Application of Ventilation Effectiveness for the Ventilation Design in Dutch Classrooms to Enhance Air Quality

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Investigating the need for Multi-Zone Demand Control

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Application of Ventilation Effectiveness for the Ventilation Design in Dutch Classrooms to Enhance Air Quality

Investigating the need for Multi-Zone Demand Control

By

Ayda Golahmadi

A thesis submitted in partial fulfillment of the requirements for the degree of
Engineering Doctorate (EngD)
The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct

Dr.ir. Marcel G.L.C. Loomans, university supervisor

Dr.ir. Rick. P. Kramer, university supervisor

ir. Paul Noom, company supervisor

Eindhoven, the Netherlands

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This thesis has been developed in collaboration with

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Executive Summary

Poor indoor air quality in schools can impair students' cognitive abilities. The Dutch government has taken several steps to combat this issue, including establishing the LCVS team (Landelijk Coördinatieteam Ventilatie in Scholen), allocating funding through the SUVIS (Specifieke uitkering ventilatie in scholen) program, and equipping schools with low-cost CO_2 meters. The ECoS-IAQ project is a part of that program, which aims to improve indoor air quality (IAQ) in schools by proposing new strategies for improving performance of ventilation systems in Dutch schools.

This study explores the concept of ventilation effectiveness as a strategy to improve IAQ in classrooms. It demonstrates the potential of improving ventilation effectiveness rather than merely increasing airflow rates to meet indoor air quality needs.

Taking the concept of ventilation effectiveness to define relevant performance indicators for the assessment of the effectiveness, the research compares two major room ventilation strategies that can be applied to address the IAQ in classrooms, displacement, and mixing ventilation. Computational Fluid Dynamics (CFD) simulation is used to analyse these strategies, based on a selection of the placement of supply and exhaust in the classroom.

The findings reveal that displacement ventilation systems create a more uniform air distribution horizontally, at head level, reducing the need for a multi-zone approach. However, the mixing ventilation systems showed a clear division of the classroom into two main zones. One zone was located near the ventilation units, and the other was on the opposite side of the room. The zone near the ventilation units had a longer mean age of the air, indicating a less efficient circulation of fresh air compared to the displacement ventilation systems. The outcomes are sensitive to the supply conditions in the case of applying a mixing ventilation solution. It emphasizes the importance of considering a multi-zone concept when designing mixing ventilation systems, avoiding the design of single supplies to achieve a mixing situation.

The research underscores the impact of external temperatures on the age of air within the room for the displacement concept, especially in areas close to windows. This is particularly crucial in areas near cold surfaces, such as windows in the winter.

Apart from the ventilation effectiveness, thermal comfort needs to be achieved, in this case mainly focused on the draught rate as this can significantly affect the comfort and well-being of students seated in areas where draught or large temperature gradients result from the ventilation concept applied.

The research also investigates the concept of multizone demand control based on air quality. For mixing ventilation, it suggests that, through the distribution of supplies, different ventilation rates could be applied in the identified zones. This approach could enhance indoor air quality and potentially reduce energy consumption.

However, the study has limitations, as only an extremely limited number of cases could be investigated. Furthermore, the modelling requires several assumptions and simplifications that depart from reality. These notions have to be taken into account when analysing the outcomes and design guidance, however, can be extended by analysing more cases, and parameters within the case, through the method as applied.

The findings of this thesis contribute to the ECoS-IAQ project, which aims to arrive at effective solutions to address the complex IAQ problem in Dutch schools and provide a design guidance for ventilation engineers and designers.

Chapter 1: Introduction

1.1 General introduction

Indoor air quality (IAQ) is a critical factor that has a significant impact on the health and academic performance of students in schools. Due to the fact that students spend a significant portion of their time in school buildings, the quality of indoor air becomes crucial for their well-being. Poor IAQ can lead to numerous negative health impacts, including headaches, nausea, dizziness, and respiratory problems. Over time, these short-term impacts can evolve into severe long-term effects, such as chronic respiratory disorders, allergies, and asthma [1]–[3].

Research has proven a correlation between poor IAQ and a decrease in students' cognitive abilities, particularly affecting their attention span and short-term memory retention [4]. Consequently, improving IAQ has become a critical aspect of improving students' academic performance, and therefore is a concern that has caught the attention of parents and relevant authorities. Numerous studies have highlighted that an improvement in ventilation rates can significantly boost students test scores [5].

One of the primary causes of poor IAQ in schools is inadequate ventilation [6]; therefore, in recent years, ventilation systems in schools have become a significant point-of-attention in many countries, including the Netherlands. Despite being recognized as early as 1987 [6], the issue remains unresolved. Current findings from 3455 schools reveal that at least 22.5% of Dutch schools do not meet recommended ventilation standards [6].

The Dutch government has undertaken multiple measures to address this issue [7]–[9]. A 2016 survey by the Algemene Rekenkamer found that 12.5% of schools were in need of immediate renovation or replacement due to having inadequate ventilation. In addition, almost 50% of the schools do not fully comply with the Frisse Scholen Class C guidelines [10]. Moreover, many schools still rely on natural air supply systems that have significant drawbacks in control in terms of comfort, energy consumption, and air quality [11]. To address this problem, the Dutch government has implemented several measures, including the incorporation of the Landelijk Coördinatieteam Ventilatie in Scholen (LCVS) team [12], funding through the Specifieke uitkering ventilatie in scholen (SUVIS) program for school ventilation improvement [13], distribution of low-cost CO_2 meters in every school [6], [14]. In an effort to improve the air quality in schools, the Dutch government has introduced the more stringent Frisse Scholen 2021 guidelines for school ventilation design [10]. Based on the CO_2 concentration, and the ventilation flow rate that can be derived from that information, classrooms are divided into three classes: A, B, and C [15]. In class A, the air supply should be 12 dm^3/s (43.2 $m^3/hour$) per person. The maximum CO_2 concentration allowed in the breathing zone during usage time is 800 ppm. Class B allows for a slightly lower air supply of 8.5 dm^3/s (30.6 $m^3/hour$) per person and a higher maximum CO_2 concentration of 950 ppm in the breathing zone. Class C has the most relaxed requirements, with a minimum air supply of 6 dm^3/s (21.6 $m^3/hour$) per person and a maximum CO_2 concentration of 1200 ppm in the breathing zone [15]. These different classes provide schools with a clear guideline to meet the air quality needs of their specific situation [15].

In line with the above, the Dutch government introduced the ECoS-IAQ project. This project wants to arrive at effective solutions to address this complex IAQ problem. Essential stakeholders in the Dutch school ventilation market, including Kropman Installatietechniek, Lucas Onderwijs, Ned Air BV, Camfil, Building G100, and ISSO, have joined forces to collaborate closely. The main objectives of the ECoS-IAQ project addressed in the research addressed in this report include:

1. To investigate the concept of ventilation effectiveness as a strategy to improve IAQ in classrooms.
2. To demonstrate the potential of improving ventilation effectiveness rather than increasing airflow rates to meet indoor air quality needs.

3. comparing the performance of two common systems (mixing ventilation and displacement ventilation) in terms of air change efficiency, and air quality.

4. To assess the need and potential for a multi-zone demand control strategy in the classroom based on the investigated case studies.

Overall, the ECoS-IAQ project aims to improve the school ventilation systems in the Netherlands, leading to better indoor air quality, health, thermal comfort, and higher energy efficiency.

In this study, the following research questions are answered:

1. Why is ventilation effectiveness important in assessing classroom environments and how can its best indicators be determined?
2. How can Computational Fluid Dynamics (CFD) be used to assess ventilation effectiveness in classrooms?
3. What are the differences in performance between mixing ventilation and displacement ventilation systems in terms of ventilation effectiveness in Dutch schools?
4. What is the need and potential for a multi-zone demand control strategy in classrooms based on the investigated case studies, and how can this be implemented effectively to improve indoor air quality and reduce energy consumption?
5. How can the ECoS-IAQ project contribute to improving the school ventilation system?

1.2 Overview of the ECOS-IAQ project and stakeholder requirements

The ECOS-IAQ project is divided into two distinct phases, with eight work packages in total. Figure 1 displays the distribution of these work packages, with grey boxes indicating the work packages and relevant stakeholders involved in each one. Green boxes indicate the expected outcomes from each work package. This flow has been prepared in collaboration with Vinayak Krishnan and focuses mainly on WP3, WP4, and WP5. The tasks by Vinayak Krishan have been completed, and the results can be found in his PDEng report [6]. The details of the work-package distribution can be found in the original project proposal [16].

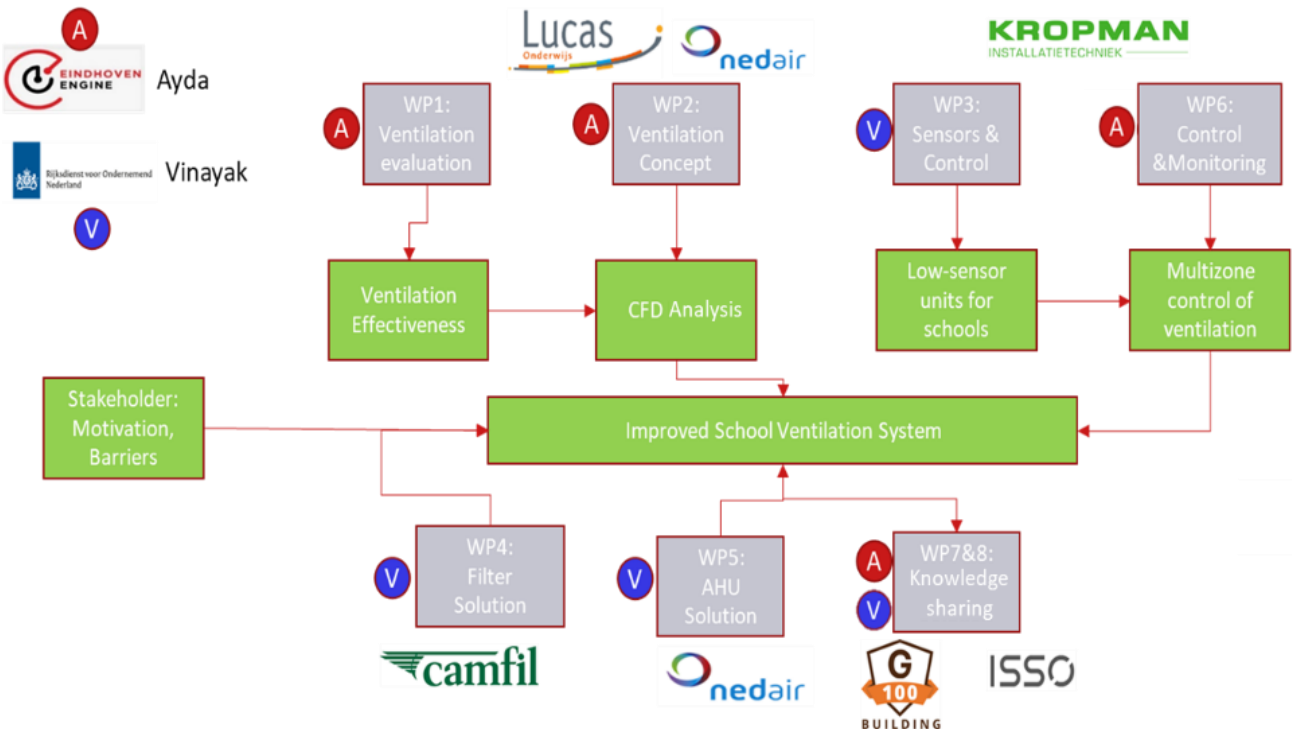


Figure 1: The ECoS-IAQ project work package distribution. The work packages are indicated in grey. Additionally, the relevant stakeholders closely involved in a work package are listed near it. The outcomes are highlighted in green. 'V' represents Vinayak Krishnan, and 'A' represents Ayda Golahmadi

The project was initiated, beginning with the field studies conducted by Vinayak Krishnan in collaboration with Lucas Onderwijs as a part of WP2. The studies included a large-scale quick assessment and a detailed study in one school, providing insights into IAQ and thermal comfort within Dutch classrooms. Design concepts for AHUs, focusing on filter concepts, were developed in collaboration with Ned Air BV and Camfil in WP4 and WP5. Low-cost IAQ sensors for school applications were tested in cooperation with other researchers and Kropman Installatietechniek in WP3.

