysed the relationship between the level of activity and the amount of exhaled CO2, and expressed it in a mathematical model to predict the probability of infection (Peng et al., 2021). Figure 5 illustrates that there is a relationship between the level of activity, the amount of exhaled CO2, and the probability of infection. When the level of activity increases, more potentially infected air is inhaled, leading to a higher probability of infection. While the parameters used in the mathematical model may not be trivial for the general public to estimate and implement, other authorities can offer assistance in developing tools or methods based on the model to reduce the spread of COVID-19. Nevertheless, even if the model is too complicated and the surrounding parameters unknown, the CO2 level and physical intensity and vocalization level of activities can be kept as low as practically feasible in indoor environments would prove to be adequate. This led to the conclusion that CO2 can indeed be used as a proxy to represent the indoor environment.

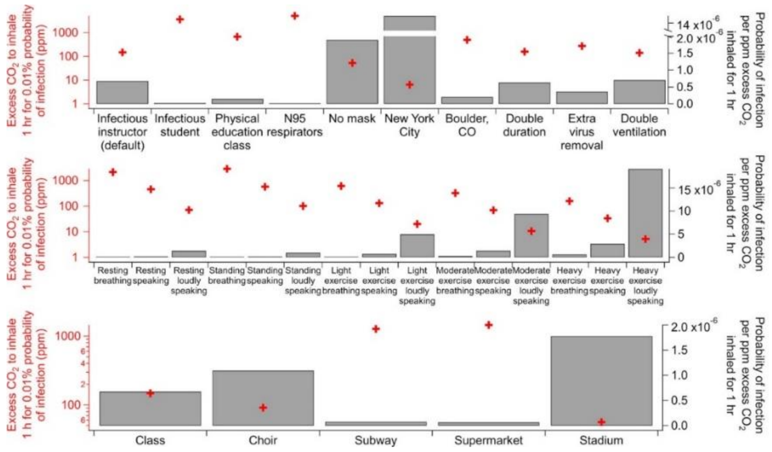


Figure 5 Relation between activity level and CO2 levels ; From Peng et al., (2021). Relation between activity level and CO2 levels. Environmental Science and Technology

Further evidence supporting the use of CO2 as a proxy for airborne transmission came from a study conducted by Di Gilio et al. This study was based on the works of Rudnick and Milton (2003) and Peng and Himenez (2021). It involved surveying eleven classrooms located in the Apulia Region in the south of Italy to monitor CO2 levels inside the classrooms. The objective of the surveillance was to assess the effectiveness of ventilation guidelines and suggest corrective actions to limit the risk of COVID-19 transmission. These results were compared to CO2 limits recommended in the literature and by the World Health Organization (WHO). A study by Marr et al., (2020) recommended that CO2 limits to be set at 700 PPM inside classrooms and 550 PPM in hallways, which are more stringent than the WHO guidelines of 1000 PPM (WHO Regional, 2000). The research conducted by Di Gilio et.al concluded that the development and integration of customized ventilation guidelines based on real-time CO2 concentrations improved the air exchanges inside rooms, while keeping the comfort of the occupants adequate. Despite that, there were still classrooms that didn't stay below the limits, which can be attributed to the structural limitations of the building.

Concluding, it can be stated that while there is not an abundance of evidence to suggest that CO2 is a perfect proxy for infectious airborne particles, it remains a valuable tool for measuring the indoor environment and estimating the probability of infection during a time when such tools are necessary. Therefore for this research thesis it would be an adequate tool to measure and calculate the possibility of infection using the Rudnick & Milton method.

2.3.3 CO2 production of humans

In order to effectively apply the Rudnick and Milton formula for the assessment of infection risk in indoor environments, it is important to gather knowledge regarding the carbon dioxide (CO2) production by humans. Therefore, relevant literature was examined to accurately determine the CO2 production associated with human respiration.

Under normal circumstances, it has been found that a healthy adult human at rest inhales and exhales approximately 4 to 9 litres of fresh air per minute, as indicated by Buteyko (2021). The amount of carbon dioxide exhaled during this process is estimated to be around 3.8% or 38000 parts per million (PPM), as mentioned by CO2 Meter (2022). These findings are supported by various articles, including those by Ejaimi et al. (2016), Persily et al. (2017), and Pleil et al. (2021).

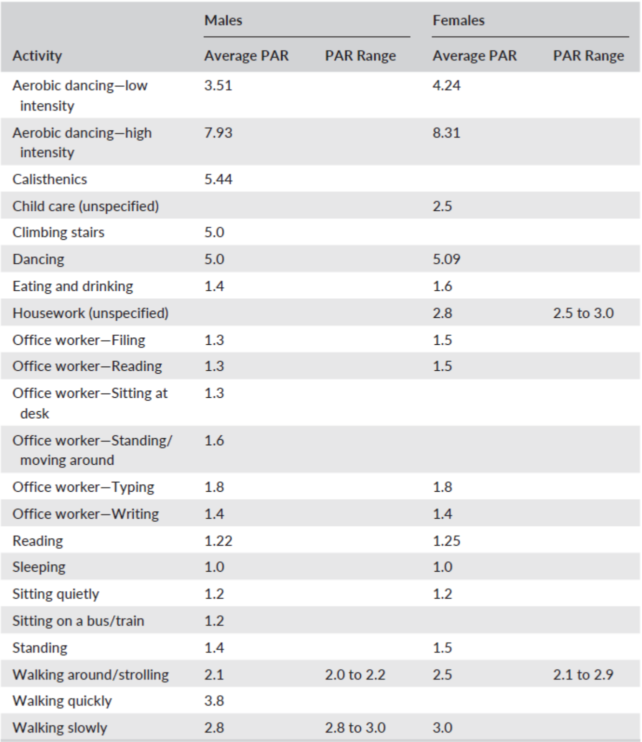
Ejaimi et al. (2016) provided a table in their article, which is presented as Table 1, containing information about the composition of inhaled and exhaled air. According to their article, the CO2 concentration exhaled in a single breath ranges from 4% to 5.3%. This concentration is slightly higher than the value reported by the CO2 meter source. Additionally, Persily et al. (2017) reported that the CO2 concentration in exhaled breath is approximately 5%, along with an exhaled breath volume of approximately 0.5 litres per breath and a respiration rate of 12 breaths per minute, resulting in an exhaled air volume of approximately 6 litres per minute.

Gas	Amount in inhaled air	Amount in exhaled air
Oxygen	20,84 %	13,6 – 16 %
Carbon Dioxide	0,04 %	4 – 5,3 %
Nitrogen	78,62 %	78,04 %
Water vapour	Small amount (0,05%)	Large amount
Argon	0,96 %	1 %

Table 1 Breath composition; Ejaimi et al., (2016). Airway Assessment and Management. Annals of International Medical and Dental Research.

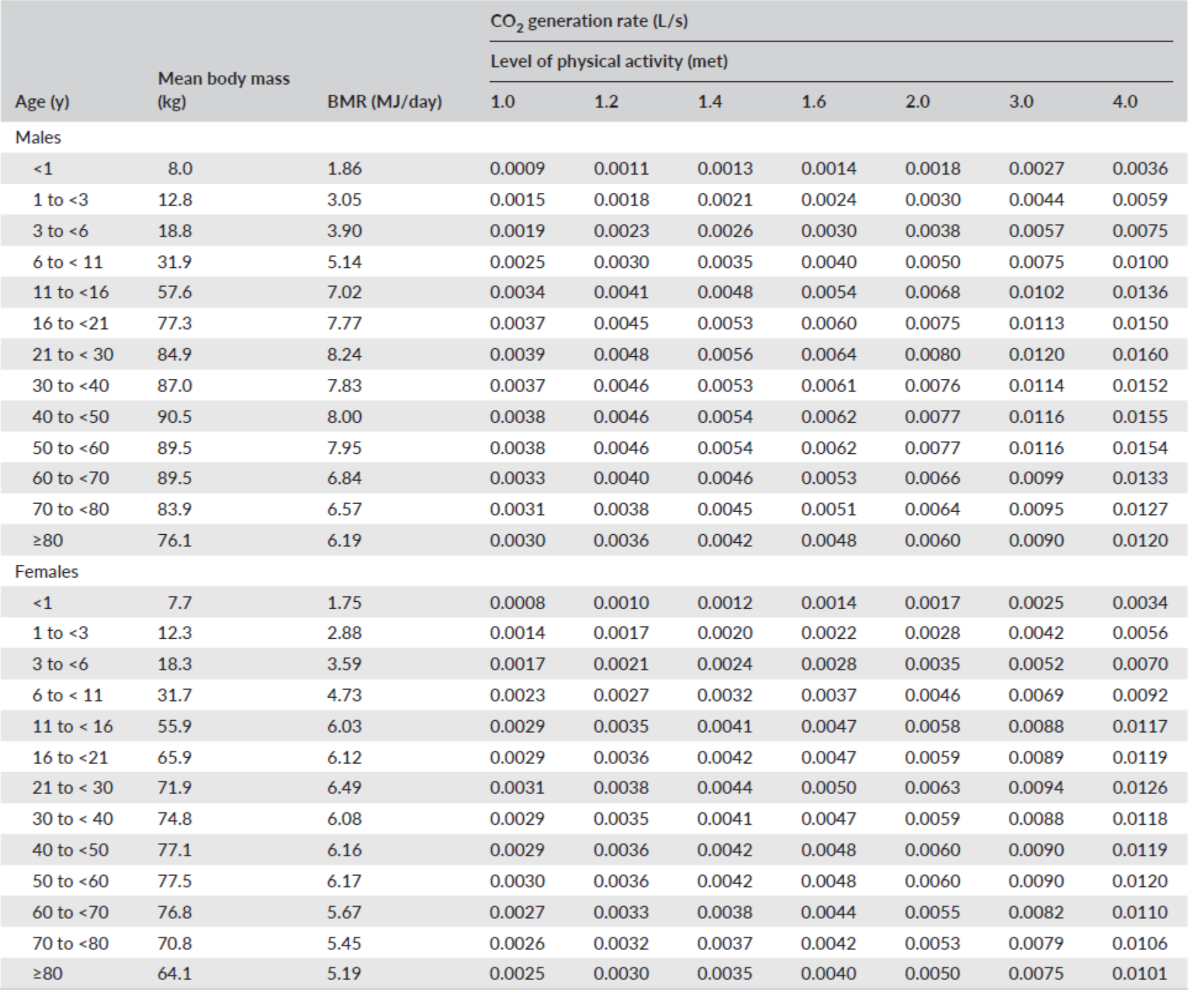
The article by Pleil et al. (2021) adopted a slightly different approach in understanding CO2 generation. This study described the CO2 generation of people and also associated it with the physical activity level of the individuals. Their findings indicated that higher activity levels corresponded to increased CO2 generation in individuals. Within this article two tables which are provided on the next page, which are Table 2 that presents the different levels of activity, while Table 3 provides the corresponding CO2 generation for each age group along with their respective activity levels. From these tables what can interpreted is that students (age group 21 to 30) with an activity level of 1,3 (sitting) generate 0,0056 L/s of CO2. Which is equal to 5,6 % of the 6 litres of exhaled breath.

Overall, the literature indicates that the carbon dioxide (CO2) production of an individual at rest varies between 3.8% and around 5,5%, influenced by factors such as age, gender, and activity level. In the context of this study, a conservative estimate of 5% will be adopted as the CO2 production rate by individuals. This value strikes a balance between underestimating the CO2 levels in the room, which would present an too favourable scenario, and accounting for the potential influence of more intense activities that may result in higher CO2 concentrations.



Activity	Males Average PAR	 PAR Range	Females Average PAR	 PAR Range
Aerobic dancing—low intensity	3.51		4.24	
Aerobic dancing—high intensity	7.93		8.31	
Calisthenics	5.44			
Child care (unspecified)			2.5	
Climbing stairs	5.0			
Dancing	5.0		5.09	
Eating and drinking	1.4		1.6	
Housework (unspecified)			2.8	2.5 to 3.0
Office worker—Filing	1.3		1.5	
Office worker—Reading	1.3		1.5	
Office worker—Sitting at desk	1.3			
Office worker—Standing/ moving around	1.6			
Office worker—Typing	1.8		1.8	
Office worker—Writing	1.4		1.4	
Reading	1.22		1.25	
Sleeping	1.0		1.0	
Sitting quietly	1.2		1.2	
Sitting on a bus/train	1.2			
Standing	1.4		1.5	
Walking around/strolling	2.1	2.0 to 2.2	2.5	2.1 to 2.9
Walking quickly	3.8			
Walking slowly	2.8	2.8 to 3.0	3.0	

Table 2 levels of activity; The physics of human breathing. Institute of Physics



			CO$_2$ generation rate (L/s)						
			Level of physical activity (met)						
Age (y)	Mean body mass (kg)	BMR (MJ/day)	1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

Table 3 levels of CO2; The physics of human breathing. Institute of Physics

2.3.4 Reducing Covid-19 spread in classrooms through ventilation

In light of the COVID-19 pandemic, authorities worldwide have sought ways to reduce the transmission of the virus. Where proper ventilation has been highlighted as an important measure. Several recent studies, including those by Ding et al. (2022), Izadyar et al. (2022), and Chen et al. (2021), have investigated the effectiveness of various ventilation strategies. The term ventilation strategies refers to elements such as the method of distributing air inside the room and the ventilation rate which can be provided by ventilation systems such as mechanical, mixed and natural ventilation. These strategies were evaluated on capability on reducing the infection risk of COVID-19. Based on this investigation recommendations have been made on how to improve the indoor environment. Furthermore in this subsection the use of masks is also discussed and how it affects the research at hand.

The collection of data pertaining to the current ventilation strategies employed in classrooms constitutes a fundamental initial phase in this investigation. This data acquisition serves to facilitate a systematic evaluation of the prevailing conditions and the subsequent recommendation of measures aimed at enhancing indoor air quality. This approach is supported in the work of Ding et al. (2022), who conducted a review of literature encompassing classrooms situated across various continents, including Europe, the Americas, and Asia. The research conducted by Ding et al. sheds light on the limitations associated with commonly employed mixed and fully natural ventilation systems when it comes to effectively mitigating airborne transmission within classrooms. The study reveals that these ventilation systems, which are reliant on fluctuating external airflows, prove to be inadequate in ventilating and removing infectious particles. This inadequacy has impact on the short-range and long-range transmission of the virus. ventilation strategies employed in classroom ventilation systems predominantly adhere to the steady-state, well-mixed model, which proves effective in managing long-range transmission but falls short in addressing the short-range transmission.

A similar study was conducted by Izadyar et al. (2022). A significant number of articles were reviewed to evaluate the effectiveness of ventilation strategies in both clinical and non-clinical settings. From the examination into natural ventilation and mixed mechanical ventilation, it became apparent that in both clinical and non clinical settings the natural and mixed mechanical ventilation were not adequate in providing a healthy indoor environment. As it was found that in hospitals using these types of systems had ten times the concentration in terms of bio aerosols compared to a mechanically ventilated hospital (Stockwell, 2019). Similar conclusions can be drawn in non-clinical settings, as evidenced by two studies by Irga et al. (2016) and Li et al. (2014). Irga et al. examined the impact of different ventilation strategies on the concentration of pollutants in several office spaces. The study recorded higher concentrations of pollutants in naturally ventilated office spaces compared to office buildings with mixed mechanical ventilation and mechanical ventilation. While Li et al.(2014) highlighted the problems associated with natural ventilation in removing indoor pollutants, namely indoor airflow patterns and wind direction, which severely affect the efficiency of natural ventilation in removing pollutants.

Other findings from this study are drawn from the examination into mechanical systems. Generally a lot of attention is paid to the air change rates (ACH) of rooms and the ventilation rates per person. However these are not the only important factors that play a large role in reducing the spread of airborne particles in rooms (Cheong et al. 2018). As there is a limit on how more effective a mechanical ventilation system can be become by increasing the ACH. Studies have shown that the size of contaminants has a considerable impact on mechanical ventilation's system performance (Faulkner et al., 2015). Research indicates that the impact of ACH on particle concentration is dependent on the virus-laden droplet size (Ren et.al, 2021). Increasing the ventilation rate can reduce the concentration of small particles (<40 µm); however, it does not decrease the concentration of larger particles (D > 40 µm) to same effect. In a 2019 study by Jaio et al., while it was found that while MV is generally effective, its effectiveness is dependent on a variety of other factors, such as the amount of supply and exhaust openings, their location in relation to the source of the pollutant and the distance to the source of the pollutant. Furthermore, Aganovic et al. (2019) recommends that to control the spread of virus-laden respiratory particles and lower the risk of infection, ventilation strategies such as Under Floor Air Distribution (UFAD), Displacement Ventilation (DV), and Protected Occupied Zone Ventilation (POV) should be integrated further into room designs as these methods have proven to be effective in mitigating airborne transmission (Xiaoping et al., 2011). It is important to acknowledge that while MV systems have been shown in literature to reduce the spread of COVID-19 in various circumstances, these are not a flawless solution for all scenarios due to their dependence on numerous factors and design choices.

Lastly, other methods to reduce the amount of particles in the air is to use filters, masks and controlling relative humidity. Studies have shown that they are capable to block the particles from becoming airborne. Both smaller and larger particles were blocked from becoming airborne (Howard et al., 2021). Other studies have found that HEPA filters placed close the source of pollutants could effectively reduce the amount of virus laden airborne particles (Akbari et al., 2019). Furthermore, it was found that relative humidity between 40 – 60% to promote healthier conditions compared to when the relative humidity was either below 40 or higher than 60% (Verheyen et al., 2022).

In conclusion, it can be gathered from this subsection that natural ventilation is not suitable for dealing with airborne transmission of viruses due to its inconsistent and unpredictable nature. On the other hand mechanical ventilation has proven to be more effective, but the literature suggests that the emphasis on air change rate in ventilation system design is excessive. Other factors such as location, supply and exhaust and the different types of mechanical ventilation systems should be taken more into account. While masks and filters have been shown to be effective measures, they are beyond the scope of this thesis; which focuses on how ventilation systems impact indoor air distribution and CO2 concentration. Thus, while it is understood that these measures are significant and must be considered in the grand scheme of things, they are outside the scope of this thesis. Overall, for the research at hand greater emphasis will be placed on the various factors of the mechanical ventilation to investigate their impact on the interior environment and the distribution of airborne particles in the room.

2.3.5 Indoor air quality measuring methods

An important tool to gauge the performance of the indoor environment are measurements. Since measurements can gather data on how the indoor environment is used in real time and under ‘normal’ usage circumstances. There are multiple methods to conduct a measurement to get specific data from the indoor environment. Therefore for this thesis research careful consideration is needed to choose which methods are suitable to use. To help with choice of a suitable methods a couple studies have conducted into the effectiveness of the various methods.

One such study is the one by McNeill et.al (2022). Within this study multiple approaches to conduct a measurement of the indoor air quality are presented. As it is shown in table 4, for each of these approaches advantages and disadvantages are given. Additionally, based on multiple case studies the measurement methods are applied under different circumstances to highlight various factors, while also showing the similarities and differences of the measuring methods.

Approach	Technique	Advantages	Disadvantages
Direct Flow	Balometer or anemometer	• Accepted method, accessible to building managers • Measures total flow of recirculated/ outdoor air	•Inconclusive measurements in spaces with no mechanical ventilation • Not possible to separate outdoor and recirculated air exchange rates with this measurement alone
Controlled Release	CH4 or C2H6	• Indicates outdoor air exchange rate, gives results for spaces with no mechanical ventilation • Low natural background • High sensitivity • Few indoor sources, occupancy does not interfere with measurements	• Generally requires research instrumentation • Flammable gas
	CO2	• Gives results for spaces with no mechanical ventilation • Low-cost, reliable sensors readily available • Non-flammable, readily available gas	• Requires empty room since CO2 emission from the occupants interfere with measurements • Potential for interference from recirculated CO2
	Noninfectious aerosol particles	• Dispersion experiments provide insight into airflow patterns, movement of aerosol within a space	• Technically challenging to generate and detect aerosols • Loss of particles to surfaces, filtration, and resuspension must be accounted for
Passive	CO2	• Collect data during normal facility operation, occupancy • No expertise required • Directly shows of the impact of human exhalation on indoor air	• Uncontrolled conditions Complicate interpretation of the results • Other CO2 sources (vehicles, cooking, recirculated air) may cause interference
	PM2	• Provides valuable indoor air quality data during normal facility operation • Characterize impact of indoor air pollution sources	• Uncontrolled conditions Complicate interpretation of the results • Respiratory particles are greatly outnumbered by ‘background’ PM • Loss of particles to surfaces, filtration, and resuspension must be accounted for

Table 4 measurement methods; McNeill et.al (2022). Room-level ventilation in schools and universities. Atmospheric Environment: X, 13, 100152

When it comes to conducting measurements the placement of the devices is important because it can significantly affect the accuracy and representativeness of the measurement. The concentration of pollutants can vary greatly depending on their source and distribution in the indoor environment, as well as the airflow and ventilation patterns within the space (Olmedo et al., 2012). Therefore, it is crucial to place the measurement devices in locations that are representative of the indoor air quality in the entire space or the areas of interest. For instance, placing a measurement device near a pollution source or in stagnant areas where pollutants tend to accumulate can lead to higher readings and could give a misleading picture of the overall indoor air quality (Olmedo et al., 2012). On the other hand, placing the device in areas with high ventilation or near air inlets/outlets can result in lower readings and underestimate the true levels of pollutants. Therefore, the selection of measurement locations should take into account the specific objectives of the measurement and the characteristics of the indoor environment.

Evidently, this is shown in a study conducted by Zhang et.al, (2022). In this study a laboratory test was carried out in the Sense Lab's Experience room at the TU Delft. In this room a total of eighteen measurement devices were placed inside the room As it is shown in figure 6, six of the devices were positioned inside the room on top of the desks at a height of 1,1 meters above the ground; two were positioned in the middle and at the front of the space at 1,1 (red plane) and 1,6 (green plane) meters; and the remaining eight were positioned on the room's four walls at the same heights also at the heights of 1,1 and 1,6 meters. These measurements were conducted for the ventilation types of natural, mechanical, and mixed ventilation (Zhang et al., 2022).

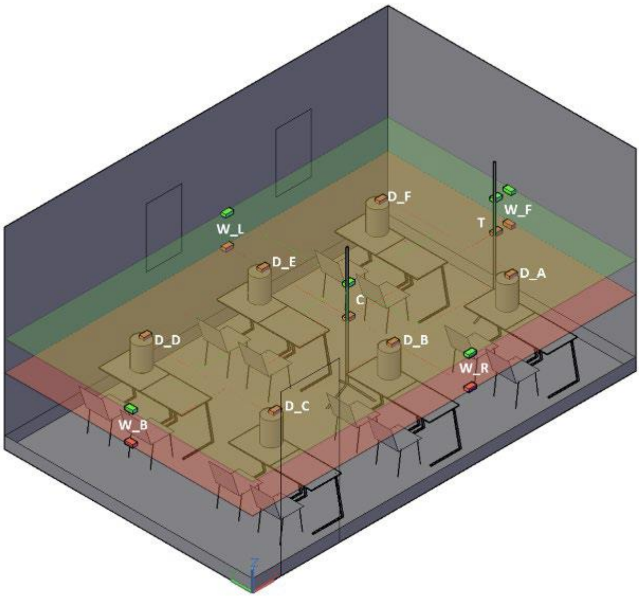


Figure 6 Setup measurement; Zhang et al., (2022). CO2 monitoring to assess ventilation rate: CLIMA 2022 Conference

From the results of the lab measurement, it was observed that the concentration of CO2 varied across different locations of the measurement devices, especially when natural ventilation was used to ventilate the room. This finding supports the argument that relying on a single point of measurement is insufficient for naturally ventilated rooms. Conversely, when mechanical ventilation was employed, the air inside the room was found to be more uniformly mixed. Although theoretically, one measurement point may suffice for mechanical ventilation systems, it is not recommended as it may result in inaccurate readings. Additionally, the measurements consistently showed that the locations of the devices positioned along the walls had the highest CO2 concentrations for both ventilation systems. Therefore, it is advisable to at the least place the measurement devices at the wall locations when measuring the indoor air quality of a room.

In conclusion, the research in this thesis requires careful consideration of both the measurement method and device placement. The focus of this thesis is to measure the impact of the ventilation system on CO2 distribution under normal usage conditions. As such, the passive CO2 method has been chosen, as it gathers ample data while minimally impacting the room. Additionally, the recommendation to place sensors along the walls will be taken into account and tested to verify its applicability to this research.

2.3.6 Decentral-, SMART-, and personal ventilation

Decentral ventilation

Decentralized ventilation is an alternative approach to the traditional centralized ventilation systems. Unlike centralized systems, decentralized ventilation allows for air supply and extraction at individual room or zone levels. Therefore it should offer greater control over indoor air quality and also could reduce the energy consumption. This flexibility makes it suitable for projects where centralized ventilation systems are not possible due to space constraints for ductwork, making it an appealing alternative for renovations projects of existing buildings (Ratajczak, 2022).

Figure 7 Decentralised ventilation unit SCHOOLAIR-D. (n.d.). TROX GmbH.

The COVID-19 pandemic has increased interest in decentralized ventilation systems for reducing the risk of infection in various settings. While mechanical ventilation is still preferred for optimal air quality control and natural ventilation can be effective if windows and doors are opened, the latter option is highly dependent on external conditions (Asanati et al., 2021; Stabile et al., 2021). Consequently, both these systems may not always be feasible, leading to the exploration of other alternatives such as decentralised ventilation systems (Ratajczak et al., 2020).However the amount of research on this topic is limited in the context of COVID-19.

One of these studies is the one conducted by Ratajczak (2022), where the effectiveness of decentralized ventilation in nurseries under different conditions was assessed through the use of simulations. The results indicated that decentralized units with heat recovery were more cost-effective than centralized ventilation, while also maintaining CO2 levels below 1000 PPM (Ratajczak, 2022). While the decentralised ventilation systems adequately supplied filtered and heated air per person, challenges such as inadequate airflow distribution within rooms were observed. More importantly it was observed that Air change per hour (ACH) should not be solely relied upon as a measure of a healthy indoor environment (de Man et al., 2021; Elsaid and Ahmed, 2021; Gettings et al., 2021). Instead, the focus should be put on ventilation rates per person for more accurate evaluations of rooms. As ACH may at times be excessively designed for larger rooms and fall short for smaller rooms with high occupancy (Blocken et al., 2021; Ratajczak, 2022).

This research highlights the limited information available on the performance of decentralized ventilation systems, as most studies primarily focus on mechanical ventilation for COVID-19 prevention. The commonly used metric, ACH, may not always provide accurate assessments. Therefore, adopting an individual-centric approach, considering the ventilation rate per person, is crucial for a more precise evaluation of indoor environments.

SMART ventilation

Smart ventilation systems are also gaining attention in the field of ventilation in the context of COVID-19. These systems, driven by intelligent sensors and algorithms, continuously monitor and analyse indoor parameters. They offer real-time data on air quality, enabling dynamic adjustment of ventilation rates to meet occupants' needs while minimizing energy usage Smart ventilation systems adapt to changing conditions, adjusting ventilation rates, airflow direction, and distribution within different zones of a building. They could be integrated with other building automation systems, optimizing comfort and energy efficiency (AIVC, 2018).

Amidst the COVID-19 pandemic, SMART ventilation systems have gained significant attention as effective strategies for ventilation. A recent study by Li and Cai (2022) proposes a novel CO2-based demand-controlled ventilation strategy to mitigate the spread of COVID-19. This strategy involves integrating a smart ventilation system with a control system that regulates a damper located in the air terminal, allowing for the adjustment of airflow. The system measures the CO2 concentration and compares them to predetermined threshold values. When the measured values approach the maximum threshold, the controller calculates the necessary change in the damper angle and adjusts it to provide increased fresh air. To verify the efficacy of this CO2-based demand-controlled ventilation method, a test site was created to closely simulate various locations, which includes a library, a restaurant, and a gym. Within this test it was demonstrated that the ventilation system successfully maintained CO2 levels below the specified threshold in all simulated locations. Moreover, this approach led to a notable reduction in energy consumption of approximately 30% to 50% (Li et al., 2022).

While smart ventilation systems offer advantages, they also have their drawbacks and considerations. These systems rely on relatively expensive sensors and require regular calibration and maintenance. Additionally, proper installation is crucial, which includes strategic sensor placement and positioning of air terminals (Pei et al., 2019). Failing to consider these factors can lead to wrong readings of the air quality and compromise the comfort of the occupants.

In summary, smart ventilation systems exhibit promising potential in reducing the risk of infection in indoor environments while concurrently decreasing energy consumption. However, further investigation is needed to determine the optimal placement of sensors for monitoring room conditions and the positioning of air terminals. Thus, this research thesis aims to explore the effective sensor placements, as well as the optimal positioning of exhausts, supply points, and the number of openings required for efficient ventilation.

Personal ventilation

The final ventilation system explored in this thesis focuses on personal ventilation, which delivers conditioned air in close proximity to individuals for customized comfort and air quality.

These devices can take the form of portable fans, as shown in Figure 8 or even personal air purifiers, as depicted in Figure 9. However, within the context of this research thesis personal ventilation encompasses a concept more akin to what is illustrated in Figure 10. This particular type of personal ventilation system operates similarly to conventional mechanical ventilation systems by supplying fresh air and exhausting stale air, but it operates at a personalized level, with the supply and exhaust outlets positioned in close proximity to a single user. By directing a stream of conditioned air towards the individual, personal ventilation systems create a microenvironment that caters to the specific needs and preferences of each occupant.

One of the key advantages of personal ventilation is its ability to address individual comfort requirements in spaces with varying occupancy levels or thermal preferences. In shared environments like open-plan offices or classrooms, where individuals may have different temperature preferences, personal ventilation allows occupants to customize their immediate surroundings without impacting others (Boerstra, 2016). Furthermore, personal ventilation systems can contribute to improved indoor air quality. By creating a local airflow, these systems help exhaust exhaled breath and airborne contaminants away from the breathing zone, reducing the risk of exposure to pollutants or pathogens (Boerstra, 2016; Melikov et al., 2002). Especially in light of the COVID-19 pandemic these type of systems are gathering more interest to find how effective these systems are in reducing the risk of infection.

Figure 8

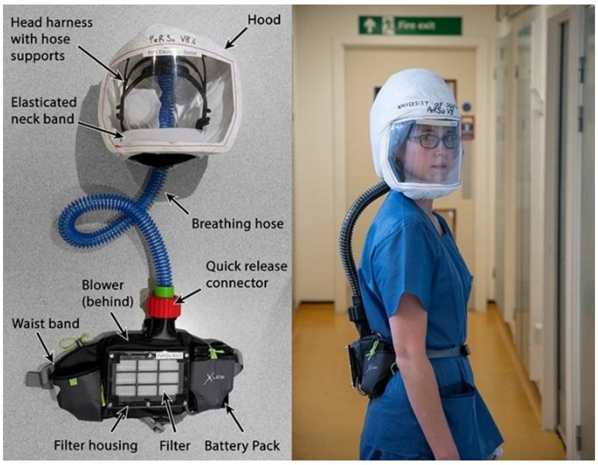


Figure 9 Personal ventilation system (Elkington et al., 2021)

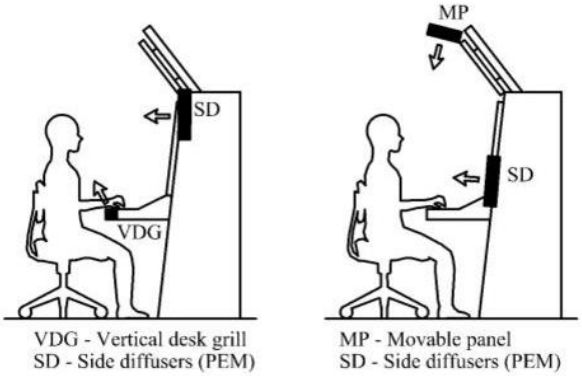


Figure 10 personal ventilation system, table side Melikov et al. (2002)

Melikov et al. (2002) showed in a study that the effectiveness of the personal ventilation systems is dependent on the distance between the user and the opening of the ventilation system. Additionally, studies have shown that PV systems have better performance in reducing the spread and dispersion of small particles than other ventilation systems (Liu et al., 2007). Melikov and Kaczmarczyk (2012) studied the effects of indoor air flow on perceived air quality (PAQ) and sick building syndrome based on 124 human subjects. Their study found that increased local ventilation rates improved IAQ and relieved building syndrome symptoms, which was the foundation for the later development of PV.

Additionally, Liu et al. (2007) simulated the particle dispersion associated with the use of PV by considering three cases with different airflow speeds: (a) no airflow, (b) 32 m3/h of personalized airflow, and (c) 32 m3/h of mixed supply airflow from the ceiling. After studying the air temperature field and pollutant concentration field in these 3 cases, it was found that personalized airflow was effective at removing particles smaller than 2 µm, but was not effective if the particles were larger than 7.5 µm.

While the dispersion of particles is important, there are concerns that the comfort of the people using these systems can be impacted. As result, Song et al. (2022) reviewed and analysed the use of smart personalized ventilation systems. This study examined individual PV systems using smart controls and CO2 concentration as a control parameter. Additionally the article summarized the current challenges and provides logical solutions for integrating PV systems with smart control technologies in real-world applications. Results from the literature study conducted in this article have found that air terminal devices (ATD) used for personal ventilation at effective reducing sick building syndrome, but it may cause thermal discomfort and dryness (Melikov et al., 2012). In principle, increasing the temperature of the PV airflow requires simultaneously increasing the airflow speed to maintain the convective heat dissipation of the human body, However this increase in the airflow speed in the PV device usually takes away more heat and causes the air temperature to drop (Faulkner et al., 2003). Therefore, the flow rate of the personal ventilation air terminal device (PVATD) should be set to the necessary minimum value, at which the supply flow is strong enough to break the plume of free convection layer of the human body (Khalifa et al., 2009; Russo et al., 2009; Chaudhuri et al., 2019).

All the investigated smart control systems, sensors or machine learning strategies, have demonstrated the huge prospects for the integration with PV systems. However, chaotic control logic and comfort indicators that are difficult to quantify have become the main obstacles to the development of smart PV systems, resulting in PV systems still staying in traditional ventilation modes, and the related studies are mostly centred on equipment such as ducts, vents, installation location, etc. A flexible and smart control method is more necessary to improve the performance of PV system, which could supply comfort micro-environment, reduce building energy consumption, and improve indoor environment.

2.3.7 Simulations change this

To assess infection probability in relation to geography and time, the article "CFD modelling of airborne pathogen transmission of COVID-19 in confined spaces under varied ventilation techniques" proposes a method. Using Eulerian-Lagrangian theory, a CFD model of exhaled droplets is created (Motamedi et al., 2022). Ventilation strategies including cross-ventilation (CV), single-ventilation (SV), mechanical ventilation (MV), and no-ventilation (NV) are evaluated using this framework. A case study room measuring 4m x 4m x 3.2m (L x W x H) is simulated, and the results are compared to a wind tunnel experiment for validation (Akabayashi et al., 1996; Kubota et al., 2008).

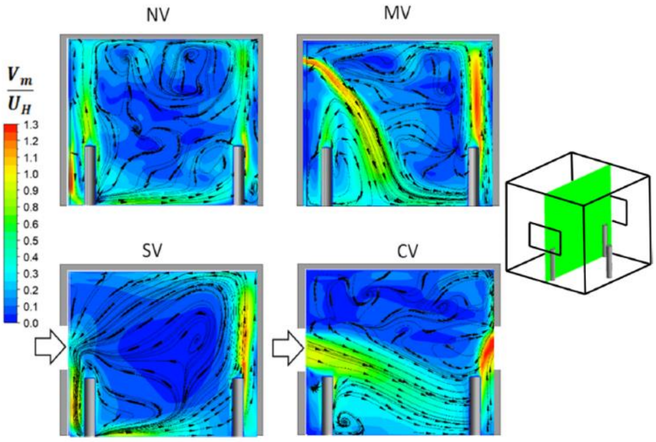


Figure 11 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022).

The evaluation shows that SV carries the highest infection risk, and NV and SV result in the greatest spread of airborne pathogens within the room. The velocity contours depicted in Figures 11 and 12 reveal that NV and SV have lower air velocity in the middle of the room, while the thermal plume of occupants causes upward air motion near the walls. In contrast, MV and CV exhibit higher air velocity in the middle (Motamedi et al., 2022). This indicates that occupants' positions significantly impact airflow and airborne transmission, particularly in the NV and SV cases, but to a lesser extent in the MV and CV cases.

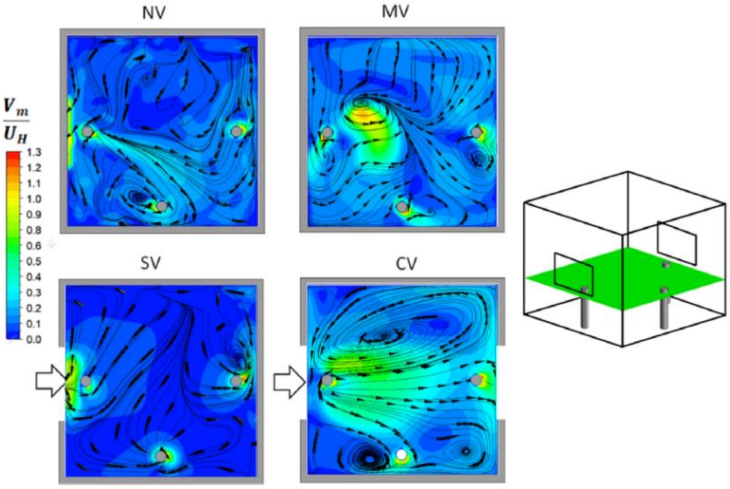


Figure 12 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022).

2.4 Guidelines, standards and regulations

Guidelines, standards, and laws play crucial roles in designing a healthy indoor environment. Since guidelines offer recommendations on how to design an indoor environment, while standards establish the minimum requirements and laws enforce legal obligations for building owners, designers, and operators. Together, they provide a framework to ensure indoor environments promote occupant health and well-being. However, the COVID-19 pandemic has revealed shortcomings in existing guidelines, standards, and laws. This literature study reviews, analyses, and evaluates the effectiveness of current guidelines, standards, and laws in light of the pandemic. Specifically, the study examines the following documents:

- Het Bouwbesluit 2012,
- Frisse scholen,
- ASHRAE 62.1-2022
- REHVA ventilation effectiveness.

By assessing these resources, the study aims to identify areas for improvement and enhance the preparedness of indoor environments for future challenges.

2.4.1 Bouwbesluit 2012

The Dutch building regulation known as Bouwbesluit 2012 establishes minimal requirements for buildings in the Netherlands. It consists of nine chapters addressing construction, use, and demolition regulations. For this research, chapters 3 and 5 are of relevance. Chapter 3 covers air quality, air exchange rates, and air velocity inlets, while chapter 5 focuses on building energy efficiency and the environment. However, these chapters have limited coverage, particularly regarding indoor air quality. The requirements primarily specify minimal ventilation requirements for different building functions and maximum air velocity within rooms (Rijksoverheid, 2022). The relevant requirements for this study are as follows:

- Ventilation requirement per person:
  - The ventilation requirement for educational function is set to 8,5 dm3/s per person.

- The second: related to the residence area and the living spaces inside the residence area.
  - The requirement for a residence area is set to 0,9 dm^3/s per m^2 floor area with a minimum of 7 dm^3/s and for the living spaces this is set to 0,7 dm^3/s per m^2 floor area with a minimum of 7 dm^3/s.

- The air velocity inside a room cannot exceed 0,2 m/s.

While the scope of these requirements is limited, it is justified from a government's standpoint. As their purpose is to establish a satisfactory minimum level of comfort within the indoor environment. Therefore building designers have the option to set requirements higher than the minimum. It is worth noting that these minimum requirements may not be sufficient in light of the COVID-19 pandemic. While the primary emphasis of these requirements is on comfort, it has become that there is need to shift the focus more towards prioritizing health considerations when designing indoor environments. Which means that either current requirements need to be adjusted by increasing the values of the requirements or new requirements need to be added.

2.4.2 Frisse Scholen 2021

The Frisse Scholen 2021 provides guidelines for creating energy-efficient and healthy learning environments in new or renovated schools. It is structured into six main themes: energy, air, temperature, light, sound, and quality insurance. Each theme consists of multiple topics and requirements, categorized into three levels: C (passing), B (good), and A (excellent). This research focuses on the indoor air quality guidelines, which include topics such as air exchange, space volume, incoming air quality, and particulate matter. Table 4 provides a summary of these topics and their corresponding requirements (Programma van Eisen Frisse Scholen, 2021).

Topic	Level C	Level B	Level A
Air exchange	- CO2 concentration < 1200 PPM - Flow rate p.p ≥ 6,5 dm3/s	- CO2 concentration < 1000 PPM - Flow rate p.p ≥ 8,5 dm3/s	- CO2 concentration < 800 PPM - Flow rate p.p ≥ 12 dm3/s
Space volume	- Height from floor to ceiling ≥ 2,6	- Height from floor to ceiling ≥ 2,8	- Height from floor to ceiling ≥ 3,2
Quality of the incoming air	- No duct materials that negatively impacts the indoor air quality. - No recirculation (room-level recirculation is permissible). - Heat recovery systems; separation between air supply and return air. - Distance between outlet and the fresh air inlet below dilution factor 0.01, as calculated using NEN 2757. - Ventilation design allows for hygienic maintenance and replacements. Prior to use, thorough internal cleaning is necessary.	Same as level C	Same as level C
Particle matter	- Avoid locations with fine particle matters. - Mechanical ventilation systems are equipped with filters in the air supply with an ePM1 efficiency of at least 70% (NEN-EN-ISO 16890: ODA 2 / SUP2). - Mechanical ventilation systems fine particle heavy areas are fitted with filters with an ePM1 efficiency of at least 80% (NEN-EN-ISO 16890: ODA 3 / SUP2).	Same as level C	- Avoid locations with fine particle matters. - Mechanical ventilation systems are equipped with filters in the air supply with an ePM1 efficiency of at least 80% (NEN-EN-ISO 16890: ODA 2 / SUP1). - Mechanical ventilation systems fine particle heavy areas are fitted with filters with an ePM1 efficiency of at least 90% (NEN-EN-ISO 16890: ODA 3 / SUP1).

Table 4 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022).

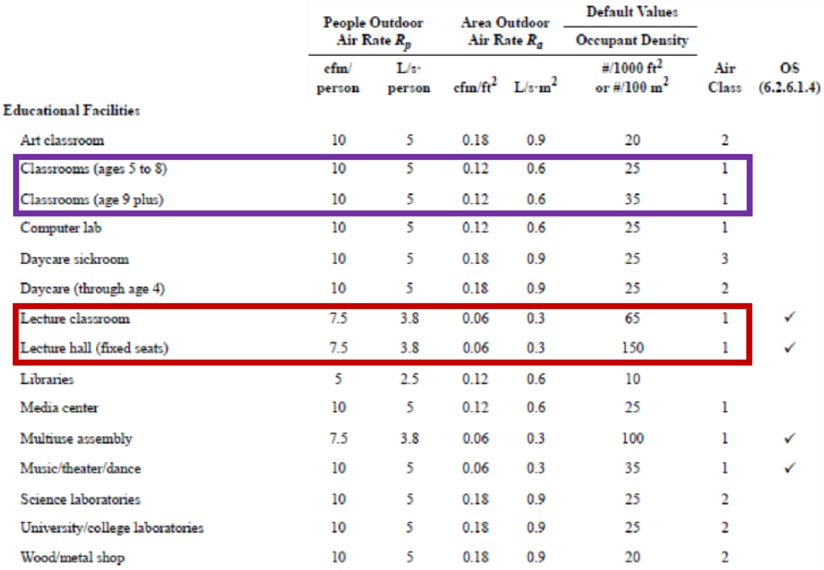
To summarize, what these guidelines show is that while both level C and level B requirements align with the building degree standards, the document does include more stringent criteria that are more consistent with the literature, such as the 800 PPM guideline for the maximum allowed CO2 concentration inside the rooms. Nevertheless, it is important to note that these level A guidelines are optional and not mandatory for the creation of healthy and comfortable classroom environments. However, in light of the pandemic it can be argued that it would have been better for all buildings even to be required to reach level A, as this level might better protect the occupants.

2.4.3 International Standards

In addition to adhering to local Dutch regulations and guidelines, an examination was conducted of international standards and guidelines. This was done to ensure a comprehensive understanding of various perspectives on the indoor environment.

2.4.3.1 ASHRAE 62.1-2022 - Ventilation for Acceptable Indoor Air Quality.

Similar to the Dutch Building degree, the ASHRAE 62.1-2022 aims to establish minimum ventilation rates and strategies for satisfactory indoor air quality (IAQ) while minimizing potential health effects(ASHRAE, 2022). It applies to new buildings and renovated buildings. Additionally, it also provides guidance for improving IAQ in existing structures. The standard includes specific guidelines for airflow rates for different applications. In Figure 1, the indicated guideline in purple states that classrooms only require 5 litres per person in terms of the ventilation rate and that of the lecture halls, marked in red, is even lower at 3,8 litres per person. When this is compared to the Dutch regulation, these guidelines are below that.



	People Outdoor Air Rate R_p		**Area Outdoor Air Rate R_a**		**Default Values Occupant Density**		
	cfm/ person	**L/s· person**	**cfm/ft^2**	**L/s·m^2**	**#/1000 ft^2 or #/100 m^2**	**Air Class**	**OS (6.2.6.1.4)**
Educational Facilities							
Art classroom	10	5	0.18	0.9	20	2	
Classrooms (ages 5 to 8)	10	5	0.12	0.6	25	1	
Classrooms (age 9 plus)	10	5	0.12	0.6	35	1	
Computer lab	10	5	0.12	0.6	25	1	
Daycare sickroom	10	5	0.18	0.9	25	3	
Daycare (through age 4)	10	5	0.18	0.9	25	2	
Lecture classroom	7.5	3.8	0.06	0.3	65	1	✓
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3	150	1	✓
Libraries	5	2.5	0.12	0.6	10		
Media center	10	5	0.12	0.6	25	1	
Multiuse assembly	7.5	3.8	0.06	0.3	100	1	✓
Music/theater/dance	10	5	0.06	0.3	35	1	✓
Science laboratories	10	5	0.18	0.9	25	2	
University/college laboratories	10	5	0.18	0.9	25	2	
Wood/metal shop	10	5	0.18	0.9	20	2	

Figure 13 Educational facility ventilation rate requirement (ASHRAE, 2022).

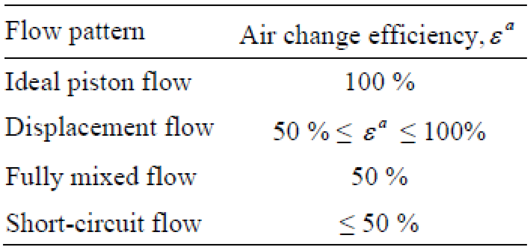
2.4.3.2 REHVA Ventilation Effectiveness

The REHVA Ventilation Effectiveness guideline is a comprehensive framework developed by the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) to assess and optimize the performance of ventilation systems in buildings. This guideline aims to ensure that ventilation systems effectively deliver fresh air to indoor spaces while minimizing energy consumption and maintaining a healthy indoor environment (REHVA, 2004).

Within this guideline a methodology is presented to calculate the ventilation efficiency of the ventilation system responsible for ventilating the room. The formula to calculate the ventilation efficiency is given in formula (3):

$$\varepsilon^a = \frac{\tau_n}{\tau_r} * 100 = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 \tag{3}$$

The results from this calculation what type of flow pattern is currently present in the room in question. As is presented in figure 6 to 10 there are in total four types of flow patterns.



Flow pattern	Air change efficiency, ε^a
Ideal piston flow	100 %
Displacement flow	$50\ \% \leq \varepsilon^a \leq 100\%$
Fully mixed flow	50 %
Short-circuit flow	$\leq 50\ \%$

Figure 14 Air change efficiencies (REHVA, 2004)

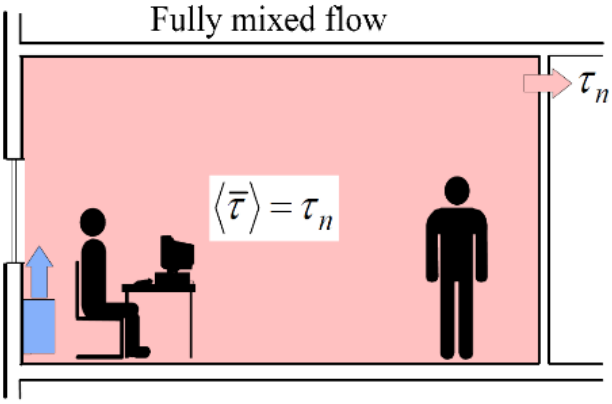


Figure 15 Fully mixed flow (REHVA, 2004)

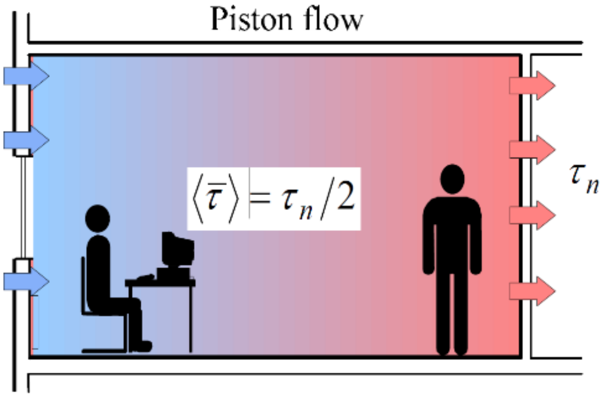


Figure 16 Piston flow (REHVA, 2004)

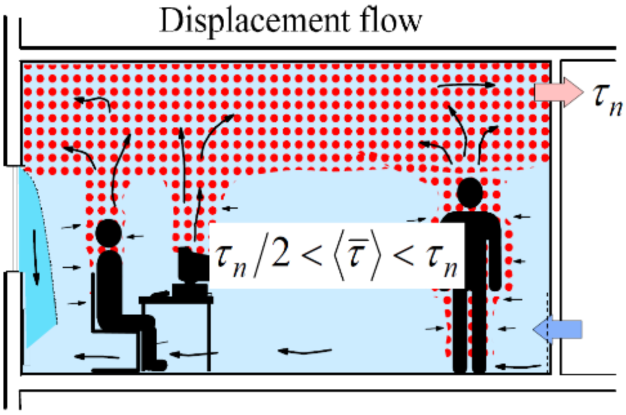


Figure 17 Displacement flow (REHVA, 2004)

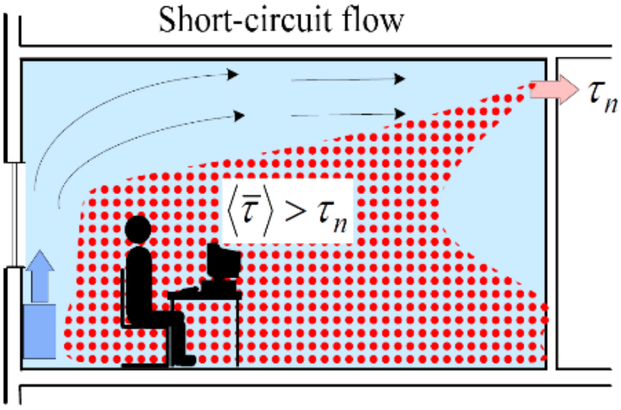


Figure 17 Short-circuit flow (REHVA, 2004)

2.5 Comfort

Comfort refers to the physical and psychological well-being of occupants, contributing to an healthy and satisfactory indoor environment (Bluyssen, 2015). It involves creating conditions that promote a sense of relaxation, ease, and contentment for individuals residing in a building or space. The physical aspect of comfort relates to maintaining optimal thermal conditions ensuring that the temperature is neither excessively hot nor cold. It also involves providing adequate ventilation to regulate indoor air quality (IAQ), including considerations such as airflow distribution and draft prevention. On the other hand, psychological comfort is linked to the mental well-being of occupants and their perception of the environment (Carlucci, 2013).

Comfort can be classified into four main categories: thermal comfort, indoor air quality, acoustic comfort, and visual comfort. While each of these categories holds its own importance. In this research, the focus is put on the thermal comfort and IAQ for the occupants. The main objective is to investigate the impact of the ventilation system on the thermal comfort and IAQ experienced by individuals within the room.

Thermal comfort in this research is evaluated primarily using the thermal comfort models of predicted mean vote (PMV), predicted percentage of dissatisfaction and thermal sensation surveys. PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) are two commonly used indices in thermal comfort analysis.

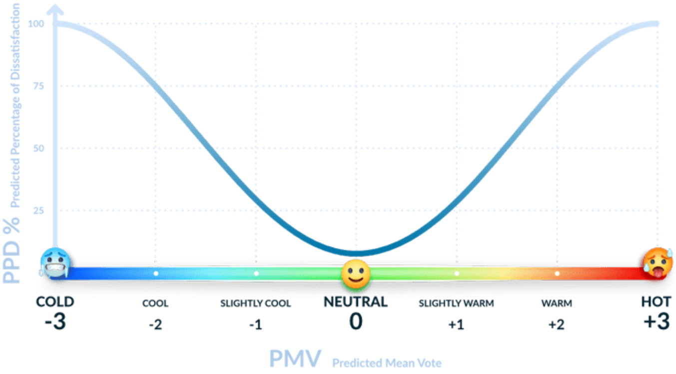


Figure 18 PMV & PPD scale Guenther (2023)

PMV represents the average thermal sensation vote of a group of people and predicts their perception of thermal comfort. It takes into account factors such as air temperature, humidity, air velocity, and clothing insulation. As it is shown in figure 18 the PMV scale ranges from -3 (feeling very cold) to +3 (feeling very hot), with 0 indicating a neutral thermal sensation. Directly connected to the PMV is the PPD (Predicted Percentage of Dissatisfied). While PMV is utilized to estimate the average thermal sensation experienced by a group of individuals. PPD quantifies the percentage of individuals within that group who may feel dissatisfied with the prevailing thermal conditions (Carlucci, 2013).

In addition to assessing thermal comfort, this research also focuses on evaluating the impact of the ventilation systems on the indoor air quality (IAQ) within the examined space. IAQ is a crucial aspect of occupant comfort, as it pertains to the quality and cleanliness of the air they breathe. To evaluate IAQ, various methods are employed in this research. First, measurements of key parameters such as carbon dioxide (CO2) levels, particulate matter (PM) concentration, and volatile organic compounds (VOCs) are taken using appropriate monitoring devices. These measurements provide quantitative data on the air quality within the room. Furthermore, subjective assessments from occupants regarding odours, perceived freshness, and overall air quality are collected through questionnaires or surveys. By combining objective measurements with subjective feedback, a comprehensive understanding of IAQ is obtained. This allows for an assessment of how the ventilation system influences the air quality experienced by occupants and provides insights into potential improvements to enhance IAQ levels.

2.6 Economics and practicality

This chapter highlights the importance of economics and practicality in ventilation system design, particularly in relation to reducing infection risks in rooms. Evaluating the cost-effectiveness and feasibility of implementing ventilation systems is crucial, considering the that not all parties have resources available for retrofitting rooms and the ventilation systems. It would be unsatisfactory if a ventilation system proves to be costly but offers only minimal effectiveness in reducing the infection risk. Therefore, this research includes a cost-analysis of three ventilation system designs: decentralized, SMART, and personal ventilation systems. The analysis identifies cost sources for each system. Decentralized units primarily incur costs for the unit itself and some ductwork, while the SMART system involves expenses for ductwork, air terminals, and additional sensors. As for the personal ventilation system, costs mainly pertain to materials and extensive ductwork. The costs of the systems and ductwork are presented in Table 5 and Figure 19, respectively, providing an overview of cost estimation.

MONTEREN OF VERVANGEN KANAAL, RECHTHOEKIG, NIET GEÏSOLEERD

Tabel

Afmeting in mm		Hulpstukken	Kosten per m	
Hoogte	Breedte		Monteren	Vervangen
200	400	Geen	86,40	91,55
		Weinig	106,00	113,00
		Veel	145,00	156,00
300	400	Geen	107,00	114,00
		Weinig	129,00	139,00
		Veel	175,00	189,00
	600	Geen	124,00	131,00
		Weinig	153,00	164,00
		Veel	211,00	229,00
	800	Geen	141,00	148,00
		Zonder	177,00	188,00
		Veel	248,00	267,00
400	600	Geen	134,00	141,00
		Weinig	166,00	177,00
		Veel	231,00	249,00
	800	Geen	151,00	158,00
		Weinig	191,00	203,00
		Veel	271,00	294,00

Figure 19 Costs of ducts, Bouwkosten.nl (n.d.)

System	Amount	Costs
Decentral system		
Sense air 1000	1 pack; which includes the unit and accessories	€ 9000 - € 13000; depending on size and flow amount.
SMART system		
Air terminals	Per unit	€40-100
Sensors	Per unit	€200 – 500
PV system		
MDF 4 mm	Per m2	€ 3,40
Ventilator 100 m3/h	Per unit	€27,54

Table 5 costs of various ventilation products

Similarly, the practicality of a ventilation system also plays an important role. In the context of this research practicality refers to the ease of installation and the impact on the room or space in which it is implemented. For example if a ventilation system is difficult to install or negatively impacts the environment (e.g., obstructing views in a classroom with extensive ductwork), the design then becomes a problem. Therefore, each ventilation system design is analysed in terms of how much they impact the room and the occupants.

2.7 Products and systems

Within building engineering there are a diverse range of ventilation products aimed at ensuring optimal indoor air quality and comfort. This section provides an small overview of various ventilation systems available on the market today.

Decentral Ventilation Units:
Decentral ventilation units are designed to provide room-specific ventilation solutions. The come in various applications, including ceiling-mounted, wall-mounted, and floor-mounted options. Decentral ventilation units offer flexibility in terms of installation and in theory can be easily integrated into existing spaces or new construction projects. A couple of these units that are suitable for this research are provided in table 6 For the purpose of this study a Sense 1000 unit is used the Decentral ventilation system.

Unit brand	Name	Size	Ventilation rate	Mount
Systemair	Sense 1000	2,2m x 1,4m x 0,7m	1000 m3/h	Ceiling mounted
TROX Technik	SCHOOLAIR-D-HV-EH	3,9m x 1,1m x 0,4m	1100 m3/h	Ceiling mounted
TROX Technik	FSL-U-ZAS	1,1m x 0.9m x 0,2m	150 m3/h	Floor mounted

Table 6 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022). Environment: X, 13, 100152

Smart Ventilation Systems:
SMART ventilation systems utilize sensors to monitor and regulate indoor air quality. Smart ventilation systems adapt their ventilation rates based on real-time measurements of parameters such as temperature, humidity, and occupancy. Most often these types of systems are a combination of a ventilation system and an accompanying sensor. A couple of these given in table 7. While for this study non of these products are used, a design is made based on the idea of applying a SMART system that uses sensors to control the indoor environment.

Unit brand	Type	Name
Itho Daalderop	Sensor / ventilation system	BaseFlow
BUVA	CO2 controlled valve	SmartValve
BUVA	Sensor	SmartSense CO2-sensor
Vent-Axia	Sensor / Ventilation system	Vent-Axia Multihome

Table 7 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022). Environment: X, 13, 100152

Personal ventilation Products:
Lastly, personal ventilation systems. Personal ventilation systems are not a specific product per se, but rather a design concept. The concept of a personal ventilation system revolves around the use of a ventilator that provides or removes air in close proximity to an individual. Consequently, the search results yielded no specific products categorized as "personal ventilation systems." While there were ventilation systems available, such as desk fans, that recirculate air in close proximity to the user, there were no systems identified that are connected to the main ventilation system and positioned to supply or exhaust air in close proximity to an individual.

2.8 Parameters

This section provides a concise overview of important factors discussed in the literature that impact the indoor environment and the spread of infection. Such parameters include volume, ACH (Air Changes per Hour), distance between exhaust and supply openings, quantity of openings, and their placement in the room. These parameters play a significant role in the design process and have been highlighted in the literature as influential in shaping the indoor environment. Table 8 presents these parameters and their importance as identified in the literature.

Parameters	**Importance according to literature**	**Literature**
Air exchange rate/Room size	ACH is important but insufficient for assessing indoor environments as it can result in excessive ventilation for larger rooms and inadequate ventilation for smaller rooms.	de Man et al., 2021; Elsaid and Ahmed, 2021; Gettings et al., 2021; Blocken et al., 2021; Ratajczak, 2022; Somsen et.al; Ng et.al; Van Doremalen
Ventilation rate per person	Ventilation rate is crucial as it directly impacts infection risk and particle concentration in the room. The emphasis should be on finding a threshold that promotes a healthy indoor environment without causing discomfort.	de Man et al., 2021; Elsaid and Ahmed, 2021; Gettings et al., 2021; Blocken et al., 2021; Ratajczak, 2022; Ding et al.,2022; Liu et al., 2007; Melikov and Kaczmarczyk, 2012; Song et al., 2022 Melikov et al., 2012 Chen et al.,2021
Co2 concentration	CO2 is not a perfect representative for infectious particles in the air, however it does serve as adequate enough of a proxy to perform tests.	Rudnick, S. N., & Milton, D. K. 2003; Peng et al.,2021; Di Gilio et al.,2021 Zhang et.al., 2022
Distance/location in relation to the exhaust	Proximity to the exhaust affects pollution dispersion.	Song et al.,2022; Melikov et al., 2002; Jaio et al., 2019; Liu et al.,2017
Relative humidity	RH of 40-60% is optimal for healthier conditions.	Verheyen et al., 2022
Temperature	Has no significant on the transmission of the virus, but does have an impact on the comfort of the people, when considering the utilisation of ventilation system.	Boerstra, 2016; Song et al., 2022; Melikov et al., 2012; Park et al., 2022
Comfort	Comfort does not have a direct impact on the transmission, however it is influenced by measures taken to reduce infection risk in the room.	(Bluyssen, Philomena M., et al.). Boerstra, 2016). Melikov et al., 2012).
Costs	The ratio of effectiveness of the measures taken must and the cost taken into account.	-
Practicality	The measures taken need to take practically in terms of ease of install and impact on the room into account.	-

Table 8 Total overview of parameters

3. Research method ; from here with the sources

In this chapter, the research approach of the thesis is determined and explained. Chapter 3.1 defines the research gap and the main question followed by the methodology of the research in chapter 3.2. Chapters 3.3, 3.4, and 3.5 discuss the location, measurement and survey setup and the simulation setup, respectively.

3.1 The research gap and main question

Through the review of the literature, it has become evident that there is information lacking regarding the appropriate application of ventilation systems during airborne pandemics. While methods for calculating infection risks have been established and recommendations for ventilation systems have been provided, the precise implementation of these recommendations remains unclear. For instance, the World Health Organization (WHO) advises ventilating rooms, but the specific methods for achieving remain ambiguous. Additionally, discrepancies arise concerning the recommended acceptable concentration of CO2 within enclosed spaces. While the WHO suggests a limit of 1000 PPM (WHO Regional, 2000), the literature advocates for more stringent thresholds, such as 700 PPM (Marr et al., 2020). Furthermore, it has become apparent that alternative ventilation systems, including decentralized ventilation, smart ventilation and personal ventilation have gained increased interest. However, comprehensive guidance on their efficient and human-centric utilization is lacking (Ding et al.,2022; Zhang et.al., 2022). Lastly, the literature has pointed out that a couple of important parameter such as, volume, ACH, ventilation rate and distance to the exhaust and supply can have implications for the infection risk inside rooms (Melikov et al., 2012). Consequently, the literature study leads to the conclusion that a gap exists among the three areas of interest within this study, which are ventilation design, COVID-19-related knowledge, and the practical implementation of ventilation systems. Therefore, the primary objective of this research is to bridge this gap or at the very least provide improved interpretation and application of the recommendations aimed at enhancing ventilation systems. Which translates to the following research question:

How can smart, personal or decentralised ventilation improve the ventilation system design to make it more COVID-19-proof while not negatively impacting the comfort of the occupants in an educational environment and being both practical and cost-efficient?

To provide comprehensive insights into several key terms utilized within the main research question, the following explanations are provided:

COVID-19-proof:
The proof of a ventilation system's effectiveness in making an indoor environment more resilient against COVID-19 is shown through the use of the Rudnick and Milton calculation method. This approach expresses the infection risk within the room as a percentage. Therefore, if the calculated percentage for a specific system is lower than the percentage determined for the baseline scenario, it can be concluded that the particular system has enhanced the indoor environment's COVID-19 resistance.

Comfort of the occupants:
As discussed previously in subsection 2.5 on comfort, evaluating the comfort of occupants is difficult due to its subjective nature. However, there are generally accepted parameter ranges that are considered comfortable. If the obtained results significantly deviate from these ranges or fall in them, the comfort level can then be assessed based on how the occupants perceive the room's comfort.

Practicality:
Within the context of this research, practicality primarily pertains to the system's impact on the occupants' utilization of the room, including ease of use and installation. If the system excessively hinders occupants' activities or necessitates extensive services to the extent that implementing a new system becomes more practical, it indicates a lack of practicality.

Cost-efficiency:
Irrespective of the domain, cost-efficient design holds significant importance as it minimizes unnecessary expenditures. The same principle applies to ventilation systems, where costs can escalate rapidly. Thus, to demonstrate a system's value for the costs incurred, the expenses are weighed against the system's effectiveness in reducing the room's infection risk.

To support the main question a couple of sub-questions are formulated surrounding the key terms to bring the research closer to addressing the information gap between the three domains of knowledge. These sub-questions are mainly aimed at the application of the other ventilation systems and their application in this study.

- How can the ventilation system be adapted in response to Covid-19?
- How does the comfort of the occupants get impacted by use of the ventilation system to reduce the spread COVID-19?
- What are the practical considerations for designing buildings with smart personal, or decentralized ventilation systems?
- What are some of the key points to account for when trying to design a ventilation system as economically as possible?

The theoretical framework for the sub questions is found within the literature study, while the application and the practical aspects are researched and presented in later chapters of this report.

3.2 Methodology

As depicted in Figure YY, the research in this thesis follows a structured approach consisting of three main phases. The first phase, Phase 1, focuses on data collection and defining the research gap. The primary objective is to establish a solid theoretical foundation by conducting a comprehensive literature review. This review identifies gaps in existing research and defines the most significant parameters of the ventilation systems. This data collection in the first phase is needed, as it serves as input for the setup and is used to explore what elements are present in real life and which are the core elements that need to be included as parameters in the simulation models. These parameters serve as the basis for the testing conducted in the second phase, which is done through the use of simulation and measurements.

Phase 2 of the research shifts its focus towards design and experimentation. It encompasses the setup of four distinct testing situations: the baseline-, the decentralized-, the smart- and the personal-ventilation situation. Each situation aims to test the location under different conditions and gather data about how utilisation of the ventilation system and different parameters could affect the infection risk. Firstly, the baseline is established, which serves as the reference point for comparison. This situation tests the room under normal usage conditions and sets the baseline for evaluating the effectiveness of the proposed ventilation system in reducing infection risk. Additionally, the baseline examines the impact of parameters identified from the literature study. The remaining situations involve testing designs incorporating decentralized-, SMART- and personal- ventilation systems. These evaluations primarily use simulations supplemented by measurements and surveys whenever feasible. Further details regarding the measurement, survey, and simulation setups are provided in Chapters 3.4 and 3.5, respectively.

After completing the simulations, measurements, and surveys, the research enters its third phase. This phase involves analysing and comparing the data collected. The data is examined to understand how different ventilation systems impact the transmission of COVID-19. Comparisons are made between the simulation data of the baseline situation and the other designs to evaluate their effects on air distribution patterns, room air circulation and the overall effectiveness of various ventilation systems. Additionally, an assessment of the ventilation products is conducted considering factors such as material and labour costs and practicality as well as providing an overview of the occupants' comfort level.

After completing these phases, the research as a whole is concluded through a discussion and a final conclusion. In the discussion, the results are examined, and their implications and significance are explored. The conclusion provides a summary of the research findings, highlighting key takeaways and offering potential avenues for further study and improvement.

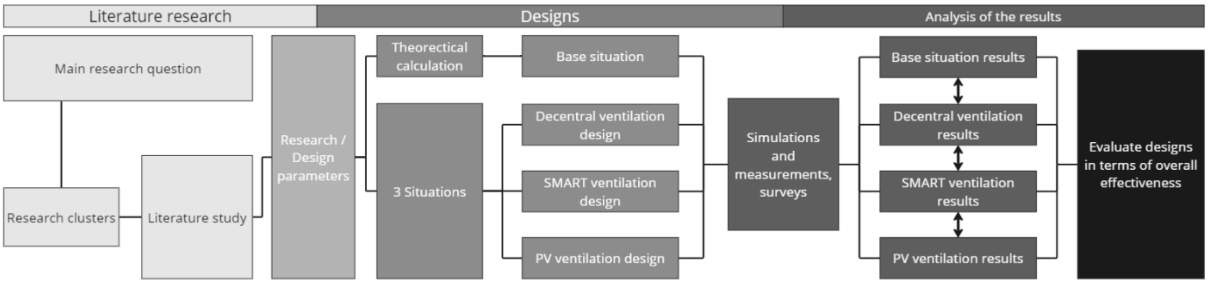


Figure 19 flowchart of the process

3.3 Location

The selection of the research location requires careful consideration, as it can significantly impact the final results. Although within the TU Delft Faculty of Architecture & the Built Environment multiple locations are available, the decision-making process behind choosing the appropriate room is a bit more complex. In this research thesis, the location is chosen based on several factors centred around the concept of a 'standard classroom'. This raises the question:

What defines a standard classroom?

A detailed explanation of the standard classroom definition is provided in Appendix A. However, for the purpose of this study, a standard classroom is defined by the following factors, as presented in Table 9:

Parameter	Quantity/Type
Space	Approximately 50 m2
Students	Approximately 30 students
Personnel	1 or 2 teachers
Facilities	Educational: tables, chairs, projector with screen, and a general writing board
Satisfying basic requirements	Comfort: heating, ventilation, and windows
Flexibility	Ability to transform the room from a lecture setup to a workshop setup

Table 9 Classroom parameters

Based on these parameters, several locations come to mind that fulfil these criteria, namely Halls P and Q. Although these rooms are actually around 80m2 in size, they are currently arranged to accommodate approximately 32 and 28 students, respectively. Additionally, as depicted in Figures 20 and 21, both rooms possess the necessary facilities for teaching purposes and satisfy the flexibility requirement. Therefore, considering the relatively similar characteristics of the halls, hall P is chosen for the purpose of this study. This decision is based on the fact that hall P can accommodate a slightly larger number of occupants without requiring significant modifications.

Figure 20 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022). Environment: X, 13, 100152

Figure 21 Airflow distribution vertical mid-section plane. (Motamedi et al., 2022). Environment: X, 13, 100152

3.4 Measurement and survey setup

This subsection provides an overview of the methodology employed during the measurement within this research. The main objective of the measurement is to evaluate the chosen location in terms of CO2 levels, humidity, and temperature. Additionally, a study conducted by Zhang et al. (2022) recommended positioning the measurement devices at heights of 1.1 and 1.6 meters, corresponding to sitting and standing heights, respectively. Furthermore, their research indicated that the areas adjacent to the walls of the room exhibited the highest concentrations of CO2. To find out this is also the case in this research, attention is paid to the location of the measurement devices.

Shown in figure 22 are the HONEYWELL room wired sensors used for this measurement. These sensors are capable of measuring the CO2 concentrations, temperature and humidity inside the room. The measurements takes place for the duration of a single class. A single class can last from 2 hours to 4 hours. During a class the interval for when data is logged to the device is set to every 10 minutes. Furthermore, the data will also be logged for an hour before and if possible an hour after the class to find out what concentration, temperature and humidity the room rests at when the room is empty.

As illustrated in Figure 23 five sensors are positioned on the walls, while the remaining four sensors are situated closer to the interior. This arrangement ensures adequate sensor coverage throughout the room. The heights of the devices are also indicated in Figure IIII. The original objective was to set the sensors at 1.1 meters, which mimics the height of the sitting position. However, due to the table only being 0.7 meters in height, the sensors were unable to be set at that height. A compromise was done and the sensors were set at a height of 0.9 meters. The only sensor placed at a different height is the one located at the front of the room, which corresponds to standing height. This is the area where individuals present at the front of the room.

Figure 22 HoneyWell sensor, self made

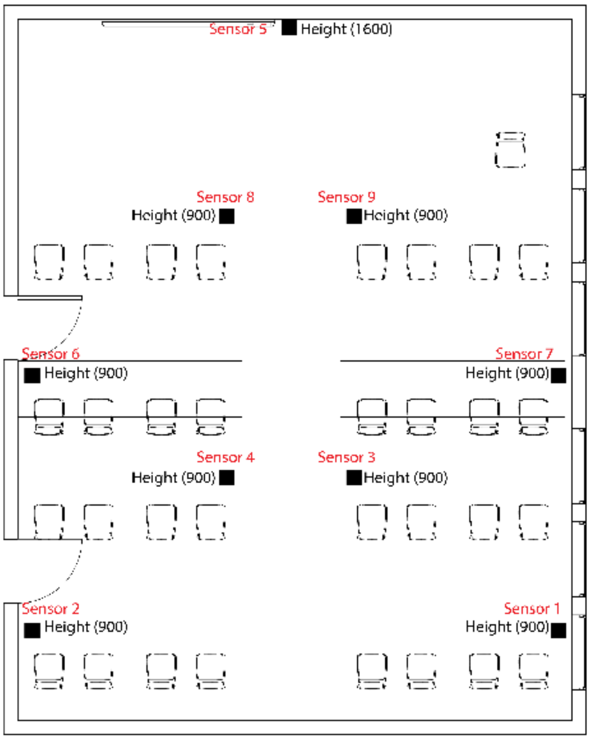


Figure 23 Floorplan with sensor placement

The current supply air inside the room is facilitated through a fabric ventilation tube (Figure 24), while the exhausts are positioned in the walls connecting to the hallway in two locations (Figure 25). The current supply of the room 960 m3/h with the exhaust equal to that, but divided in 2 for each exhaust point. The ventilation system that is connected to the these air terminals is a Rosendaal liberty 1530 ventilation system, which has an capacity of 11500 m3/h and comes equipped with an F7 bag filter to filter out particles from the airflow.

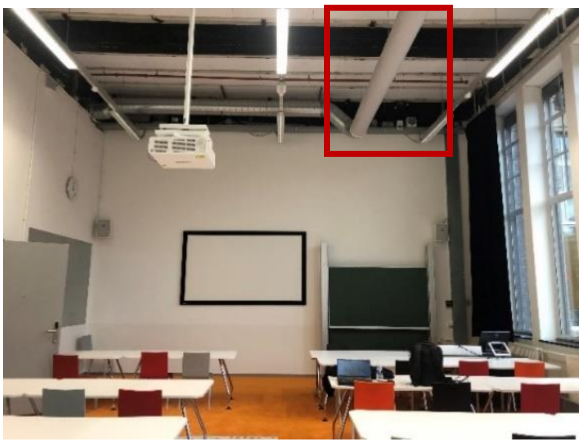


Figure 24 Photo room, self made

Figure 25 Photo room, self made

Survey

In addition to the simulation setup, a measurement and survey are also conducted to complement the research. The survey aims to assess the comfort levels of the occupants, specifically focusing on indoor air quality, thermal comfort, and acoustic comfort. By gathering feedback from the occupants, valuable insights can be obtained regarding their subjective experience in the space. A version of the survey used in this study is included in Appendix B, providing a comprehensive overview of the questions and factors considered in evaluating occupant comfort.

3.5 Simulation setup and comparison to the measurement

In this subsection, the simulation setup for the research is described and how to convert the results from the CO2 concentration simulations. The simulation is performed using CHAM UK Phoenics, a Computational Fluid Dynamics (CFD) program. The purpose of the simulation is to accurately replicate the real situation. In order to do so, a set of parameters needs to be specified in terms of the values used. These parameters can be essentially be grouped in four groups, which are the setup of the room, the domain settings, the supply and exhaust ventilation parameters and the human CO2 production parameters. Based on the findings of a thesis conducted by Cai, (2022), it was found that special attention needs to be given to the domain settings within the model. As it was found that converge control, which is explained further down, of the pollutant was difficult. However, first it starts with the setup of the room.

Setup of the room

Figure 26 and 27 depict the utilization of the same layout as the measurement in the simulation. When setting up the layout, the primary consideration is to simplify the model to optimize simulation performance and calculations.

Hence, as illustrated in figure 6, the tables has been simplified to include only the table slabs, and the occupants have been represented by boxes with attributes equivalent to people. To accurately represent the occupants these boxes also have a heat generation of 80 Watts.

Furthermore, as shown in figure 7, three walls of the room are connected to either a hallway or another classroom, while one wall is exposed to the outside. The three interior walls are set as adiabatic, whereas the wall adjacent to the outside has a surface temperature of 16 degrees.

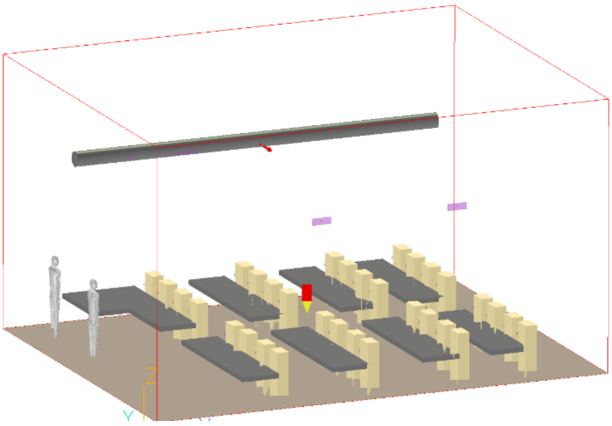


Figure 26 room layout, isometric

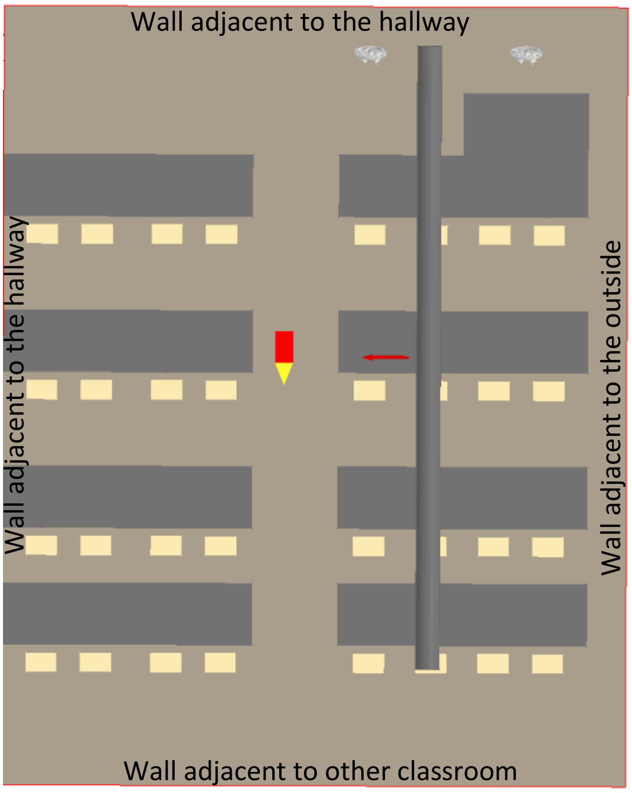


Figure 27 Room layout, top down

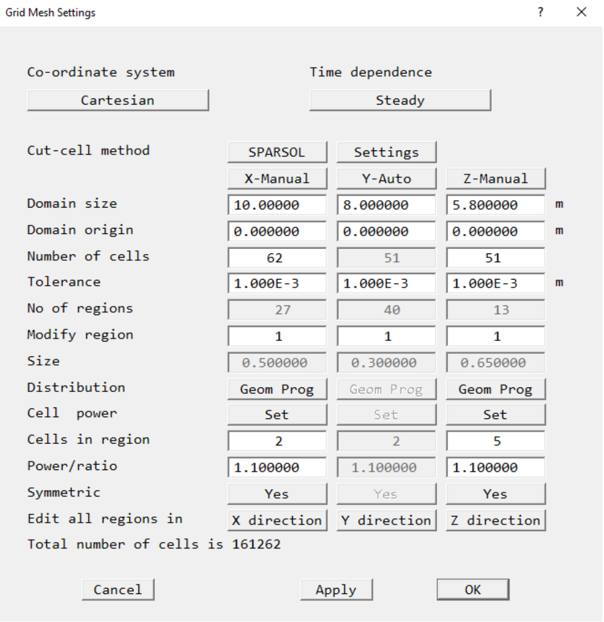
Domain settings

Within the domain, there are four categories of model inputs that require attention to obtain precise results from the simulation. These categories are the geometry, models, and numerics. The following section provides a detailed discussion of the exact input values for each of these categories, commencing with the geometry values.