Subsequently, my role in the ECOS-IAQ project entails undertaking the initial step of critically analysing and comprehending the definition, indicators, and methodologies pertaining to ventilation effectiveness, as part of Work Package 1 (WP).The purpose of Work Package 2 is to develop a CFD model that can assess different ventilation concepts (mixing and displacement ventilation) based on the indicators defined from WP1. The goal of this work package is to achieve and compare ventilation effectiveness based on the placement of the supply and exhaust in the classroom, regarding to Ned Air and Kropman's preferred ventilation systems, which are also among the most used systems in the Netherlands. The placement also results in two distinct room ventilation concepts, mixing and displacement ventilation. Work Package 6 (WP6) is designed to illustrate the impact of implementing multi-zone ventilation concepts and methodologies. One of the critical questions that should be addressed within this scope is the necessity for distinct zones within a classroom setting. The insights and understanding gained from this project, via the CFD analyses, will be shared with the public via WP7 and WP8, with the collaborative efforts of both ISSO and Building G100 contributing for the dissemination process.

Therefore, this part of the work of the ECOS-IAQ initiative is focused on understanding and improving the ventilation effectiveness of mechanical ventilation systems in schools. This approach prioritizes mechanical ventilation over natural ventilation methods. Selecting mechanical ventilation systems takes into consideration several factors, including the weather conditions in the Netherlands and the proven performance of mechanical systems [17], [18]. This also includes the potential energy efficiency when applying a balanced type of mechanical ventilation system. Further details regarding the selection process, as well as the challenges associated with both mechanical and natural ventilation systems, are provided in Appendix A for a more comprehensive understanding.

Moreover, one of the main objectives of the ECOS-IAQ project is to compare the ventilation performance of two prevalent mechanical ventilation solutions: mixing ventilation and displacement ventilation. All information and characteristics about the general features regarding both displacement and mixing ventilation are provided in Appendix A.

Identifying appropriate evaluation criteria is important before moving forward with a comparative analysis. Consequently, an important research question that must be answered to guide this study is: "How to assess the performance of ventilation, and which specific indicators are most effective in assessing the performance of ventilation systems?"

1.3 Reader guidance

This report is built up into four main chapters. Chapter 2 wants to answer the research question mentioned above (WP1). Chapter 3 will be the main chapter of this report, discussing the CFD modelling, presenting the results of the investigated cases, and a discussion of that (WP2) also and the issue of multizone control is discussed from the results obtained from Chapter 3 (WP6). Chapter 4 will describe the conclusions and answer the questions of this thesis. Chapter 5 will provide guidance on the best design use of the information that has come available from the CFD scenarios investigated.

Chapter 2: Performance indicators (WP1)

2.1 Overview of the ventilation effectiveness (WP1)

According to building regulations in the Netherlands, the efficiency of a ventilation system is primarily defined by one main factor: the air flow rate (air change rate) within a room. However, these metrics may not accurately reflect how well the air is distributed throughout the room.

For instance, the air change rate measures how much air circulates in a room, but it doesn't provide a thorough understanding of the air's movement or its even distribution across the room. Essentially, a room could have an adequate supply of ventilated air, but it's not clear whether this air is efficiently distributed and if it reaches the people in the room. It relies on the assumption that the air is (theoretically) perfectly mixed. In reality that cannot be achieved.

As a result, increasing the fresh air supply rate may not be a sufficient indicator regarding the air quality in the room [19], [20]. That is why ventilation effectiveness has been proposed in the literature as a better alternative. The concept of ventilation effectiveness, first introduced by Sandberg in 1981 [21], [22], has been a key consideration for ventilation system designers and manufacturers in recent years.

2.2 Ventilation Effectiveness Indicators

Researchers have considered several indicators to assess ventilation effectiveness [23]. Contaminant removal effectiveness (CRE) and air change effectiveness (ACE) are the most commonly utilized measures for measuring ventilation efficacy at room level [23]. Local indicators can be derived from these room-based indicators. Table 1 illustrates a summary of ventilation effectiveness indices, which are divided into two groups. Group A can be used when little or no information on contaminant sources is available. In contrast, the contaminant removal indices in Group B can be utilized when specifically, location information on contaminant sources is available [20].

Table 1: Indices related to ventilation effectiveness [20]

Ventilation Effectiveness includes	
Group A Indices representing the ability of a system to Exchange the air in the room	**Group B** Indices representing the ability of a system to remove air-borne contaminants
• Air change efficiency (ACE), ε_a . • Local air change index (LACI), ε_p^a	• Contaminant removal effectiveness (CRE), ε_c • Local air quality index (LAQI), ε_c^p

2.3 Air change efficiency and local air change index group [A] and the age of air concept

The air change efficiency can be used to quantify a system's ability to replace the air in a room. The air change efficiency reflects how rapidly the air in a room is replaced in comparison to the theoretically fastest rate with the same ventilation airflow rate [20].

The concept of air change efficiency, denoted as ε^a, is characterized as the proportion between the shortest possible air change time for a complete air exchange in the room, termed as the nominal time constant τ_n, and the actual air change time taken for this process, represented as τ_r.

Alternatively, assuming the air change efficiency for the most optimal (piston) flow situation is 100%, and a perfect mixing flow situation is 50%, it can be represented as the ratio of the lowest possible mean age of the air in the room $\tau_n/2$ to the actual air change time τ_r or mean age of the air present in the room, denoted as τ [20].

$$Air\ Change\ efficiency = \frac{shortest\ possible\ air\ change\ time}{actual\ air\ change\ time}$$

$$\varepsilon^{a} = \frac{\tau_n}{\tau_r}.100 = \frac{\tau_n}{2[\tau]}.100\ [\%] \qquad \tau_n = V/q_v$$

The nominal time constant in this definition can be calculated by dividing the room volume V, and the ventilation flow rate q_v [20]. The shortest possible air change time is obtained with a piston flow. Examples of other generic flow patterns that can occur in a room are also included in Figure 2: ideal piston flow, displacement flow, fully mixed flow or short-circuit flow.

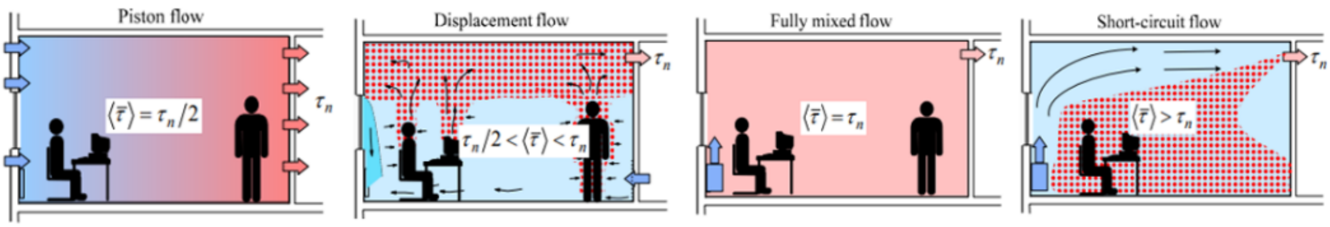


Figure 2: Illustration of the different flow patterns possible in a ventilated room [24]

Table 2 shows the flow patterns and corresponding ACEs for each pattern.

Table 2: Evaluation of air change efficiency across distinctive flow patterns [20]

Flow Pattern	Air change efficiency ε_a
Idea piston flow	100%
Displacement flow	50%≤ ε_a ≤100%
Fully Mixed flow	50%
Short-circuit flow	≤ 50%

2.4 The Age of air concept

Sandberg (1981) introduced the age of air concept [21], which is a useful method to assess ventilation effectiveness. The concept of air age describes the amount of time air has been present in a certain zone and room. It is an important parameter for assessing the performance of ventilation systems in terms of a system's capacity to distribute fresh air in indoor environments. The age of air can be measured in two ways: the local mean age of air and the room average age of air. When there is perfect piston flow across a room, the room's average age of air is the lowest it can be (see Figure 2). The fact that the oldest air is present in the exhaust unit characterizes piston flow [4]. The local mean age of air (τ_p), measures the air quality at a given location. Theoretically, the local mean age of air in a fully mixed condition will be the same throughout the space. On the other hand, the local mean age of air will be low in a short-circuited zone and high in a stagnant zone if there is a shortcut from the supply device to the exhaust device. The local mean age of air in the exhaust is always equal to the nominal time constant (even in a short circuit flow) [20]. In conclusion, the air change efficiency is evaluated by using the age of air concept.

2.5 The local air change index

The local air change index, symbolized as ε_p^a, is an indicator that measures the ventilation conditions at a specific point P within the room. It serves as a means to analysis the variability of ventilation performance across different areas in the room. This index can vary considerably based on the position in the room. For example, it may be high near the supply but low in areas where ventilation is insufficient. It is defined by the ratio of the nominal time constant (the time it takes for an air volume equivalent to the room volume to be supplied to the room) to the local mean age of the air at a specific point [20].

The Equation below represents the local air change index. Under ideal conditions of complete mixing, the local mean age of air is uniform throughout the room, equating to the nominal time constant. This situation results in a local air change index of 100% [20].

$$\varepsilon_p^a = \frac{\tau_n}{\tau_p} \cdot 100\ [\%]$$

2.6 Contaminant removal effectiveness and local air quality index

The contaminant removal effectiveness (CRE), which is represented by ε^c, indicates how quickly air-borne contaminants are eliminated from the room. At steady state, CRE is defined as the ratio of the concentration of contaminant in the exhaust air, c_e, and the mean concentration in the room, $\langle c \rangle$ [20], [23], [24].

$$CRE = \frac{Concentration\ in\ the\ exhaust}{mean\ concentration\ in\ the\ room}$$

$$\varepsilon^c = \frac{c_e}{\langle c \rangle}$$

When the room is perfectly mixed, the concentration in the exhaust is the same as in the entire room, giving CRE a value of 100%. Depending on the location of the contamination, CRE may vary from very small to very large values [20]. It is important to note, that the CRE is not only a function of the air distribution in the room, but also of the source location (see Figure 3).

2.7 Local air quality index

The local air quality index, denoted as ε_c^p , is an indicator of the concentration of a contaminant at a specific location within a room as compared to the contaminant concentration in the exhaust. As a result, it is calculated as the ratio of the steady-state concentration of the contaminant at the exhaust air C_e divided by the steady-state concentration of the same contaminant C_p at a given point P within the room.

This index can have any positive value and is impacted by the room's airflow pattern as well as the pollutant source's location. If the airflow directly connects the contamination source and the air exhaust, the local contaminant concentration, C_p, in a large part of the room will be low, and ε_c^p will exceed 1 [20].

$$\varepsilon_c^p = \frac{C_e}{C_p}$$

Figure 3 shows three different contaminant locations in the room and their effect on ventilation effectiveness in the space. As the 1st and 2nd example in the figure show, the contaminant removal effectiveness can differ for the same ventilation design. It is source location dependent.