The geometry category determines the size of the simulation domain and the grid layout within the model. In this research, the domain size matches that of the room itself, as depicted in Figure 28. The room has dimensions of 10 meters in length, 8 meters in width, and a height of 5.8 meters.

Regarding the grid field, it can be set automatically or manually. For this simulation, the grid was initially set up automatically, with the minimum cell fraction set to 2.5%. This establishes the smallest allowable cell size as a fraction of the domain size in that direction. Subsequently, the grid settings were modified to allow manual adjustments. This was done to introduce additional cell divisions in areas near the ventilation and pollution sources, aiming for a more precise representation of the room.

Figures 29 and 30 illustrate the final grid configurations used within the room in the X and Z directions, respectively.



Grid Mesh Settings

Co-ordinate system: Cartesian

Time dependence: Steady

Cut-cell method	SPARSOL	Settings		
	X-Manual	Y-Auto	Z-Manual	
Domain size	10.00000	8.000000	5.800000	m
Domain origin	0.000000	0.000000	0.000000	m
Number of cells	62	51	51	
Tolerance	1.000E-3	1.000E-3	1.000E-3	m
No of regions	27	40	13	
Modify region	1	1	1	
Size	0.500000	0.300000	0.650000	
Distribution	Geom Prog	Geom Prog	Geom Prog	
Cell power	Set	Set	Set	
Cells in region	2	2	5	
Power/ratio	1.100000	1.100000	1.100000	
Symmetric	Yes	Yes	Yes	
Edit all regions in	X direction	Y direction	Z direction	

Total number of cells is 161262

Figure 28 Grid mesh settings

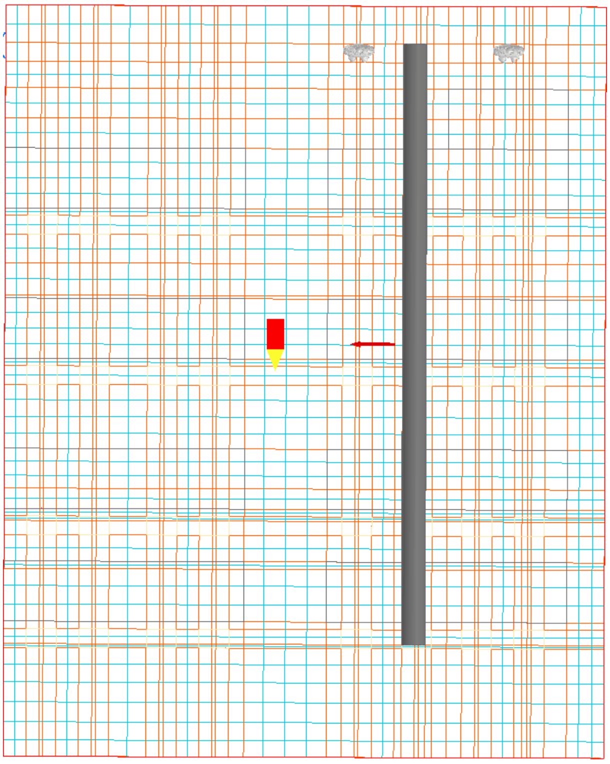


Figure 29 Mesh grid horizontal layout

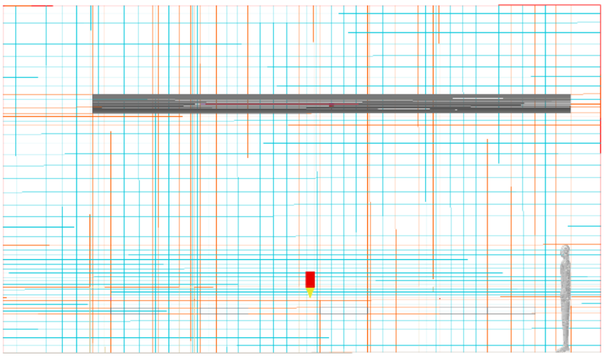
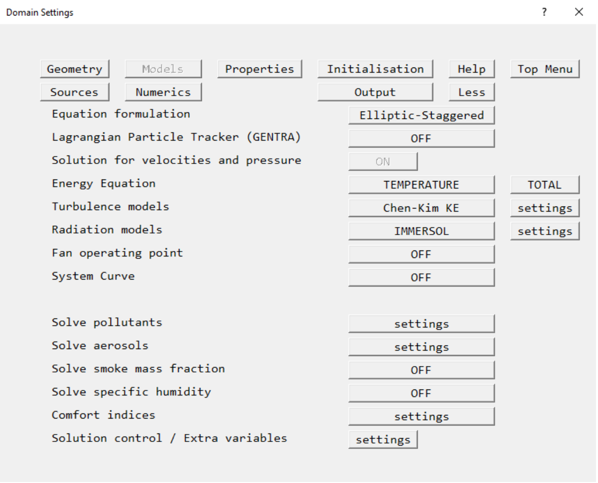


Figure 30 Mesh grid vertical layout

Next are the model settings. These settings are responsible for the type of calculation models used within the model. Additionally, within these settings is also possible to add pollutants and aerosols, such as CO2, other gasses and particles of different sizes to the model.

As it is shown in figure 31, the turbulence model that is used in this simulation is the Chen-Kim KE model and the radiation model is set to the IMMERSOL model.

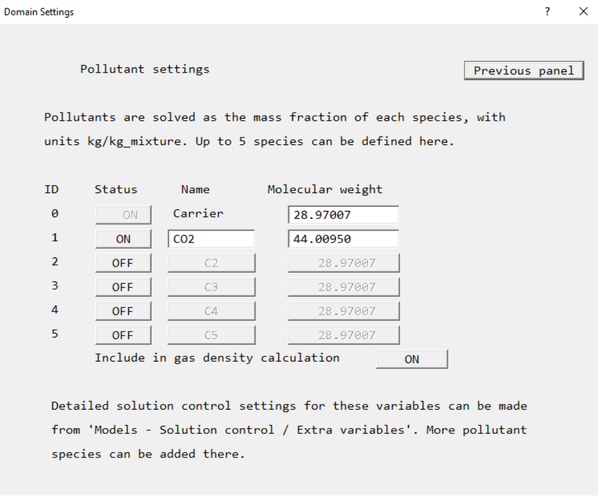


Equation formulation Elliptic-Staggered
Lagrangian Particle Tracker (GENTRA) OFF
Solution for velocities and pressure ON
Energy Equation TEMPERATURE TOTAL
Turbulence models Chen-Kim KE settings
Radiation models IMMERSOL settings
Fan operating point OFF
System Curve OFF
Solve pollutants settings
Solve aerosols settings
Solve smoke mass fraction OFF
Solve specific humidity OFF
Comfort indices settings
Solution control / Extra variables settings

Figure 31 Model settings

Regarding the pollutants, the primary focus of the simulation is to replicate CO2 concentration inside the room. To achieve this, the pollutant settings involve specifying the molecular weight of CO2, which is 44.0095 g/mol (El-Khayatt, 2010). This enables the model to calculate the CO2 concentration within the grid field.

The concentration given in the simulation is expressed in kg/kgmixture. As results, this concentration can not be immediately used as representative for the concentration for CO2, as that is normally given in Parts Per Million. Thus this must be first converted using the following method:



Pollutant settings

Pollutants are solved as the mass fraction of each species, with units kg/kg_mixture. Up to 5 species can be defined here.

ID	Status	Name	Molecular weight
0	ON	Carrier	28.97007
1	ON	CO2	44.00950
2	OFF	C2	28.97007
3	OFF	C3	28.97007
4	OFF	C4	28.97007
5	OFF	C5	28.97007

Include in gas density calculation ON

Detailed solution control settings for these variables can be made from 'Models - Solution control / Extra variables'. More pollutant species can be added there.

Figure 32 Pollutant setting

Starting with:

$$X * \frac{kg_{CO_2}}{kg_{mixture\,(air)}} = X * \frac{Volume\ CO_2}{Volume\ mixture(air)}$$

Which then can be rewritten to:

$$concentration_{\ CO_2} = X * \frac{\left(\frac{x}{\rho_{CO_2}}\right)}{\left(\frac{1}{\rho_{Air}}\right)} = concentratie_{\ CO_2} = X * \frac{\rho_{Air}}{\rho_{CO_2}}$$

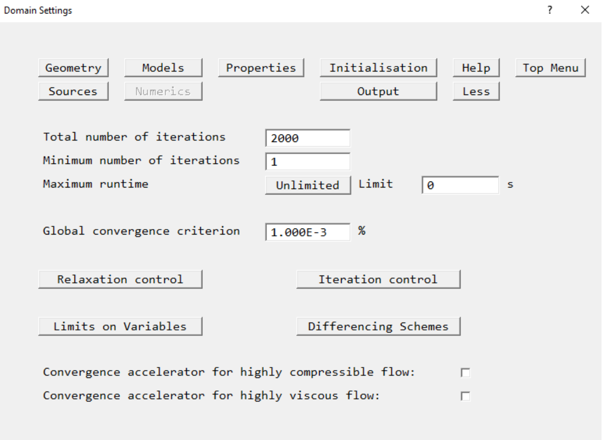
Which finally leads to

$$concentratie_{\ CO_2} = X * \frac{1,2}{1,8}$$

With the density of air at 20 degrees Celsius being: 1,2 (The Engineering ToolBox, 2003)
With the density of CO2 at 20 degrees Celsius being: 1,8 (The Engineering ToolBox, 2018)

Additionally, the model does not consider the background CO2 concentration that is consistently present. Therefore, it is necessary to incorporate the background CO2 concentration into the converted result. However, it's important to consider the context of the situation as there may be a difference between the simulated and measured values. For instance, if the concentration is already at 1000 PPM and the simulation shows 1075 PPM, a difference of 7% may not significantly impact the room since the concentration present is already high. Therefore, as long as the standard deviation is within 10%, the values from the simulation can be considered accurate.

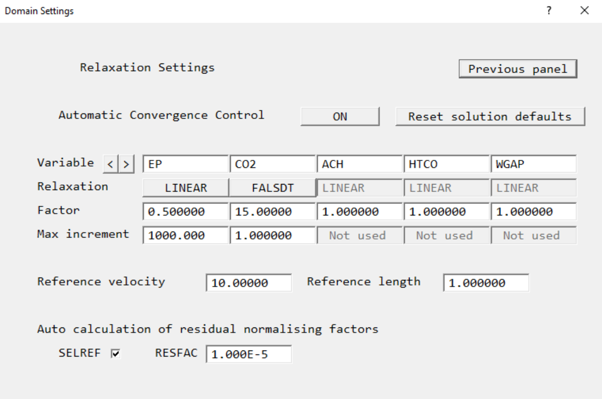
The last domain settings are the numerics settings, as figure 33 shows. The numerical settings in the domain are crucial for the convergence control during the simulation. Convergence control in Phoenics refers to the process of achieving a stable and accurate solution by iteratively solving the running equations until the changes in solved-for values become small enough to be negligible. It ensures that the simulation results reach a consistent state and that the solution is reliable.



Total number of iterations 2000
Minimum number of iterations 1
Maximum runtime Unlimited Limit 0 s
Global convergence criterion 1.000E-3 %
Convergence accelerator for highly compressible flow: ☐
Convergence accelerator for highly viscous flow: ☐

Figure 33 Numerics settings

Convergence can be controlled using various methods during the simulation. However one of the primary methods is adjusting the relaxation factor, which determines the rate at which the solution updates and converges. The relaxation factor balances the stability and efficiency of the simulation. A higher relaxation factor can lead to faster convergence but may sacrifice accuracy, while a lower relaxation factor can improve accuracy but increase computation time. Under normal circumstances it is advised to leave the relaxation factors as there are, without changing anything.



Automatic Convergence Control ON

Variable	EP	CO2	ACH	HTCO	WGAP
Relaxation	LINEAR	FALSDT	LINEAR	LINEAR	LINEAR
Factor	0.500000	15.00000	1.000000	1.000000	1.000000
Max increment	1000.000	1.000000	Not used	Not used	Not used

Reference velocity 10.00000 Reference length 1.000000

SELREF ☑ RESFAC 1.000E-5

Figure 34 Relaxation settings

The choice of type within the relaxation significantly influences the convergence rate. There are two types of relaxation models, which are the Linear relaxation is generally preferred over the false-time-step alternative. The latter option is challenging to select appropriately, as the optimal value for one domain size may not be suitable for another, even with similar flow characteristics.

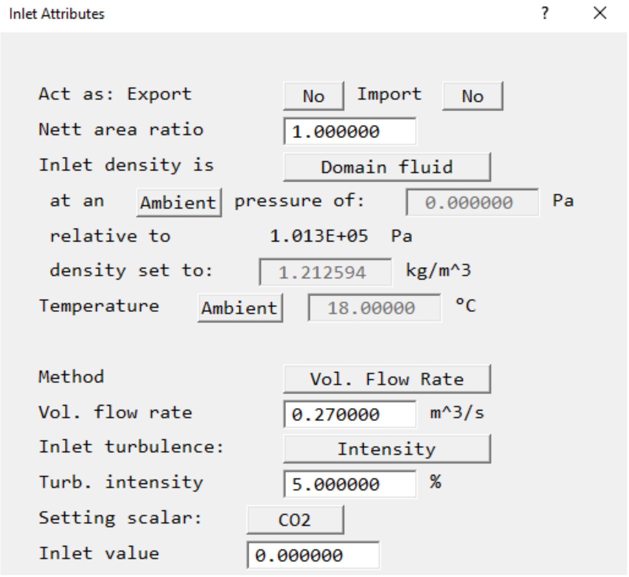
For the simulation in this research the pollutant of CO2 is introduced. As result for this parameter the relaxation factor also must be set. After running a couple of test simulations with normal and various other relaxation factors, it was found that using the advised relaxation factor, the model would not converge. As result from the testing the relaxation model FALSDT with factor of 15 was used for the CO2 parameter. As lower relaxation factors did not lead to convergence and higher relaxation factors would prove to be inaccurate (CHAM UK, n.d.; Cai, 2022).

Supply and exhaust ventilation parameters

The third group of settings are the in put values used for the supply and exhaust of the room. As it was made clear in the measurement setup, this room has an a rated supply of 960 m3/h and the exhausts, which are split into two air terminals, have each an exhaust rated of 480 m3/h. Within the simulation model these ventilation rates need to put in m3/s. in terms of the supply this would convert to around 0,27 m3/s and for the exhaust to around 0,13 m3/s

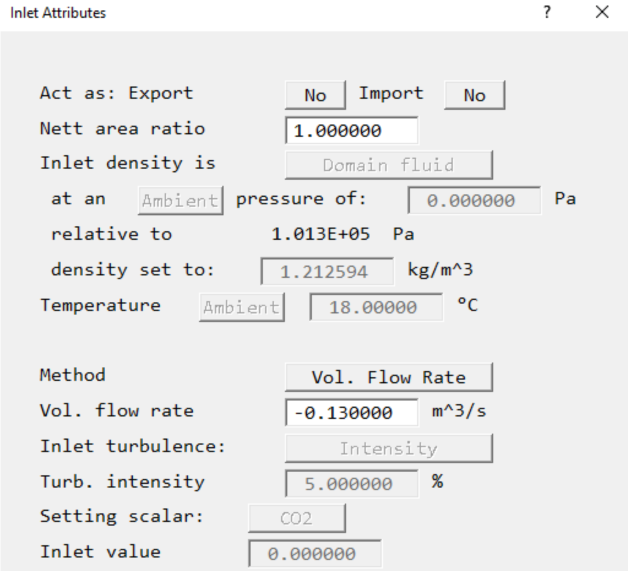
The human CO2 production parameters

The final category relates to the production of CO2 by the occupants within the room. As discussed earlier in the model setting group of the domain settings, it is now possible to assign the pollutant to a specific source, which in this case is the occupants themselves. Figures 37 and 38 illustrate the representation of the nasal and oral openings as pink squares and the value used of the inlet value, respectively. With an area of 0.000357 m2 based on literature (Schriever et al., 2013), corresponding to a diameter of 0.02 m. However, during test simulations using squares of this size, the model encountered accuracy issues, particularly around these pink squares. Consequently, a size of 0.05 by 0.05 was chosen, as it provided the smallest size that yielded accurate results during testing. Additionally, as was previously discussed in subsection 2.3.3, the inlet value is equal to the percentage of CO2 exhaled in one breath, which was 5%.



Act as: Export No Import No
Nett area ratio 1.000000
Inlet density is Domain fluid
at an Ambient pressure of: 0.000000 Pa
relative to 1.013E+05 Pa
density set to: 1.212594 kg/m^3
Temperature Ambient 18.00000 °C
Method Vol. Flow Rate
Vol. flow rate 0.270000 m^3/s
Inlet turbulence: Intensity
Turb. intensity 5.000000 %
Setting scalar: CO2
Inlet value 0.000000

Figure 35 Supply ventilation settings



Act as: Export No Import No
Nett area ratio 1.000000
Inlet density is Domain fluid
at an Ambient pressure of: 0.000000 Pa
relative to 1.013E+05 Pa
density set to: 1.212594 kg/m^3
Temperature Ambient 18.00000 °C
Method Vol. Flow Rate
Vol. flow rate -0.130000 m^3/s
Inlet turbulence: Intensity
Turb. intensity 5.000000 %
Setting scalar: CO2
Inlet value 0.000000

Figure 36 Exhaust ventilation settings

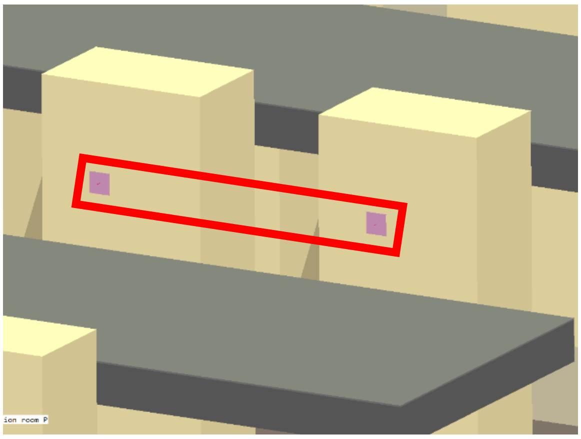
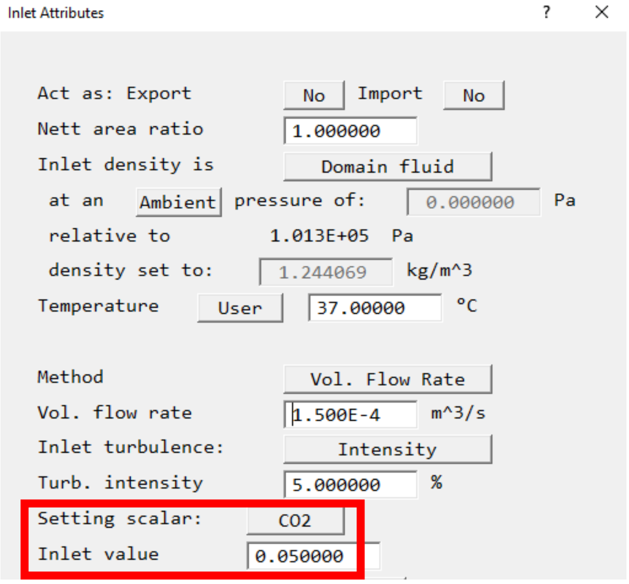


Figure 37 Representation nose and mouth



Act as: Export No Import No
Nett area ratio 1.000000
Inlet density is Domain fluid
at an Ambient pressure of: 0.000000 Pa
relative to 1.013E+05 Pa
density set to: 1.244069 kg/m^3
Temperature User 37.00000 °C
Method Vol. Flow Rate
Vol. flow rate 1.500E-4 m^3/s
Inlet turbulence: Intensity
Turb. intensity 5.000000 %
Setting scalar: CO2
Inlet value 0.050000

Figure 38 Settings nose and mouth

4. The baseline

In this chapter the base situation is researched and defined. Additionally parametric research is conducted here, with the goal is to find out the impact each of the parameters defined back in subsection 2.8 parameters.

4.1 Theoretical approximation

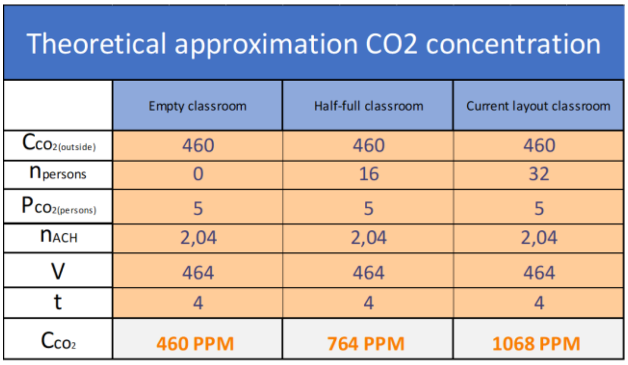
The first step in analysing a location in terms of performance is to conduct a theoretical approach. This will give an indication on what CO2 concentrations can be expected from measurements and simulations. The formula to calculate the CO2 concentration inside the room is then as follows (Bokel, 2021):

$$(4): \qquad c_{CO_2} = c_{CO_2(Outside)} + \frac{n_{persons} \cdot P_{CO_2(persons)}}{\mathrm{n}_{ACH} \cdot V} \cdot (1 - \mathrm{e}^{-\mathrm{n}_{ACH} \cdot \mathrm{t}})$$

Where:

c_{CO_2}	Theoretical CO2 concentration inside (PPM),
$c_{CO_2(Outside)}$	CO2 concentration outside (PPM),
$n_{persons}$	the number of persons in the room,
$P_{CO_2(persons)}$	CO2 production of one person (cm3/s),
n_{ACH}	amount of air changes per hour,
V	Volume of the room (m3),
t	Total time (h),

In figure XX three theoretical situations are depicted with the location's capacity at zero, half and full. The values used in the formula are derived from the following sources:



Theoretical approximation CO2 concentration

	Empty classroom	Half-full classroom	Current layout classroom
$C_{CO_2(outside)}$	460	460	460
$n_{persons}$	0	16	32
$P_{CO_2(persons)}$	5	5	5
n_{ACH}	2,04	2,04	2,04
V	464	464	464
t	4	4	4
C_{CO_2}	**460 PPM**	**764 PPM**	**1068 PPM**

Figure 39 Theoretical approximation

- CO2 concentration outside: The recorded value at this location was approximately 460 PPM, which will be used for calculations.
- Number of individuals inside the room: Ranges from empty to full capacity. The current layout of the room accommodates a maximum of 32 students.
- CO2 production per person: Generally accepted value is 5% or 5 cm^3/s (source).
- Air change per hour is *464/960= 2.04* times per hour.
- Duration of the lecture: For calculation purposes, a duration of 4 hours will be used.

Based on these values, at zero capacity the co2 concentration inside the room would be equal to the co2 concentration outside the room, while at half capacity the room theoretically could reach 764 PPM in terms of Co2 concentration and at full capacity with the current layout the room would reach 1068 PPM. These results compared to the guidelines and literature show that this room does not meet the recommendations set by the WHO and Frisse Scholen level C. The WHO recommends a maximum concentration of 1000 PPM for renovated buildings, which this room exceeds. Additionally, according to the literature the room surpasses the 700 PPM recommendation at both full capacity and half capacity.

Using these CO2 concentrations, it is also possible to estimate the theoretical risk of infection within the room. The calculation of this risk is based on the formula developed by Rudnick and Milton, which is reiterated below as formulas (5) and (6):

(6) $f = \frac{C - C_0}{C_a}$

(7) Rudnick-Milton : $P = 1 - e^{-\frac{flqt}{n}}$

For each capacity, the risk of infection is calculated, taking into account the various variants of COVID-19. The average quanta values of these variants are used in the calculation. The results of these calculations are presented in table ZZ. Upon examining the results, it becomes evident that during the early stages of the pandemic when the ALFA variant of the COVID-19 virus was predominant, the infection risk was estimated to be between 13% and 18% using the minimum and maximum quanta, respectively. However, as new variants emerged over time, the infectivity increased, leading to higher calculated infection risks for each variant. Reaching as high 97% with the current OMICRON strains.

An interesting observation can be made regarding the relationship between the number of people present and the fraction of exhaled breath. As these factors increase linearly, the risk of infection remains the same. It is important to note that the calculation of infection risk using the theoretical approach does not account for the distance between individuals or the varying concentrations of CO2 within different areas of the room. As the calculation for the CO2 concentration is made for a well-mixed global average of the room for a point in time.

Rudnick en Milton - Infection risk - Theorectical approach			
	Empty classroom	Half-full classroom	Current layout classroom
	460 PPM	764 PPM	1068 PPM
	Quanta	Quanta range	
	Alfa	89 - 165	
	Delta	312 - 935	
	Omicron	725 - 2345	
	Empty classroom	Half-full classroom	Current layout classroom
C	0,00046	0,000764	0,001068
C0	0,00046	0,00046	0,00046
Ca	0,05	0,05	0,05
f	0	0,0061	0,0122
	ALFA VARIANT		
	Empty classroom	Half-full classroom	Current layout classroom
I	0	1	1
f	0	0,0061	0,0122
q	89 and 127	89 and 127	89 and 127
t	4	4	4
n	0	16	32
P	0 ■ 0	13% ■ 18%	13% ■ 18%
	DELTA VARIANT		
	Empty classroom	Half-full classroom	Current layout classroom
I	0	1	1
f	0	0,0061	0,0122
q	312 and 935	312 and 935	312 and 935
t	4	4	4
n	0	16	32
P	0 ■ 0	38% ■ 76%	38% ■ 76%
	OMICRON VARIANT		
	Empty classroom	Half-full classroom	Current layout classroom
I	0	1	1
f	0	0,0061	0,0122
q	312 and 935	725 and 2345	725 and 2345
t	4	4	4
n	0	16	32
P	0 ■ 0	67% ■ 97%	67% ■ 97%

Figure 40 Calculation infection risk – theoretical situation

In conclusion, it can be determined that the theoretical approach utilized provides valuable insights into the risks associated with the presence of an infected person in a room. However, it is important to acknowledge that this approach does not account for the spatial distance between occupants, nor does it consider the parameters related to the placement of exhaust or supply ventilation. These additional factors, including the concentration of CO2 within the room, could potentially influence the actual infection risk, resulting in variations that are not accounted for in the theoretical assessment. Therefore, to obtain a more comprehensive understanding of the potential risks in a given environment, it is crucial to consider both the theoretical indications, the specific conditions related to CO2 concentration, spatial distancing, and the appropriate placement of ventilation systems.

4.2 Situation 1: Baseline situation

In this section, the results of the measurement of the base situation are presented. Prior to discussing these results, it is relevant to briefly recap the events that occurred during the measurement process to provide some context to the results.

4.2.1 Measurement results and observations

The measurement was conducted on April 24th, 2023 with 18 individuals present in the room, occupying just over half of its maximum capacity. Figure 41 shows the seating arrangement of the individuals and the location of the measurement devices were previously shown in subsection 3.4. While the class was scheduled to start at 13:45 PM, the measurement already began at 10:45 AM to establish a baseline reading when the room was occupied by 1 person, which was the author of this thesis to setup the devices for the measurement and keep an eye on the gathered data.

As depicted in Graph 1, the initial measurement revealed a range of CO2 concentrations in the room, varying from 460 to 560 PPM. Notably, sensor 5 exhibited a higher concentration compared to sensors 1 to 4 and sensor 7. Additionally, sensors 6, 8, and 9 recorded lower CO2 levels. On average, there was an 80 PPM difference observed between the value sensor 5 and the lowest value observed by sensor 8. This deviation must be taken into account when analysing the results from when the class starts.

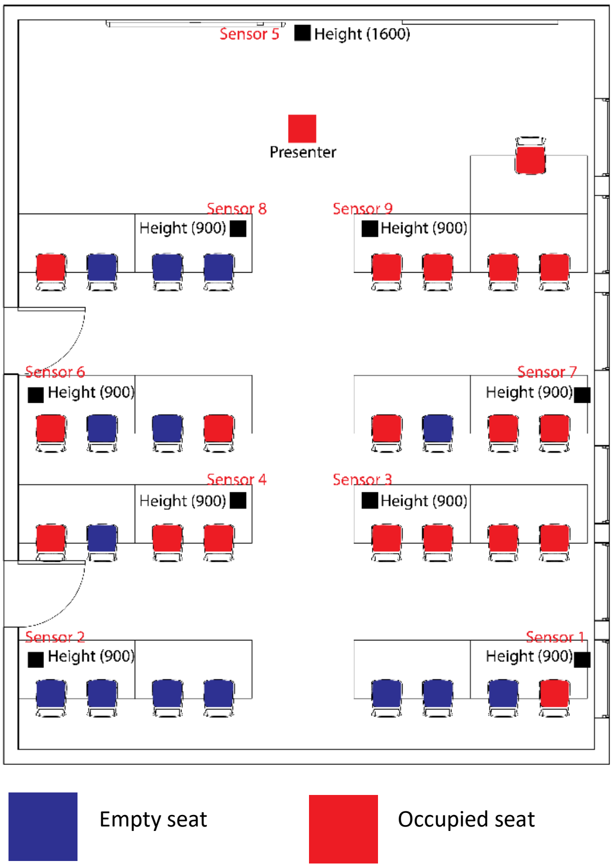
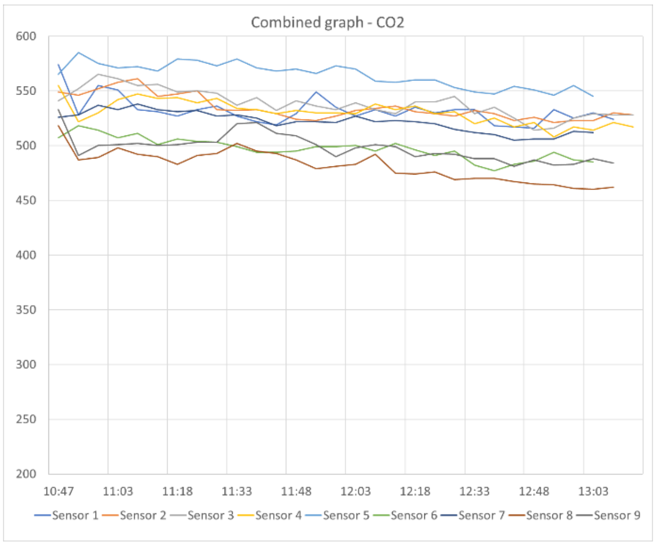


Figure 41 layout Occupied seats

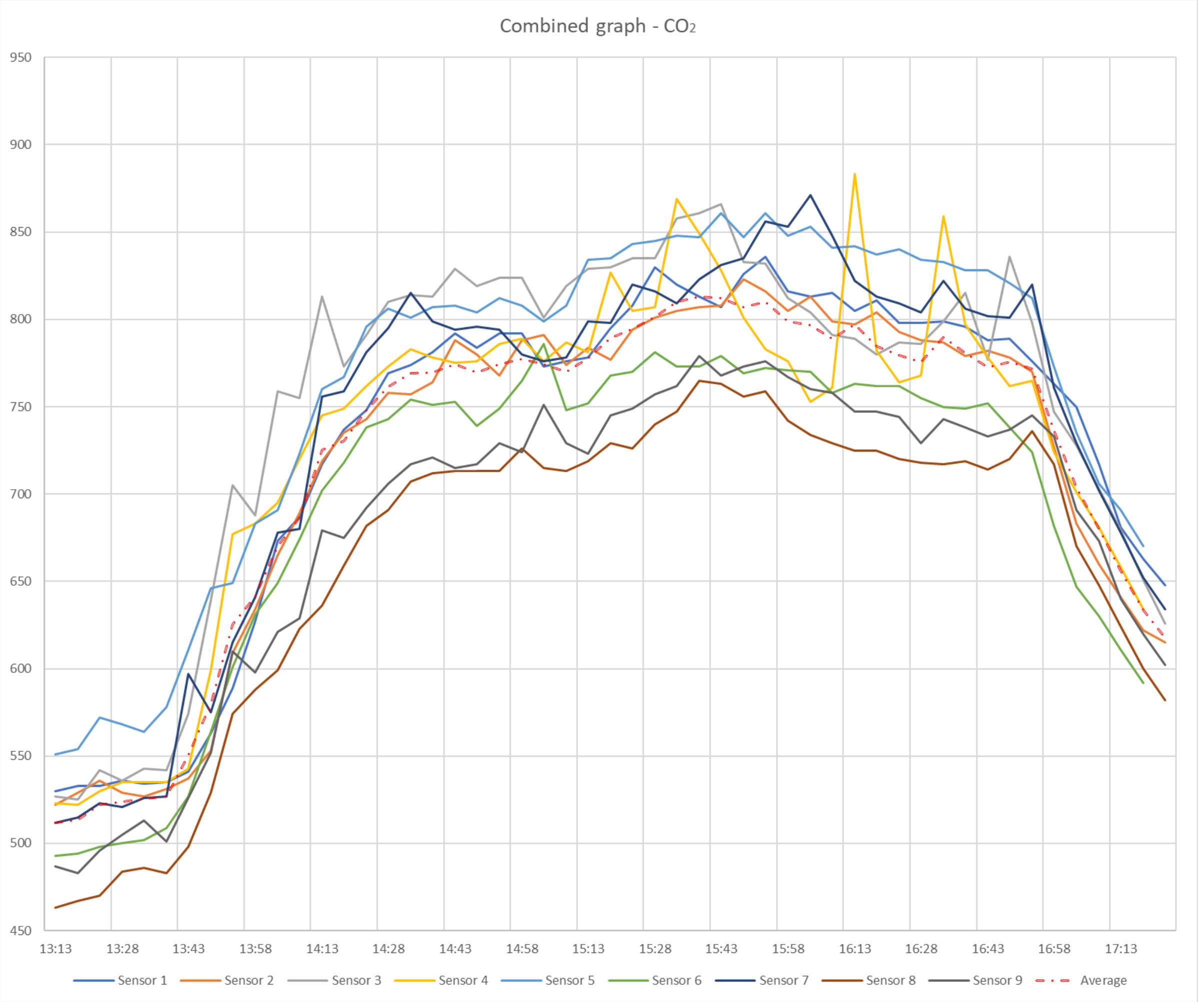


Graph 1 Empty room measurement

Moving on to the baseline measurement, Graph 2 presents the recorded CO2 concentrations from each sensor in the baseline scenario. The average concentration of the room between 14:28 and 16:43 stabilized between the 760-820 PPM. Additionally, the graph reveals that sensors 3, 5, and 7 registered the highest levels of CO2 within the room, occasionally accompanied by spikes from sensor 4. These occasional spikes and subsequent drops in sensor 4 readings could be attributed to its proximity to an individual who accidently exhaled towards it.

Furthermore the higher CO2 concentrations detected by sensors 5 and 7 appear to align with the findings of Zhang et al. (2022), who discussed that areas near the walls tend to exhibit higher levels of CO2. However, sensors 2 and 6, which were positioned on the left wall adjacent to the hallway, recorded average and below-average CO2 concentrations, respectively. Thus deviating from the literature. This disparity could be attributed to the differences in occupancy and distribution between this research and the study conducted by Zhang et al. (2022). As the current measurement was conducted in a partially occupied room with uneven distribution, while the previous study examined a fully occupied classroom with even distribution of occupants.

Finally, sensors 8 and 9 recorded the lowest CO2 concentrations in the room, with values being below the average. Sensor 8's lower reading can be attributed to its placement in a less populated area near the frequently opened door. However, it is peculiar that sensor 9, situated in an area with closer proximity to occupants, also registered a low reading. This anomaly suggests a possible calibration issue, as this deviation was observed even when the room was unoccupied.



Graph 2 18 People measurment

The next phase of the analysis aims to determine the significance of the differences in the collected data. This involves calculating the standard deviation and standard error of the averages obtained from the measurement conducted in an almost empty room and the measurement conducted with the room occupied. Additionally, the difference between the averages is calculated and the standard error is determined. These calculations help identify the sensors that exhibit significant differences.

Sensor	Average empty room	Standard deviation	Standard error
1	532	12	2
2	534	11	2
3	539	14	2
4	530	11	2
5	571	11	2
6	499	14	3
7	524	16	3
8	482	14	3
9	498	12	2

Table 9 Averages empty room

Sensor	Average Full room	Standard deviation	Standard error
1	804	17	4
2	796	14	3
3	822	23	5
4	798	34	8
5	834	19	4
6	765	12	3
7	815	26	6
8	732	17	4
9	749	19	4

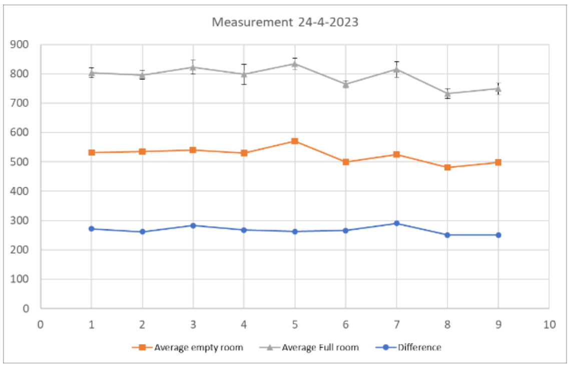
Table 10 Averages occupied room

Table 9 presents the averages obtained from the sensors during the measurement in the room with one person, while table 10 provides the averages from the measurement conducted with the room occupied. The recorded values span from the start of data recording until 13:08 for the one-person measurement, and from the moment the CO2 concentration reached a steady state (14:23 to 16:23) for the measurement with the room occupied. These values are plotted in graph 3, and the corresponding standard deviation and standard error are calculated.

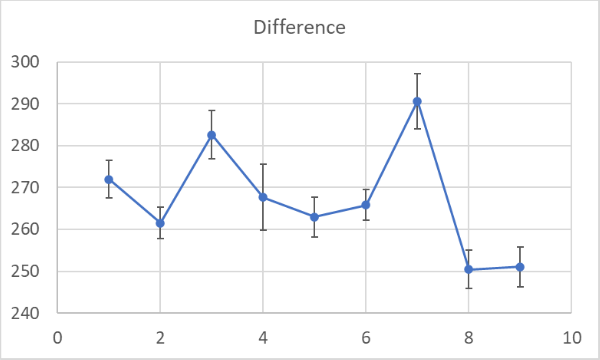
Sensor	Difference	Standard error
1	272	4
2	262	4
3	283	6
4	268	8
5	263	5
6	266	4
7	291	7
8	250	5
9	251	5

Table 11 Differences & standard error

Subsequently, the differences between the two sets of averages are calculated and their standard errors are determined. The results are then plotted in graph 4, which illustrates that sensors 3 and 7 deviate from the other sensors by exhibiting higher values, while sensors 8 and 9 deviate by displaying lower values. This indicates that the data obtained from sensors 3, 7, 8, and 9 is statistically significant.



Graph 3 Overview values



Graph 4 Comparison deviation

4.2.2 Simulation results and observations

This subsection presents simulation results for two scenarios: one with 18 people and another with 32 people. It also includes the findings from the parametric research.

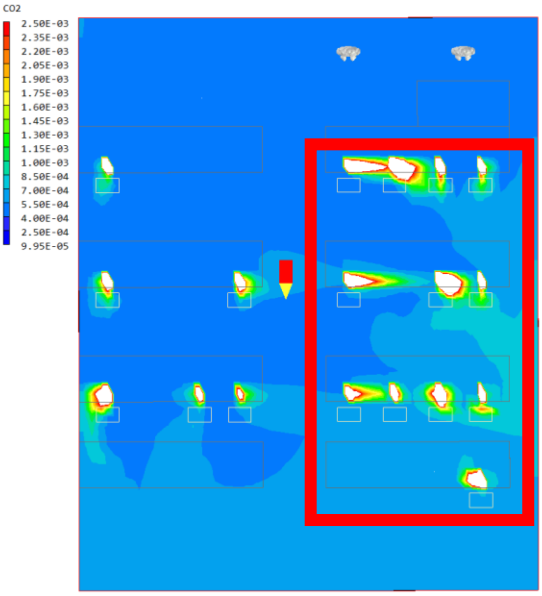
4.2.2.1 The baseline situation

The simulation into the base situation includes two main scenarios: the measurement day with 18 people and a full classroom setting. These scenarios were researched for two reasons. Firstly, the measurement data was collected on a day when the class was not at maximum capacity. Conducting a simulation with a full classroom allows us to understand the indoor environment under such conditions. Secondly, the measurements only captured data on CO2 concentrations, temperature, and humidity within the room. To gain a comprehensive understanding of the room, additional data is required. Hence, these simulations were conducted. The obtained results are presented in Table 12.

Type of result	Reasoning
CO2 concentration	Tied to the infection risk calculation
Age or air	Tied to the manual ventilation effectiveness calculation
Temperature	Tied to comfort
Ventilation effectiveness	A calculation performed by the simulation, in terms what they calculate what that the ventilation effectiveness is.
PMV	Tied to the comfort of people – Thermal sensation of the room
PDD	Tied to the comfort of people – higher percentage, higher likelihood of discomfort.

Table 12 Obtained Results

Firstly, the scenario involving 18 individuals is presented. The initial CO2 concentrations within the room are depicted in figure 42, shown by the red square. On the day of the measurement the majority of individuals were positioned on the right side of the room, with 12 individuals in that area. The simulation reveals that the CO2 concentration on the right side and at the back of the room appears to be higher, ranging from 886 PPM to 936 PPM after applying the conversion, while the left side of the room is more in the range of 804 PPM. The average CO2 concentration of the entire room is 871 PPM.



🟦 517 $\text{kg/kg}_{\text{mixture}}$ = 804 PPM

🟦 639 $\text{kg/kg}_{\text{mixture}}$ = 886 PPM

🟦 714 $\text{kg/kg}_{\text{mixture}}$ = 936 PPM

Figure 42 Baseline 18 CO2 concentrations

Based on this simulation, it is also evident that the CO2 concentrations surrounding the individuals within the room appear to be mixing. This implies that in the event an infected person is present in these areas, potential transmission of infections is occurring under the current room setup.

Additionally, when these concentrations are compared to the measured values, they appear to be very similar. With the difference between the averages being 6,7%, calculated as (871-813)/871 x 100%. In terms of higher concentrations, sensor 7 which was located in the same area, recorded a peak concentration of 856 PPM. The difference between the simulation and the measurement is 8,5% in this spot, calculated as (936-856)/936 x 100%. As these differences are less than 10%, they can considered acceptable and indicative of an accurate representation of the room.

In figure 43, the age of the air inside the is shown. While the simulation shows that room has an average age of air of 1902 (32 minutes) seconds, there are large discrepancies in the age of air in different locations of the room. Basically the room can be divided into three distinct area with distinct different ages of air. These are the areas 1, marked in green, 2, marked in yellow and 3 marked in orange and red. The green area has an age of air of 1638 (27 minutes) seconds, the yellow area and age of air 1702 seconds (28 minutes) and the red area an age of air of 2421 seconds (40 minutes). What this shows is that alongside the right side and the back of the room, especially the lower right corner, is not ventilated properly. This is concerning as it signifies that older air, potentially containing infectious particles, remain in the room for an extended duration. However it must be taken note of that in general the air inside the room is old, as the average already sat at 32 minutes.

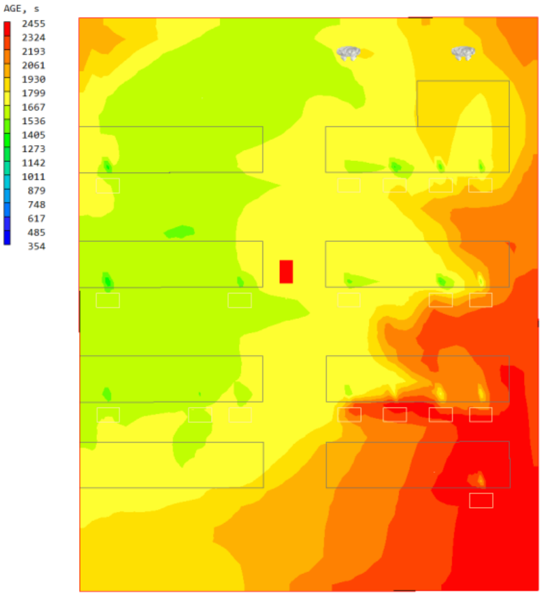


Figure 43 Baseline 18 age of air

In figure 44, the air velocity within the room is presented. This figure shows that indeed alongside the right side and the back of the room the air moves little. As the air velocity there sits at a velocity of 0,02 m/s, while the overall average inside the room sits at a velocity of 0,07 m/s. While in the middle of the room, there red yellow probe is located, the air velocity is 0,13 m/s.

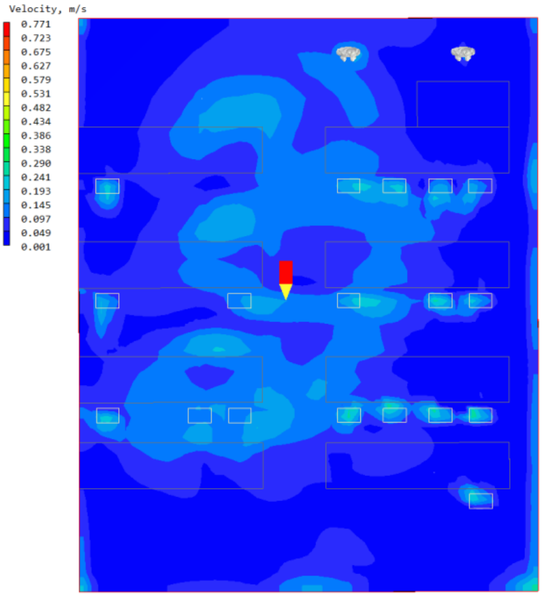


Figure 44 Baseline 18 air velocity

Additionally, the area around the people is a bit higher at 0,14 m/s. As it is shown in figure 45 marked in red, this can be explained due the thermal rise of air around the people.

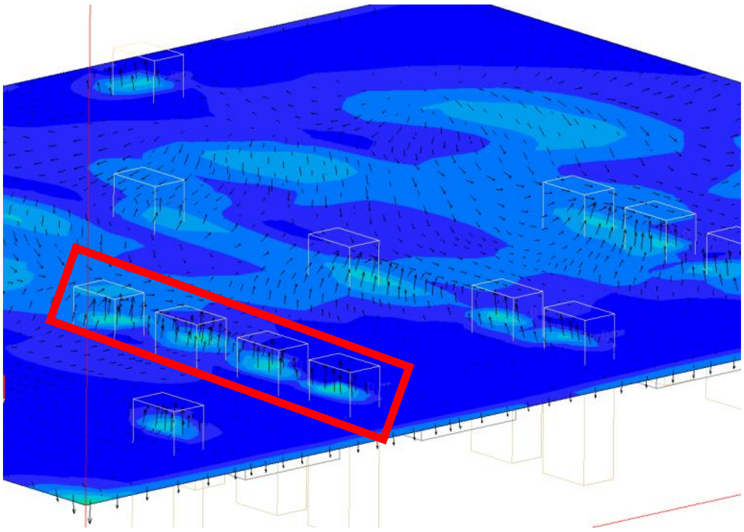


Figure 45 Baseline 18 air velocity rising

Figures 46, 47 and 48 show the temperature, PMD (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), respectively.

Figure 46 shows that the majority of room has an average temperature of 20,2 degree Celsius. While the brighter spots of green at the location of the red yellow probe have a marginally higher temperature of 20,8 degrees. The temperature of the temperature that is radiated from the occupants in the room is 21,5 degrees.

Moving to Figure 78, the simulation results indicate a PMV value of -1.40, indicating a cooler thermal sensation for the room occupants. The figure shows a relatively uniform distribution of thermal sensation within the room, with only a few yellow areas exhibiting a slightly higher PMV value of -1.20.

Lastly the PPD in figure 48 shows that the PPD inside the room is on average 45%. Just like in the case of the PMV a similar distribution is visible. The PPD distribution inside the room ranges from 40 to 50 %, with a couple spots that being 60%. What these results shows is actually a relatively high chance to dissatisfied with the thermal comfort inside the room, if the room is only filled to half capacity.

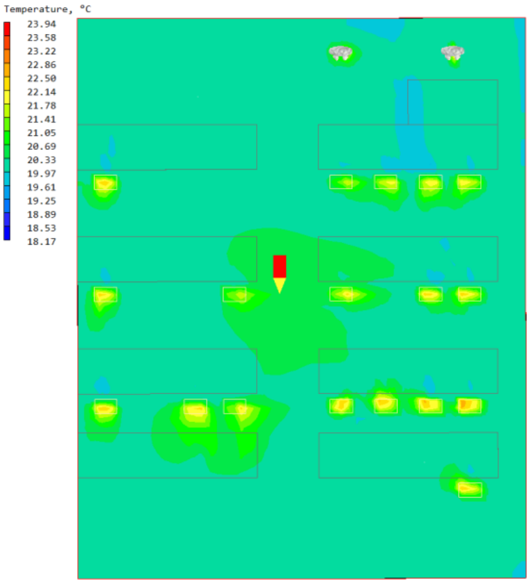


Figure 46 Baseline 18 temperature

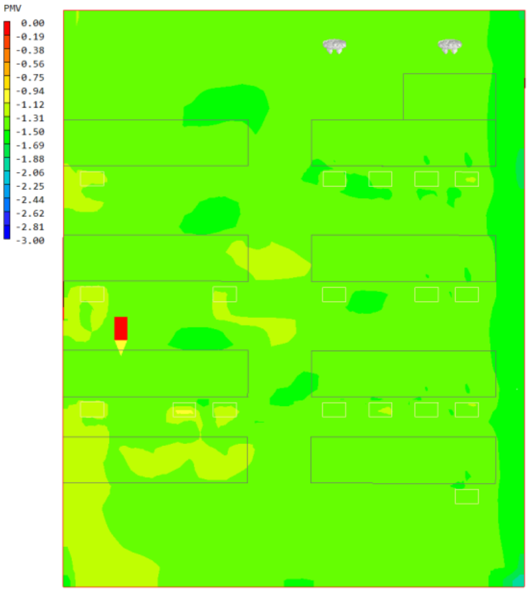


Figure 47 Baseline 18 PMV

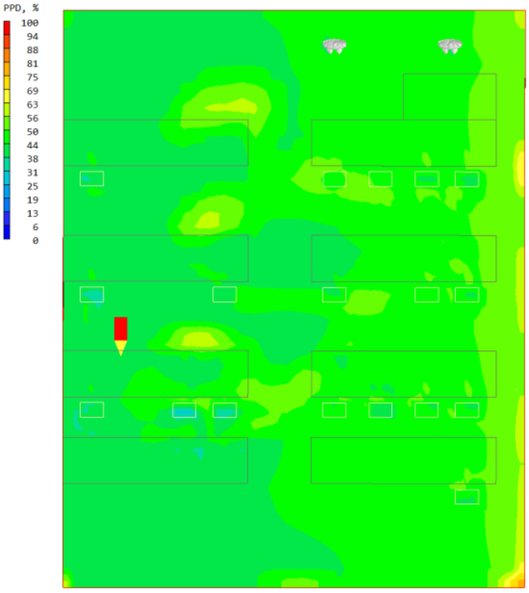


Figure 48 Baseline 18 PPD

Baseline full class

The second set of figures illustrates the simulation conducted with a full class occupying the room. Figure 49, 50, and 51 depict the CO2 concentration, age of air, and velocity, respectively.

Figure 49 displays the distribution of CO2 concentration within the room. Three notable observations can be made. Firstly, the room is divided into light blue and light green areas representing CO2 concentrations of 1062 PPM and 1100 PPM, respectively. Secondly, it is evident that the exhaled CO2 from individuals at each table is intermixing, where the peak concentration is measured to be 1292 PPM. Indicating a high potential for infection if someone is indeed infected. Thirdly, the average CO2 concentration inside the room is already elevated at 1156 PPM, suggesting inadequate ventilation overall. This high concentration poses a significant infection risk, which will be elaborated further on in subsection 4.2.4 'the risk of infection'.

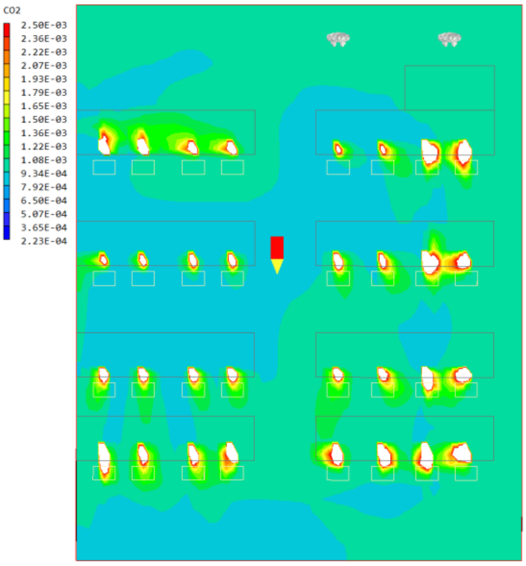


Figure 49 Baseline full class CO2 concentrations

Figure 50 presents the age of air within the room. In contrast to the simulation with 18 people, the distribution of air ages within the fully occupied room is worse. The simulation reveals an average age of air of 1763 seconds (~30 minutes) throughout the room. Notably, areas of stagnant air are observed along the front, middle, and right sides of the room, where air ages range between 1884 and 1908 (~32 minutes) seconds. In the yellow area, the age of air measures 1545 seconds (~26 minutes), likely due to its proximity to the room's exhausts. The air change rate in this room is 2,04 times per hour. Overall, it can be concluded that the age of air in the fully occupied room is worse compared to the room with 18 people. However, in both scenarios, the air can be considered stale based on these time measurements.

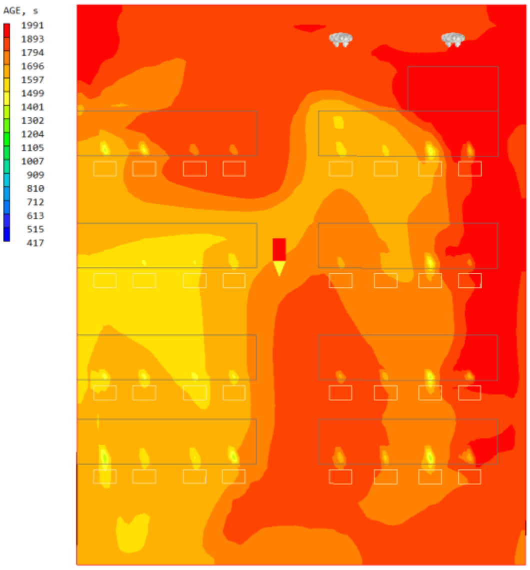


Figure 50 Baseline full class age of air

Regarding the air velocity in the room shown in figure 51. While it looks like the air velocity inside the room is all over the place, the majority of the room is covered by the dark blue to light blue area, where the air velocity ranges from 0,13 m/s to 0,18 m/s. The green area's have air velocity of 0,23 m/s which slightly exceed the threshold that is allowed inside rooms.

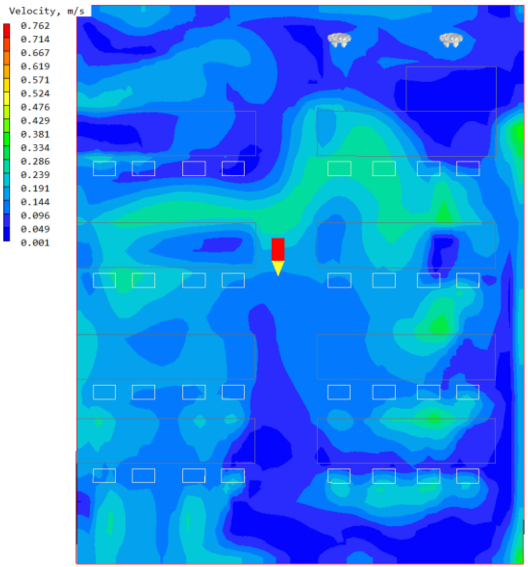


Figure 51 Baseline full class air velocity

Figures 52, 53 and 54 show the temperature, PMD (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied), respectively

Figure 52 shows that the room has an average temperature of 21.9 degrees Celsius, which is slightly higher than the scenario with 18 people. This slight increase can be attributed to the natural heat generation from the occupants themselves. Additionally, it is evident in the figure that the areas between the people are also slightly warmer than the average, with a temperature of 22.5 degrees Celsius. However, it is worth noting that two tables on the left, being in the direct flow path of the ventilation, have a temperature equal to the room average.

Moving to Figure 53, the simulation results indicate a PMV value of -1.07, indicating a slightly cool thermal sensation for the room occupants. In contrast the distribution shown back in figure 78, figure 99 shows a non-uniform distribution of thermal sensation within the room. The yellow and orange parts of the room have show a PMV value of -1,04 and -0,9, respectively. While the green parts, where the air velocity are also higher, have an PMV value of -1,37. This value is also found alongside the right side of the room where it averages between -1,17 and -1,40. This indicates that the people located on the side feel an slightly cooler sensation compared to the people seated more inwards.

This distribution of the thermal sensation inside the room translated to the distribution of the PPD in figure 54. While the average PPD inside the room is 29,8%, PPD values in the blue areas range between 22% and 25%, while the green areas reach as high as 46%. Indicating that people in the room with the current ventilation setup are for the majority less likely to feel dissatisfied with the thermal comfort in room, if the room is filled to capacity.

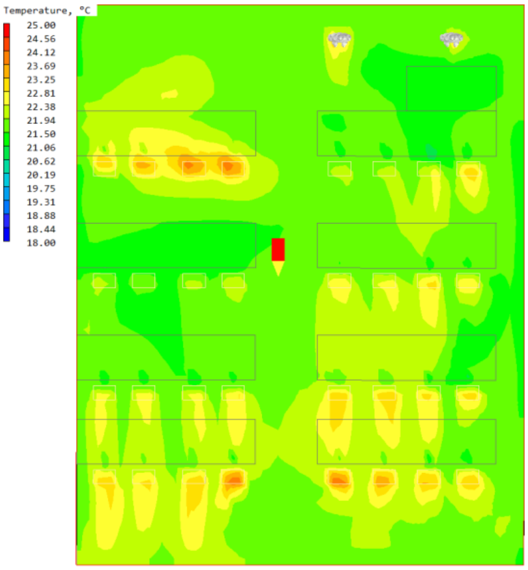


Figure 52 Baseline full class temperature

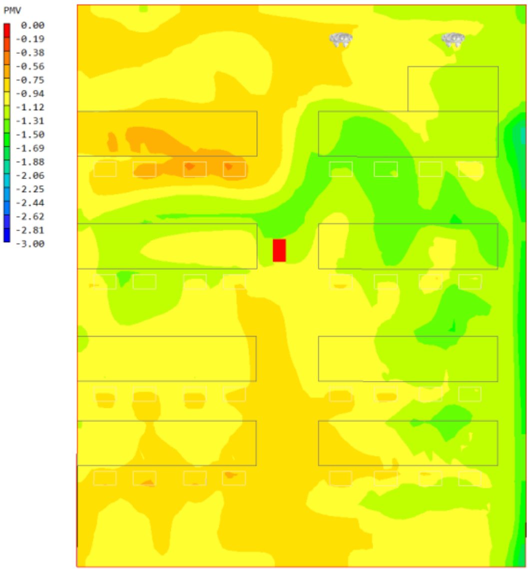


Figure 53 Baseline full class PMV

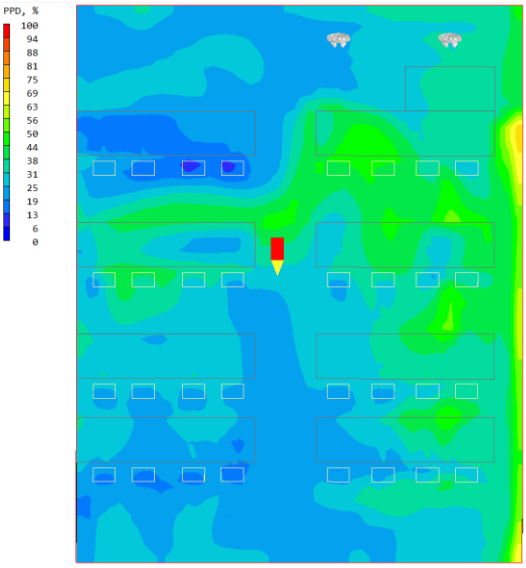


Figure 54 Baseline full class PPD

4.2.2.2 Parametric research

Parametric studies were conducted as part of this research, focusing on room volume and ventilation rate's impact on CO2 distribution and concentration. The CO2 concentration and the age of air were primarily analysed for the infection risk, staleness and potential to carry infectious particulates. This comparison primarily considers scenarios with 32 occupants. The initial experiments explored three heights (3.2m, 2.8m, and 2.6m), which are shown in figures 55, 56, and 57; corresponding to volumes of 256m3, 224m3, and 206m3, respectively. These heights are based on Frisse Scholen guidelines.

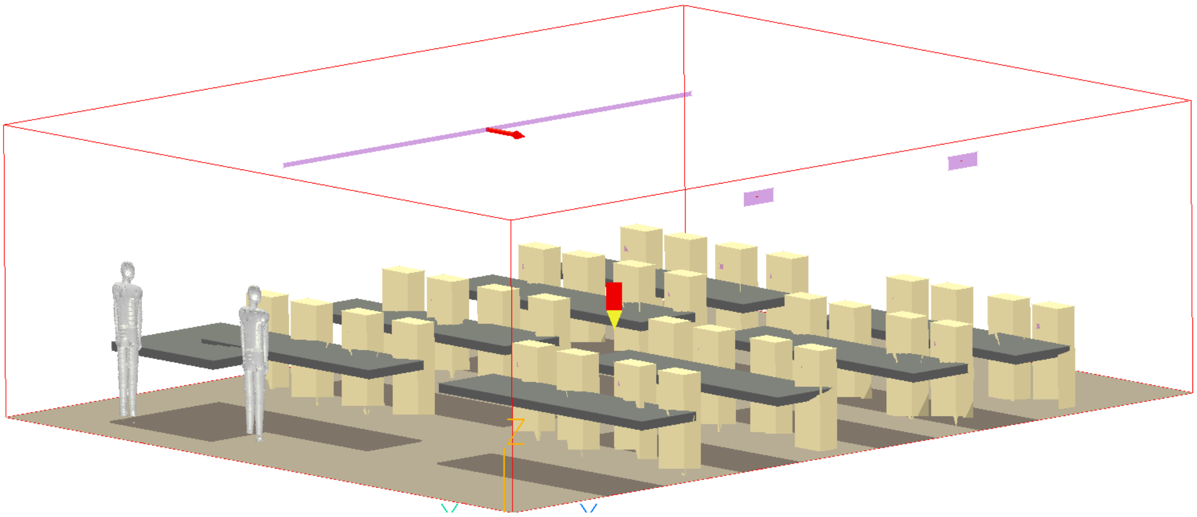


Figure 55 Room height 3,2 metres

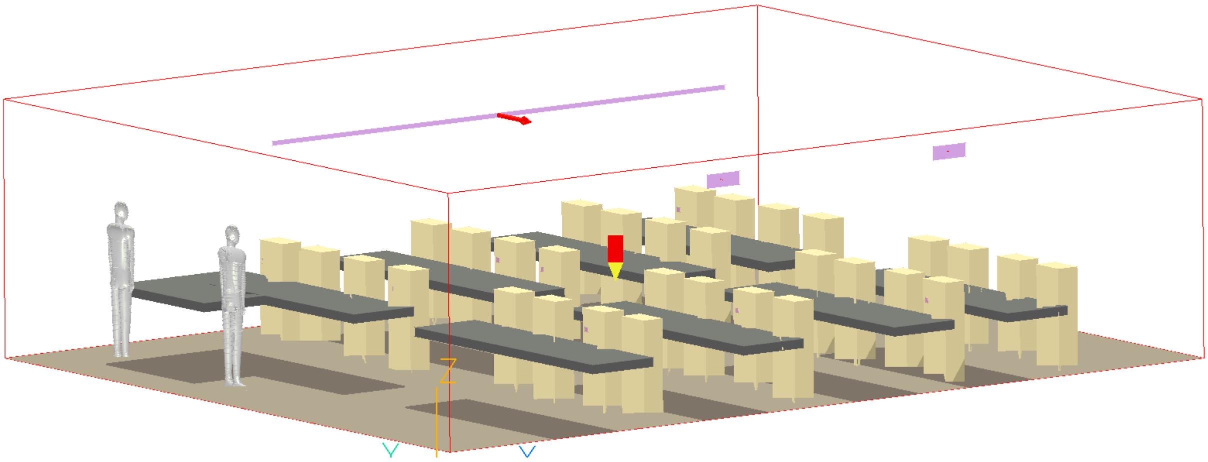


Figure 56 Room height 2,8 metres

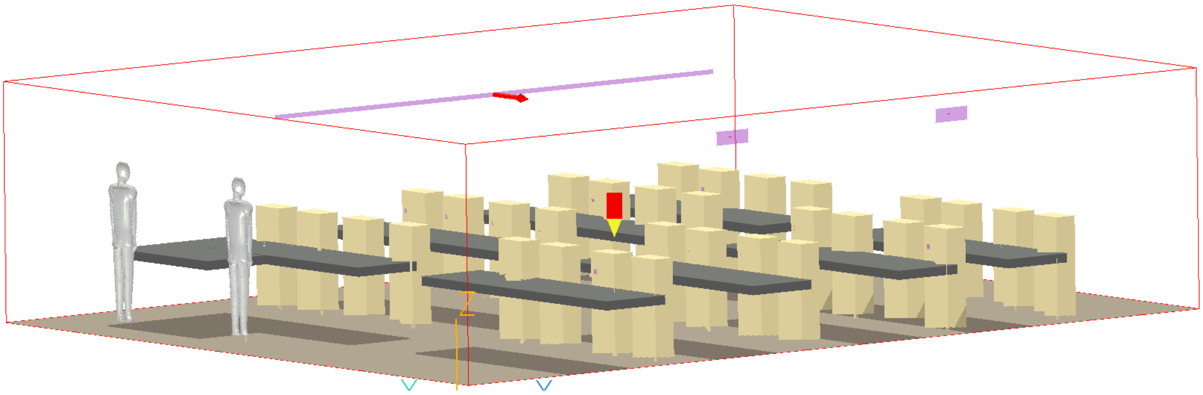


Figure 57 Room height 2,6 metres

Figures 58 to 61 present the CO2 concentration distribution within the room for the original height and three alternative heights. Several notable observations can be made from these figures. First, despite lowering the height, the average CO2 concentration in the room remained consistent at 1156 PPM. However, figures 59 to 61 illustrate that the CO2 plume between individuals expanded with each reduction in height. This indicates a worsening intermixing of CO2 with each height reduction, resulting in higher concentrations. This can be attributed to the airflow entering at a lower height, resulting in higher air velocity within the room. The reduced space restricts the air from slowing down due to air drag. It is important to note that in three of the scenarios, the CO2 concentration exceeded both the recommended thresholds of 1000 PPM by the WHO and the literature's suggested limit of 700 PPM (Marr et al., 2020). Overall, the results suggest that lowering the ceiling and reducing the room volume had a negative effect by increasing CO2 concentrations between individual.

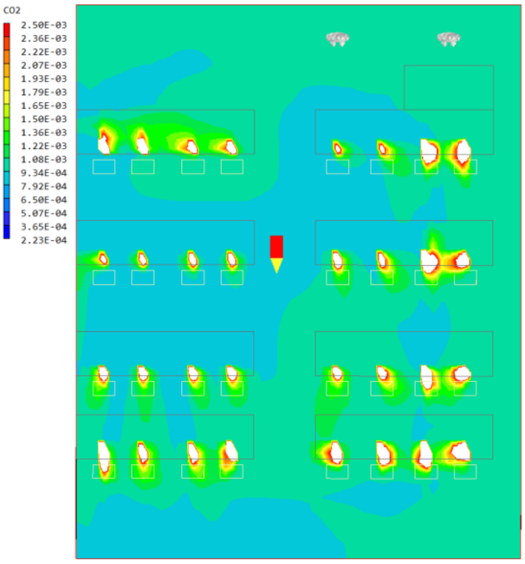


Figure 58 Original situation – CO2 distribution

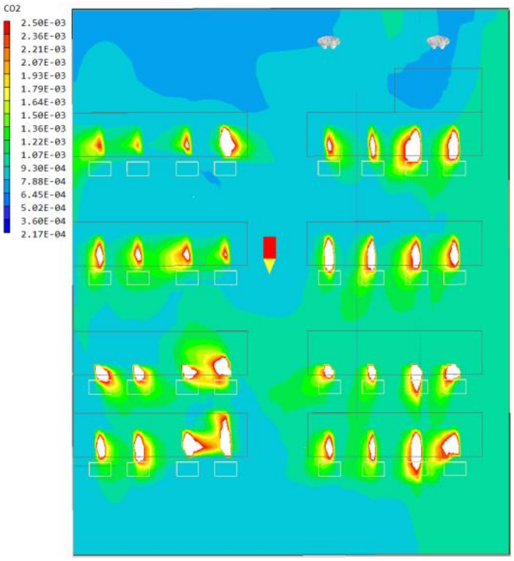


Figure 59 3,2m – CO2 distribution

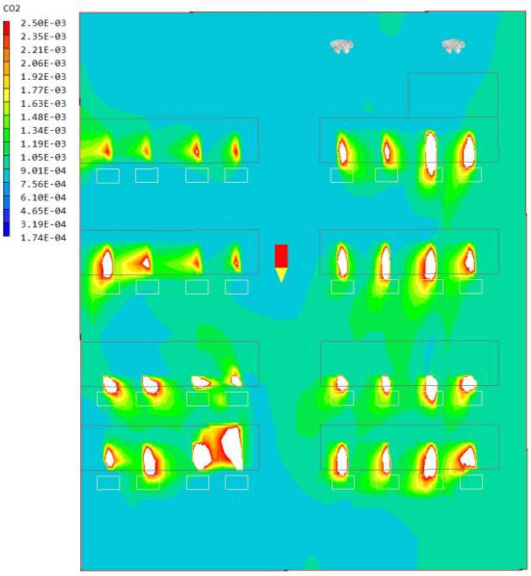


Figure 60 2,8m – CO2 distribution

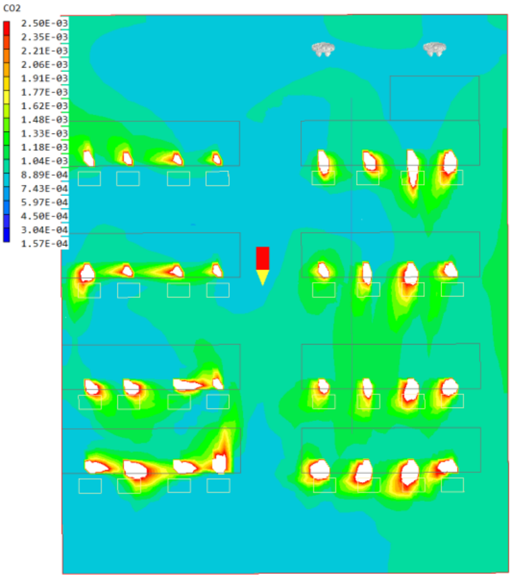


Figure 61 2,6m – CO2 distribution

Figures 62 to 65 depict the age of air within the room for the original situation and the three alternative heights. Several observations can be made from these figures. First, by reducing the ceiling height, the age of air inside the room has approximately halved. The original age of air was recorded at 1736 seconds, whereas the average ages of air in the scenarios presented in Figures 63, 64, and 65 are 955 (15 minute), 834 (14 minutes), and 774 (13 minutes) seconds, respectively. The observed difference can be attributed to the significantly higher air changes per hour (ACH) in the three scenarios compared to the baseline situation. The ACH in the baseline scenario was 2.04 times per hour. Whereas in the three alternative scenarios, the ACH values were 3.75 times (960/256), 4.3 times (960/224), and 4.7 times (960/206) per hour, respectively. This finding aligns with the recommendation put forth by Ratajczak (2022), indicating that ACH alone is not an effective indicator for achieving a healthy indoor environment. As it is dependent on the volume of the room and would lead to different ventilation rates.

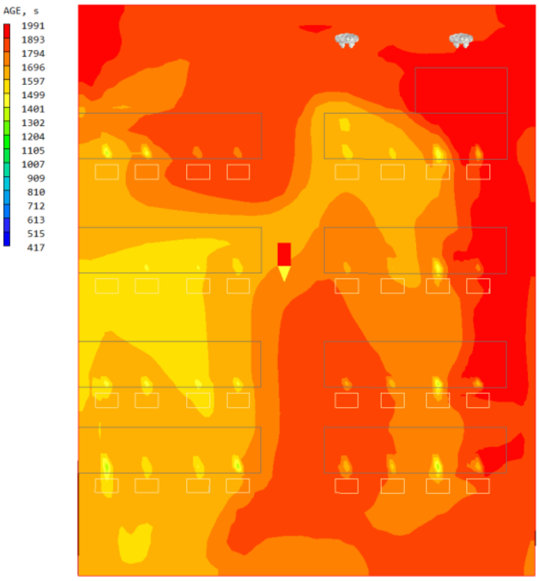


Figure 62 original baseline – age of air

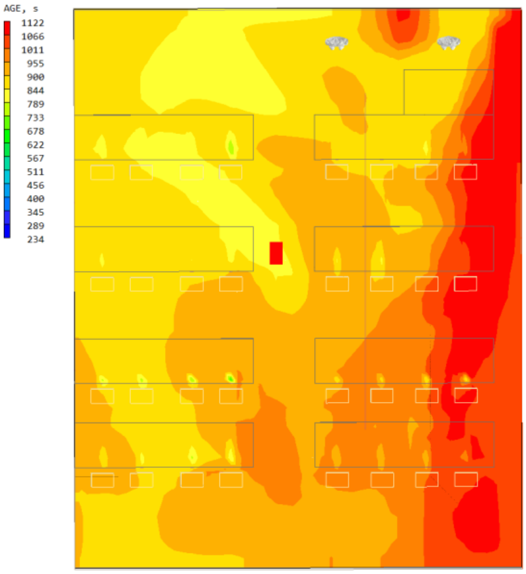


Figure 63 3,2m – age of air

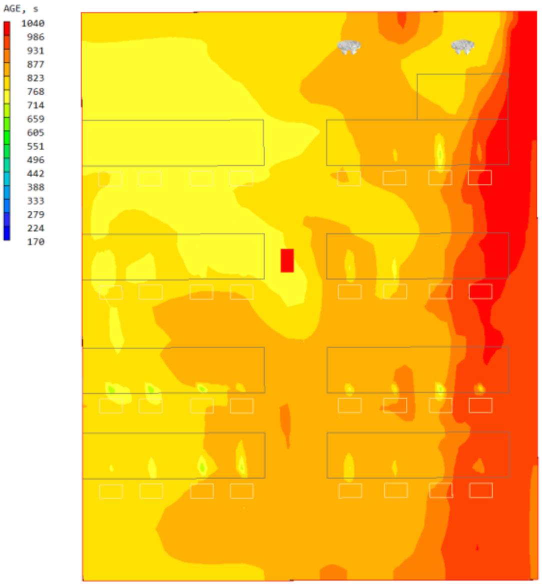


Figure 64 2,8m – age of air

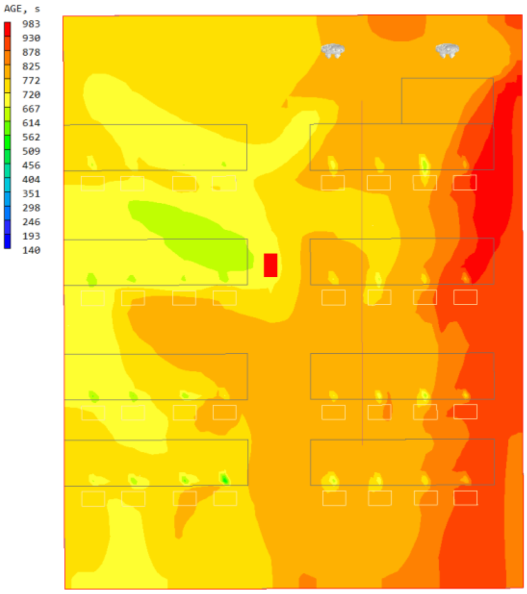


Figure 65 2,6m – age of air

Following the parametric research on room volume, the subsequent investigation delves into ventilation rates based on the findings of Chen et al. (2021). The literature suggests two specific rates: 10 litres/s per person and at least 15 litres/s per person. Two simulation are conducted using these ventilation rates with the original layout of the room. Figures 66 to 68 showcase the corresponding CO2 concentrations for the original ventilation rate, as well as the rates of 10 and 15 litres/s per person, respectively. As result from the increase of the ventilation rate, the total ventilation rate

These simulations have revealed that the ventilation rate has a greater impact on the risk of infection compared to the volume of air available in the room. In the original scenario, the average CO2 concentration was 1156 PPM. While in the scenario with a ventilation rate of 10 litres/s per person, the average concentration slightly decreased to 1057 PPM, and in the scenario with a ventilation rate of 15 litres/s per person, the average concentration further decreased to 881 PPM. Moreover, in comparison to the original scenario, the intermixing of CO2 plumes, although still present and relatively high, exhibited reduced concentrations of 974 PPM as opposed to the original value of 1292 PPM.