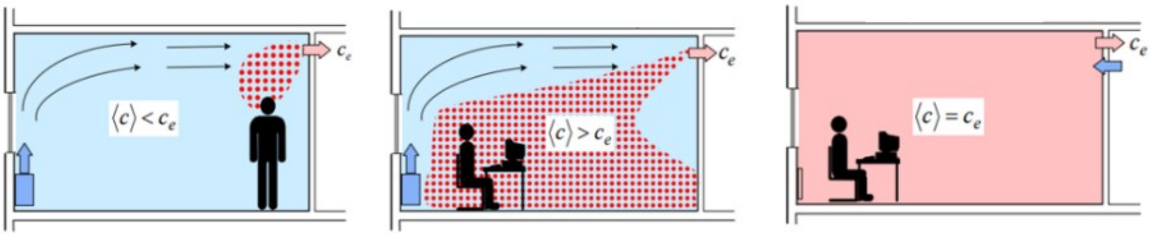


Figure 3: Steady state mean concentration in the room and steady state concentration in the exhaust in three different situations [20]

2.8 Assessment of local thermal discomfort indicators

The necessity for higher ventilation rates in school buildings can contribute to vertical temperature differences and may potentially lead to draught problems. The risk of draught is a significant factor in thermal comfort. According to the Frisse Scholen standard, the draught risk should not exceed 20% to meet the Class B thermal discomfort design criteria. For Class C, it should remain below 30%, and for Class A, it should not surpass 10%. The predetermined thresholds for these parameters, such as those outlined in the Frisse Scholen standard [15], are referred to in this context. The percentages have been simplified to prescribed maximum air velocities for summer and winter conditions assuming an air temperature and turbulence intensity present. The percentage of people dissatisfied due to draught, can be calculated based on the air temperature, air velocity, and turbulency intensity [25].

$$DR = (34 - Ta)\ (va - 0.05)/0.62(0.37 \times va \times Tu + 3.14)$$

When va < 0.05 m/s: va = 0.05 m/s should be used

Ta = local air temperature [°C].

va = local average air speed [m/s].

Tu = local turbulence intensity [%]; turbulence intensity is defined as the standard deviation of a fluctuating air velocity, divided by the mean of the velocity (times 100%).

2.9 Discussion

In the ECoS-IAQ project, the decision was made to utilize Group A indicators, specifically the air change efficiency and the local air change index. This choice was made because these indicators align more closely with the research objectives of the project.

Firstly, these indicators are in line with the primary aim of the project, which is to investigate ventilation effectiveness as a strategy to improve indoor air quality (IAQ) in classrooms. By focusing on how efficiently air is replaced in a room and the variability of this efficiency across different locations within the room, Group A indicators provide a comprehensive measure of ventilation effectiveness. For example, air change efficiency measures how quickly the air in a room is replaced compared to the theoretically fastest rate with the same ventilation airflow rate. It provides valuable insights into the effectiveness of air exchange within a classroom and can help identify areas where the performance of the ventilation system could be improved. As the source variability can be large in a classroom, this indicator provides a better overview of the overall performance of the ventilation as compared to the contaminant removal effectiveness, as this should be investigated for individual source locations and therefore is more difficult to comprehend.

In the ECoS-IAQ project, the focus is on air change efficiency as a crucial performance indicator. The project's primary goal is to discover the most advantageous strategies to significantly enhance indoor air quality (IAQ) in classroom environments. This approach is in direct alignment with the initial two objectives of the project.

Secondly, the choice of Group A indicators is informed by their compatibility with computational fluid dynamics (CFD) simulations. As the third research question suggests, the project use of CFD as a tool to investigate ventilation effectiveness for different ventilation concepts. Group A indicators, particularly the local air change index, can be effectively calculated using CFD, providing detailed visualizations of how the value of this index is distributed throughout the room.

Thirdly, detailed contaminant data for the classrooms is lacking, and Group A indicators can be effectively utilized even when minimal or no information about contaminant sources is available. On the other hand, Group B indicators, which focus on the removal of airborne contaminants, require complete information about contaminant sources and their location. In the context of the ECoS-IAQ project, this information may not always be readily available, making Group B indicators less suitable for the assessment of ventilation effectiveness [20].

Additionally, Group A indicators are well-suited to the development of a multi-zone demand control strategy, a key consideration of the ECoS-IAQ project. By offering localized information on ventilation effectiveness, this indicator can help identify zones within a classroom that may require more or less ventilation, thereby contributing to the development of a more efficient demand control strategy. In summary, using Group A indicators along with CFD simulations offers a feasible and practical approach for assessing and enhancing ventilation effectiveness in Dutch schools, fulfilling the ECoS-IAQ project's objectives.

Chapter 3: CFD analysis of classroom ventilation concepts

This section of the report is a comprehensive explanation of the simulation of the airflow in a classroom to assess ventilation effectiveness. This simulation is performed with the use of the computational fluid dynamics (CFD) technique and is a representative representation of a typical Dutch classroom with the main relevant details incorporated. Important aspects of the classroom environment are taken into consideration in this detailed approach, as well as all steps in the creation of the model in CFD as well as the results of the ventilation performance of the different ventilation systems analysed for the classroom.

3.1 General methodology

In the following part of this report, a six-phase method is employed to simulate classroom ventilation effectiveness. The initial phase involves setting up a computational fluid dynamics (CFD) geometry that represents a typical Dutch classroom. Next, different mesh types are generated to ensure the accuracy of the results. The third phase looks into boundary conditions such as temperature at the supply, air velocities, and heat generation. In the fourth phase, the next step is to validate the simulation results. The paper from Awbi et al. [34], which describes a measurement study for a classroom, is used to validate the velocity, temperature, and age of the air of the developed and simulated CFD model [34]. Comparison is done at the identified monitor points where measurement data is available. Lastly, the results of the reference case are generated by the model, and these results are the basis for the ventilation scenarios that are investigated and detailed further in section 3.7.

Figure 4 presents an overview of the general methodology that is applied to the analyses of the classroom ventilation concepts.

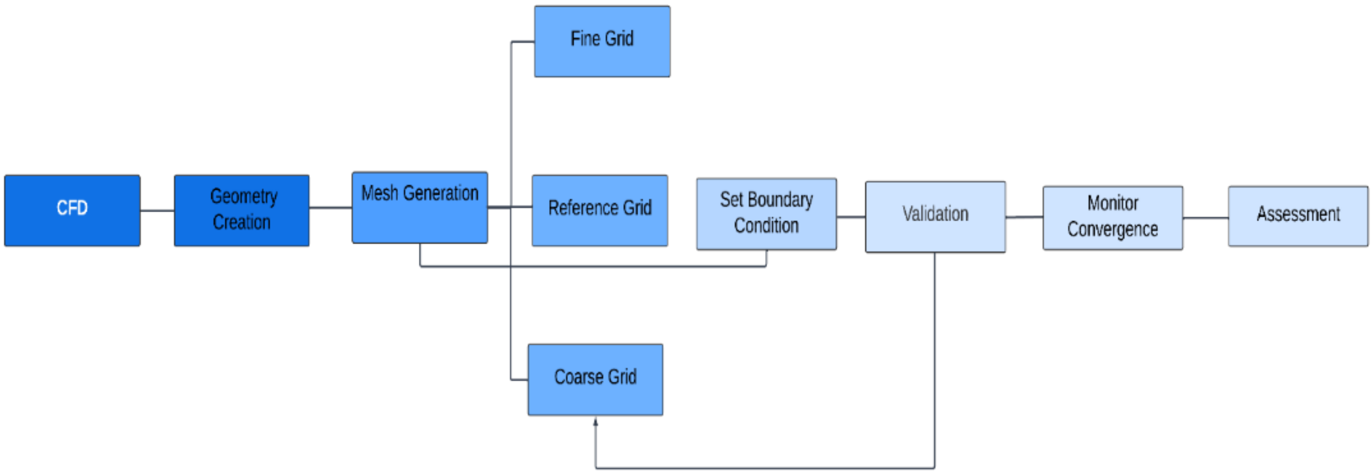


Figure 4: The six-phase method applied to analyses the computational fluid dynamics (CFD) model

3.1.2 Geometry detail

The classroom modelled in has an area of 60 square meters and follows the information as provided for by the paper of Awbi [26], [27]. The details of the geometry of the classroom are illustrated in Figure 5. To simulate a full classroom, the model includes 25-person simulators, representing 24 students and one teacher. In the simulation, the presence of students is represented by 12 boxes (pairs of two students), each with a length of 1m wide, a depth of 0.3 m, and a height of 1.2 m. Additionally, a teacher is represented by half the size of a box [27].

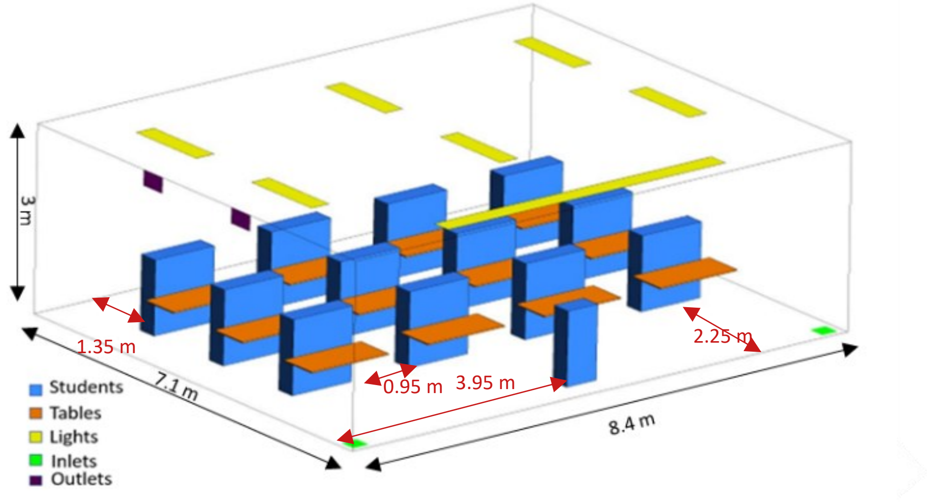


Figure 5: Schematic representation of the computational fluid dynamics (CFD) model for the classroom environment. Each box in the model symbolizes a pair of students

As part of the simulation for validation, a window is assumed in the façade of the classroom on the right-hand side of the teacher. The ventilation system for the classroom consists of two supplies located in the corners of the floor of the classroom at the side of the teacher (coloured in green), with a total surface area of 0.125 m^2 (each 0.0625 m^2), and two exhausts at the side wall left of the teacher, near the ceiling, with a surface area of 0.1 m^2 each. The total surface area is 0.2 m^2. These supplies and exhausts are used to provide ventilation in the classroom [27].

3.1.3 Boundary condition details

The simulation study aimed to analysis the airflow distribution within a classroom environment. To achieve this, a constant supply airflow rate of 10 dm^3/s per person was applied [27].

As further information is lacking, the supply boundary condition was defined by a uniform velocity (u) in meters per second (m/s), which was calculated using experimental data through the Equation below:

$$u = \frac{Q}{A_i}$$

In this equation, Q represents the supply flow rate (m^3/s),and A_i is the supply opening area (m^2). The supply velocity is assumed to be 2 m/s, and the temperature is 18°C based on the reference Awbi case [27]. Turbulence intensity at the supply boundary condition is set to 5%. It is important to note that this value may vary in different cases, and the specific properties of each case can be found in Table 3. A static pressure of zero was specified at the exhaust.