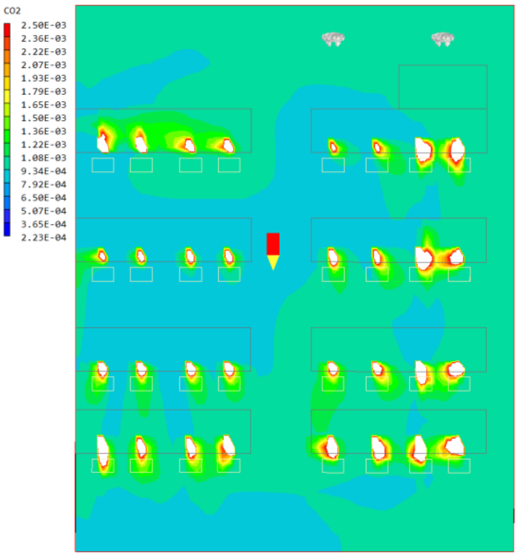


Figure 66 Original baseline – CO2 concentrations

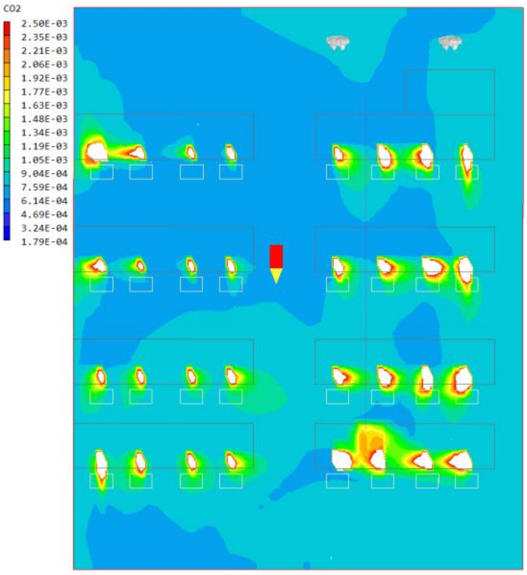


Figure 67 10 l/s – CO2 concentrations

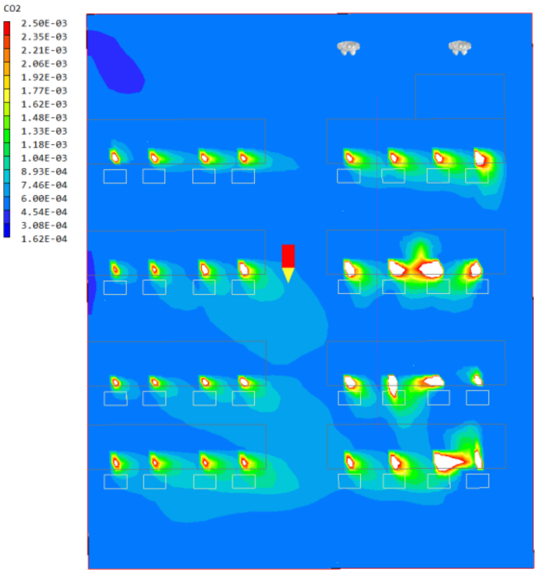


Figure 68 15 l/s – CO2 concentrations

Figures 69 to 71 display the age of air within the room for the original scenario and the two scenarios with different ventilation rates. In figure 70 with a ventilation rate of 10 litres/s per person, the total ventilation flow rate in the room is calculated as 1152 m3/h (32 x 10 x 3.6). In figure 77 with a ventilation rate of 15 litres/s per person, the total ventilation flow rate is increased to 1728 m3/h (32 x 15 x 3.6), which is 192 m3/h and 768 m3/h higher than the original situation, respectively. The figures show that increasing the ventilation rate from the original 8.5 litres/s to 10 litres/s only slightly impacts the age of air, reducing it to 1419 seconds (24 minutes). However, increasing the ventilation rate to 15 litres/s significantly reduces the age of air to 974 seconds (17 minutes).

When comparing the impact of reducing the room volume to increasing the ventilation rate, it is evident that increasing the ventilation rate has a lesser effect on the age of air unless the increase is two times the current requirement set by the Bouwbesluit for new buildings. Additionally, the Frisse Scholen guidelines recommend a ventilation rate of 12 litres/s to achieve a level A designation for a healthy and comfortable educational environment.

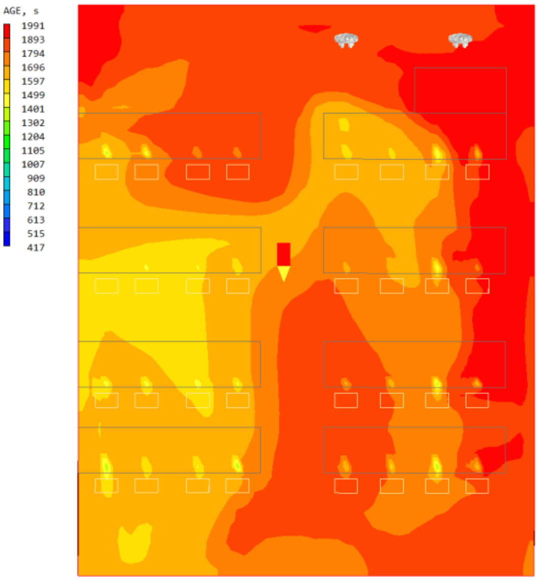


Figure 69 Original baseline – age of air

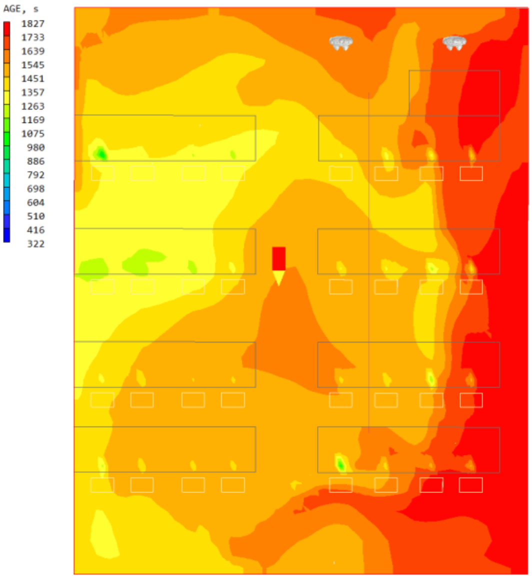


Figure 70 10 l/s – age of air

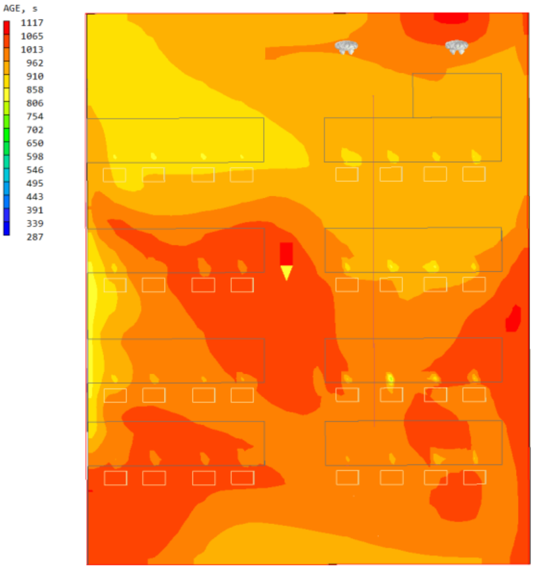


Figure 71 15 l/s – age of air

4.2.3 Survey results

In this section, the results from the survey are presented. The questionnaire covered various aspects, including both thermal comfort and indoor air quality(IAQ) and acoustic comfort. These responses were used to assess the overall satisfaction with the indoor environment.

The survey results provide valuable insights into the thermal sensation and preferences of the occupants within the surveyed space. As is shown in figure 72 a significant majority of the participants reported feeling slightly cool in the room. The survey results in figure 73 revealed that one third of the participants inside the room are feeling dissatisfied with inside the room. Lastly figure 74 revealed that a large portion of the participants actually preferred a warmer room in terms of thermal preference.

This suggests that the occupants' preferred thermal environment may differ from their actual experienced sensations. However, it is noteworthy that despite the disparities in thermal sensation and preference, the overall satisfaction level of the occupants with the room was generally positive. The survey indicated that the majority of occupants were satisfied with the overall thermal comfort, with only a small portion expressing slight dissatisfaction.

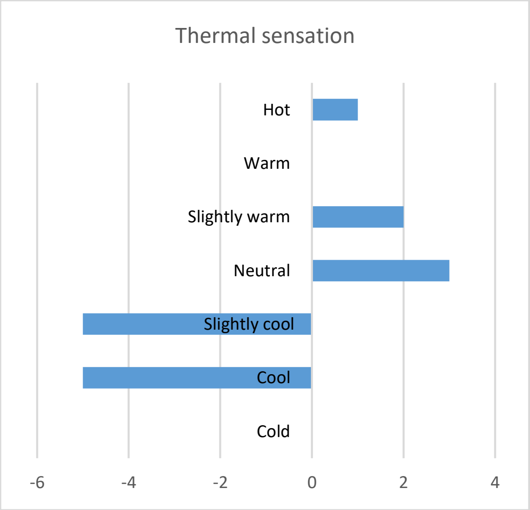


Figure 72 Thermal sensation

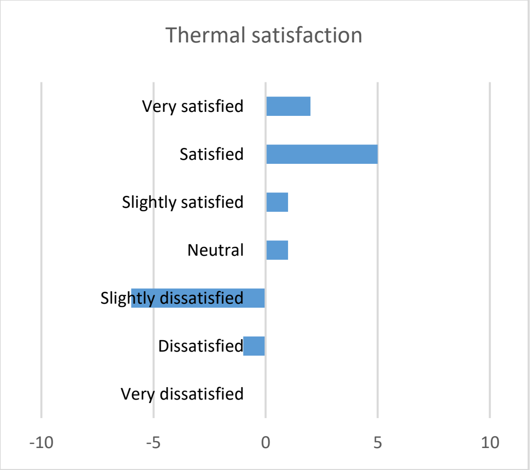


Figure 73 Thermal satisfaction

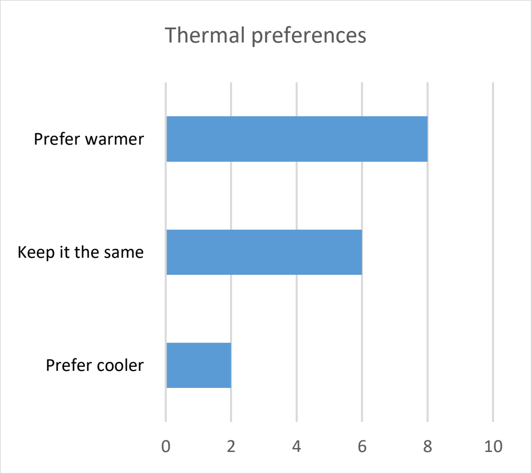


Figure 74 Thermal preferences

In terms of the indoor air quality, the results of the survey indicated that a slightly large majority of the respondents expressed satisfaction with the indoor air quality of the room. This suggests that the ventilation system in place effectively met their expectations in terms of providing fresh and clean air. However, when it came to the sensation of the room, the responses were predominantly neutral. This indicates that while the indoor air quality was deemed satisfactory, the overall comfort level or ambiance of the space did not elicit strong positive or negative reactions from the occupants.

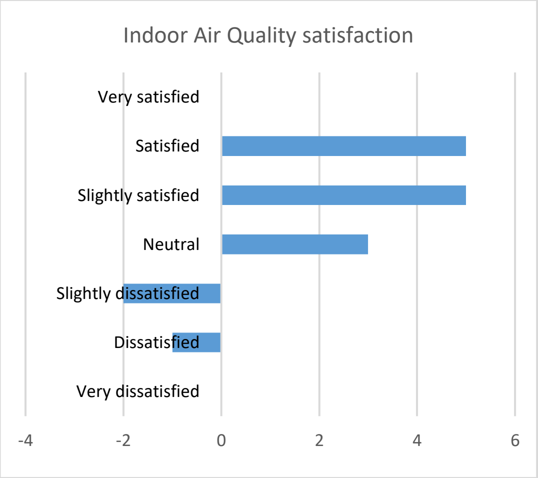


Figure 75 Indoor air quality satisfaction

Another noteworthy finding from the survey was that the occupants expressed satisfaction with the acoustics inside the room. This implies that the room's design and construction elements contributed to an environment that facilitated good sound quality and minimal noise disturbance. The respondents likely perceived clear speech and reduced reverberation, enhancing their overall experience and ability to communicate effectively within the space.

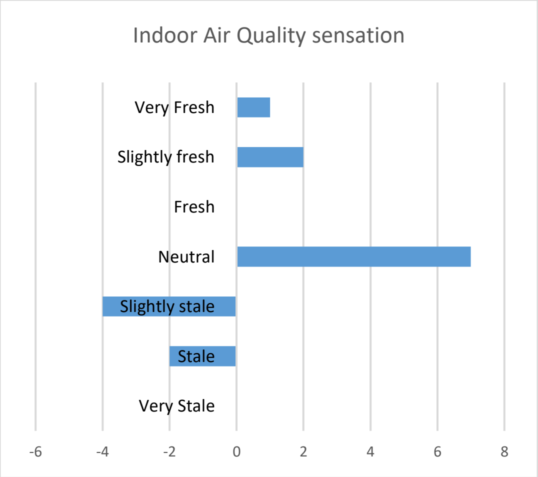


Figure 76 Indoor air quality sensation

These results highlight the importance of considering multiple factors when evaluating the indoor environment. While the majority were content with the indoor air quality, it is crucial to also focus on other aspects such as thermal comfort, lighting, and overall spatial design to create a truly satisfying experience for occupants. By addressing these different elements holistically, it becomes possible to enhance the overall comfort and well-being of individuals within indoor spaces.

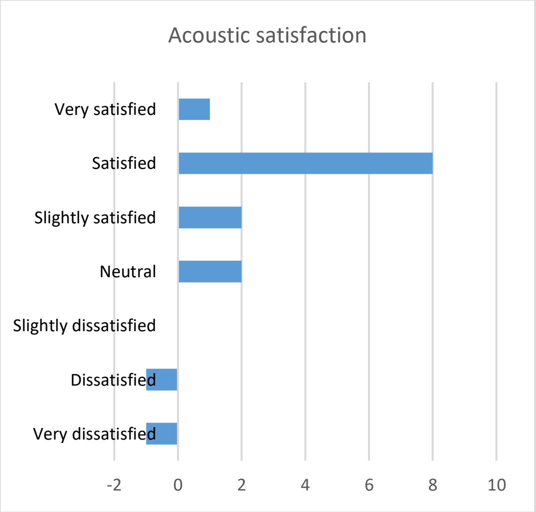


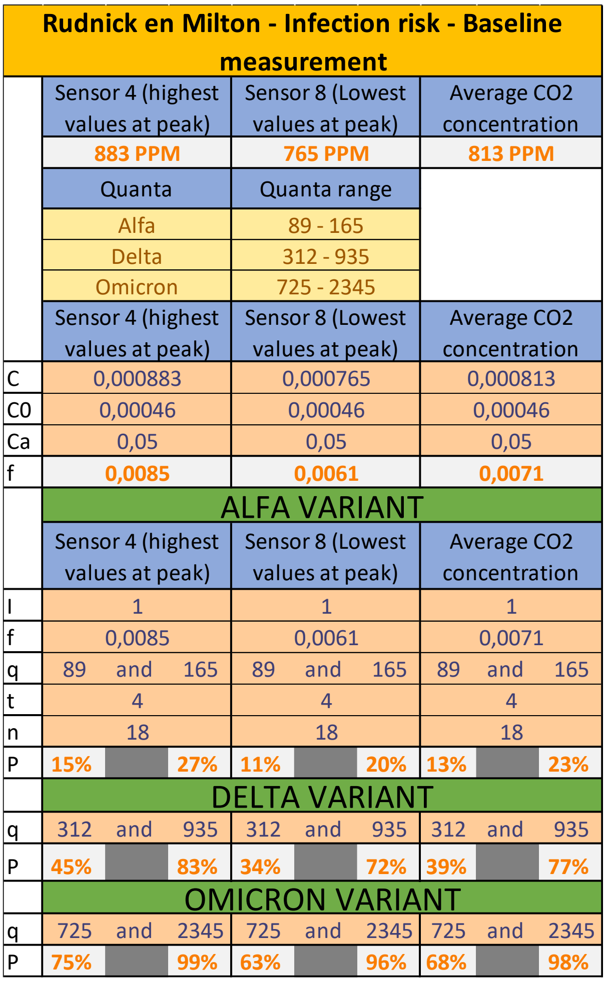
Figure 77 Acoustic satisfaction

4.2.4 Risk of infection and ventilation effectiveness

In this section, similar to the theoretical approach, the infection risk for the baseline scenario is calculated. The key results from the measurements are summarized in figure 84, highlighting the most influential sensors: sensor 4 (highest peak CO2 level) and sensor 8 (lowest peak CO2 concentration). Figure 79 presents the risk of infection from the simulations. For all calculations the lowest and highest quanta ranges are utilised in the calculation to consider both the best and worst case scenarios.

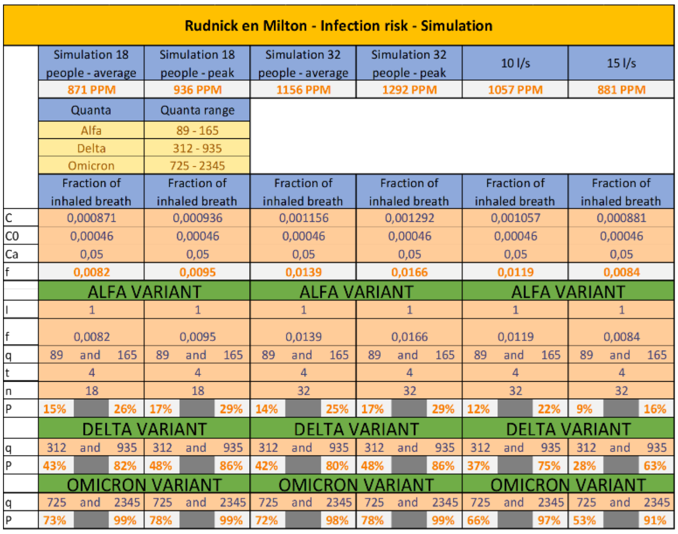
Analysing the data in table 78 reveals varying infection risks for the two locations. For the ALPHA COVID-19 strain, the risk ranges from 11% to 27%, with a difference of 4% to 7% between the two peaks in the best and worst case scenarios, respectively. For other strains the risk of infection is significantly higher, with substantial variations between the best and worst case scenarios. For example, the DELTA variant shows a risk range of 34% to 83%, while the OMICRON variant ranges from 63% to 99%. This trends is also visible in the calculation of the risk of infection for the simulations.

It is important to highlight that the early strains of the COVID-19 virus had relatively lower infection risks. Therefore, it is crucial to take immediate action to reduce this percentage as much as possible. A reduction of 10% in the early stages is significantly impactful when the overall risk ranges between 12% and 29%. In contrast to the later strains, which have infection risks of at least 60% and 90%. Thus, even though ventilation may have diminishing returns in mitigating the risk, it is still advisable to take measures to create a healthier environment.



Rudnick en Milton - Infection risk - Baseline measurement			
	Sensor 4 (highest values at peak)	Sensor 8 (Lowest values at peak)	Average CO2 concentration
	883 PPM	**765 PPM**	**813 PPM**
	Quanta	Quanta range	
	Alfa	89 - 165	
	Delta	312 - 935	
	Omicron	725 - 2345	
	Sensor 4 (highest values at peak)	Sensor 8 (Lowest values at peak)	Average CO2 concentration
C	0,000883	0,000765	0,000813
C0	0,00046	0,00046	0,00046
Ca	0,05	0,05	0,05
f	**0,0085**	**0,0061**	**0,0071**
	ALFA VARIANT		
	Sensor 4 (highest values at peak)	Sensor 8 (Lowest values at peak)	Average CO2 concentration
I	1	1	1
f	0,0085	0,0061	0,0071
q	89 and 165	89 and 165	89 and 165
t	4	4	4
n	18	18	18
P	**15%** **27%**	**11%** **20%**	**13%** **23%**
	DELTA VARIANT		
q	312 and 935	312 and 935	312 and 935
P	**45%** **83%**	**34%** **72%**	**39%** **77%**
	OMICRON VARIANT		
q	725 and 2345	725 and 2345	725 and 2345
P	**75%** **99%**	**63%** **96%**	**68%** **98%**

Figure 78 Risk of infection measurement



Rudnick en Milton - Infection risk - Simulation						
	Simulation 18 people - average	Simulation 18 people - peak	Simulation 32 people - average	Simulation 32 people - peak	10 l/s	15 l/s
	871 PPM	**936 PPM**	**1156 PPM**	**1292 PPM**	**1057 PPM**	**881 PPM**
	Quanta	Quanta range				
	Alfa	89 - 165				
	Delta	312 - 935				
	Omicron	725 - 2345				
	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath
C	0,000871	0,000936	0,001156	0,001292	0,001057	0,000881
C0	0,00046	0,00046	0,00046	0,00046	0,00046	0,00046
Ca	0,05	0,05	0,05	0,05	0,05	0,05
f	**0,0082**	**0,0095**	**0,0139**	**0,0166**	**0,0119**	**0,0084**
	ALFA VARIANT		ALFA VARIANT		ALFA VARIANT	
I	1	1	1	1	1	1
f	0,0082	0,0095	0,0139	0,0166	0,0119	0,0084
q	89 and 165	89 and 165	89 and 165	89 and 165	89 and 165	89 and 165
t	4	4	4	4	4	4
n	18	18	32	32	32	32
P	**15%** **26%**	**17%** **29%**	**14%** **25%**	**17%** **29%**	**12%** **22%**	**9%** **16%**
	DELTA VARIANT		DELTA VARIANT		DELTA VARIANT	
q	312 and 935	312 and 935	312 and 935	312 and 935	312 and 935	312 and 935
P	**43%** **82%**	**48%** **86%**	**42%** **80%**	**48%** **86%**	**37%** **75%**	**28%** **63%**
	OMICRON VARIANT		OMICRON VARIANT		OMICRON VARIANT	
q	725 and 2345	725 and 2345	725 and 2345	725 and 2345	725 and 2345	725 and 2345
P	**73%** **99%**	**78%** **99%**	**72%** **98%**	**78%** **99%**	**66%** **97%**	**53%** **91%**

Figure 79 Risk of infection simulation

The last step in analysing the baseline situation is to calculate the ventilation efficiency. This can be done with the formula provided back in subsection 2.4.3.

The formula:

$$\varepsilon^a = \frac{\tau_n}{\overline{\tau_r}} * 100 = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 \text{ (Mundt, 2004).}$$

ε^a = Air change efficiency [%]
τ_n = Nominal time constant → $\tau_n = V/q_v$

With:

V = The volume of the room m^3
q_v = Ventilation flow m^3/h
$\overline{\tau_r}$ = The air change time for all the air in the room
$\langle\bar{\tau}\rangle$ = The room mean age of air
$\frac{\tau_n}{2}$ = Lowest amount of stay time of the air

According to the simulation the average mean age or is $\langle\bar{\tau}\rangle$ = 1639 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:

$\langle\bar{\tau}\rangle$ = 1639 /3600 = 0.455 [h]

V = 5,8 $m \times 10\ m\ \times 8\ m = 464\ [m^3]$ (length x height x width)

$q_v = 960\ [m^3/h\,]$
$\tau_n = \frac{464}{960} = 0.483$ [h]

$$\varepsilon^a = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 = \frac{0.483}{2\times 0.455} * 100\% = 53.08\ \%$$

With a percentage of 53,08% the room would be considered a displacement type of airflow. The main principle behind displacement ventilation is to create a stratified air distribution within the occupied zone. While the goal is that cool supply air enters the space at a slightly lower temperature than the room occupants, creating a vertical temperature gradient. The fresh air forms a lower, cooler layer near the floor, while the warmer air rises and accumulates in the upper part of the room. However, As it is shown in figure 80 this is only for the left side of the room, while the rise of the warmer air on right side of the room is supressed due to the airflow flowing down on that side.

Figure 80

4.2.5 Assessment baseline situation

The results obtained from the baseline scenario, encompassing measurements and simulations, have yielded interesting findings. One notable observation is the close alignment between the theoretical approximation, measurements, and simulations. However, it should be noted that the measurements show slightly higher values within the room, indicating their superiority in accurately capturing the data. Additionally, the analysis of the measurements conducted in the 18-person scenario confirmed the recommendation by Zhang et.al, (2022) to place sensors on the walls of the room, as the CO2 concentration was one of the highest in those locations. However, upon examining the deviation from the measurements, it is advisable to consider placing sensors also in more inward position within the room. This is evident from the higher concentrations measured by sensor 3, which was positioned closer to the middle of the room. Furthermore, the distribution of CO2 indicated by the simulations also revealed elevated concentrations in the middle of the room and among the individuals seated within it.

Secondly, the research has revealed a relationship between CO2 concentrations and the risk of infection. It is apparent that lower CO2 concentrations result in a slight decrease in the risk of infection, as evidenced by the comparison of average and peak concentrations. However, it is important to acknowledge that this reduction in infection risk is minimal and exhibits diminishing returns the moment the quanta levels increases. Nonetheless, this does not imply that no action should be taken, as a 10% reduction in the early stages of a pandemic, when quanta levels are still relatively low, can have a substantial impact when the overall risk ranges between 12% and 29%. In contrast, to the later strains with infection risks of at least 60% and 90%. Therefore, despite the diminishing returns of ventilation in mitigating the risk, it is still advisable to implement measures to establish a healthier environment.

Third, from the parametric research the conclusion can be drawn that ventilation rate, in alignment with the literature (see subsection 2.8 table 9 parameter ventilation rate for the list of literature) has most impact on the room. Whereas setting requirements to the ACH alone is not an effective indicator for achieving a healthy indoor environment. As it is dependent on the volume of the room and would lead to different ventilation rates, which in some cases could to under ventilating the room Ratajczak, (2022).

The fourth and last point, the analysis of the results has highlighted that the baseline situation represents Room P under normal conditions with a displacement type of airflow. In terms of occupant comfort, the majority of individuals reported a slightly cooler thermal sensation, indicating their satisfaction. Additionally, the majority of respondents expressed satisfaction with the indoor air quality. It is important to note that these survey results were obtained from a class with 18 individuals, and it is anticipated that these findings may vary with a larger occupancy in the room.

5. The situations

This chapter covers the design research conducted on the decentral, smart, and personal ventilation systems aiming to assess their effectiveness in reducing the risk of infection. Each system is approached through a systematic process that involves proposing a design, performing simulations, and assessing the outcomes.

5.1 Situation 2: decentral ventilation

Situation 2 presents the findings of the research conducted on decentral ventilation. In this situation, no measurement results are available due to practical limitations associated with the size of the unit and the need for additional resources, such as a separate fuse box from the main electrical network of TU Delft.

5.1.1 Proposed design decentral ventilation system

The decentral ventilation unit, being a single unit responsible for both the supply and exhaust of ventilation within the room, has certain limitations in terms of the parameters that can be tested. Specifically, the amount and location of openings for exhaust and supply are predetermined by the unit itself. Consequently, the primary parameter that can be examined in this case is the placement of the unit, which significantly impacts the airflow patterns and the subsequent distribution of CO2 within the room. Therefore, for this particular unit simulation two locations are tested, namely the front and left side of the room. These 2 locations are chosen to test if the location has any large effect on the distribution of CO2 and the comfort of the occupants. The left and back side mirror these two locations. A visualisation of these designs are given in figure 82 and 83


Figure 81 Decentral ventilation unit System air Sense 1000

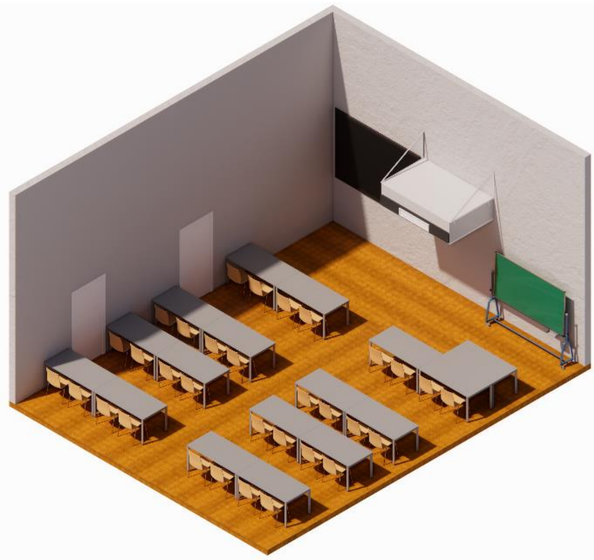


Figure 83 Design 1 front location

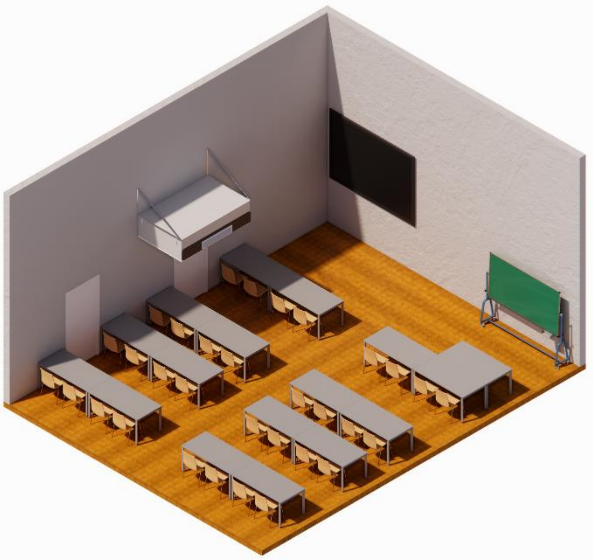


Figure 84 Design 2 left location

5.1.2 Results from the decentral ventilation simulation

The simulation parameters described in subsection 3.5 remain applicable, with a few additional parameters specific to the decentral unit. These unit-specific parameters are outlined in Table 13.

Decentral ventilation unit	Amount	Units
Flowrate	1000	M3/h
Size unit	2,2 x 1,4 x 0,7	Length x width x height (meters)
Size exhaust	0,5 x 0,39	Length x width (2 exhausts underside)
Size supply	0,86 x 0,2	Width x height

Table 13 unit specific parameters

From Figure 85, several conclusions can be drawn. First, the room is divided into light blue and light green areas, representing CO2 concentrations of 967 PPM and 1034 PPM, respectively. Second, the intermixing of exhaled CO2 between individuals at each table is particularly noticeable, with concentrations reaching 1134 PPM. Third, the average CO2 concentration inside the room exceeds the 1000 PPM threshold, measuring at 1033 PPM. Additionally, the CO2 plumes, highlighted by the blue ring, travel a greater distance along the walls compared to the seats in the centre. This indicates that the use of the decentralised ventilation system has no discernible positive impact and may even have a negative effect on the room. In essence, there is no significant difference in CO2 concentrations compared to the baseline scenario at full capacity.

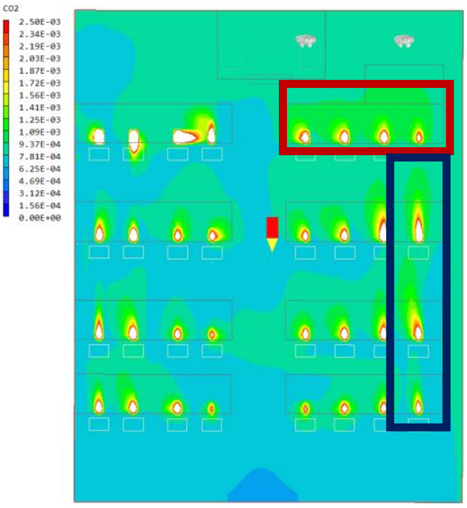


Figure 85 Front location CO2 concentration

Regarding the flow of the room and the accompanying velocity, as depicted in Figures 86 and 87, a prominent central flow is evident due to the nature of the ventilation unit. This flow reaches a velocity of 1.5 m/s in close proximity to the supply opening. Consequently, the flow manages to extend to the far end of the room. Figure 3 illustrates that the edges of the room experience higher velocities, surpassing the indoor air velocity limit of 0.2 m/s. This elevated velocity level significantly impacts the comfort of the occupants.

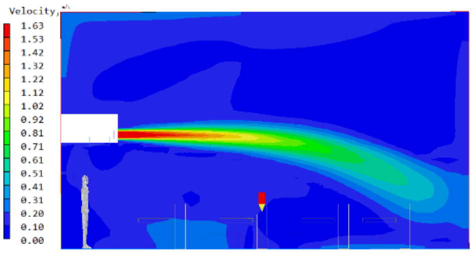


Figure 86 Front location vertical section velocity

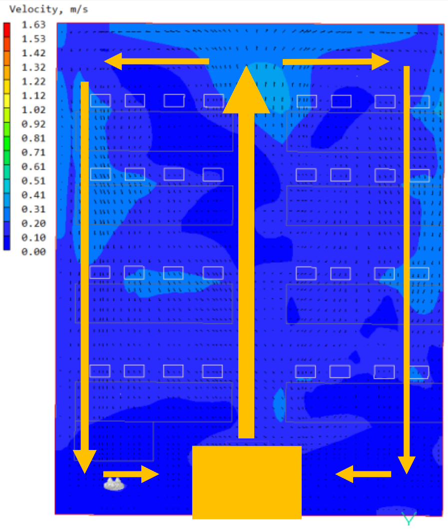


Figure 87 Front location air velocity

Furthermore this means that the airflow inside the rooms moves from the supply grill from the unit to the back wall and then gets split moves back to the unit along side the side walls. Which would explain the larger travel distances of the CO2 plumes around the edges. Therefore, it is crucial to highlight that the edges of the room are particularly impacted by the flow of the airflow generated by the supply unit. This could potentially pose a risk if an infected individual were seated in those areas. Therefore, careful consideration should be given to seating arrangements and the positioning of the ventilation system to minimize the potential transmission of infections.

Figures 88, 89, 90, and 91, present the temperature, air age, PPD, and PMD, respectively. Figure 88 reveals the temperature distribution within the room, ranging between 21 and 23 degrees Celsius. With an average temperature of 21,7 degrees Celsius. Due to how the air flow now is concentrated through one large single flow that reaches the back the room, the temperature there is lower.

Examining the average air age in figure 89, the figure displays distinct variations across different areas of the room. The yellow region, directly exposed to the unit's airflow, measures an air age of 1190 seconds, whereas the red region beneath the decentral ventilation unit has an air age of 1719 seconds. The overall average air age within the room is 1462 seconds.

The PMV and PPD values are illustrated in to Figure 90 and 91. The average PMV value of -1.13 suggests a slightly cooler sensation for occupants in any location of the room. However, when compared to the baseline, the PPD value is relatively lower, averaging at 32%, primarily concentrated in the blue areas of the room. The greener areas, influenced by the airflow directed alongside the walls by the unit, exhibit higher PPD values than the baseline. As a result, individuals seated towards the back and along the walls are more susceptible to feeling colder compared to those seated in the front.

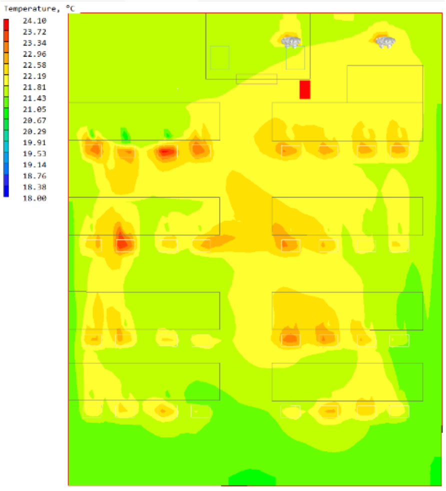


Figure 88 Front location Temperature

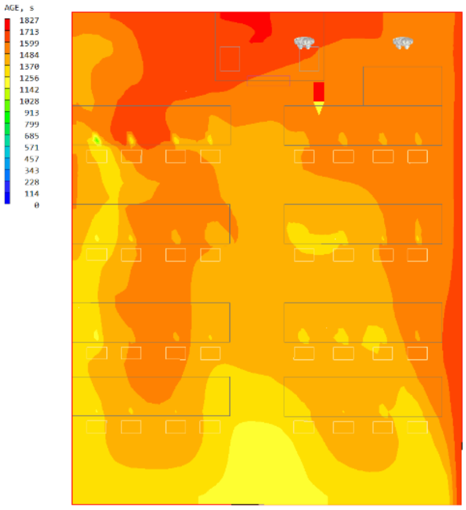


Figure 89 Front location age of air

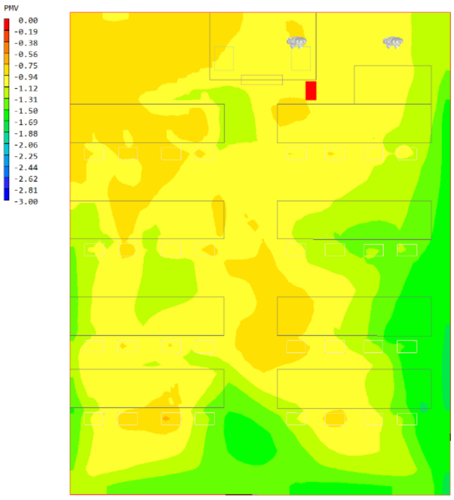


Figure 90 Front location PMV

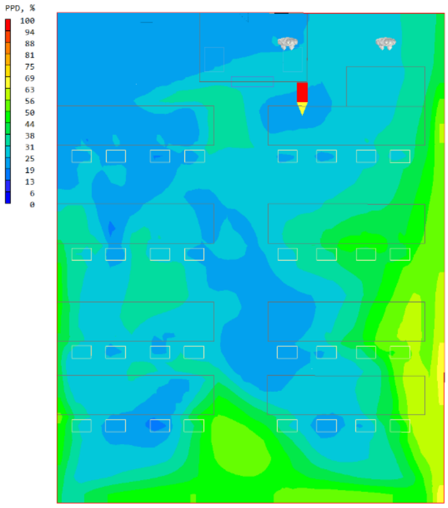


Figure 91 Front location PPD

Moving on to the next location, the ventilation unit was repositioned alongside the left wall of the room. The simulation results revealed a notable increase in the average CO2 concentrations within the room compared to when the unit was located at the front. Instead of the previous concentration range of 967 PPM and 1034 PPM with occasional pockets of higher concentration, the new range now varies at a higher concentration, which is from 1020 PPM to 1454 PPM. While the majority of the room concentration is around 1020 PPM, the highest concentrations, marked in red, are observed within the green area, with the brightest regions reaching the 1454 PPM. Meaning with only an adjustment in the placement can has so much impact on the concentration of CO2 in the room.

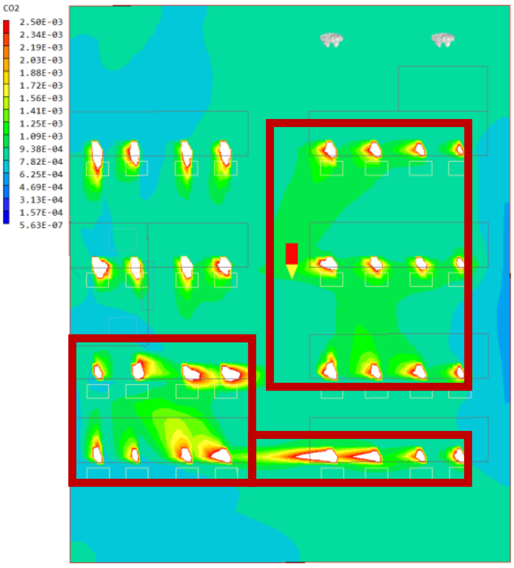


Figure 92 Left location CO2 concentration

In terms of air flow patterns and velocities, the overall flow within the room remains similar to the previous simulation with the unit in the front location, although flipped 90 degrees. However, a notable observation is the high air velocity along the wall opposite the ventilation unit. In contrast to the front location where the flow had more space to be slowed down by air resistance, the current location does not allow that, thus resulting in increased velocity that pushes the airflow towards the sides.

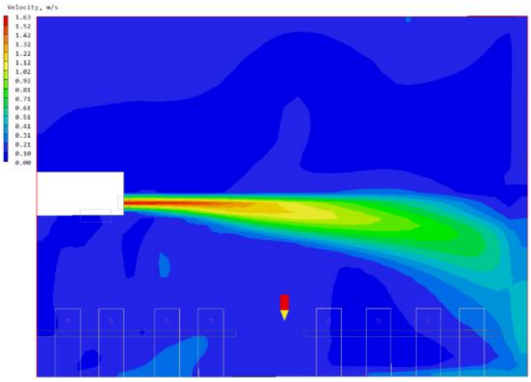


Figure 93 Left location air velocity vertical

These findings indicate that while the room still maintains a even distributed with an average CO2 concentration of 1020 PPM, there are now larger hotspots with higher concentrations of CO2. Unlike the front location where only one notable hotspot was identified, multiple overlapping areas now form hotspots with elevated CO2 concentrations. Additionally, the increased air velocity along the wall opposite the ventilation unit highlights the need to consider placement of these type of system, as the room geometry impacts the airflow and the distribution of CO2 within the space.

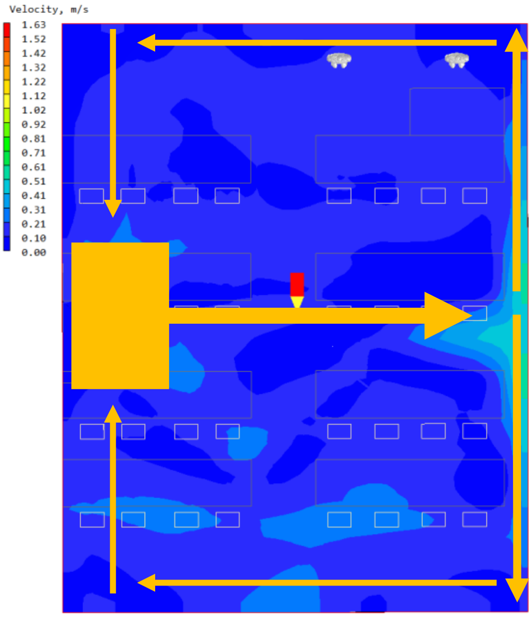


Figure 94 Left location air velocity

In Figure 95, 96, 97, and 98 the temperature, age of air, PPD (Predicted Percentage of Dissatisfied) and PMD (Predicted Mean Vote) are provided, respectively. Figure 95 reveals that the average temperature inside the room with this design is 21 degrees Celsius. In terms of the average age of the air, which is shown in figure 96 sits at 1618 seconds, whereas the more red spots inside the room sit at 1761 seconds, which translates to 27 minutes and 30 minutes respectively.

Proceeding to figures 97 and 98, they depict the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) values, respectively. The PMV value of -1.16 indicates that occupants throughout the room experience a slightly cooler sensation. While this is comparable to the baseline scenario where the average PMV for occupants was -1.38, the location where individuals perceive the cooling effect has shifted. In the baseline scenario, the entire room felt cooler, whereas now the sensation is concentrated in the area where the airflow from the unit strikes the opposite wall. Conversely, occupants in the yellow areas feel slightly less cold, with an average PMV of -0.99. Furthermore, these observations align with the PPD estimates, which indicate that around 25% of occupants in the middle of the room are likely to feel dissatisfied with the thermal conditions. However, in the vicinity where the airflow meets the wall, this percentage increases to 62% and even as high as 85%. As a result, employing this design with the unit in its current location would significantly impact the comfort of the occupants.

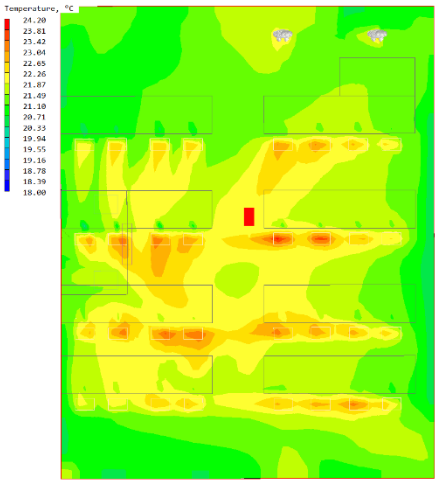


Figure 95 Left location temperature

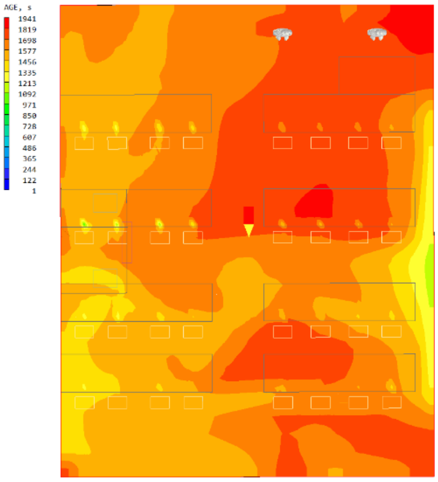


Figure 96 Left location age of air

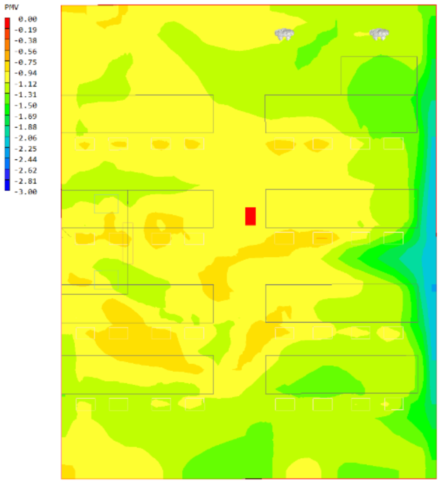


Figure 97 Left location PMV

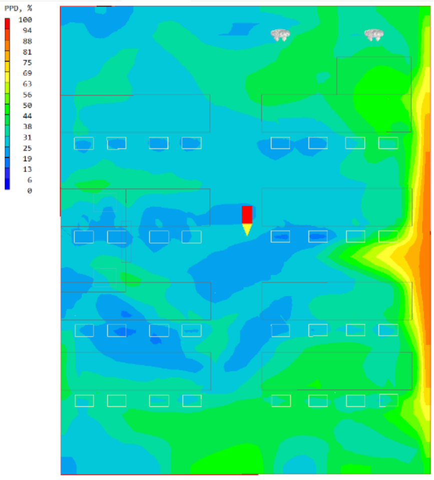
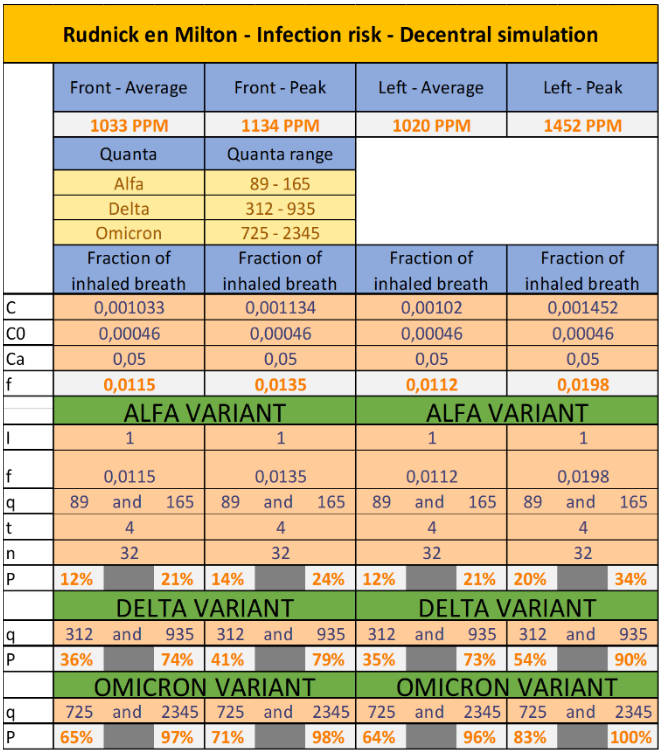


Figure 98 Left location PPD

5.1.3 Risk of infection and ventilation effectiveness

For the calculation of the risk of infection for the decentral ventilation system the average and the peak values were used for both of the scenarios. Which are 1033 PPM and 1134 PPM for the front location and 1020 PPM and 1452 PPM for the left position.

Upon analysing the data presented in figure 99, it becomes apparent that the infection risk in both locations is comparable to the baseline scenario. The risk of infection ranges from 12% to 34% for the ALPHA strain, with a marginal difference of only 3% when compared to the baseline. Consequently, it can be inferred that the decentral ventilation system yields minimal improvement in reducing the risk of infection.



Rudnick en Milton - Infection risk - Decentral simulation				
	Front - Average	Front - Peak	Left - Average	Left - Peak
	1033 PPM	1134 PPM	1020 PPM	1452 PPM
	Quanta	Quanta range		
	Alfa	89 - 165		
	Delta	312 - 935		
	Omicron	725 - 2345		
	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath
C	0,001033	0,001134	0,00102	0,001452
C0	0,00046	0,00046	0,00046	0,00046
Ca	0,05	0,05	0,05	0,05
f	0,0115	0,0135	0,0112	0,0198
	ALFA VARIANT		ALFA VARIANT	
I	1	1	1	1
f	0,0115	0,0135	0,0112	0,0198
q	89 and 165	89 and 165	89 and 165	89 and 165
t	4	4	4	4
n	32	32	32	32
P	12% 21%	14% 24%	12% 21%	20% 34%
	DELTA VARIANT		DELTA VARIANT	
q	312 and 935	312 and 935	312 and 935	312 and 935
P	36% 74%	41% 79%	35% 73%	54% 90%
	OMICRON VARIANT		OMICRON VARIANT	
q	725 and 2345	725 and 2345	725 and 2345	725 and 2345
P	65% 97%	71% 98%	64% 96%	83% 100%

Figure 99 risk of infection decentral ventilation

Using the same formula as last the time, the air change efficiency for the two scenarios comes down to:.

The formula:

$$\varepsilon^{a} = \frac{\tau_n}{\overline{\tau}_r} * 100 = \frac{\tau_n}{2\langle\overline{\tau}\rangle} * 100 \text{ (Mundt, 2004).}$$

The front position:
According to the simulation the average mean age or is $\langle\overline{\tau}\rangle$ = 1526 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:

$\langle\overline{\tau}\rangle$ = 1526 /3600 = 0.424 [h]

V = 5,8 $m \times 10\ m\ \times 8\ m = 464\ [m^3]$ (length x height x width)

$q_v = 960\ [m^3/h\ ]$

$\tau_n = \frac{464}{960} = 0.483$ [h]

$$\varepsilon^{a} = \frac{\tau_n}{2\langle\overline{\tau}\rangle} * 100 = \frac{0.483}{2\times 0.424} * 100\% = 56{,}96\ \%$$

The left position:
According to the simulation the average mean age or is $\langle\overline{\tau}\rangle$ = 1618 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:

$\langle\overline{\tau}\rangle$ = 1618 /3600 = 0.449 [h]

$$\varepsilon^{a} = \frac{\tau_n}{2\langle\overline{\tau}\rangle} * 100 = \frac{0.483}{2\times 0.449} * 100\% = 53{,}78\ \%$$

With the percentages of 56,96 % and 53,08% the room in both cases are considered to be displacement flow.

5.1.4 Aspect of economics and practicality

Based on the proposed design an indication of what this type of system can cost is provided in table 14.

Materials	Amount	Costs	Total
Sense air 1000 pack	1 pack, which includes accessories	€ 9000 - € 13000* depending on size and flow amount. For this research sense 1000 was needed for the room	€ 13000**
Ducts	2 meters	€ 107 per meter	€ 214
Grills	0	0	0
Total price single room			€ 13214***
*** Source: https://www.systemair.com/en-gb/products/air-handling-units/sense?sku=9995363 28th may 2023 prices** **** Disclaimer: prices are subject to change, depending on conversion rates. Conversion rate on 28th of may; £ 1- € 1,15** ***** Total price does not include materials such as fuse boxes and other electronic materials. This price is mainly based on what needs to be paid for the ventilation system itself.**			

Table 14 Cost analysis

Considering the costs associated with implementing this particular decentralized ventilation system design, the price for applying it to a single room amounts to 13214 euros. It is important to emphasize that this cost pertains to a single room only. The TU Delft Faculty of Architecture & the Built Environment has multiple rooms, both larger and smaller. For instance, the faculty includes a total of 20 lecture halls. Multiplying this price by 20 results in a total requirement of €264,280 to retrofit all the lecture halls. This is a substantial cost that is not justifiable given the marginal improvement in infection risk.

Furthermore from a practical standpoint, the unit itself measures 2.2 meters in length, 1.4 meters in width, and 0.7 meters in height with a weight of 200 kilograms. During attempts to set up a measurement for this system, it became evident that the size and weight of the unit posed significant problem. Since the lecture hall doors are not all double doors, the unit will need to be flipped on its side to be able to fit through the door. In essence, employing this type of system in the Faculty of Architecture & the Built Environment is impractical.

5.1.5 Assessment decentral ventilation situation

In conclusion, the simulation results for the decentral ventilation design have provided valuable insights. It is evident that the unit's location impacts its effectiveness, occupant comfort, and ability to reduce infection risk.

Comparing the decentral unit's placement to the baseline scenario, both the front and left positions did not lead to a notable decrease in CO2 concentration. The average CO2 concentrations in these positions were 1033 PPM for the front and 1020 PPM for the left, which are be considered high, since the concentrations exceed the WHO's recommended threshold of 1000 PPM (WHO Regional, 2000). Notably, the left position resulted in even higher concentrations, with areas reaching up to 1452 PPM. Additionally, for the unit in the front position the age of the air was reduced to 1462 seconds compared to the baseline duration of 2038 seconds, representing a significant improvement of 10 minutes. However, the infection risk remained similar to the baseline, ranging from 12% to 24%. Furthermore, the use of a single stream of supply air in the decentral unit negatively impacted occupant comfort, particularly for individuals seated near this stream.

The left position performed even worse than the front position. The average age of the air and areas with high age were similar to the front position, with averages of 1618 and 1761 seconds, respectively. The infection risk reduction was also worse, with a larger portion of the room experiencing infection risk values ranging from 34% to 100% in the worst case scenarios for the ALPHA and OMICRON strains, respectively. Moreover, the airflow in this location collided forcefully with the opposite walls, lacking the opportunity to slow down due to air drag observed in the front position, resulting in discomfort for individuals near those walls.

Considering the costs and practicality, implementing this decentral ventilation system design would incur a significant cost of €13,214 per room. With 20 lecture halls in the Faculty of Architecture & the Built Environment, the total expenditure to retrofit all halls would amount to €264,280. This substantial financial investment cannot be justified by the lack of improvement in infection risk. Additionally, the practicality of the system poses a challenge, as the unit's dimensions and weight require careful manoeuvring through doorways, making it impractical for installation in the Faculty.

Based on these findings, it is clear that the decentral ventilation design has severe limitations in terms of effectiveness, cost, and practicality, especially when considering its implementation in the classrooms of the Faculty of Architecture & the Built Environment. The system does not provide sufficient justification for its utilization in this context, given the inherent challenges and drawbacks it presents.

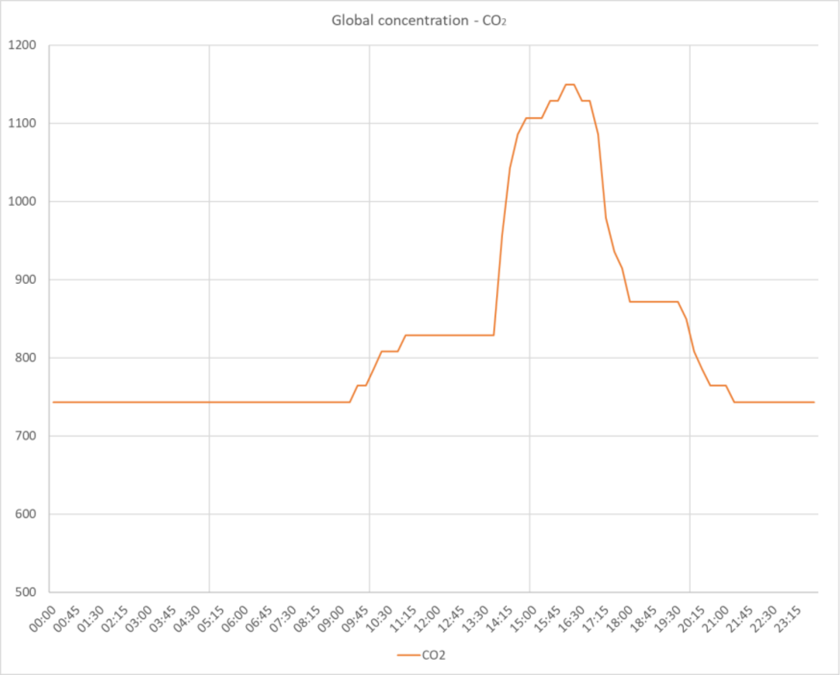
5.2 Situation 3: SMART ventilation

Situation 3 presents the findings of the research conducted into the SMART ventilation system.

5.2.1 Current system sensor results

Originally room P was already designed with a SMART system that incorporates a sensor within the duct system. This sensor is responsible for continuously measuring the CO2 concentrations within the room, enabling the system to adjust a valve that modulates the amount of air supplied to the space. Thanks to the TU Delft's campus real estate department for granting access to the sensor data. These results are graphically presented in Graph 5, which displays the trends observed within the room. After analysing the data, it appears that the sensor is inaccurately calibrated. Since, early in the morning and late at night, the recorded CO2 concentration remains 743 PPM. While the expected value for the CO2 concentration should stabilize between the range of 400 and 500 PPM.

Furthermore, upon analysing the measured CO2 concentrations, it is evident that the data obtained from the sensor in the room consistently reflects values approximately 250-300 PPM higher than the average data from the manually conducted measurements. For instance, the peak CO2 concentration manually measured on April 24th was 883 PPM by sensor 4, whereas the sensor located in the duct system of Hall P recorded a peak measurement of 1150 PPM, indicating a difference of 267 PPM. This disparity raises concerns regarding the reliability and adequacy of using a single sensor to monitor a room. Relying on a single sensor could lead to an inaccurate representation of the room's CO2 levels, potentially resulting in an excessive ventilation flow being directed to the room. While increased ventilation can help reduce the risk of infection, it may also impact the occupants' comfort. Nonetheless, this data is still valuable as it highlights the importance of sensor placement and the need for multiple sensors to ensure accurate monitoring.



Graph 5 Room sensor measurement

5.2.2 Proposed design SMART ventilation system

The successful application of a smart system design that provides an healthy and productive indoor environment is dependant on the a lot of factors. One of which is setting a right threshold; Place the threshold to high and the systems works too late, place it too low and the system works unnecessarily. Furthermore the placement of the sensor is also an important. As it was made clear within the baseline situation that there significant differences between locations and their CO2 concentrations.

Therefore in the context of improving SMART systems, a unique approach is taken with the design is proposed. As it is shown in figure 100 and 101, in this design, the exhaust and supply outlets are strategically positioned above each table. Additionally, a sensor is placed at each table to measure the localized CO2 concentration in its vicinity.

Figure 100 SMART system design isometric

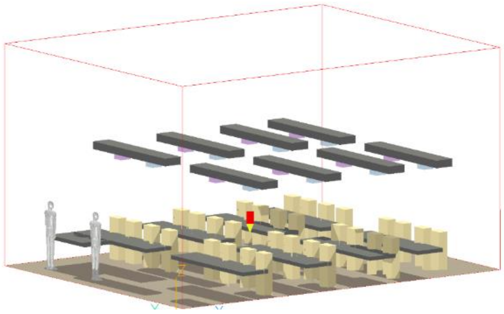


Figure 101 SMART system inside phoenics

Air terminal	Amount	Units
Supply	8 x 120	Unit/M3/h
Exhaust	8 x 120	Unit/M3/h

Table 15 SMART system supply and exhaust amounts

This design takes into account the observation from the baseline situation, where it became evident that CO2 concentrations vary when there are fluctuations in the number of occupants within the room. By incorporating these localized sensors, the smart system can dynamically adjust the ventilation system based on real-time occupancy data and CO2 concentrations. It enables the system to respond promptly by either reducing or increasing the airflow to ensure optimal air quality and comfort for the occupants at each table. This adaptive approach maximizes energy efficiency while maintaining a healthy and conducive indoor environment. Furthermore, the exhausts and supply inlets are directly placed above each table, which allows for efficient removal of CO2 emissions and other contaminants produced by the occupants. This is done by positioning the exhaust terminals relatively close at a height of 2,7 metres to the source of pollutants, the system can effectively extract it from the occupied zone. As it is show in table 15, there in total 8 supply points and 8 exhaust points with flow and exhaust rate for an individual point being 120 m3/h.

The integration of sensors at each table plays a crucial role in the smart system's functionality. As these sensors continuously monitor the CO2 concentration levels in their respective areas, providing real-time feedback to the ventilation system. Based on the collected data, the smart system can intelligently adjust the ventilation parameters to maintain optimal indoor air quality. The combination of strategically positioned exhaust and supply outlets, along with localized sensors, should allow for targeted ventilation control. This ensures that the ventilation system adapts to the specific needs of each occupied area, maintaining a healthy and comfortable environment.

5.2.3 SMART ventilation simulation results

Similar previous scenarios, the distribution of CO2 within the room appears to be a distribution pattern. The majority of the room is covered by the light green region, measuring CO2 concentrations of 1012 PPM, whereas the light blue area indicates concentrations of 973 PPM. While the average of the room sits at 1058 PPM. Notably, compared to previous situations, the occurrence of large concentration hotspots has significantly reduced. Although there are a few smaller hotspots, marked in red in figure 102, their size is comparatively smaller than those observed previously. The concentration of these spots sat at 1121 PPM Moreover, in figure 103, a vertical section illustrates that the CO2 plume remains more localized, with a distinct anomaly highlighted in blue.

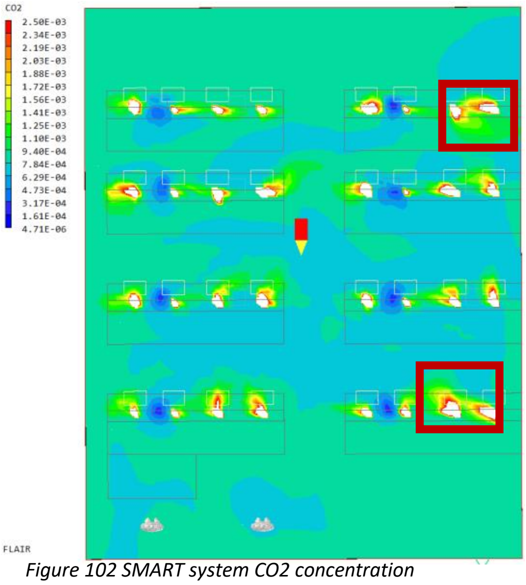


Figure 102 SMART system CO2 concentration

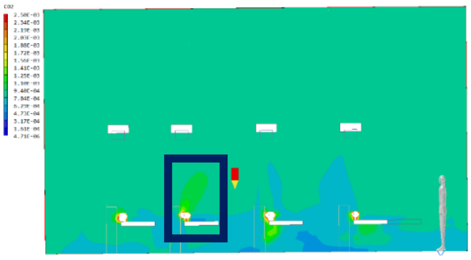


Figure 103 SMART system CO2 concentration vertical

In terms of the air flow and velocity in the room, it can be noted in figure 104 that the airflow movement, which is drawn in red and orange, is more localised due to the ventilation system being placed more close by. Furthermore, as it is shown in figure 105, since the supply flow is now equally divided into eight supply grills the velocity has been cut down to 0,2 m/s which is a more comfortable air velocity.

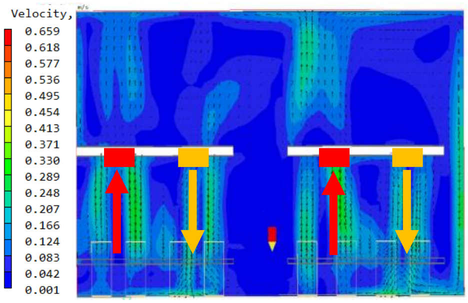


Figure 104 SMART system air velocity vertical

Also as result of the design where both the supply and exhaust are located above the occupants, there is little airflow that pushes the air side to side, as the airflow between table is around 0,034 m/s. This reduces the chance that possible infected air gets blown from one table to another.

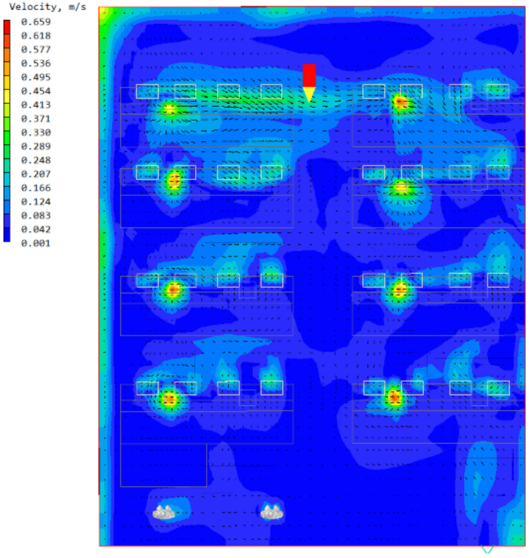
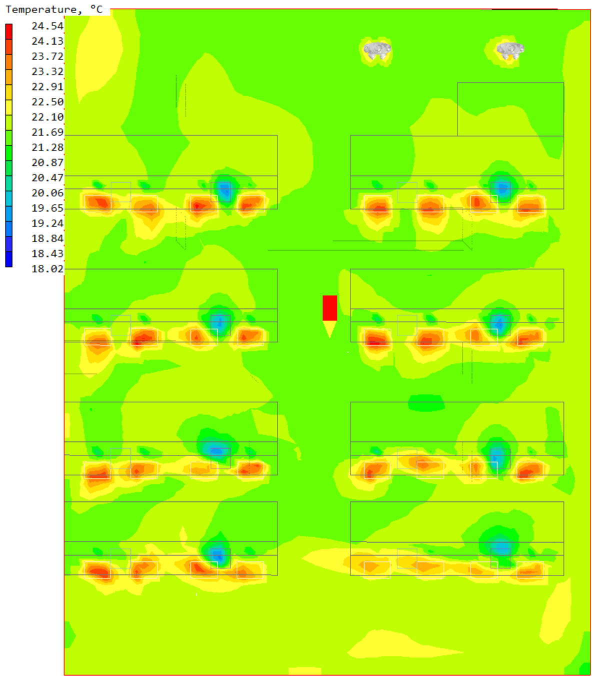


Figure 105 SMART system air velocity

In figures 106, 107, 108, and 109 are the temperature and age of air provided, respectively. Figure 106 reveals that the average temperature inside the room with this design is 21,8 degrees Celsius. Furthermore, with the design of the this ventilation system, it is to be expected that on the locations where the air enters the room the temperature would be lower. This is indeed the case as it is shown in figure 107. Encircled in black, the air that enters through the supply vent sits at an temperature of 20 degrees. This is slightly cooler than the average temperature and thus might cause some discomfort the occupant sitting directly in the flow. In terms of the average age of the air, which is shown in figure 108, sits at 1603 seconds, whereas the more yellow spots inside the room sit at 1458 seconds, which translates to 27 minutes and 24 minutes respectively. However, while the around the people is younger, the age of the air in the front of the room is actually 1972 seconds, which is 33 minutes.



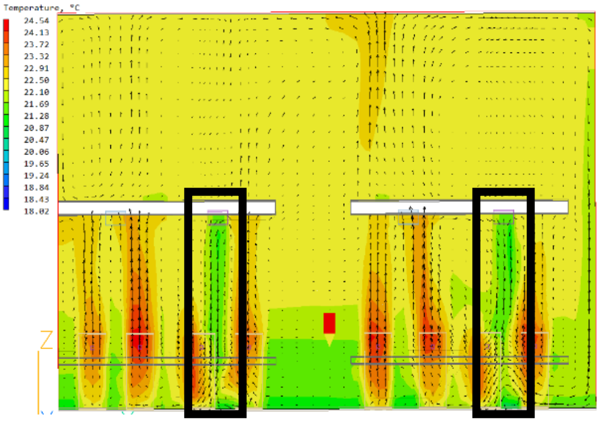
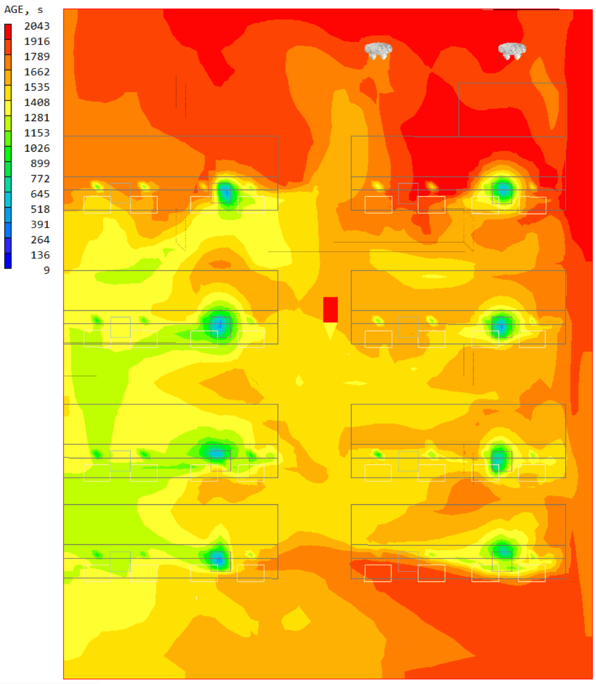


Figure 107 SMART system Temperature vertical

Figure 106 SMART system Temperature horizontal



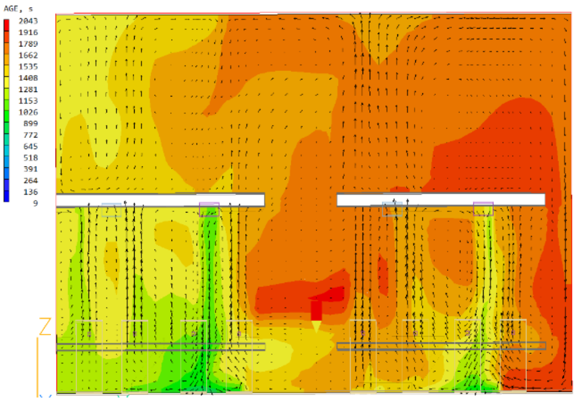


Figure 109 SMART system age of air vertical

Figure 108 SMART system age of air horizontal

Moving on to figures 110, 111, 112 and 113, which present the PMV and PPD respectively. The PMV value of -1.00, suggests that also with this design the occupants in any location of the room experience a slightly cooler sensation. This is a marginal improvement compared to the previous situations as the occupants there had an average PMV between -1,16 and -1,38. In terms of the PPD, the change here to feel dissatisfied is also around the 25%, however when an occupant is directly under the supply vent the PPD jumps to 93% which is almost an certainty that the occupant will feel dissatisfied. However this problem can be fixed by using a ventilation grill that disperses the air.

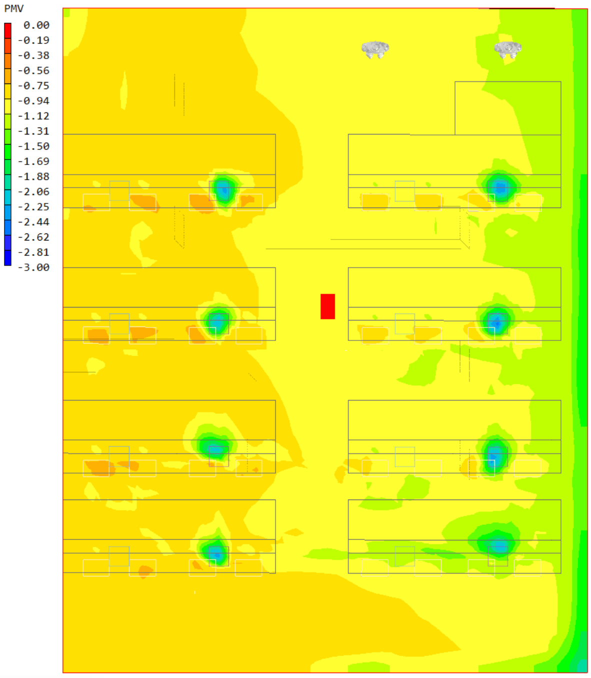


Figure 110 SMART system PMV horizontal

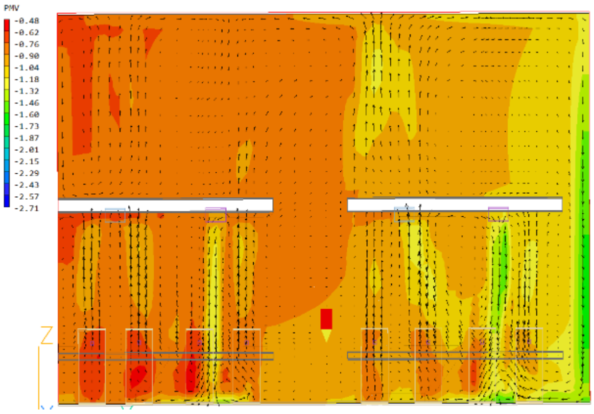


Figure 111 SMART system PMV vertical

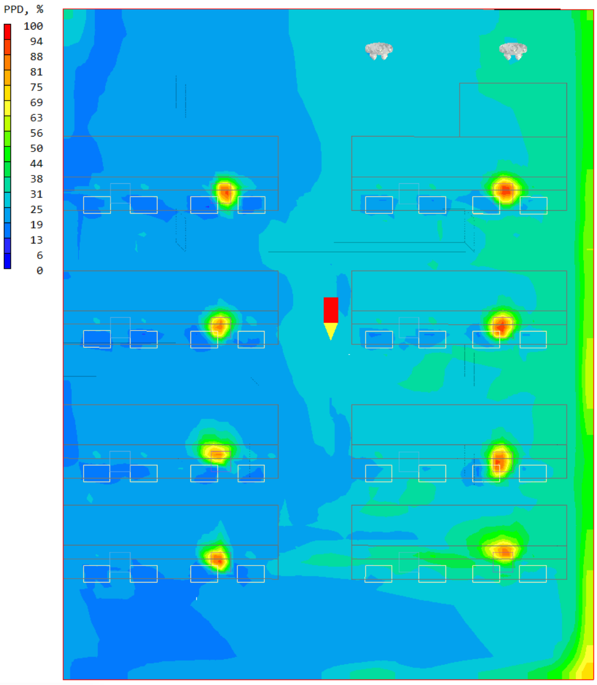


Figure 112 SMART system PPD horizontal

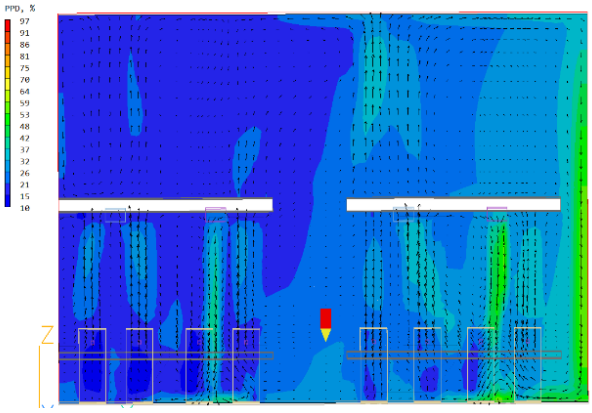


Figure 113 SMART system PPD vertical

5.2.4 Risk of infection and ventilation effectiveness

For the calculation of the risk infection for the SMART system the values 1058 and 1121 PPM are used. Analysing the data presented in figure 114, it is evident that this design in terms of the infection risk is similar to both the baseline situation and decentral ventilation design. With the infection risk ranging from 12% to 22%. However the SMART system design had far less hotspots in the room. This is an improvement compared to both the baseline and decentral ventilation design.

Using the same formula as last the time, the air change efficiency for the two scenarios comes down to:.

The formula:

$$\varepsilon^a = \frac{\tau_n}{\bar{\tau}_r} * 100 = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 \text{ (Mundt, 2004).}$$

According to the simulation the average mean age or is $\langle\bar{\tau}\rangle$ = 1637 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:

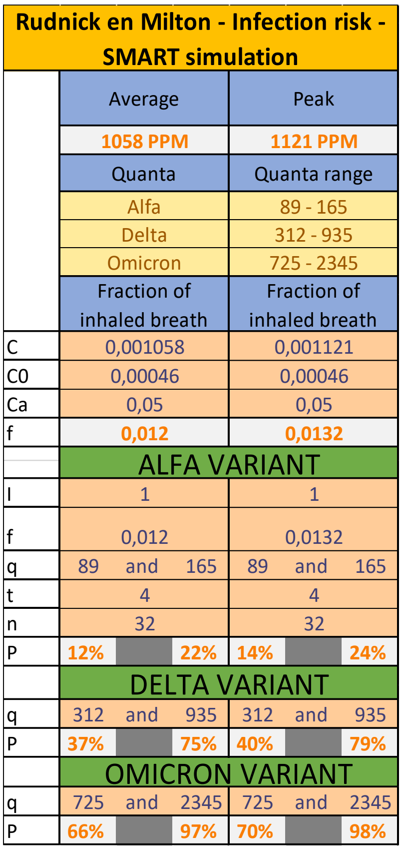
$\langle\bar{\tau}\rangle$ = 1637 /3600 = 0.454 [h]

V = 5,8 $m \times 10\ m\ \times 8\ m = 464\ [m^3]$ (length x height x width)

$q_v = 960\ [m^3/h\ ]$

$\tau_n = \frac{464}{960} = 0.483$ [h]

$\varepsilon^a = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 = \frac{0.483}{2\times 0.454} * 100\% = 53{,}2\ \%$, this would in the category displacement flow.



	Rudnick en Milton - Infection risk - SMART simulation					
	Average			Peak		
	1058 PPM			1121 PPM		
	Quanta			Quanta range		
	Alfa			89 - 165		
	Delta			312 - 935		
	Omicron			725 - 2345		
	Fraction of inhaled breath			Fraction of inhaled breath		
C	0,001058			0,001121		
C0	0,00046			0,00046		
Ca	0,05			0,05		
f	0,012			0,0132		
	ALFA VARIANT					
I	1			1		
f	0,012			0,0132		
q	89	and	165	89	and	165
t	4			4		
n	32			32		
P	12%		22%	14%		24%
	DELTA VARIANT					
q	312	and	935	312	and	935
P	37%		75%	40%		79%
	OMICRON VARIANT					
q	725	and	2345	725	and	2345
P	66%		97%	70%		98%

Figure 114 risk of infection

5.2.5 Aspect of economics and practicality

For the SMART ventilation system retrofit design, the costs of the system is primarily in the amount of ducts and air terminals and sensors that need to be laid down. An indication of what this could cost is given in table 15.

Materials	Amount	Costs	Total
Sensors	8	€ 200 – 500*	€ 1600 – 4000
Ducts	20 meters	€ 107 per meter	€ 2140
Air terminals	16	€ 40-100	€ 640-1600
Total price single room			€ 4380 – 7740**

*** Source: https://www.ventilatieland.nl/co2-meter**
**** Total price does not include the air handling unit as this design is a retrofit of the current design where present air handling unit is still in use. This price is indication of what will need to retrofit.**

Table 15 Cost analysis SMART system

Taking into account the implementation costs of a SMART ventilation system design, the price for equipping a single room ranges from 4380 to 7740 euros. This represents a considerable reduction compared to the decentralized ventilation system, as it amounts to either a half or quarter of the cost. However, when multiplied by 20 to retrofit multiple rooms, the total expenditure ranges from 87600 to 154800 euros. This is still a significant investment, however the advantages of the SMART system in terms of reducing infection risks and prioritizing occupant comfort make it more justifiable.

Moreover, the practical aspects of installing the SMART ventilation system are also more favourable compared to the decentralized approach. This system only requires mounting brackets, ducts, and sensors, which are smaller in size and easier to transport. This easier installation process adds to the convenience and feasibility of implementing the SMART ventilation system.

5.2.6 Assessment SMART ventilation situation

In conclusion, the simulation results of the SMART ventilation design have gathered interesting insights, highlighting the importance of a well-designed system that considers parameters such as location and distance.

First, similar to previous situations, the SMART system exceeds the WHO's recommended threshold of 1000 PPM (WHO Regional, 2000), as the systems maintains CO2 concentrations between 973 and 1012 PPM, with the average concentration in room at 1058 PPM. Additionally, the age of the air is significantly reduced to 1603 and 1458 seconds, representing an impressive improvement of 7 to 10 minutes compared to the baseline situation. However, despite this progress, the infection risk remains similar to that of the baseline situation and decentral design. With risks of infection across the three strains being marginally lower ranging from 3 to 6 to 8 for the ALPHA, DELTA and OMICRON strain, respectively. The implications of these findings indicate that improved ventilation design, considering factors such as location and distance, would result in enhanced ventilation efficiency as recommended by literature (Song et al., 2022; Melikov et al.,2002; Jaio et al., 2019). However, the primary approach to reducing the risk of infection lies in increasing the ventilation rate within the room, as demonstrated by the parametric research conducted in the baseline scenario.

Second, the implementation costs of the SMART ventilation system design need to be considered. Equipping a single room ranges from 4380 to 7740 euros marking a substantial reduction compared to the decentralized ventilation system, as this amounts to either a half or quarter of the costs of a single room decentral ventilation system. However, when scaling up to retrofit multiple rooms, the total expenditure ranges from 87600 to 154800 euros. Although still a considerable investment, the advantages of the SMART system in terms of reducing infection risks and prioritizing occupant comfort make it a more justifiable expense.