The total heat load is composed of 2375 W generated by 25 students and an additional 525 W from lighting, totaling 2900 W. As radiant heat transfer was not included in the simulations, the heat load for a seated person is reduced based on information from literature on the convective and radiative parts of the heat load. According to numerical studies on heat transfer around a seated person, 45% of the total heat flux is allocated to convection and 55% to radiation [28], [29]. As a result, the convective heat generated by students is set to 27.9 W/m^2 and for the teacher to 23.75 $\frac{W}{m^2}$, and for lighting, 145.8 W/m^2 is assumed [27].

In accordance with the guidelines provided by Awbi [27], the simulation initially assumed that the walls of the room were adiabatic, which means they do not exchange heat with the indoor environment. However, after obtaining the results, two distinct scenarios are considered, representing summer and winter conditions. To simulate these conditions, the window temperatures are set at -2°C for the winter scenario and +23°C for the summer scenario.

To assess the simulation results, monitoring points are placed in the occupied zone to determine the simulated air temperature, velocity, and the local mean age of the air. The position of the monitoring points are shown in Figure 6. At these monitoring points, temperatures, velocities, local mean age, and local air quality index are recorded at heights of 0.1 m and 1.2 m (the height of a student's breathing zone) above the floor.

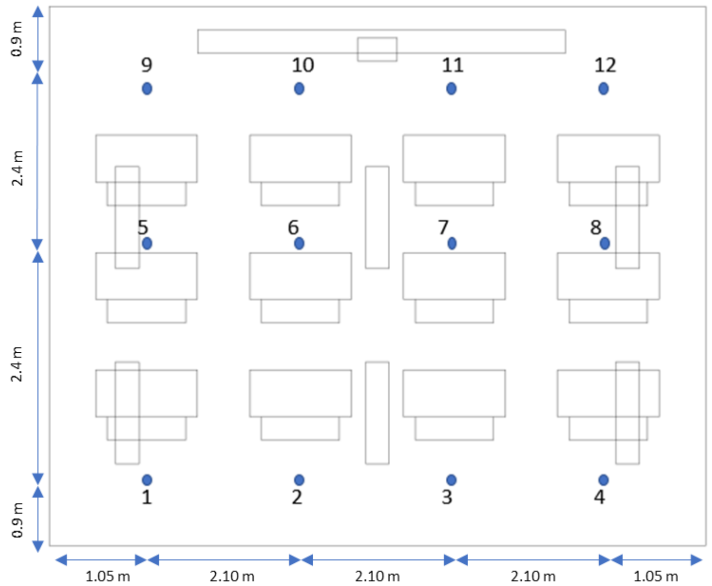


Figure 6: Plan layout of the classroom highlighting air supply positions. this plane view presents the classroom layout with marked air supply positions. all dimensions are provided in meters for accurate interpretation and analysis

Table 3 provides a summary of the properties related to ventilation system supplies and exhausts. In addition, Table 3 also provides detailed information about the physical dimensions of the student and teacher simulators used in the model. This contributes to a more precise understanding of the classroom environment as it is represented in the simulation.

Furthermore, this table includes information about heat generation in the classroom. This covers not only the heat produced by the student and teacher simulators but also the heat emanating from the classroom's lighting.

Table 3: Comprehensive overview of boundary conditions

	Students	**Exhaust**	**Teacher**	**Supply Reference Case**	**Supply of Displacement ventilation**	**Supply of Mixing ventilation**	**Lights**	**Classroom**
Dimensions	H:1.2(m) L:1(m) W:0.3(m)	L:0.4(m) W:0.25(m)	H:1.2(m) L:0.5(m) W:0.3(m)	L:0.25(m) W:0.25(m)	-	-	L:1.3(m) W:0.3(m)	H:3(m) L:8.4(m) W:7.1(m)
Heat load	27.9 W/m^2	-	23.75W/m^2	-	-	-	145 W/m^2	-
Velocity	-	-	-	2 m/s	0.4 m/s	2.3 m/s	-	-
Temperaturere	-	-	-	18 °C	18°C	20 °C	-	-

3.1.4 Solver and turbulence model

A steady-state solver is utilized in CFX to calculate the airflow in a classroom. The standard k-ε turbulence model is employed to simulate the turbulence of airflow. In the k-ε model, there are two additional equations introduced to model turbulence: k for turbulent kinetic energy and ε for turbulent dissipation rate. They describe the production, transport, and dissipation of turbulent kinetic energy and the rate of dissipation of that energy, both contributing to the turbulent viscosity. The standard k-ε turbulence model has been shown to be a robust model to model turbulent air flows. It can handle many flow conditions, such as those that occur in enclosed spaces like classrooms [30]. It can predict mean velocity and turbulent kinetic energy with accuracy. Variations in the turbulent modelling are available, but their performance is case dependent. The choice was made to use the robust standard k-ε model in this work and consider it an appropriate choice for simulating classroom airflow [30]. The transport equation is utilized to calculate the age of air. The mean age of air is not automatically included as a predefined variable in Ansys CFX. In the pre-processing stage, it can be defined as an additional variable. Details about calculating the local mean age in Ansys CFX are included in Appendix D.

Monitor points were placed in the classroom to monitor velocity, age of air, and temperature and ascertain that a converged solution was arrived at. The equations were solved using a second-order scheme and a convergence criterion with respect to the residuals in the order of 10^{-8}.

3.2 Grid sensitivity analysis

To further improve the accuracy of the simulation, a Grid Convergence Index (GCI) calculation is performed on the surface cells.

In order to perform a grid-sensitivity analysis, two additional grids are generated: a fine grid, a reference grid, and a coarse grid. The results are refined with an overall linear factor of √2. The fine grid has 15,147,271 cells, the reference grid has 10,819,479.3 cells, and the coarse grid has 7,728,199.49 cells. The GCI method developed by Roache [31], [32] was used to determine the optimal grid size.

Cells around heat sources such as students, teachers, lighting, and areas with high (velocity) gradients like the supply and exhaust were refined to capture the details of the complex flow field that develops. Table 4 provides detailed information on the mesh conditions used in the simulation. The results of the grid-sensitivity analysis are applied to arrive at grid-independent outcomes. Figure 7 provides the shapes of the meshes.

Table 4: Detailed parameters of computational fluid dynamics (CFD) mesh conditions across scenarios for mixing and displacement ventilation techniques

Mesh type	Ventilation type	Boundary type	Cell size	Maximum layer	Number of cells
Fine mesh	ventilation Scenario (D1-D2) (M1-M2)	Walls/ceiling/floor Supply/exhaust students	0.01 0.005 0.005	10	15,147,271
Reference mesh	ventilation Scenario (D1-D2) (M1-M2)	Walls/ceiling/floor Supply/exhaust students	0.012 0.006 0.006	10	10,835,877

Coarse mesh	ventilation Scenario (D1-D2) (M1-M2)	Walls/ceiling/floor Supply/exhaust students	0.015 0.007 0.007	10	7,386,952

It is important to note that all these aspects have been considered and implemented in the case study referred to in Awbi's research. Figure 7 shows the different types of meshes generated.

(a) (b) (c)

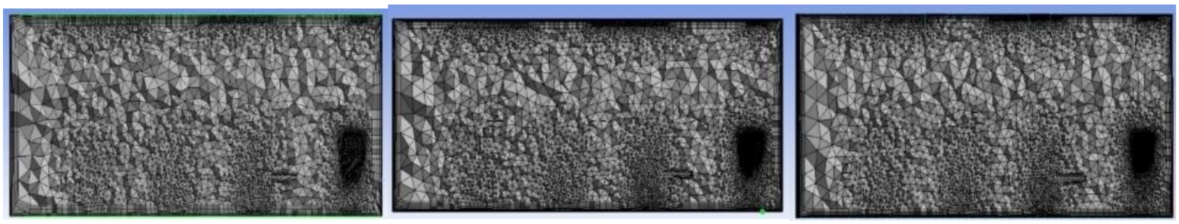


Figure 7: Computational grids for grid-sensitivity analysis: (a) coarse grid (7,386,952 cells), (b) reference grid (10,835,877 cells) and (c) fine grid (15,147,271 cells).

In Figure 8 a detailed analysis of temperature, age of air, and velocity is depicted at a height of 0.1 meters for twelve specific points. The illustration includes the utilization of the grid outcomes to display the data in an organized manner.

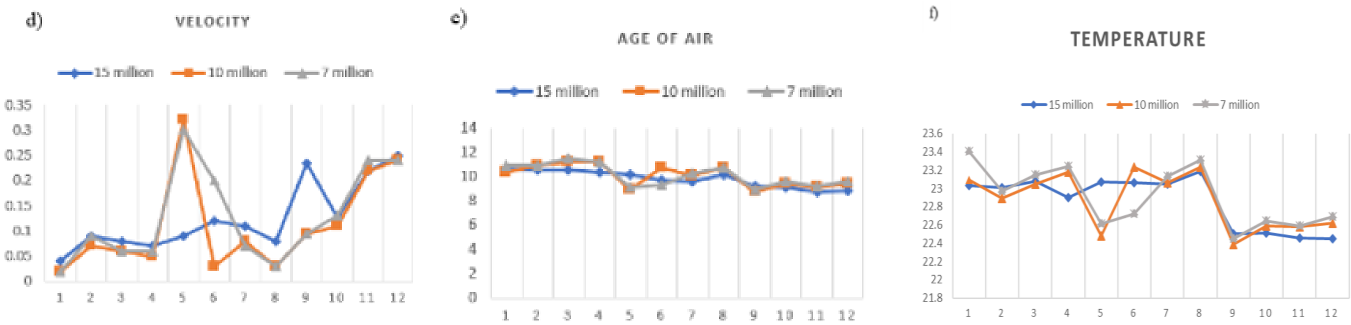


Figure 8: The influence of grid resolution on velocity, age of air (def), and temperature across the twelve monitoring points (as indicated in Figure 6), at a resolution of 0.1 meters [31],[32]

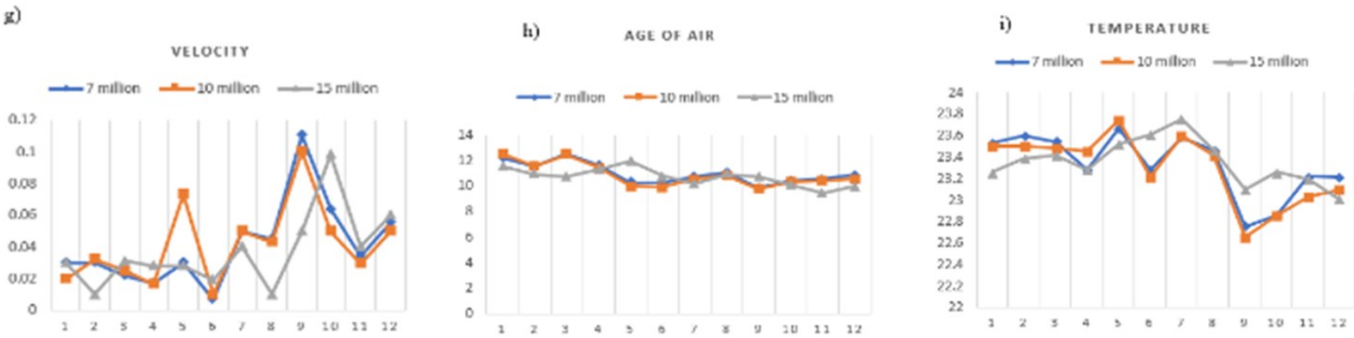


Figure 9: The influence of grid resolution on velocity, age of air (def), and temperature across twelve monitoring points (as indicated in Figure 6), at a resolution of 1.2 meters [31],[32]

The data shown in Figures 8 and 9 provide insight into variations of velocity, age of air, and temperature across different mesh sizes at two specific heights (0.1 meters and 1.2 meters). For this analysis, the 15 million mesh size will be referred to as the fine grid, the 10 million mesh as the reference grid, and the 7 million mesh as the coarse grid. The absolute differences in temperature range from 0.01 K to 0.46 K between the fine grid and the reference grid in12 points. The differences are 0.3 K when the fine grid and the coarse grid are compared.

The age of air reveals absolute differences between 2 seconds and 47 seconds when comparing the fine grid to the reference grid. These differences range from 3 seconds to 44 seconds when comparing the coarse grid to the fine grid.

Moving on to a height of 1.2 meters, comparisons yield similar results. The differences in the temperature range from 0.04 K to 0.26 K between the fine grid and the reference grid. The differences range from 0.03 K to 0.24 K when comparing the coarse grid with the fine grid.

For the age of air at 1.2 meters, the differences range from 4 seconds to 59 seconds when comparing the fine grid and the reference grid. These differences range from 1.2 seconds to 58.2 seconds when comparing the fine grid and the coarse grid.

Despite these minor variations in parameters such as temperature and age of air at the two different heights, the data overall indicates a high degree of similarity across the results. Taking into account these minimal differences, along with the simpler computational model, the coarse grid (7 million mesh size) has been selected for further analysis.

3.6 Validation of CFD model

Table 5 presents the comparison of velocities measured in a classroom, as documented in Awbi's paper [27], and velocities predicted by the CFD-model at four distinct points within the room. The consistency between the measured and predicted velocities, as displayed in the table 5, suggests that the CFD model can be a trusted method for forecasting airflow patterns in such environments.

Table 5: Comparison of velocities and local age of air at points 5, 6, 7, and 8, positioned at the height of 0.1m above the floor. 'W' represents the winter situation and 'S' represents the summer situation.

	5		**6**		**7**		**8**	
Local Mean Age [min]	**Measured Reference data**	**CFD data**	**Measured Reference data**	**CFD data**	**Measured Reference data**	**CFD data**	**Measured Reference data**	**CFD data**
	W 14.4	W 13.1	W 11.1	W 11.2	W 9.5	W 11.0	W 6	W 11.3
	S 5.3	S 10.1	S 7	S 10.5	S 5.5	S 10.4	S 5	S 11.0
Velocity [m/s]	W 0.12	W 0.3	W 0.11	W 0.26	W 0.10	W 0.21	W 0.14	W 0.18
	S 0.14	S 0.04	S 0.11	S 0.01	S 0.12	S 0.05	S 0.14	S 0.03

The air flow pattern in the Awbi (reference) case is depicted in Figure 10.

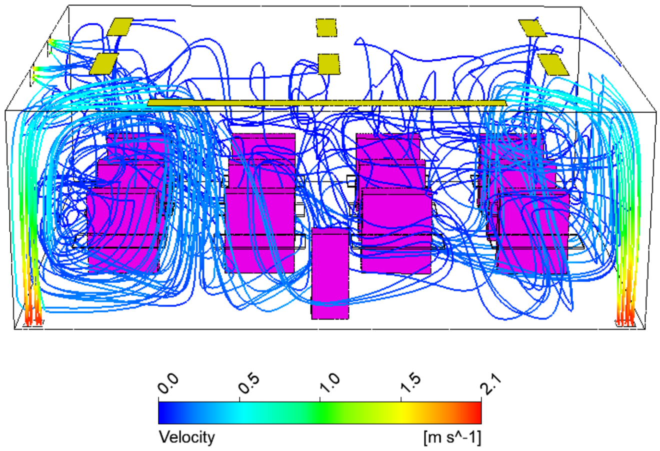


Figure 10: Velocity diagram to show air flow pattern in Awbi case (reference model)

In addition, Figure 11 illustrates the comparison of velocities measured at four different points (5, 6, 7, and 8) in the classroom using both the results outlined in the experiments from real classroom paper and the CFD model provided by Awbi's paper and the CFD model-developed for this research.

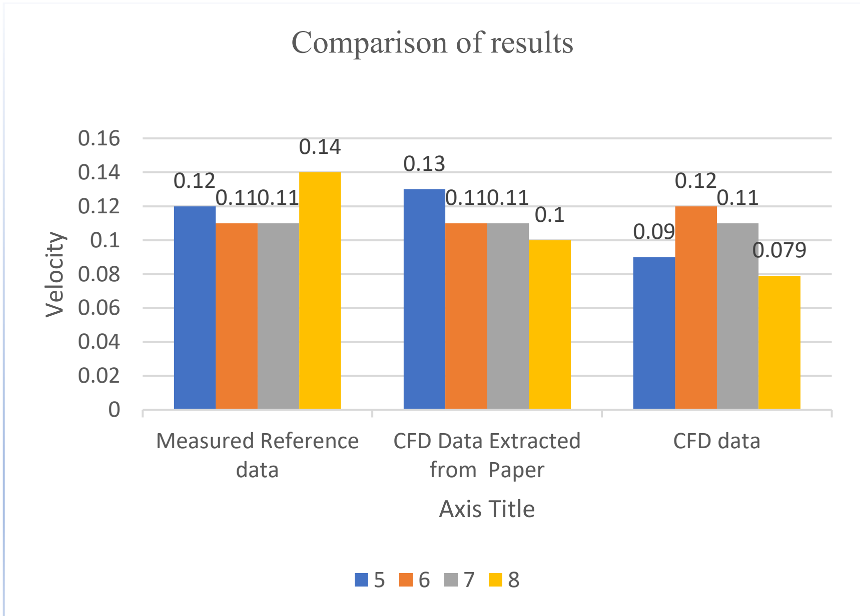


Figure 11: Comparative analysis of experimental air velocity data from Awbi's study [26] (left table), reference data from the CFD model (middle table), and novel CFD data generated by the current research (right table) for points 5, 6, 7, 8.

On the left side of the figure, the "measured reference data" is shown, which represents the experimental data collected and reported in Awbi's reference paper [27]. In the center, the "CFD Data Extracted from Published Paper" from Awbi's paper is displayed. This data serves as reference data for evaluating the CFD simulations and experimental data. Finally, on the right side, the "CFD data" from the CFD model developed in this research is presented. This data reveals the calculated air velocities at the four points in the classroom and facilitates comparison with both the measured reference data and the CFD measured reference data.

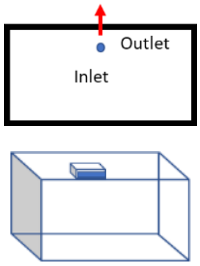
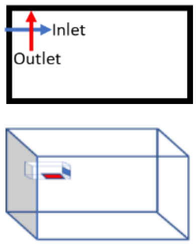
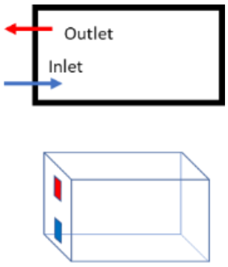
The observed closeness between the experimental data (reference data) and the results generated by the CFD model, developed in Ansys CFX, along with the representative flow field that is calculated for the validation case, indicates that the model developed is capable of reproducing the flow field in the classroom. Based on this outcome, the developed base model is regarded as sufficiently accurate to perform the further analysis of the ventilation scenarios to answer the research questions.

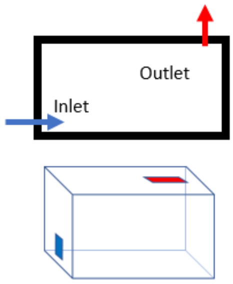
3.7 Ventilation scenarios

Based on the stakeholders' preferences, four case studies have been defined, comprising two scenarios for mixing ventilation and two scenarios for displacement ventilation. Each case study differs in terms of supply velocity, supply temperature, and the placement of supply and exhaust, as indicated in Table 6.

Table 6 presents four different scenarios, each based on the stakeholders' desired ventilation systems in the classroom. For each scenario two cases have been investigated: mixing ventilation (case M1 and case M2) and displacement ventilation (case D1 and case D2).

Table 6: Illustration of six distinct simulation scenarios incorporating two for mixing ventilation and two for displacement ventilation.

Scenario	Supply air velocity	Supply air tempera-ture	Flow Diagram	Type of ventila-tion	Flowrate
M1	2.3 m/s	20 °C		Mixing	$1080\ m^3/h$
M2					$1080\ m^3/h$
D1	0.4 m/s	18 °C		Displacement	$1080\ m^3/h$

D2					1080 $m^3/_h$

3.7.1 Results

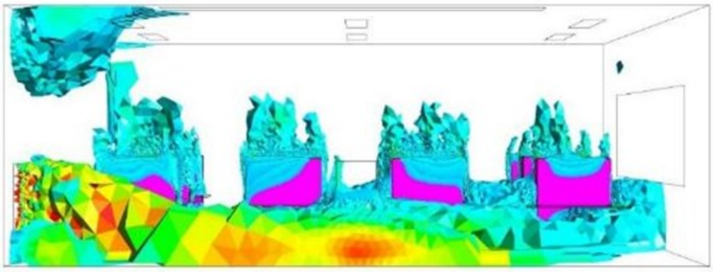
The results section begins by highlighting the airflow patterns across four different ventilation cases. Following this, a detailed depiction of the airflow pattern is provided. Next, the velocity data is presented, which is important for understanding the overall performance of the ventilation systems. The subsequent sections delve into the specifics of local thermal discomfort, air age, and air change efficiency, providing a comprehensive analysis of these key performance indicators. The impact of summer and winter conditions on the performance of ventilation systems is then discussed, highlighting the importance of considering seasonal variations in ventilation design. The influence of magnitude and direction on the airflow pattern is also examined, providing insights into how these factors can shape the effectiveness of ventilation.

Finally, the concept of multi-zone demand control ventilation is explored, demonstrating its potential for optimizing indoor air quality and energy efficiency.

3.7.2 Airflow pattern

The CFD simulation, as depicted in Figure 12 and Figure 13, provides a detailed visualization of the airflow patterns in the classroom setting investigated. These figures specifically demonstrate the dynamics of the airflow for the four investigated cases: two mixing ventilation and two displacement ventilation cases. Focusing on the displacement ventilation cases (D1–D2), the air moves throughout the entire room and then ascends towards the ceiling, a behaviour driven by buoyancy forces. For displacement ventilation systems, the supply air effectively spreads across the entire occupied area at floor level before rising. This indicates that displacement ventilation can create relatively uniform conditions across the entire floor and lower area of the room. The air rises near the heat sources, due to air density differences (buoyancy). This air then is transported upward and forms a layer near the ceiling that then is exhausted at the exhaust positioned near the ceiling. In the case of mixing ventilation systems (M1-M2), the air is introduced into the room at a high velocity from a supply near the ceiling. This powerful stream of air is capable of reaching the opposite wall. In this process, it induces air from the room and with that initiates mixing of the air in the room. As a result, the air circulates among the students before it is exhausted from the room. However, it's noteworthy that in the case of M1, due to the room's extended length, the airflow velocity is relatively high near the students seated close to the opposite wall. The results presented show the velocity iso-volume ranges between 0 m/s and 0.4 m/s for displacement ventilation, and for mixing ventilation, the value is 0 m/s to 2.3 m/s.

(a) Displacement Ventilation 1 (Section A-A)



b) Displacement Ventilation 2 (Section A-A)

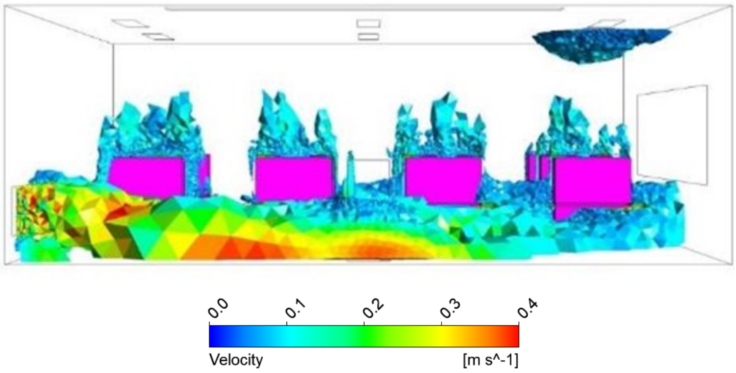
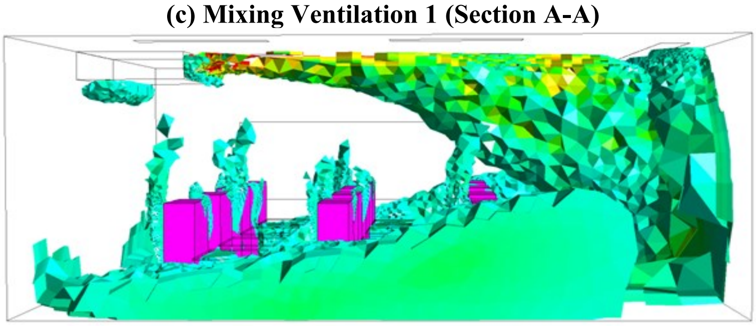


Figure 12: Airflow patterns in displacement ventilation systems (a)displacement ventilation model 1 (b)displacement ventilation model 2

(c) Mixing Ventilation 1 (Section A-A)



(d) Mixing Ventilation 2 (Section B-B)

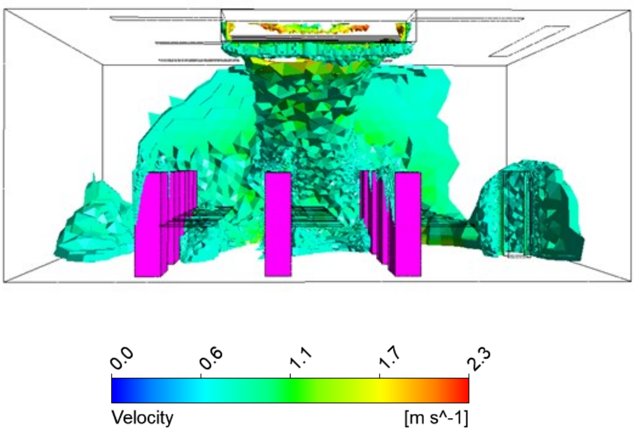


Figure 13: Airflow patterns in mixing ventilation systems (c)mixing ventilation model 1 (d)mixing ventilation model 2

3.7.3 Velocity profiles

Figures 14 and 15 display the air velocity for the investigated cases. The indicators for the analysis were set according to the Frisse Scholen [15] guidelines.

The guideline indicates that the maximum air velocity during summer and winter, should not exceed 0.23 m/s and 0.19 m/s, respectively. For the purposes of this study, the heat transfer via the walls was not considered and adiabatic condition was assumed. Thus, a consistent reference value of 0.2 m/s was assumed for all measurements.

In the displacement ventilation scenario, the air velocity throughout most of the occupied space conformed to the established guidelines. However, there were greater deviations in specific areas near the supply (D1) and in proximity to the teacher's location in both models. In the second case (D2), the first row of student seating is also exposed to an air velocity greater than 0.2 m/s. Therefore, they may experience some local thermal discomfort. When analysing the mixing ventilation cases, the air velocity was found to exceed the reference value of 0.2 m/s near the walls, which were situated opposite the location of the mixing ventilation unit (split). Furthermore, it was observed that a high air velocity of around 2 m/s is present near the ceiling in both mixing ventilation systems.

The airflow patterns produced by the mixing ventilation systems resulted in higher air velocities in a part of the living zone where the students are seated. This might lead to discomfort and suggests that alterations might be necessary for more effective and comfortable air distribution.

(a) Displacement Ventilation 1 **(b) Displacement Ventilation 2**

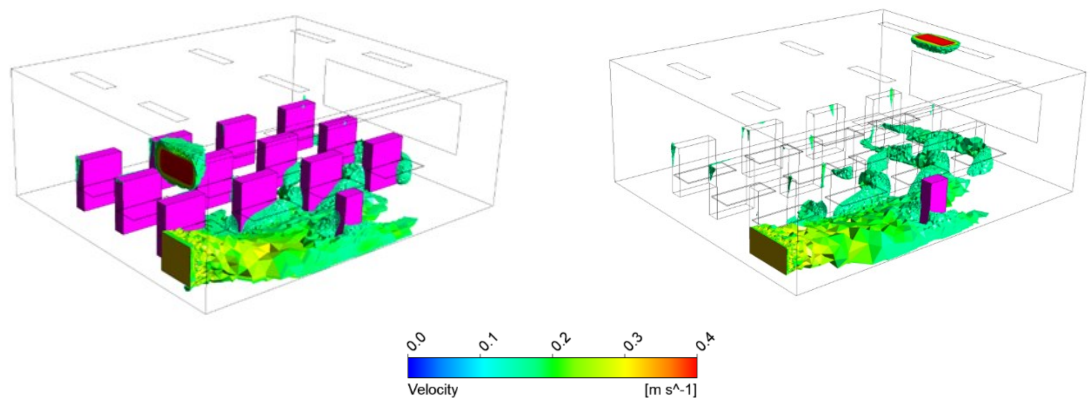


Figure 14: Air velocity distribution in displacement ventilation (D1 left-D2 right)

(c) Mixing Ventilation 1 **(d) Mixing Ventilation 2**

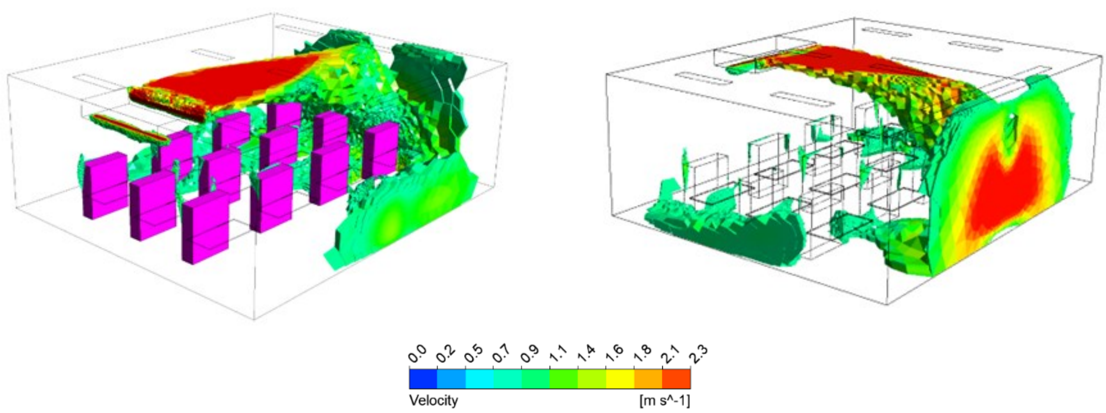


Figure 15: Air velocity distribution in mixing ventilation (M1 right-M2 left)

3.7.4 Local thermal discomfort

The assessment of local thermal comfort, specifically pertaining to the risk of draught, is carried out in all investigated cases. This assessment involves the examination of the draught rate at the breathing zone. Figure 16 shows the result of that analysis.

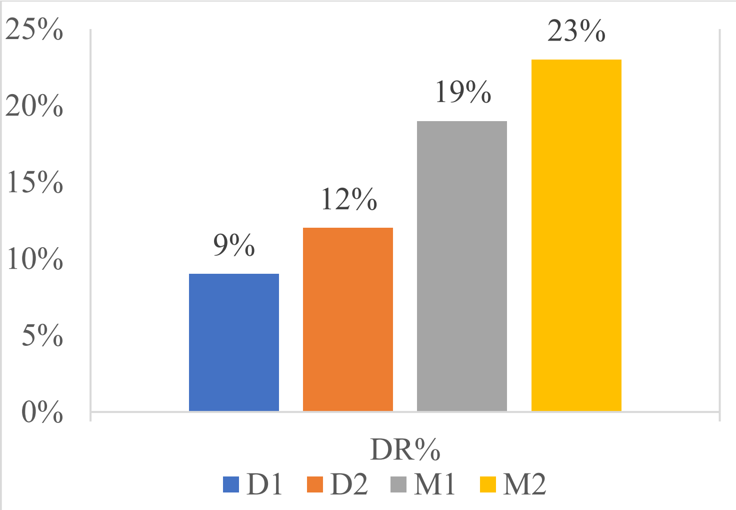


Figure 16: The draught rate in breathing zone 1.2 meters height

Upon comparing the draught risks across the various ventilation systems, an increased risk is identified in M1 and M2 systems, registering draught risks of 19% and 23%, respectively. As per the design criteria set by Frisse Scholen, these risk percentages categorise the M1 system under Class B and the M2 system under Class C. On the contrary, the displacement ventilation systems, D1 and D2, demonstrate lower draught risks, registering at 9% and 12% respectively. Accordingly, D1 falls into Class A, and D2 into Class B based on the same criteria. Note that the absolute supply temperature for the mixing cases was 2 K higher as compared to the displacement ventilation cases. Assuming the same absolute temperature, the differences in draught risk between the displacement and mixing cases will even be larger. As the throw of the supply for the mixing case may be affected, the risk even may be higher.

In summary, the research findings demonstrate that all four scenarios investigated (D1-D2 and M1-M2) have the capability to produce a draught risk at the breathing zone height, which meets or exceeds the Class B criteria outlined in the Frisse Scholen Standard.

3.7.5 Age of air and air change efficiency

The results of the simulation of the age of air distribution for both the displacement and mixing ventilation case, focus on two heights: 1.2 meters (breathing zone seated height) and 1.8 meters (breathing zone standing height). This is illustrated in Figures 17 and 18. For displacement ventilation cases D1 and D2, the nominal time constant is 576 seconds. This means it takes about 576 seconds, or roughly 9.5 minutes, for a volume of air similar to the volume of the classroom to be exhausted and replaced by (clean) supplied air. This accounts to an air change rate of approximately 6 h^{-1}.

On the other hand, the nominal time constants for the mixing ventilation cases, is a bit longer, approximately 800 seconds and 830 seconds respectively. This is due to a somewhat lower supply flow rate. For the assessment of the air change efficiency, the difference in the nominal time constant is not very important, as the ACE is calculated relative for the nominal time constant.

Comparing both ventilation strategies, in most areas, the local mean age is lower with displacement ventilation than for mixing ventilation, even taking into account the difference in the nominal time constant of approximately 200 s. This is applicable to both displacement ventilation cases D1 and D2, considering both 1.2 and 1.8 meter height levels. Near the walls and room corners the differences are smaller.

In displacement ventilation systems (D1 and D2), fresh air is introduced near the floor of the room. This air then rises due to buoyancy-driven flows, which is particularly influenced by heat sources in the room. As a result, air with a relatively low age, is taken upwards near the heat sources, resulting in a lower local age of air near the heat sources.

Figure 18 provides a visual representation of the distribution of air age for the two mixing ventilation cases. This figure demonstrates that the air age is highest on the side of the room where the mixing ventilation units are installed. As the air circulates from this point to the opposite wall, there is a noticeable decrease in air age, near the opposite wall.

When compared to a displacement ventilation system, the air age under mixing ventilation systems is higher specifically at the height of 1.8 meters. Among the two mixing ventilation cases, M1 shows a higher air age than case M1. From this result, one can conclude that case M1 has a lower air change efficiency as compared to case M2. These observations could be crucial in assessing and optimizing the performance of these ventilation systems.

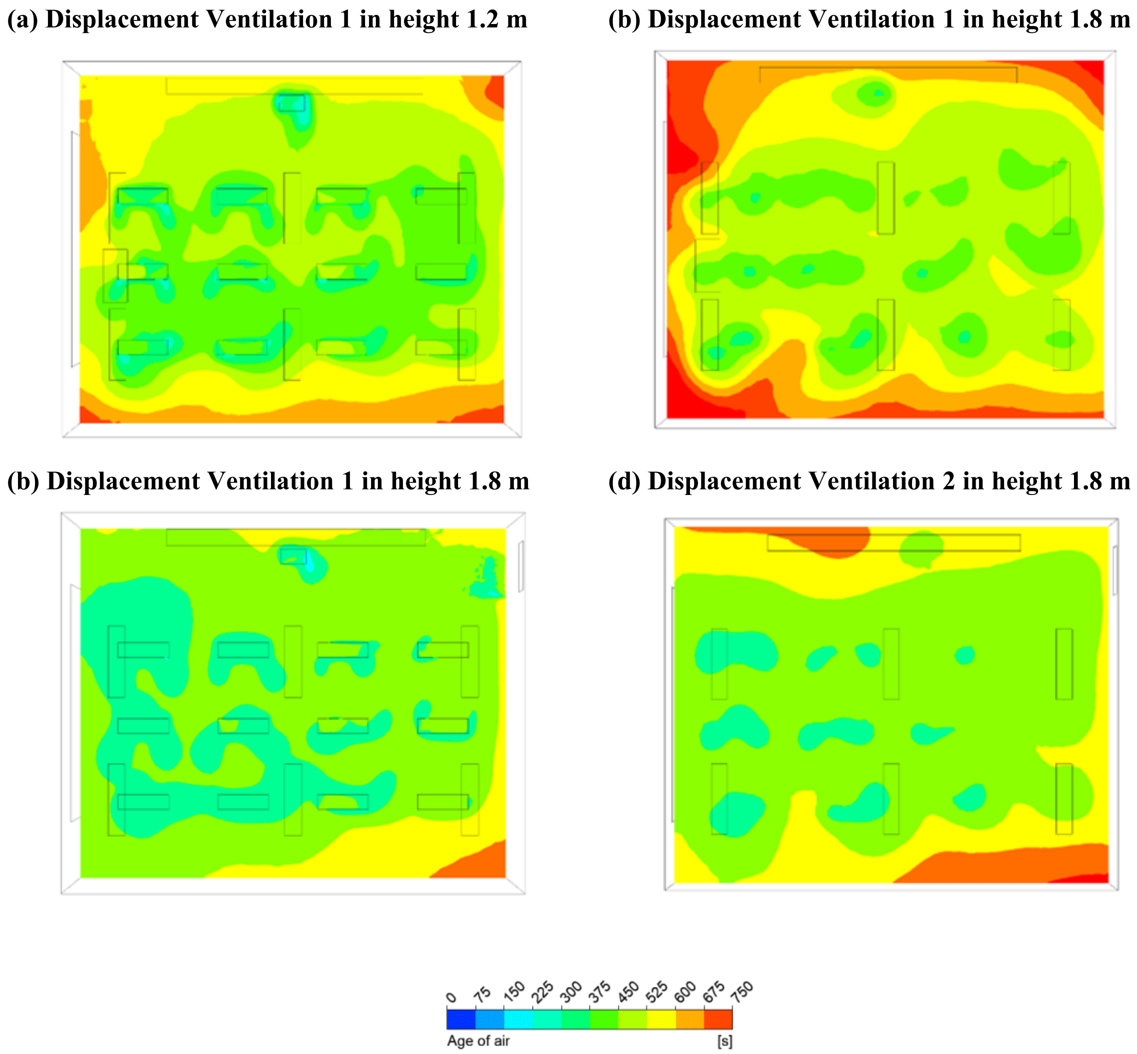


Figure 17: Comparison of air age at breathing and standing heights for both displacement ventilations (D1-D2)

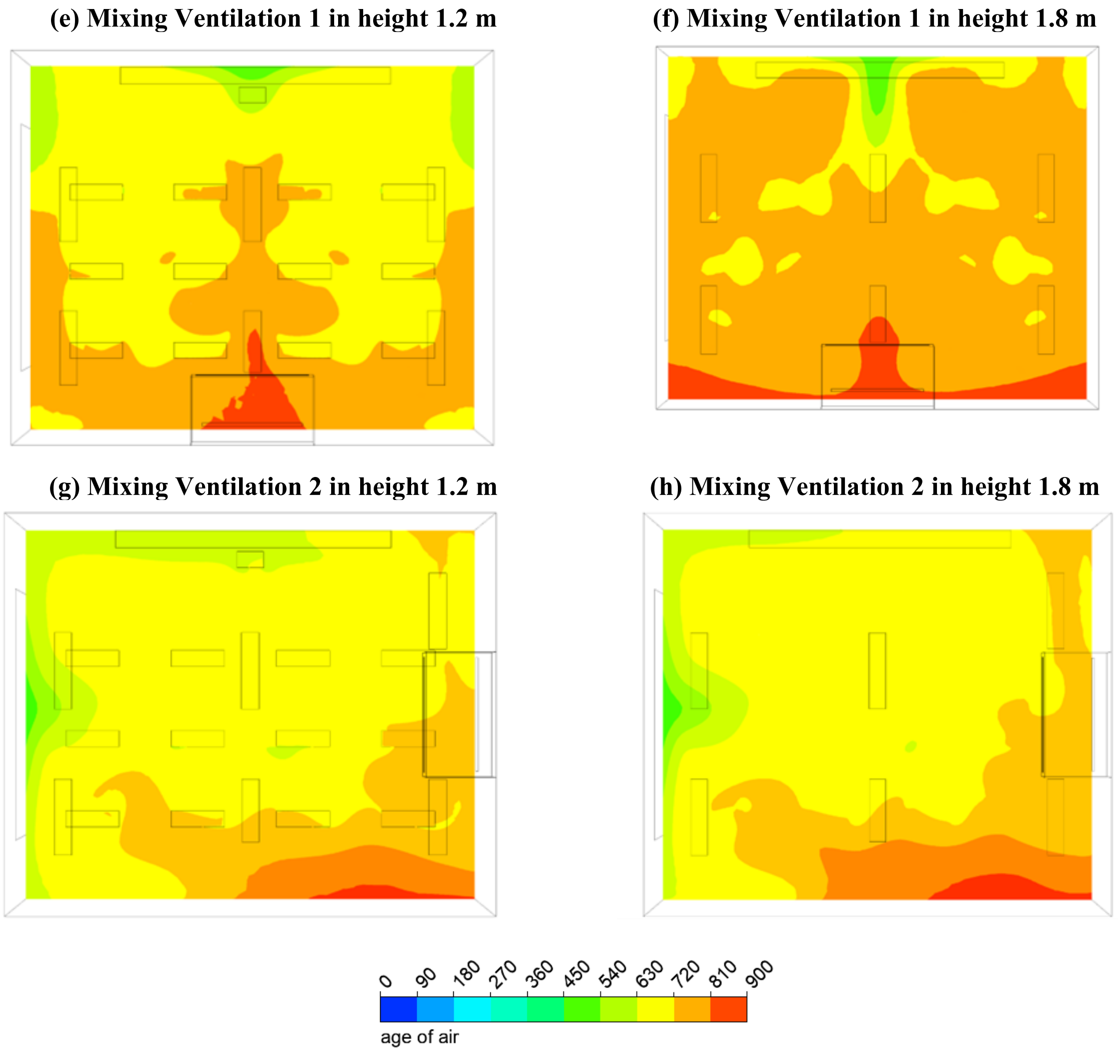


Figure 18: Comparison of air age at breathing and standing heights for both mixing ventilations (M1-M2)

Table 8 displays the average air age and air change efficiency in the occupied area. This table includes the results for the local mean age and average age of the air at seven chosen positions (points 1, 4, 5, 6, 9, 11, 12) in the room, at two different heights, 1.2 meters, and 1.8 meters. The four corners of the classroom are points 1, 4, 9, and 12, and point 12 is located near the supply and exhaust for the displacement ventilation systems also points 5 and 6 are situated in the room's center. Figure 6 illustrates where these positions are located.

The average air age for D1 at a height of 1.2m ranges from 399 seconds to 496 seconds, and at a height of 1.8m from 460 seconds to 639 seconds. For D2, the average air age at a height of 1.2m varies between 355 seconds and 442 seconds, and at a height of 1.8m between 372 seconds and 508 seconds. The mixing ventilation cases (M1 and M2) are investigated using the same parameters and measurement points as displacement ventilation (D1 and D2). The results are presented similarly to allow a direct comparison between the two ventilation strategies. In terms of local mean age and the average age of air, M1, and M2 perform are longer as compared to D1 and D2. This is partly due to the longer nominal time constant. But on average the difference is larger as would be expected from the nominal time constant.

This is also reflected in the air change efficiency for the different ventilation strategies. The mixing ventilation cases M1 and M2 are lower as compared to the displacement ventilation cases D1 and D2, indicating that displacement ventilation systems can refresh the air in the room more efficiently than mixing systems. In particular, the M1 and M2 efficiency of air changes, are recorded at 54% and 55%, respectively, while D1 and D2 are presented at 64% and 61%, respectively. The comparison between

D1 and D2 and between M1 and M2 indicate that the position of supply and exhaust affect the air change efficiency at the location of interest. So, for the design, they are important considerations.

Table 8: Summary of ventilation indices of 4 ventilation systems

Case	**Position**	**Local mean age**							**Average Age of the Air (sec)**	**Air Change efficiency**
		Point no.1	Point no.4	Point no.5	Point no.6	Point no.9	Point no.11	Point no.12		
D1	H1.2m	399 s	578 s	494 s	471 s	447 s	496 s	491 s	444 s	64%
	H1.8m	460 s	546 s	503 s	570 s	639 s	517 s	507 s		
D2	H1.2m	355 s	546 s	378 s	402 s	383 s	417 s	442 s	470 s	61%
	H1.8m	372 s	582 s	408 s	439 s	508 s	484 s	457 s		
M1	H1.2m	731 s	741 s	684 s	670 s	660 s	693 s	663 s	746 s	54%
	H1.8m	744 s	750 s	709 s	701 s	760 s	738 s	764 s		
M2	H1.2m	715 s	800 s	583 s	724 s	740 s	727 s	764 s	719 s	55%
	H1.8m	746 s	842 s	660 s	640 s	764 s	764 s	788 s		

3.7.6 The impact of summer and winter conditions on the performance of ventilation systems

This study incorporated a fixed temperature for windows into the calculations instead of the adiabatic setting, which was based on the standard data. For the summer conditions, an average window temperature of 23.3°C was assumed. In contrast, for the winter scenario, a significantly lowered temperature of -1.23°C was assumed.

Comparative analysis of the summer and winter conditions, as represented in Table 9, highlights the considerable influence of external temperatures on the effectiveness of ventilation. For each season, the average age of the air and air change efficiency were calculated from the respectively simulated cases, assuming the case from Awbi et al. as the reference.

Table 9: Comparison of winter and summer on age of air of reference (Awbi) case.

Scenario	**Average age of the Air (sec)**	**Air change efficiency**
winter	752 s	44%
Summer	580 s	59%
Adiabatic	640 s	51%

The data indicate that the average age of the air in winter is older than that in the summer and adiabatic scenarios in the classroom. This outcome can be attributed to the cold air is denser than warm air, so when it comes into contact with a cold surface, it tends to flow down along that surface. This downward flow apparently increases the mixing for this specific case, resulting in a lower air change efficiency. For the displacement ventilation scenario as discussed, a similar effect can be expected.

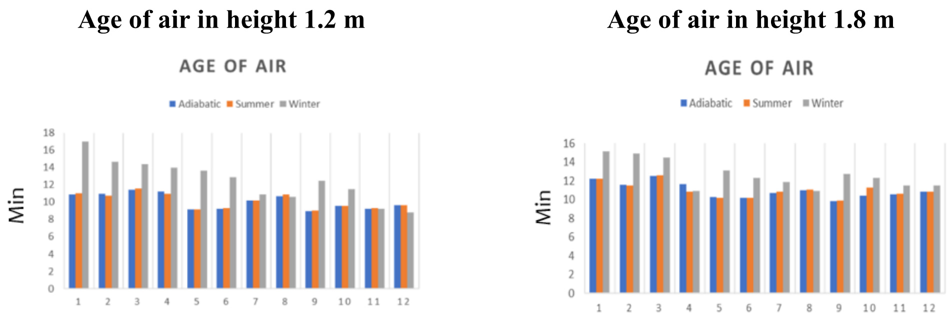


Figure 19: Age of air (in [min]) for 12 points for 1.2m(left) and 1.8m(right) height for summer and winter for Reference (Awbi) case

In Figure 19, the age of air is visualized at 12 points (shown in Figure 6) at two distinct heights: 1.2m (left) and 1.8m (right).at two distinct heights: 1.2m (left) and 1.8m (right). The summer and adiabatic conditions show comparable age of air, while a noticeable difference is observed in the winter scenario. In conclusion, the study demonstrates that external temperatures can have an impact on air change efficiency.

3.7.7 The impact of supply velocity magnitude and direction on the airflow

A sensitivity analysis was conducted to assess how the direction and magnitude of the supply velocity affect the airflow patterns within the classroom. Initially, for the cases investigated and discussed above, the air velocity was directed in two directions with a magnitude of 3.4 m/s in each direction, as shown in Figure 20. (a).

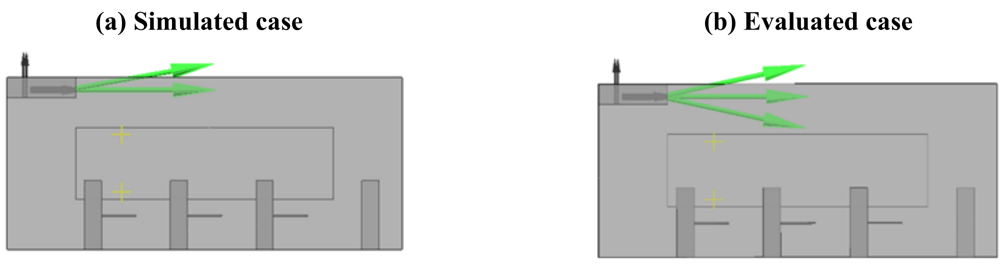


Figure 20:Direction of velocity in mixing ventilation simulated case (left image(a)) and evaluated case (right image(b))

Subsequently, the boundary condition of the supply was adjusted to simulate different scenarios. In this case, the airflow was directed in three directions, as shown in Figure 20. (b), with a magnitude of 2.3 m/s to assure that the flow rates were similar. The adapted supply condition resulted in improved air mixing, but the air tended to settle in the middle of the classroom, causing discomfort in both ventilation scenarios (M1 and M2).

Specifically, in the M1 situation, a draught was observed near the teacher's vicinity, while in M2, the draught occurred on the opposite side of the classroom near the window for around 3 students, the airflow pattern for both cases is shown in Figure 21.

(a)Mixing Ventilation 1 **(b)Mixing Ventilation 2**

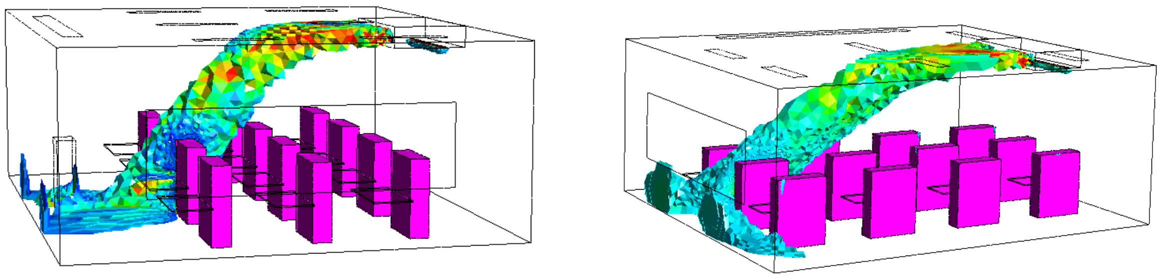


Figure 21: Draught problem visualization for both Mixing ventilation (M1 and M2)

Therefore, the simulations show that small changes in any of these parameters can have a significant impact on the airflow patterns and the distribution of air within the room.

3.7.8 multi-Zone demand control ventilation

To better understand the need for multi-zone demand control ventilation and the implementation of a multi-zone demand control system, the results derived from the age of air, as depicted in Figures 17 and 18, are first simplified. The complex patterns of air age are translated into a more manageable form that can be easily understood and controlled as is shown in Figure 22.

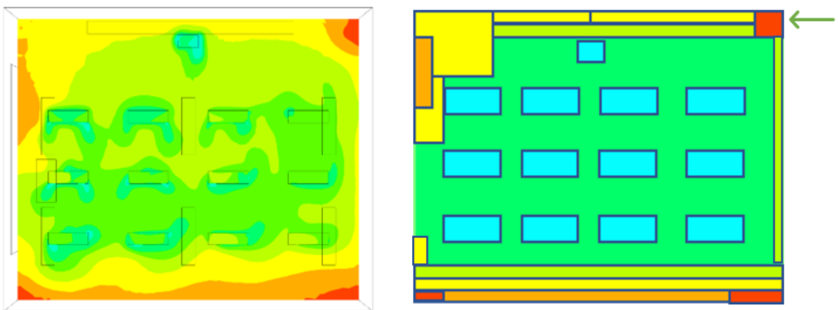


Figure 22:example to show how zones simplified and divided (D1) at height 1.2 meter.

From the simulation results the classroom is schematically divided into six distinct zones, each represented as simple cubic shapes. This division is based on the patterns of air age at a height of 1.2 meters, a typical breathing height for seated occupants.

In both displacement ventilation cases, D1 and D2, the age of air in areas close to students are colour-coded in blue, signifying an air age range of 3-5 minutes (Figure 23). With a nominal time, constant of approximately 10 minutes, the local air change index is >>100%. This indicates efficient ventilation in these zones where students are primarily located.

However, the colour representation shifts to red in the corners of the room, denoting a longer air age of 11 to 12 minutes. This implies a slower rate of air replacement in these peripheral areas, which could be due to their distance from the ventilation sources.

Throughout the majority of the classroom with displacement ventilation scenarios D1 and D2, green is the dominant colour, which represents an air age of 7 to 8 minutes. This suggests a generally efficient and homogeneous distribution of fresh air across the living zone at this height.

(a) Displacement Ventilation 1 in height 1.2 m **(b) Displacement Ventilation 2 in height 1.2 m**

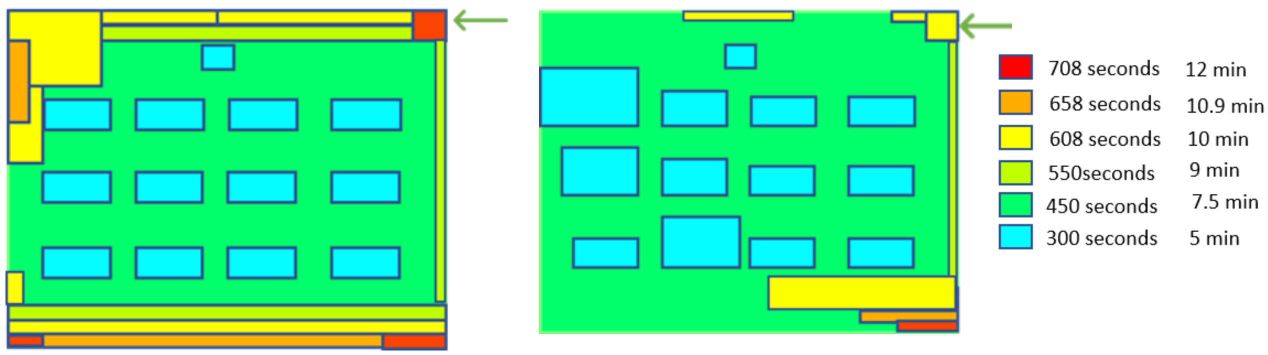


Figure 23: Schematized distribution of the age of air for the displacement ventilation cases D1 (left) and D2 (right)

(c) Mixing Ventilation 2 in height 1.2 m **(d) Mixing Ventilation 2 in height 1.2 m**

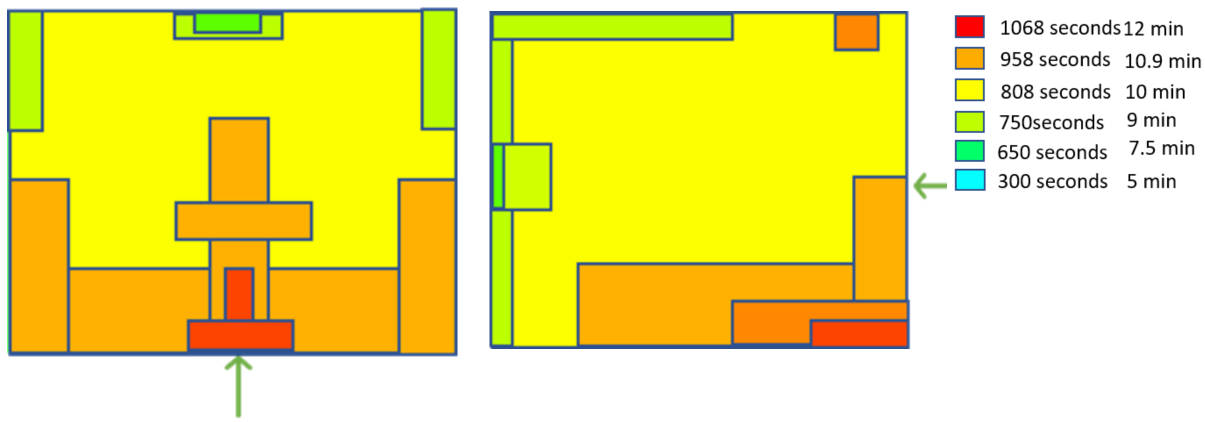


Figure 24: Schematized distribution of the age of air for the mixing ventilation cases M1 (left) and M2 (right)

On the other hand, mixing ventilation systems show a more varied age of air distribution throughout the classroom at a height of 1.2 m (Figure 24). The areas directly underneath the ventilation units where the ventilation systems are installed are marked with red and dark orange, representing a longer air age range of 13.5 to 15 minutes. This indicates a less efficient circulation of fresh air in these areas, compared to displacement ventilation.

Furthermore, the light green colour, signifying an air age of 7 to 8 minutes, is predominantly observed on the wall opposite the location of the ventilation system installed. Yellow is the dominant colour in both