Furthermore, from a practical perspective, the installation of the SMART ventilation system proves to be more favourable compared to the decentralized approach. It requires mounting brackets, ducts, and sensors that are smaller in size and easier to transport. This easier installation process enhances the convenience and feasibility of implementing the SMART ventilation system, saving time and effort in the retrofitting process.

In summary, while the SMART ventilation design offers promising outcomes, emphasizing the significance of a well-designed system that takes into account parameters such as location and distance. The results from the research indicate that these two parameters in combination with the design can only marginally improve the indoor situation, by effectively reducing the average CO2 by 100 PPM compared to the baseline situation. While achieving improvements in CO2 concentration and air age reduction, there is still room for further enhancements in reducing the infection risk. Nevertheless, with its reduced implementation costs and practical advantages, the SMART system presents a viable solution for improving indoor air quality and prioritizing occupant well-being.

5.3 Situation 4: personal ventilation

The fourth and final scenario, labelled as Situation 4, showcases the outcomes of the investigation into the personal ventilation system.

5.3.1 Proposed design personal ventilation system

In the application of the personal ventilation system, two distinct designs were simulated to assess their effectiveness in providing comfortable and healthy indoor environments in a full classroom. The first design, shown in figure 115, involves placing both the supply and exhaust openings in close proximity to the occupants. This design is aimed to create a more personalized connection between the occupants and the ventilation system, as it allows for a greater sense of control over the directed airflow. Meanwhile, presented in figure 116, the second design takes a different approach by positioning the exhaust opening close to the occupants and the supply terminals placed at a distance above the occupants. This design aimed to ensure unobstructed exhaust of CO2 and create a downward airflow to limit the spread of particles and contaminants, which is based on recommendations by a study conducted by Melikov et al., (2012).

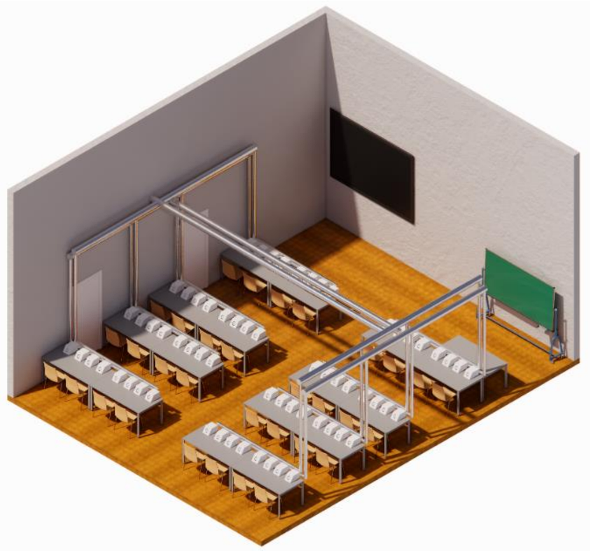


Figure 115 PV design 1

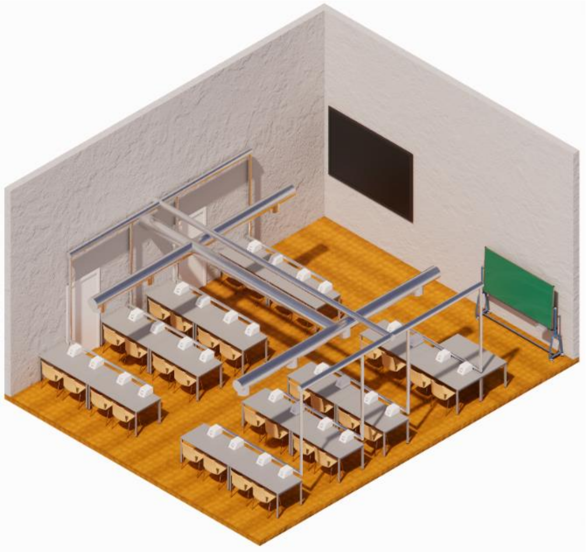


Figure 116 PV design 2

Additionally, a proof-of-concept test was conducted to evaluate an individual personal ventilation system. Figures 117 to 120 illustrate the test setup and components of the personal ventilation system. The system consisted of an MDF box with a slanted side that featured perforations. It was equipped with a standard 100m3/h ventilator connected to flexible ducts. This system provides an airflow directly to the test subject, while the exhaust is also located to the side.

Figure 117 top down view PV system

Figure 118 front view PV system

Figure 119 Test setup

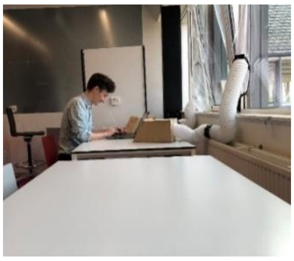


Figure 120 participant at the setup

5.3.2 Measurement results and observations

On May 22nd, 2023, a measurement was conducted to assess the proof-of-concept design for the personal ventilation system in Room W. This smaller room measures 5.4 meters in length, 4.9 meters in width, and 3.36 meters in height, resulting in a total surface area of 26.46 square meters and a volume of 88.9 cubic meters.

Room selection was influenced by the need for access to fresh outside air. To achieve the prototype's objective of both exhausting stale air and supplying fresh air, a window in the room (as shown in Figure 121) was opened and sealed tightly using tape. Two small slits were then made in the plastic to enable the connection of flexible ducts. This configuration effectively facilitated the exhaust and supply of air, preventing air recirculation within the room. The exhaust was positioned on the left side of the laptop, while the supply was situated on the right side.

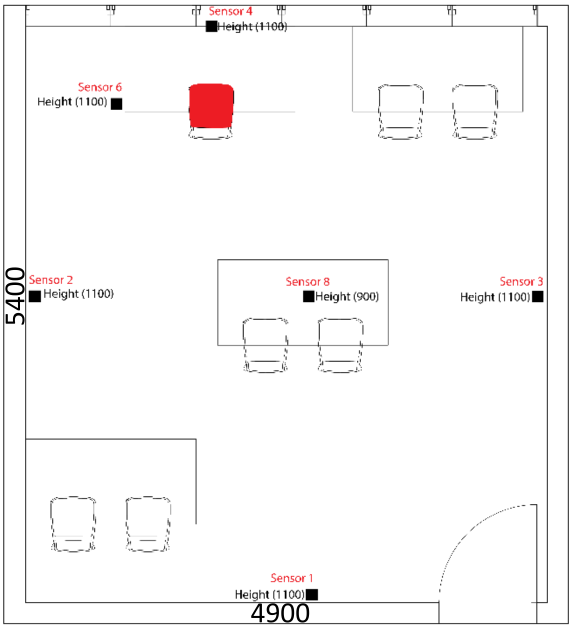
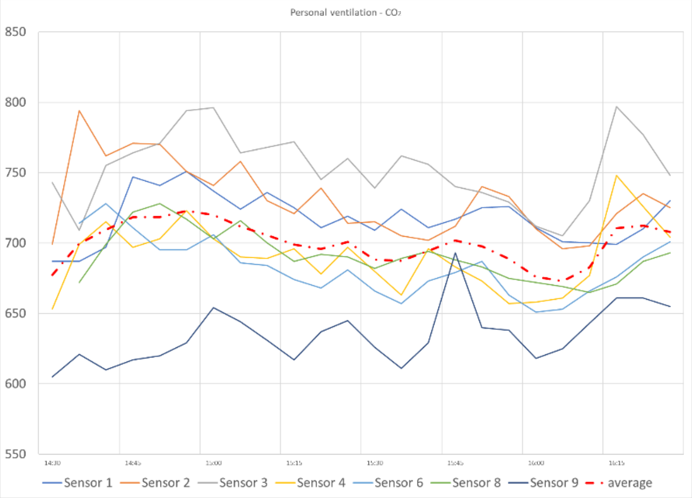


Figure 121 floorplan test setup

The measurement took place from 14:30 to 16:30. The initial empty room measurement, conducted from 14:30 to 15:00, yielded an average CO2 concentration of 700-710 PPM across the sensors, excluding Sensor 9, which was designated for measuring CO2 concentration outside the room. During the measurement, two individuals, the subject and the tester, were present in the room. Therefore it must be noted that the CO2 concentration could be influenced by it. Additionally sensors 5 and 7 were not used due to the room already being sufficiently covered by the other sensors.

Figure 122 close up test setup

In graph 6, Sensor 9, positioned outside the room throughout the measurement, consistently registered CO2 levels between 600 and 650 PPM. While the average in room is 700 PPM. The spike in the graph resulted from someone briefly entering the room. As result the concentration across all the sensors decreased. Sensors 1, 2 and 3 recorded the above average CO2 concentrations within the room, averaging between 730 and 800 PPM. With the peak value of 797 PPM at sensor 3. While sensors 4, 6, and 8 recorded concentrations that were below and close the average of the room ranging from 650 to 700 PPM.

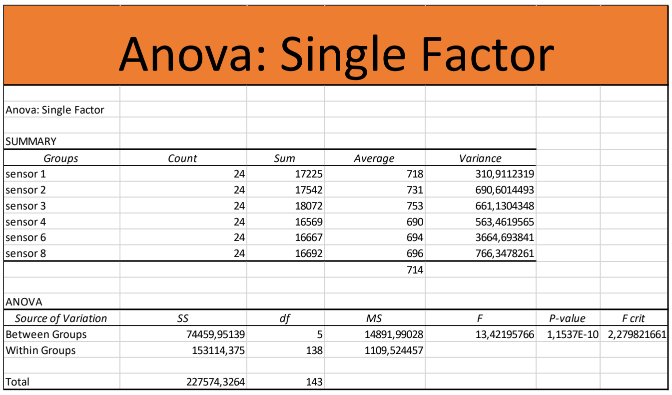


Graph 6 measurement test setup

In terms of comfort it was reported by the participant that, the direct flow of the unit was uncomfortable. After adjusting the unit to make sure the flow was directed to the chest instead of the face, the unit was deemed comfortable to use.

Similar to the previous instance of baseline measurements, it is necessary to assess the statistical significance of the data obtained. The ANOVA single test results, as illustrated in Figure XX, indicate that the data recorded from the sensors are statistically significant.

As depicted in Figure YY, Further analysis with the Bonferroni correction reveals that the data from sensors 4, 6, and 8 are the ones that are statistically significant. Therefore, it can be concluded that from this correction that the utilization of the personal ventilation (PV) system effectively reduces the concentration of CO2 in the specific area where it is installed to a significant extent.



Anova: Single Factor

Anova: Single Factor

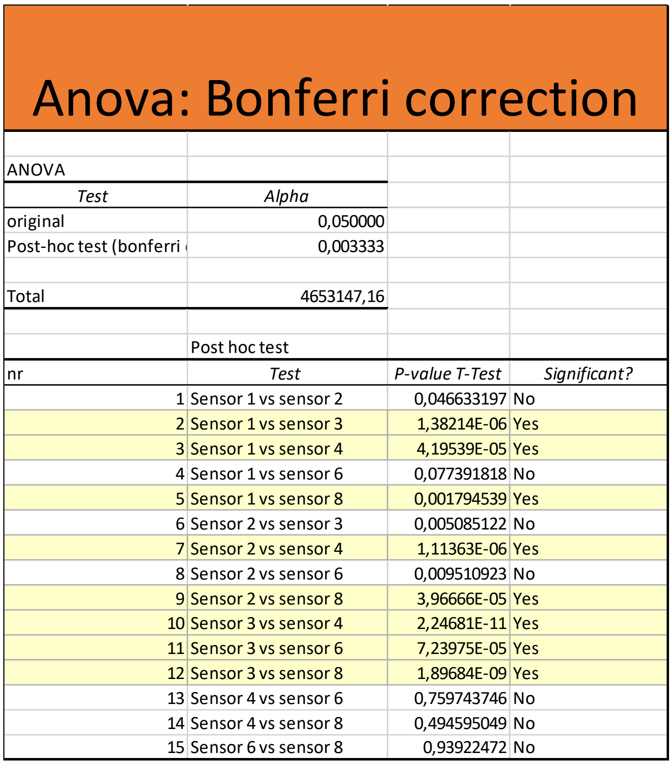
SUMMARY

Groups	Count	Sum	Average	Variance
sensor 1	24	17225	718	310,9112319
sensor 2	24	17542	731	690,6014493
sensor 3	24	18072	753	661,1304348
sensor 4	24	16569	690	563,4619565
sensor 6	24	16667	694	3664,693841
sensor 8	24	16692	696	766,3478261
			714	

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	74459,95139	5	14891,99028	13,42195766	1,1537E-10	2,279821661
Within Groups	153114,375	138	1109,524457			
Total	227574,3264	143				

Figure 123 ANOVA significance test



Anova: Bonferri correction

ANOVA

Test	Alpha
original	0,050000
Post-hoc test (bonferri	0,003333
Total	4653147,16

Post hoc test

nr	Test	P-value T-Test	Significant?
1	Sensor 1 vs sensor 2	0,046633197	No
2	Sensor 1 vs sensor 3	1,38214E-06	Yes
3	Sensor 1 vs sensor 4	4,19539E-05	Yes
4	Sensor 1 vs sensor 6	0,077391818	No
5	Sensor 1 vs sensor 8	0,001794539	Yes
6	Sensor 2 vs sensor 3	0,005085122	No
7	Sensor 2 vs sensor 4	1,11363E-06	Yes
8	Sensor 2 vs sensor 6	0,009510923	No
9	Sensor 2 vs sensor 8	3,96666E-05	Yes
10	Sensor 3 vs sensor 4	2,24681E-11	Yes
11	Sensor 3 vs sensor 6	7,23975E-05	Yes
12	Sensor 3 vs sensor 8	1,89684E-09	Yes
13	Sensor 4 vs sensor 6	0,759743746	No
14	Sensor 4 vs sensor 8	0,494595049	No
15	Sensor 6 vs sensor 8	0,93922472	No

Figure 124 ANOVA significance test

5.3.3 Simulation results and observations

In contrast to previous analyses of the ventilation system designs, in this analysis more focus put evaluating the individual impact of the personal ventilation system. Therefore, besides examining the overall influence on the room as a whole, it becomes crucial to assess how individuals are affected by this personalized approach. Figures 125 to 127 present the CO2 concentrations, air velocity within the room and the age of the air.

Figure 125 shows that compared to all other situations examined thus far, this configuration has the most uniform distribution of CO2 when analysing the room at large. The majority of the room, represented by the light green colour, maintains an average concentration of 1032 PPM. While in close proximity to individuals, the concentration decreases to 715 PPM, as indicated by the encircled blueish areas. Moreover, it is worth noting that the supply flow and exhaust system effectively contain the dispersion of higher CO2 concentrations. However, it is observed that the supply flow appears to be relatively strong, causing the air to be pushed from one table to the table located behind it. Furthermore this system has also reduced the amount of hotspots that are formed within the room. The white areas are the spot of the mouth and nose which generate the CO2.

Figure 126 shows the previously mentioned strong airflow that originates from each of the supply openings. With a velocity of 0,53 m/s it surpasses the recommended threshold of 0,2 m/s. This elevated velocity may result in discomfort when utilizing this design.

Figure 127 presents the age of air. The average air age in the room is approximately 1614 seconds, equivalent to around 27 minutes. However, the blue area closer to the occupants exhibits a significantly reduced air age of 544 seconds or 9 minutes, representing a substantial decrease compared to all previous designs. However, at the front of the room, the air age has actually exceeded the baseline, reaching 2270 seconds or 38 minutes.

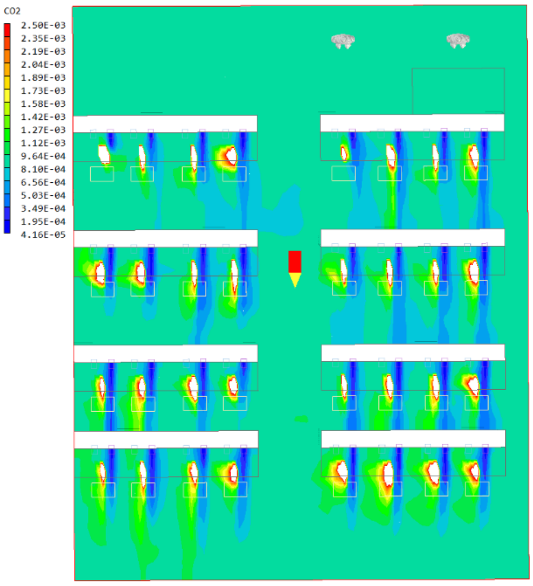


Figure 125 PV design 1 CO2 concentration

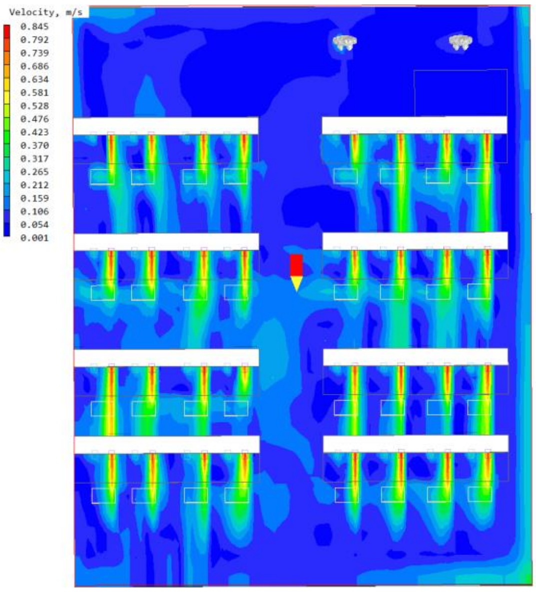


Figure 126 PV design 1 air velocity

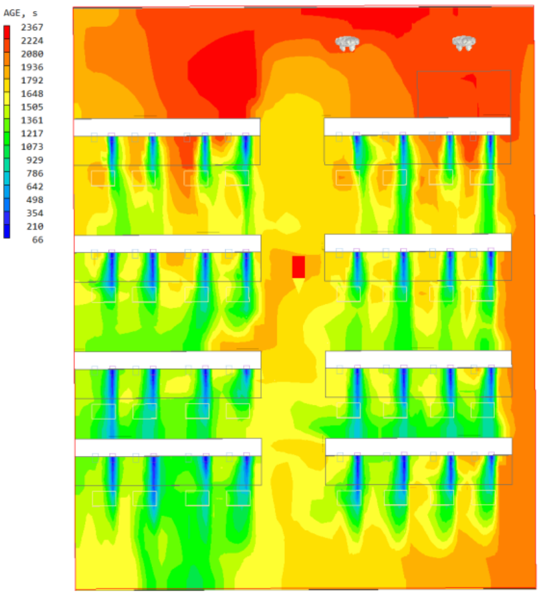


Figure 127 PV design 1 age of air

Figure 128 depicts the temperature distribution within the room, which indicates an average temperature of 22 degrees Celsius, slightly warmer than the preceding designs. However due to the design of the ventilation system the supply flow, which are the dark blue streaks, have a temperature of around 20 degrees Celsius.

In Figures 129 and 130 the PMV and PPD are provided, respectively. Figure 1 shows that the average PMV value in room is around – 1,08, which is similar to the SMART ventilation system. However, when looking closer at the occupants, the PMV decreases significantly to a value of -2,29. Leading to the conclusion that this design, while effective at reducing the CO2 concentrations, cools the occupants very much. This analysis is supported by figure 107 the PPD analysis. Since, while the average PPD value in the room is around 22% to 30%, the PPD value where the people are seated reaches as high as 90%. Which means that the design with the current setup is essentially guaranteed to cause discomfort to the user.

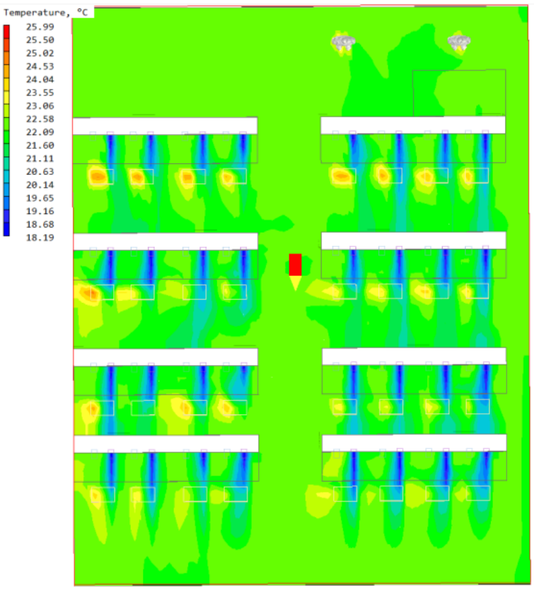


Figure 128 PV design 1 temperature

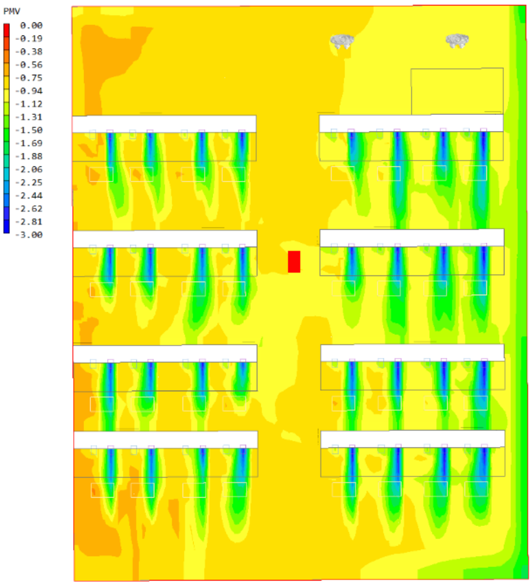


Figure 129 PV design 1 PMV

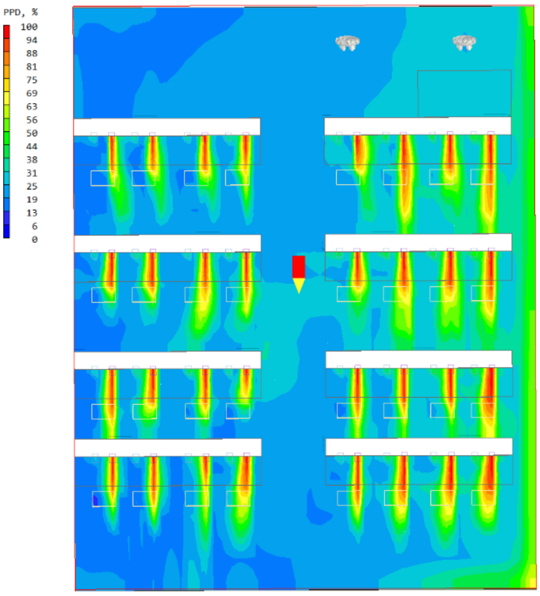


Figure 130 PV design 1 PPD

The following design involves relocating the supply opening to an overhead position while placing the exhaust directly in front of the person. This design concept draws inspiration from a literature study by Melikov et al., (2012), which highlighted the effectiveness of a personal exhaust system (PE) in efficiently removing CO2 without any nearby supply flow that could disrupt the exhaust process.

However figure 131 illustrates a different story as, the average CO2 concentration is 1158 PPM in the room, whereas in the area close to the exhaust this concentration is slightly lower at a value of 1026 PPM. These concentration are similar to that of the baseline situation. Furthermore, it is important to note that with the supply now positioned above the occupants, the mixing of the air between individuals is back. This phenomenon is clearly depicted in Figure 134. As observed, when the air descends from the supply opening, it gets diverted to the sides upon reaching the floor. This flow contributes to the effective mixing of CO2 plumes among the occupants.

In figure 132 the air velocities are presented. What is noticeable is that since the air supply has been split into 8 different air terminals the overall air velocity has been reduced in the room. The average air velocity in the room now is 0,08 m/s. However, there are spots in the room which are at a higher speed and these are directly located beneath the supply. The air velocity here is ranges from 0,3 to 0,6 m/s, which exceed the threshold 0,2 m/s that is allowed. This could cause discomfort to the people sitting close or directly beneath the flow.

Figure 133 presents the age of air. The average air age in the room is approximately 1639 seconds, equivalent to around 27 minutes. Furthermore, the green area closer to the occupants exhibits a reduced air age of 1424 seconds or 24 minutes, representing a slight decrease compared to all previous designs. However, at the front of the room, which are the dark orange and red areas, the air age has actually exceeded the baseline, reaching 2290 seconds (38 minutes) to 2500 seconds (42 minutes).

Figure 131 PV design 2 CO2 concentration

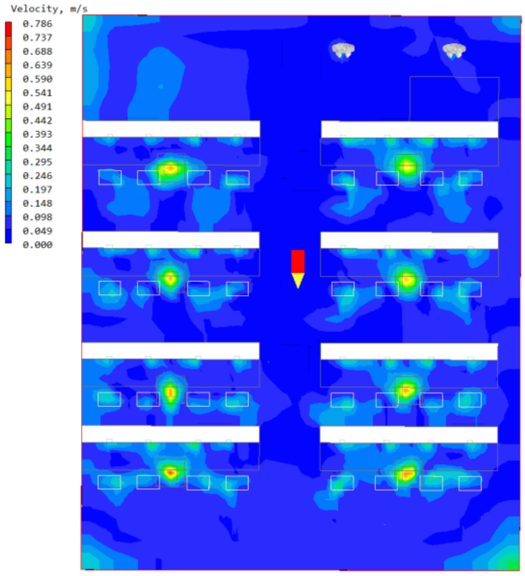


Figure 132 PV design 2 air velocity

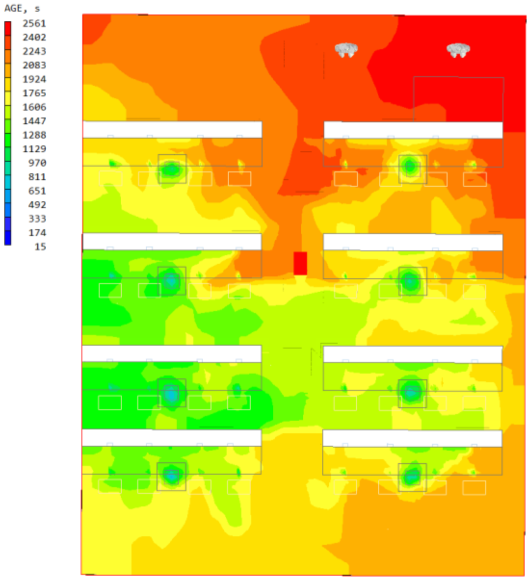


Figure 133 PV design 2 age of air

Figure 134 illustrates the temperature distribution within the room, revealing an average temperature of 23.1 degrees Celsius. It appears that this temperature is even higher than the previous PV design.

Figures 135 and 136 present the PMV and PPD results, respectively. Figure 138 highlights the average PMV value of -0.83, which is the lowest among the tested designs. This suggests that occupants in this room with the current design would experience minimal cooling sensation. However, the presence of airflow from the 8 air terminals significantly impacts the PMV, decreasing it to -2.07. Consequently, individuals positioned directly beneath the air terminals would feel noticeably cooler.

Figure 136 supports this observation, as it displays an average PPD of 20% throughout the room, but it increases to 80% beneath the air terminal. Leading to the conclusion that overall this ventilation system design would not impact the comfort of the people seated too much.

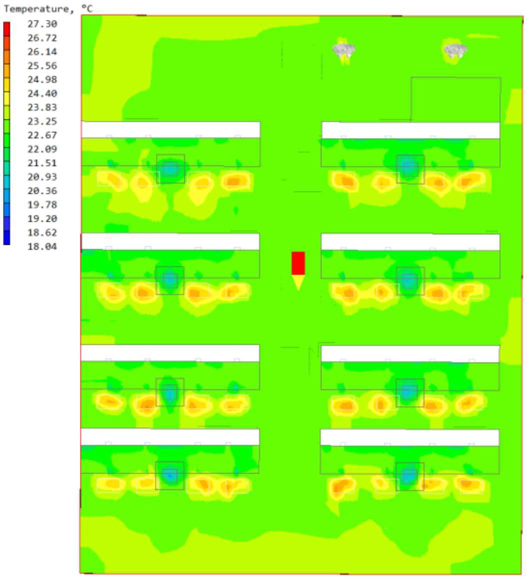


Figure 134 PV design 2 temperature

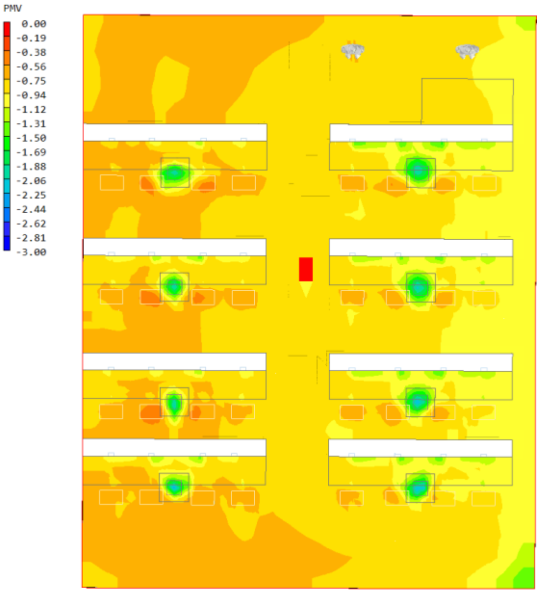


Figure 135 PV design 2 PMV

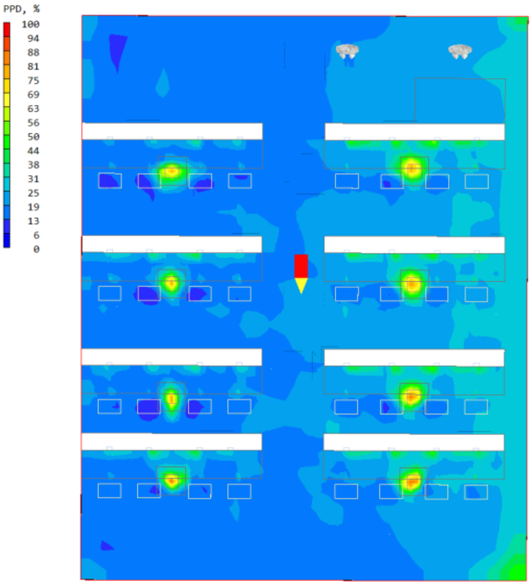


Figure 136 PV design 2 PPD

Regarding the simulation conducted for the single unit, Figure 137 presents the CO2 concentration inside the room with one person. The average concentration within the room is at 723 PPM, whereas the concentration between the PV system and the individual reaches approximately 816 PPM. It is worth noting that these values are slightly higher compared to the measurements. Examining the air velocity, depicted in Figure 138, it aligns with the observations made during the classroom-simulations. The air emerges from the supply as a jet, which can result in discomfort, and the recorded air velocity stands at 0.4 m/s, exceeding the threshold of 0.2 m/s.

Figure 139 displays the PMV value, indicating a value of -1.59 in proximity to the person. Consequently, the person would experience a cooler sensation when seated in front of this unit. Figure 140 supports this finding by illustrating the PPD in the room, which stands at 55%, but rises to 95% in the vicinity of the unit. Consequently, it can be concluded that while existing literature, such as Melikov et al. (2002 and 2012), suggested improved user comfort with the use of this system, the application and direct airflow of the system play a significant role. In this particular case, the direct flow causes discomfort to the individual using it.

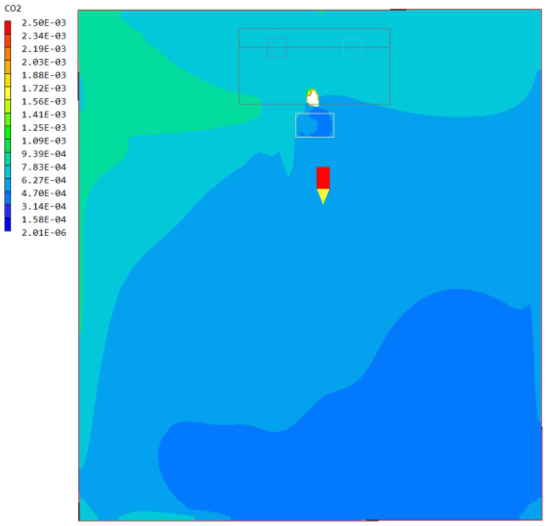


Figure 137 Single unit CO2 concentration

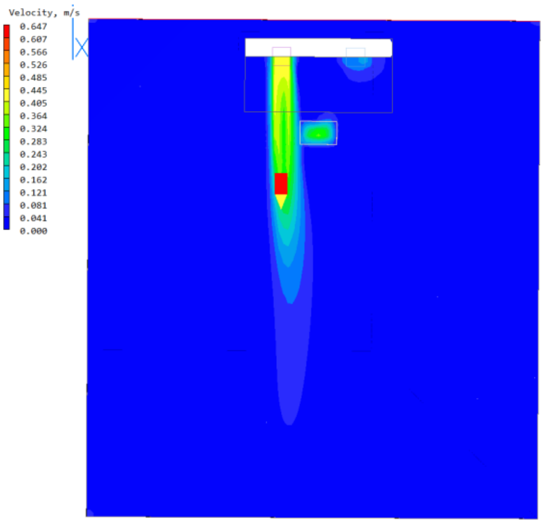


Figure 138 Single unit air velocity

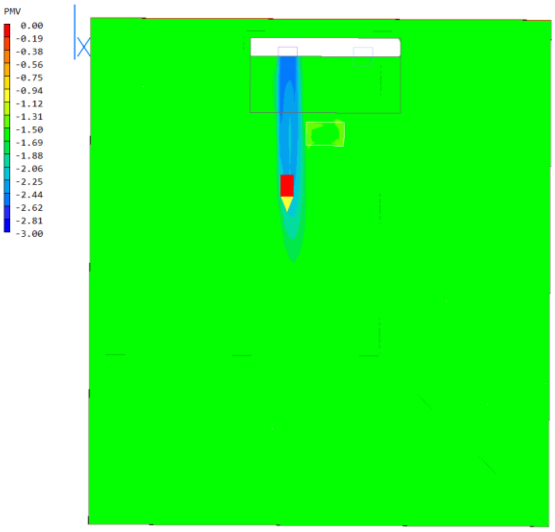


Figure 139 Single unit PMV

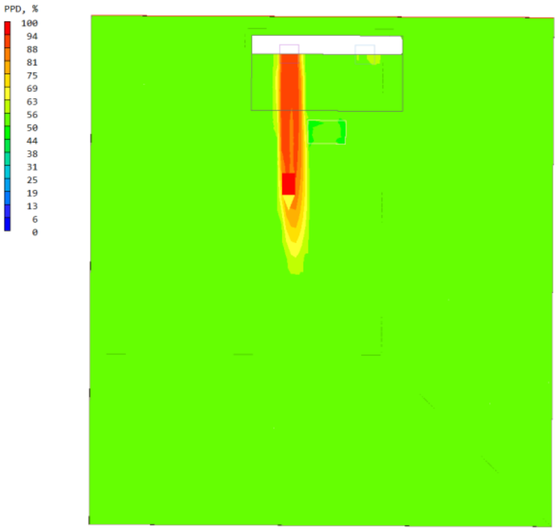
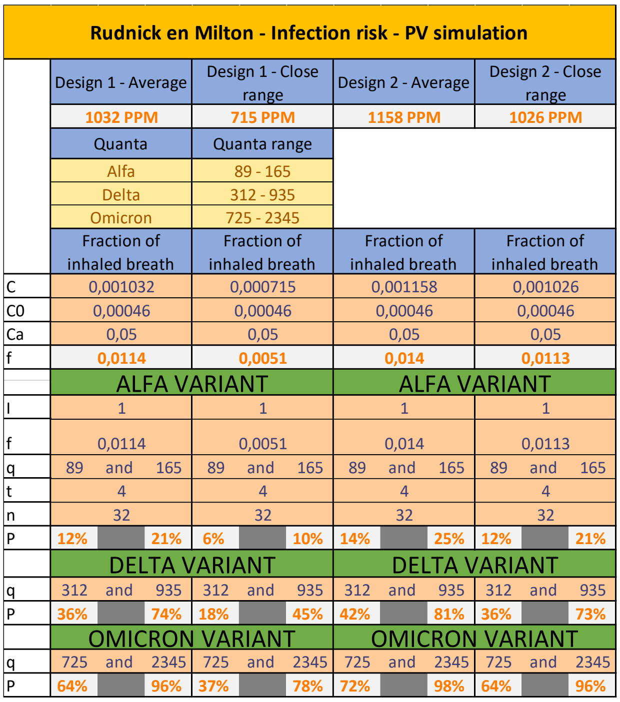


Figure 140 Single unit PPD

5.3.4 Risk of infection and ventilation effectiveness



Rudnick en Milton - Infection risk - PV simulation				
	Design 1 - Average	Design 1 - Close range	Design 2 - Average	Design 2 - Close range
	1032 PPM	715 PPM	1158 PPM	1026 PPM
	Quanta	Quanta range		
	Alfa	89 - 165		
	Delta	312 - 935		
	Omicron	725 - 2345		
	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath	Fraction of inhaled breath
C	0,001032	0,000715	0,001158	0,001026
C0	0,00046	0,00046	0,00046	0,00046
Ca	0,05	0,05	0,05	0,05
f	0,0114	0,0051	0,014	0,0113
	ALFA VARIANT		ALFA VARIANT	
I	1	1	1	1
f	0,0114	0,0051	0,014	0,0113
q	89 and 165	89 and 165	89 and 165	89 and 165
t	4	4	4	4
n	32	32	32	32
P	12% ▨ 21%	6% ▨ 10%	14% ▨ 25%	12% ▨ 21%
	DELTA VARIANT		DELTA VARIANT	
q	312 and 935	312 and 935	312 and 935	312 and 935
P	36% ▨ 74%	18% ▨ 45%	42% ▨ 81%	36% ▨ 73%
	OMICRON VARIANT		OMICRON VARIANT	
q	725 and 2345	725 and 2345	725 and 2345	725 and 2345
P	64% ▨ 96%	37% ▨ 78%	72% ▨ 98%	64% ▨ 96%

Figure 141 Risk of infection

For the PV system's infection risk calculation, design 1 utilizes CO2 concentrations of 1032 and 715 PPM, while the second design uses 1158 PPM and 1026 PPM. Figure 141 analysis reveals that the first design exhibits similar average concentration and infection risk compared to the baseline and other designs. However, a closer examination highlights a significant reduction in close-range infection risk, with the ALPHA strain seeing a halving of the risk. Other strains also experience notable decreases, with the maximum close-range risk dropping to 78% compared to a minimum of 90% in the baseline and other designs.

Conversely, the second PV design demonstrates limited effectiveness, as the risk of infection remains comparable to other designs, even at close range. Calculating the infection risk for the Single unit test becomes more challenging due to the measurement's objective of having only one person in the room. It is important to note that the CO2 concentration inside the room is influenced by the number of individuals present. If there were more people in the room, the overall CO2 concentration would have increased..

the air change efficiency for the two scenarios comes down to:

The first design:
According to the simulation the average mean age or is $\langle\bar{\tau}\rangle$ = 1526 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:

$\langle\bar{\tau}\rangle$ = 1641 /3600 = 0.456 [h]
V = 5,8 $m \times 10\ m\ \times 8\ m = 464\ [m^3]$ (length x height x width)
$q_v = 960\ [m^3/h\ ]$
$\tau_n = \frac{464}{960} = 0.483$ [h]
$$\varepsilon^a = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 = \frac{0.483}{2\times0.456} * 100\% = 53\ \%$$

The second design:
According to the simulation the average mean age or is $\langle\bar{\tau}\rangle$ = 1618 seconds (rounded up). With this value the ventilation efficiency can calculated as follows:
$\langle\bar{\tau}\rangle$ = 1639 /3600 = 0.455 [h]
$$\varepsilon^a = \frac{\tau_n}{2\langle\bar{\tau}\rangle} * 100 = \frac{0.483}{2\times0.455} * 100\% = 53\ \%$$
With the percentages of 56,96 % and 53,08% the room in both cases are considered to be displacement flow.

5.3.5 Aspect of economics and practicality

Since there are no complete systems on the market that offer an personalised ventilation (PV) system in, the costs are primarily of materials to create a single PV unit, which are given in table 190.

Materials	Amount	Costs	Total
MDF 4 mm	3 sheets	€ 3,40	€ 10,2
Ducts	8 meters	€ 7,45 per 2 meters	€ 29,8
Ventilator 100 m3/h	2	€27,54 for one piece	€ 55,09
Total price single unit	1 unit		€ 95,09
Total price room	64 units needed		€6085,76

Figure 16 PV system cost analysis

The cost of creating a single unit PV system amounts to 95,09 euros. However, considering a classroom with 32 students, a total of 64 units would be required to adequately ventilate the room, accounting for both supply and exhaust units for each student. This would result in a total cost of 6,085.76 euros, which is comparable to the SMART system and more affordable than the decentralized ventilation system. When multiplied by 20 to retrofit multiple rooms, the total expenditure would amount to 121,715.2 euros. It is important to note that this cost estimation does not include the manual labour required to create all these units, which is a significant time commitment.

However, when evaluating the practical aspects of personal ventilation systems, it becomes apparent that there are both positive and negative aspects. On the positive side, the individual units themselves are small and portable. However, each unit necessitates extensive ductwork, resulting in the entire classroom being covered in ducts. This can hinder the usage of the room and inconvenience the occupants.

5.3.6 Assessment Personal ventilation situation

In conclusion, the simulation results of the PV ventilation design have provided valuable insights into the importance of considering parameters such as distance, location, and airflow in designing an effective ventilation system.

Firstly, similar to previous scenarios, the PV designs also exhibit comparable average CO2 concentrations to the other designs. Design 1 maintains an average concentration of 1032 PPM, while the second design records 1158 PPM. Both systems surpass the WHO's recommended threshold of 1000 PPM (WHO Regional, 2000). However, closer examination reveals that in proximity to the PV system, the first design reduces the concentration down to 715 PPM, indicating improved effectiveness. In contrast, the second design shows less efficacy, with a reduction to only 1026 PPM. Consequently, this substantial decrease in close-range infection risk results in a halving of the risk for the ALPHA strain. Other strains also exhibit significant reductions, with the maximum close-range risk dropping to 78%, compared to a minimum of 90% in the baseline and other designs. These findings underscore the importance of enhanced ventilation design, considering factors such as location and distance, to achieve improved ventilation efficiency, as suggested by existing literature (Song et al., 2022; Jiao et al., 2019; Melikov et al., 2002).

Secondly, the cost analysis of implementing the PV ventilation system reveals that the price for a single unit amounts to 95.09 euros. Considering a classroom with 32 students, a total of 64 units would be required to adequately ventilate the room, resulting in a total cost of 6,085.76 euros. This cost is comparable to the SMART system and more affordable than the decentralized ventilation system. When scaling up to retrofit multiple rooms (20 in total), the total expenditure would be approximately 121,715.2 euros. However, it is important to note that this estimation does not account for the manual labor involved in creating the units, which is a significant time commitment.

Nevertheless, when evaluating the practical aspects of personal ventilation systems, both positive and negative aspects emerge. On the positive side, the individual units are small and portable, offering flexibility in installation. However, the extensive ductwork required for each unit results in the classroom being extensively covered, which may limit the room's usage and inconvenience the occupants. These factors should be carefully considered when implementing a PV ventilation system.

6. Discussion

This chapter provides a various reflections on the conducted research. Section 6.1 explores the implications in relation to existing literature. Section 6.2 addresses research choices, assumptions, limitations, and offers recommendations. Section 6.3 provides specific recommendations for policy-makers. Section 6.4 highlights the scientific and societal contributions of the thesis. Lastly, section 6.5 emphasizes the relevance of the thesis within the Building Technology master track.

6.1 Literature implications

This section reflects on the research findings in light of the reviewed literature. The results of this study may align or differ from the literature. When results do differ from the literature, reasons are sought to explain why. The relevant parameters identified in Chapter 2.8, are reiterated in Table 17 for clarity.

Parameters	Literature
Air exchange rate/Room size	de Man et al., 2021; Elsaid and Ahmed, 2021; Gettings et al., 2021; Blocken et al., 2021; Ratajczak, 2022; Somsen et.al; Ng et.al; Van Doremalen
Ventilation rate per person	de Man et al., 2021; Elsaid and Ahmed, 2021; Gettings et al., 2021; Blocken et al., 2021; Ratajczak, 2022; Ding et al.,2022; Liu et al., 2007; Melikov and Kaczmarczyk, 2012; Song et al., 2022 Melikov et al., 2012; Chen et al.,2021
Co2 concentration	Rudnick, S. N., & Milton, D. K. 2003; Peng et al.,2021; Di Gilio et al.,2021
Distance/location in relation to the exhaust	Song et al.,2022; Melikov et al., 2002; Jaio et al., 2019; Liu et al.,2017
Temperature	Boerstra, 2016; Song et al., 2022; Melikov et al., 2012; Park et al., 2022
Comfort	(Bluyssen, Philomena M., et al.). Boerstra, 2016). Melikov et al., 2012).

Table 17 Parameters

The research findings reveal that the air exchange rate per hour (ACH) is not a accurate indicator for ensuring a healthy indoor environment. It varies based on room volume, leading to inconsistent ventilation rates. This aligns with studies by de Man et al. (2021), Elsaid and Ahmed (2021), and Gettings et al. (2021) that recommend focusing on ventilation rate per person instead. The results presented in Table 9 support this approach, showing that basing ventilation on per-person rate guarantees a certain level of ventilation, while ACH-based rates can fall below the required standard, especially in smaller rooms with heights of 2.8 and 2.6 meters (Rijksoverheid, 2022).

Parameters/ height				
Room size (h)	464 (5,8)	256 (3,2)	224 (2,8)	206 (2,6)
People	32	32	32	32
Fixed ventilation per person (l/s)	8,5	8,5	8,5	8,5
Ventilation rate total (m3/h)	960	960	960	960
Calculated ACH	2,04	3,75	4,3	4,7
Fixed ACH	4	4	4	4
Ventilation rate total (m3/h)	1856	1024	896	824
Calculated ventilation rate per person (l/s)	16,1	8,9	7,8	7,15

Table 18 example calculation

Regarding the ventilation rate, the research findings align with the literature presented in Table 16, indicating that increasing the ventilation rate reduces the risk of infection within a room. However, the effectiveness of this reduction diminishes as the ventilation rate increases. For instance, increasing the rate to 15, nearly double the minimum requirement, results in a 10% risk reduction for early strains, but has less impact on later strains with higher quanta levels. Nonetheless, it is important to note that even a 10% risk reduction during the early stages of a pandemic, when quanta levels are relatively low, can have a significant impact, especially considering the overall risk ranges between 12% and 29%. In contrast, the later strains pose infection risks of at least 60% and 90%. Therefore, despite the diminishing returns of ventilation in mitigating the risk, it is still advisable to implement measures to create a healthier environment.

The accuracy of the CO2 concentration measurement method yielded interesting findings. The measurements closely aligned with theoretical approximations and simulations, although slightly higher values were observed within the room when physically measured. Furthermore, Sensor placement on the walls observed high CO2 concentrations and as result aligns with the recommendation made by Zhang et al. (2022). However, the central positions should also be considered based on deviations from measurements, as high concentrations were measured in more inward locations were measured. Which is also supported by the simulations. These highlighted elevated CO2 concentrations in the middle of the room and among seated individuals. Overall, while the measurements were more accurate, emphasizing the need to consider spatial distribution and central areas of the room.

The effectiveness of placing the supply and exhaust closer to individuals was examined as a design measure. Simulation results indicated that while distance and location had limited impact on the risk of infection, their influence was often combined with the ventilation rate of the supply air. This finding is consistent with the literature (Song et al., 2022; Melikov et al., 2002; Melikov et al., 2012). Specifically, in the SMART design and the first design of the PV systems, where the supply air rates were 120 m3/h and 30.6 m3/h respectively, and placed in close proximity to individuals, the concentration of CO2 around individuals and within the room was affected.

Lastly, regarding comfort, the analysis of the results revealed that the size of the room contributed to lower temperatures. Throughout the simulations, the Predicted Mean Vote (PMV) values ranged from -0.80 to -2.5, with the original room at -1.07, indicating a slightly cooler environment. The only design that improved the PMV was PV design 2, which involved a personal exhaust system with a exhaust placed close by and an overhead supply. This finding aligns with the literature, suggesting that such systems can enhance comfort for individuals (Melikov et al., 2012). The primary source of discomfort arose when the supply airflow directly blew towards people. In the case of PV design 1, where both the supply and exhaust were located in front of the individuals, the PMV decreased to -2.29 when seated directly in the airflow. Which is inline with multiple studies that have observed that while the temperature of the supply could increased to warm up the person, the direct airflow from the PV designs often removes more heat from individuals, leading to their cooling (Melikov et al., 2012; Faulkner et al., 2003; Khalifa et al., 2009; Russo et al., 2009; Chaudhuri et al., 2019).

6.2 Model choices, limitations & recommendations for future work

In this section, the thesis addresses the limitations inherent in the development of three ventilation system designs and the use of measurement and simulations. These factors have implications for the model's usability and the overall research. The following discussion examines the assumptions and limitations specific to each aspect of the research and provides recommendations for future work.

6.2.1 The design of the systems

The limitations of the decentralised ventilation system are as follows:

- Ineffectiveness in reducing CO2 concentration: The placement of the decentral unit in both the front and left positions did not lead to a significant decrease in CO2 concentration. The average concentrations exceeded the recommended threshold, indicating that the system did not effectively improve indoor air quality.

- Unimproved infection risk: Despite a reduction in the age of the air in the front position, the infection risk remained similar to the baseline scenario. The left position performed even worse, with a larger portion of the room experiencing higher infection risk values. This suggests that the decentral ventilation system did not effectively mitigate the risk of infection.

- Negative impact on occupant comfort: The use of a single stream of supply air in the decentral unit negatively affected occupant comfort, especially for individuals seated near the stream. Additionally, the airflow collision with opposite walls in the left position resulted in discomfort for individuals near those walls.

- High cost and impracticality: The implementation of the decentral ventilation system incurred a significant cost per room and required careful manoeuvring due to the unit's dimensions and weight. Considering the total expenditure and practical challenges, the system's cost-effectiveness and feasibility for installation in the Faculty of Architecture & the Built Environment were questionable.

Based on these limitations, it is evident that the decentral ventilation system has significant drawbacks in terms of effectiveness, cost, and practicality. These limitations suggest that the system may not be suitable or justified for implementation in the classrooms of the Faculty of Architecture & the Built Environment.

The limitations of the SMART ventilation system are as follows:

- Inadequate reduction in CO2 concentration: Although the SMART system achieves a slight improvement in average CO2 concentration compared to the baseline situation, the concentrations still exceed the WHO's recommended threshold. This suggests that the system may not effectively address the issue of high CO2 levels in the room.

- Unchanged infection risk: Despite reducing the age of the air and improving ventilation efficiency, the infection risk remains similar to that of the baseline and decentral designs. This indicates that the SMART system does not provide significant additional protection against the risk of infection.

- Limited improvement compared to location and distance: The findings suggest that while considering parameters such as location and distance in the design of the SMART system can result in some improvements in CO2 concentration and air age reduction, the overall impact on the indoor situation is marginal. Further enhancements may be necessary to achieve more substantial improvements in reducing infection risk.

- Implementation costs: While the SMART ventilation system design offers cost advantages compared to the decentralized system, retrofitting multiple rooms still incurs a considerable investment. The costs need to be carefully considered when scaling up the implementation across multiple rooms.

- Practical feasibility: The installation of the SMART system is more favourable compared to the decentralized approach, as it involves smaller-sized components and easier transportation. This enhances the practicality and feasibility of implementing the system in retrofitting processes.

Based on these limitations, it can be concluded that while the SMART ventilation system offers promising outcomes in terms of CO2 reduction and practical advantages, there are still limitations in terms of infection risk reduction and overall effectiveness. Further improvements and considerations may be required to optimize the system's performance and justify its implementation in terms of cost and impact on indoor air quality.

The limitations of the SMART ventilation system are as follows:

- Limited reduction in CO2 concentration: While the PV ventilation designs exhibit comparable average CO2 concentrations to other designs, they still exceed the WHO's recommended threshold. The effectiveness of the PV system in reducing CO2 concentration depends on the proximity to the system, with closer-range areas experiencing more significant reductions. However, the second design shows less efficacy in reducing CO2 concentration compared to the first design.

- Infection risk reduction varies: The PV system shows potential in reducing close-range infection risk, with a significant decrease in the risk for the ALPHA strain. However, the effectiveness of risk reduction varies between the two designs, with the first design achieving better results. It is important to note that while the PV system improves ventilation efficiency and reduces infection risk in close proximity, its impact on overall room air quality and infection risk across the entire space may be limited.

- Comparable cost to other systems: The cost analysis reveals that implementing the PV ventilation system is comparable to the SMART system in terms of cost and more affordable than the decentralized system. However, it is important to consider additional manual labour costs for creating the units, which can be a significant time commitment.

- Practical considerations: The PV system offers the advantage of small and portable individual units, allowing flexibility in installation. However, the extensive ductwork required for each unit may limit the room's usage and inconvenience occupants. The practical feasibility of implementing the PV system should be carefully evaluated, considering the impact on the room's layout and functionality.

Overall, the PV ventilation system shows potential in reducing CO2 concentration and close-range infection risk. However, its effectiveness in improving overall room air quality and reducing infection risk across the entire space may be limited. The cost of implementing the PV system is comparable to other systems, but additional manual labour costs should be considered. Additionally, the practical aspects of the PV system, including the extensive ductwork, should be carefully evaluated to ensure its suitability for the intended space.

6.2.2 Model choices

The model's usability and potential future extensions are subject to several limitations related to the modelling choices. Firstly, the selection of classroom Hall P for this research introduces certain limitations. While the room is intended to accommodate 32 students, its physical size allows for a larger number of students without any issues. Originally the room was intended for a total 48 students. Consequently, the room size has a considerable impact on the final results. The initial aim was to choose a location that could be considered representative of a "standard classroom. The room's height is problem, as it measures 5.8 meters, surpassing the typical height range of 2.6 to 3.2 meters for classrooms. However, during the selection it became clear that this room is not the only one within the faculty with such dimensions. Therefore for future research it would be great if studies could be conducted in location that are more suitable.
The second limitation relates to the limited data collected during the room measurements. The objective was to obtain precise data from the room to establish a baseline for comparing the designs and, importantly, to analyse the original scenario of a classroom intended for 32 students in the context of a pandemic. However, due to scheduling conflicts and unforeseen circumstances, only data from a measurement with 18 people in the room was available. While in the end it worked out. For future measurements, it is recommended to improve planning by coordinating with the relevant department responsible for scheduling and the teachers. This would involve scheduling classes with a larger number of participants to ensure feasibility and gather more comprehensive data.
The third limitation concerns the accuracy of the simulation and the input. When setting up the simulation, challenges arose regarding the model's accuracy. As more elements were added, the model became more complex and the simulation duration increased. Furthermore, the grid used in the simulation also influenced both the simulation time and the model's accuracy. Although the automatic grid generation function was utilized in the model, manual adjustments were made to refine the grid in specific areas. Additionally, the introduction of the pollutant of CO2 introduced problems with accuracy as it required deviation from the recommended setting within Phoenics and increasing the relaxation as a result. For future modelling it is recommended to run many tests with a broad grid size to dial in the needed relaxation for the pollutants, as this required the most time.

6.2.3 The results

In conclusion, the results from the various ventilation designs provide valuable insights into their effectiveness, cost, and practicality. The decentral ventilation design showed limitations in reducing CO2 concentrations and infection risk, particularly in the left position. Despite some improvement in air age and there was no reduction in CO2 concentrations using this system, as a result the infection risk remained similar to the baseline scenario. Moreover, the high costs of implementing the decentral system and its impracticality in terms of installation make it an unfavourable choice for retrofitting classrooms. On the other hand, the SMART ventilation design demonstrated better CO2 concentration control and air age reduction, though it did not significantly reduce infection risk compared to the baseline. The implementation costs of the SMART system were more reasonable, and its practicality in terms of installation was favourable, making it a more justifiable option for improving indoor air quality. Similarly, the PV ventilation design showed promise in reducing CO2 concentrations and infection risk, particularly with the first design. As it showed, that with the early virus strain the infection risk was halved. However, the cost analysis and practical considerations should be taken into account when implementing PV systems. As large amounts of ductwork is needed to facilitate the placement of 64 units in the room. Overall, while the ventilation designs showed varying levels of effectiveness and considerations, it is clear that a well-designed system, considering factors such as location, distance, and airflow, is crucial for achieving optimal indoor air quality and reducing infection risks. Balancing costs and practicality is also important in making informed decisions regarding ventilation system implementation.

6.3 Insights for policy-makers and designers

In this section, recommendations for policy-makers and designers based on the research findings are presented below:

- Although an increased recommended ventilation rate in classrooms cannot guarantee complete safety, it can significantly reduce the risk of infection, particularly in the early stages of a pandemic. Following the literature, it is advisable to increase the ventilation rate to 15 l/s per person.

- The location of the supply and exhaust should be carefully considered in conjunction with the increased ventilation rate, as it could enhance the effectiveness of the improved ventilation.

- While the research did not specifically focus on the effectiveness of masks, it is important to acknowledge that masks are effective in reducing the transmission of infectious particles. Therefore, their use should be combined with increased ventilation rates and better ventilation system designs to maximize the reduction in the risk of infection.

- Further government-funded research into the spread of COVID-19 in classrooms and the effectiveness of prevention measures is recommended due to many remaining unknown factors. Two important areas for future research that the government could support are as follows: (1) investigating the role of other classroom activities, such as shared workspaces, lunchtime interactions and meetings; and (2) exploring additional non-pharmaceutical interventions (NPIs) beyond those examined in this research, such as mask usage while sitting and group gathering protocols for coffee breaks or restroom visits. Funding for models that allow for a broader range of NPIs and facilitate easy comparison between them is also recommended.

6.4 Contribution of this research to the scientific community

The thesis has made a couple of contribution to the scientific community by shedding light on various aspects of ventilation system designs and their implications in indoor environments, particularly in the context of the ongoing COVID-19 pandemic. By conducting measurements, simulations, and analyses the research has provided insights and findings that expand our understanding of ventilation strategies and their impact on occupant safety and comfort.

Firstly, the thesis addressed the limitations and assumptions associated with different ventilation system designs. By critically examining factors such as room size, location, and supply and exhaust positioning, the research highlighted the significance of these parameters in determining the effectiveness of ventilation systems. This understanding is crucial for policymakers, designers, and engineers in making informed decisions regarding the implementation and optimization of ventilation systems. Furthermore, the thesis investigated the influence of ventilation rates on reducing the risk of infection. By recommending an increase in ventilation rates based on literature and empirical data, the research provides guidance to policymakers and designers on the importance of ensuring adequate airflow in indoor spaces. This insight is of utmost importance, especially in the context of the COVID-19 pandemic, where measures to mitigate virus transmission are of paramount concern. Additionally, the thesis highlighted the practical and cost considerations associated with different ventilation system designs. By evaluating the financial implications and practical feasibility of implementing various systems, the research provides valuable information for decision-makers in terms of cost-effectiveness and ease of installation.

Overall, the thesis's findings contribute to the scientific community by providing insights of the ventilation system designs and their implications for indoor environments. The research fills gaps in understanding by examining the effects of different parameters and considering multiple factors in the evaluation of ventilation strategies in relation to the COVID-19 pandemic. These insights can inform future research, policy development and practical applications in various sectors, including public health, building design, and engineering.

6.5 Suitability within Building Technology

This research thesis is conducted in the Building Technology masters program. The Mastertrack of Building Technology program at TU Delft focuses on the intersection of technology and architecture, providing students with a comprehensive understanding of building performance, sustainability, and innovative design strategies. The thesis aligns with the program's objectives by addressing crucial aspects of indoor environmental quality and the integration of technologies within building design.

The thesis delves into the complexities of ventilation system designs, considering factors such as location, distance, airflow and the impact on occupant’s comfort. The research conducted in the thesis aligns with the program's multidisciplinary approach combining scientific measurements, simulations, and analyses. This methodology reflects the program's emphasis on merging theoretical knowledge with practical applications, enabling a holistic understanding of building technology. Moreover, the thesis contributes to the ongoing discourse on building performance and the optimization of indoor environments particularly in light of the COVID-19 pandemic. This topic has become increasingly important in the field of building technology as architects, engineers and policy makers are seeking solutions to ensure safe and healthy indoor spaces. By addressing ventilation strategies and their implications on infection risk reduction, the thesis demonstrates an approach that resonates with the program's emphasis on sustainability and human well-being. Furthermore, the practical and cost considerations explored in the thesis align with the program's focus on real-world applications and the integration of sustainable technologies within budget constraints. The research findings provide valuable insights into the financial implications and practical feasibility of different ventilation system designs, equipping architects, engineers and policy makers with the knowledge to make informed decisions.

Overall, the thesis's relevance to the topics covered in the Master of Building Technology program, its multidisciplinary approach, and its contribution to the ongoing discourse on building performance make it an ideal fit within the program. It offers the opportunity to gain valuable insights into ventilation system design and apply this knowledge to address current and future challenges in building technology.

7. Conclusion

During the COVID-19 pandemic, the closure of schools and universities had significant negative impacts on children and young people. It is crucial to find ways to keep educational institutions open while ensuring the safety of students and staff. While measures such as mask-wearing and social distancing have been implemented, this thesis focuses on the utilization of ventilation systems, specifically decentralized, SMART, and personal ventilation (PV) systems, and their associated designs. Understanding the effects of these ventilation systems is essential in developing effective strategies. The first step in this research is to analyse the literature and identify the research gaps that currently present. From this it was found that While methods for calculating infection risks have been established and recommendations for ventilation systems have been provided, the precise implementation of these recommendations remains unclear. As results, designers, engineers and policymakers are unsure what systems or designs in combination with what thresholds would provide an healthy and safe environment during the pandemic. Hence, the primary objective of the thesis research is to help educational facilities safely stay open by providing information on the impact of ventilation systems, their designs in conjunction with the different thresholds. Consequently, a central research question has been formulated, supported by four sub-questions. The main question is then as follows:

Main question:
How can smart, personal or decentralised ventilation improve the ventilation system design to make it more COVID-19-proof while not negatively impacting the comfort of the occupants in an educational environment and being both practical and cost-efficient?

To better understand and answer this question, answers are first sought on the sub questions. Starting with the first question and it states: *How can the ventilation system be adapted in response to Covid-19?* The adaptation of the ventilation system can come in various forms, encompassing adjustments in design and increases in ventilation rate. This thesis, through the examination of diverse ventilation system designs, has contributed valuable insights into the adaptability of ventilation systems in addressing the challenges posed by COVID-19. The research outcomes underscore the significance of adjusting ventilation rates and optimizing design considerations, specifically by considering the location and distance of supply and exhaust units. However, it was observed that within the current room layout, even a doubling of the ventilation rate yielded some improvements. It is important that these improvements early on in the pandemic can have a more significant impact. Furthermore, the findings revealed that in the case of the PV system design locating both the supply and exhaust units proved more effective in maintaining lower CO2 concentrations even as low as 660 PPM, but caused discomfort due to the ventilation rate. Therefore, when contemplating the adaptation of ventilation systems in response to the COVID-19 virus, consideration must be given to the ventilation rate in conjunction with the proximity and positioning in relation to occupants.

The second sub question relates to how large the impact of the ventilation systems have on the comfort of the people: *How does the comfort of the occupants get impacted by the use of the ventilation system to reduce the spread of COVID-19?* Through the evaluation of the various ventilation system designs, this thesis has examined their impact on occupant comfort. The research findings shed light on the primary factor contributing to discomfort is closely tied to the positioning of the air supply and the corresponding ventilation rate. Certain designs, such as the decentralised ventilation system, lead to discomfort due to the inherent nature of the system, where a single large air flow is supplied. On the other hand, the SMART system, with its proposed design can cause discomfort due to the overhead positioning of the air supply. Additionally, the personal ventilation system if it is appropriately implemented, may enhance comfort for individuals in close proximity to the system. However, in PV design 1 it became that due to it close proximity to the person and the design, the supplied air came in the form a jet-like flow, even if the amount of the ventilation rate was the minimal 8,5 l/s as required by the Bouwbesluit. Thus, this underscores the significance of striking a balance between comfort and effectiveness, as exemplified by the designs.

The third sub-question is: *What are the practical considerations for designing buildings with smart personal or decentralized ventilation systems?*
This thesis has provided practical considerations for designing buildings with decentralised, SMART, and personal ventilation systems. The decentralised system, besides being ineffective, suffers from size limitations, making it impractical for installation due to its dimensions of 2.2m x 1.4m x 0.7m. The SMART system requires sensor installation, while the personal ventilation system involves extensive ductwork.

Lastly the final sub question: *What are some of the key points to account for when trying to design a ventilation system as economically as possible?* The thesis has examined the economic aspects of ventilation system design, considering the cost implications of different approaches. The research provides cost estimates for the decentralised, SMART, and PV systems, which amount to €13,214, €7,740, and €6,085.76, respectively. While reducing costs for the decentralised system is challenging due to its inherent design, cost savings can be achieved in the SMART system by selecting more affordable sensors. Additionally, improved design can help minimize ductwork costs in the PV system.

To finalize the thesis answer the main research question of *'How can smart, personal or decentralised ventilation improve the ventilation system design to make it more COVID-19-proof while not negatively impacting the comfort of the occupants in an educational environment and being both practical and cost-efficient?'.* In conclusion, this thesis has conducted comprehensive research and analysis to evaluate the effectiveness of different ventilation systems in reducing the risk of infection and ensuring the comfort of the occupant. The results indicate that certain systems demonstrate more potential in mitigating infection risks and improving indoor conditions during airborne pandemics, specifically the SMART and PV systems when their design are optimally utilised. In contrast, the decentral ventilation unit proved to be less effective overall. Additionally, the findings underscore the importance of increasing ventilation rates and optimizing the location and distance of supply and exhaust units to minimize the spread of airborne viruses. Therefore, it can be concluded that while ventilation rate and strategic component placement are crucial in ventilation system design, a nuanced approach is necessary to strike a balance between reducing infection risks, meeting comfort requirements, and considering practical and economic factors.

8. Reflection

Throughout the process of research and conducting experiments, I have encountered several challenges and reflections that have provided valuable lessons for future endeavours. One significant aspect that proved to be a source of headaches was the planning phase. Many tasks took longer than anticipated or became unavailable during certain periods. In hindsight, it would have been wise to prioritize planning earlier and allocate sufficient time, perhaps even starting the process three weeks in advance than originally planned. This would have allowed for smoother progress and mitigated unexpected delays.

Another important lesson learned was the need to balance ambition with practicality, particularly when it comes to acquiring products or implementing specific methodologies. I experienced a bout of tunnel vision while attempting to make measurements for the decentral ventilation unit. However, it eventually became evident that the required services and resources for its operation were impractical or unavailable. This served as a valuable reminder to maintain a realistic approach and set achievable research goals, avoiding unnecessary complications and frustrations.

The data collection phase also presented its own challenges. In hindsight, I realized that the process took longer than anticipated due to the constant addition of new sources, information and feedback from the mentors. While incorporating new sources is valuable, it is essential to strike a balance and avoid getting caught in a never-ending cycle of adding and analysing data. A more focused and efficient approach to data collection would have helped streamline the research process and ensure timely completion.

Similarly, simulations proved to be an iterative process that required continuous adjustments. With each simulation result, small faults were identified, prompting attempts to rectify them. However, this process of refinement and fine-tuning became an ongoing cycle. For example, even a minor change in the relaxation within CHAM UK Phoenics would impact other parameters, leading to further adjustments. Recognizing the need to strike a balance between achieving precision and progressing with the research became crucial in managing the simulation phase effectively.

In reflection, this research process has provided invaluable insights into the importance of early planning, maintaining a realistic approach, efficient data collection, and managing iterative processes such as simulations. These lessons will undoubtedly inform future research, ensuring smoother progress, timely completion, and a more focused approach to achieving research goals.

In terms of what the future research could be, if there had more space and service available to accommodate the ventilation systems and more to apply them, then a more accurate and deep research could have performed into the different parameters such as distance, location and amount of ventilation openings and exhausts.

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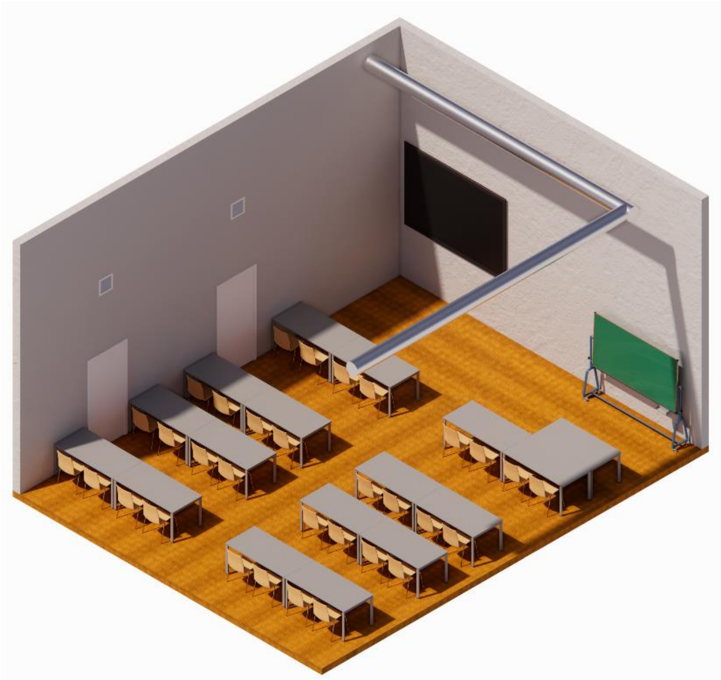
Appendix A – Research standard classroom

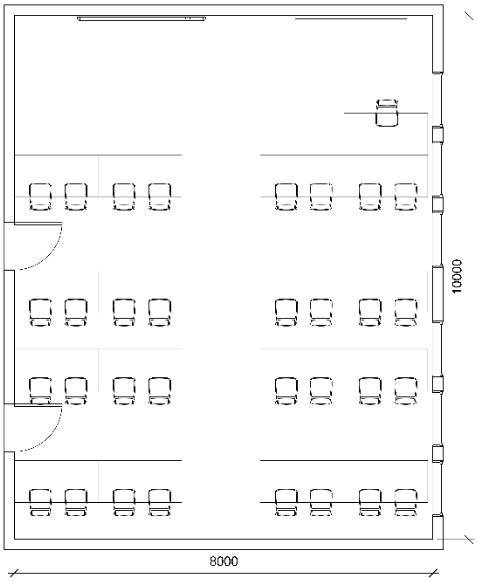
The research conducted in this thesis addresses the relationship between learning and the physical environment, drawing on the key assumptions summarized by Carol Weinstein (1981). These assumptions emphasize that the physical environment can directly impact learning and symbolically represent care for student progress. Additionally, the effects of the physical setting on learning depend on the social and instructional context, and there is no one-size-fits-all approach to creating the best learning setting. Maximizing learning requires careful consideration of the physical setting alongside other aspects of the learning situation.

Various characteristics and properties of teaching spaces including capacity, available facilities, shape, furniture, light, use of colour, temperature, and sound, contribute to their suitability for education (Lei, 2010). The MIT's School of Architecture and Planning emphasizes the importance of meeting basic human needs and creating a conducive learning environment (Syllabus Media Group, 2003). Proper air ventilation, including regulating CO2 concentration, is also crucial in classrooms (de Gids, Jacobs, de Jong, & Phaff, 2012). The Scottish Funding Council (SFC) conducted extensive research on learning spaces in further and higher education, categorizing them into seven types: group teaching/learning spaces, simulated environments, immersive environments, peer-to-peer and social learning spaces, learning clusters, individual learning spaces, and external spaces (Scottish Funding Council, 2006). Additionally the TU Delft Cookbook, created by Delft University of Technology, offers a practical approach to evaluating the suitability of teaching rooms. The Cookbook was developed through empirical research and stakeholder workshops, providing a basis for assessing teaching spaces at a technically oriented university (van der Zanden & van Loon, 2016). The Cookbook aims to generate an overview of classrooms and teaching formats, provide a checklist of requirements for designers, and establish guidelines for standardization and usability. Often used sizes for classrooms according to Boonstra, (2016) is around the 50 m2 for 28 to 30 students.

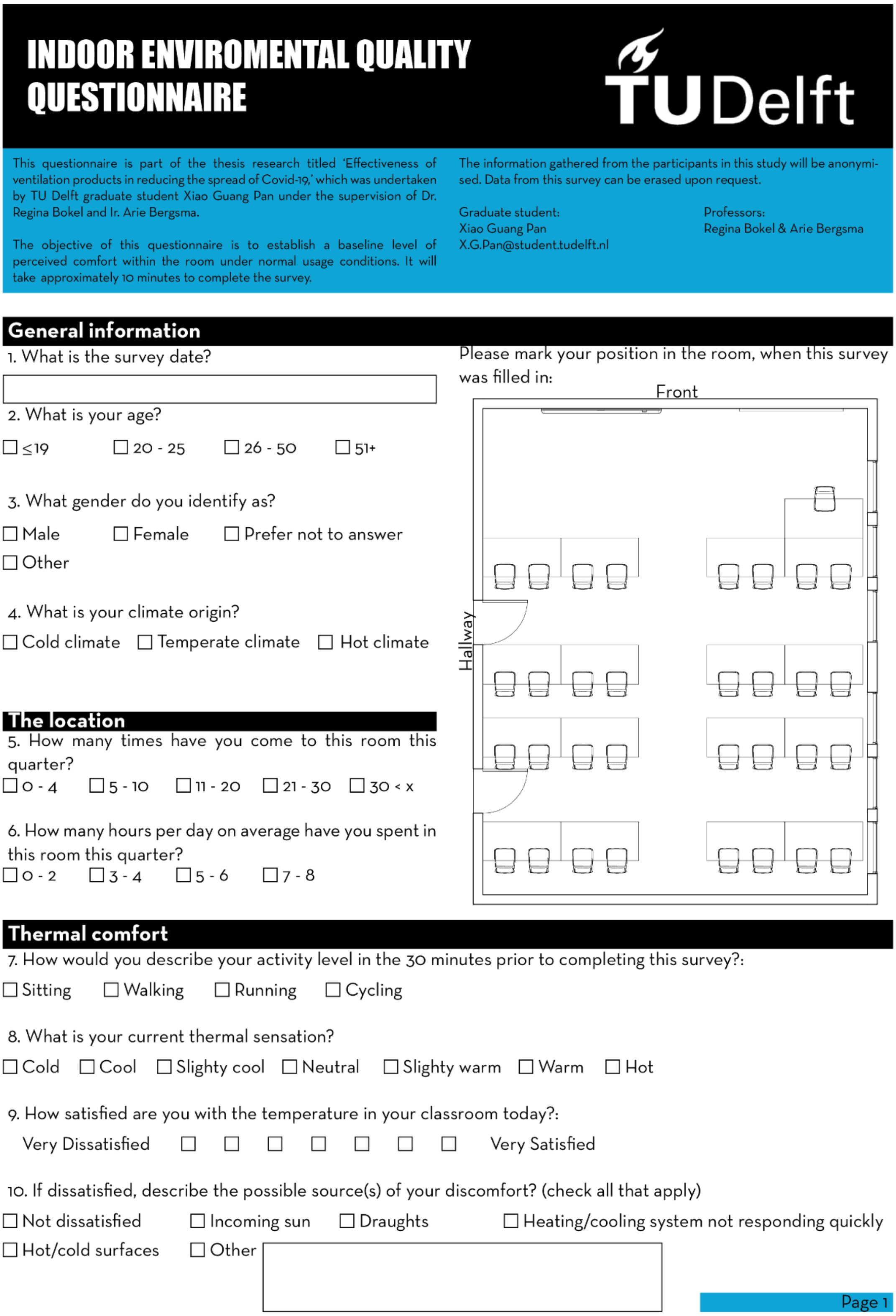
3D:



Floorplan:



Appendix B – Survey



INDOOR ENVIROMENTAL QUALITY QUESTIONNAIRE

TU Delft

This questionnaire is part of the thesis research titled 'Effectiveness of ventilation products in reducing the spread of Covid-19,' which was undertaken by TU Delft graduate student Xiao Guang Pan under the supervision of Dr. Regina Bokel and Ir. Arie Bergsma.

The objective of this questionnaire is to establish a baseline level of perceived comfort within the room under normal usage conditions. It will take approximately 10 minutes to complete the survey.

The information gathered from the participants in this study will be anonymised. Data from this survey can be erased upon request.

Graduate student:
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Professors:
Regina Bokel & Arie Bergsma

General information

1. What is the survey date?

2. What is your age?

☐ ≤19 ☐ 20 - 25 ☐ 26 - 50 ☐ 51+

3. What gender do you identify as?

☐ Male ☐ Female ☐ Prefer not to answer
☐ Other

4. What is your climate origin?

☐ Cold climate ☐ Temperate climate ☐ Hot climate

Please mark your position in the room, when this survey was filled in:

Front

Hallway

The location

5. How many times have you come to this room this quarter?
☐ 0 - 4 ☐ 5 - 10 ☐ 11 - 20 ☐ 21 - 30 ☐ 30 < x

6. How many hours per day on average have you spent in this room this quarter?
☐ 0 - 2 ☐ 3 - 4 ☐ 5 - 6 ☐ 7 - 8

Thermal comfort

7. How would you describe your activity level in the 30 minutes prior to completing this survey?:

☐ Sitting ☐ Walking ☐ Running ☐ Cycling

8. What is your current thermal sensation?

☐ Cold ☐ Cool ☐ Slighty cool ☐ Neutral ☐ Slighty warm ☐ Warm ☐ Hot

9. How satisfied are you with the temperature in your classroom today?:

Very Dissatisfied ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very Satisfied

10. If dissatisfied, describe the possible source(s) of your discomfort? (check all that apply)

☐ Not dissatisfied ☐ Incoming sun ☐ Draughts ☐ Heating/cooling system not responding quickly
☐ Hot/cold surfaces ☐ Other

Page 1

Continuation of thermal comfort

11. Do you select your clothing with this room's temperature in mind?

☐ Yes, more clothing layers ☐ Yes, less clothing layers ☐ No

12. Do you experience cold hands or cold feet?

☐ Cold hands ☐ Cold feet ☐ Both ☐ None

13. Would you prefer any changes to the thermal environment?

☐ Prefer cooler ☐ Keep it the same ☐ Prefer warmer

14. Any other comments on thermal comfort?

Indoor air quality

15. Upon entering the room did you experience any of these symptons?:

☐ No conditions ☐ Dry eyes ☐ Skin irritation ☐ Runny nose
☐ Sore/dry throat ☐ Headache
☐ Other

16. Do these symptons usually disappear upon leaving the room?:

☐ Yes ☐ No

17. What is your air quality sensation?:

☐ Very Stale ☐ Stale ☐ Slightly stale ☐ Neutral ☐ Fresh ☐ Slighty fresh ☐ Very fresh

18. How would you grade the odour of the air of this room?

☐ Very smelly ☐ Smelly ☐ Slightly smelly ☐ Neutral ☐ Slighty fragrant ☐ Fragrant ☐ Very fragrant

19. How humid or dry would you rate the room?

Dry ☐ ☐ ☐ ☐ ☐ ☐ ☐ Humid

20. How clean would you rate the room?

Dirty ☐ ☐ ☐ ☐ ☐ ☐ ☐ Clean

21. Overall, how satisfied are you with the indoor air quality of this room.

Very Dissatisfied ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very Satisfied

22. Any other comments on indoor air quality?

Acoustics

23. Can you understand the person that is speaking?

☐ Yes ☐ No ☐ No, other reasons

24. Do you experience any noise disturbance from the room's installations?

☐ Yes ☐ No ☐ No, other reasons

25. Do you experience any noise disturbance from outside?

☐ Yes ☐ No ☐ No, other reasons

26. Overall, how satisfied are you with the acoustics of this room.

Very Dissatisfied ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very Satisfied

27. Any other comments on acoustics?

If you have any comments on this questionnaire, please add them below: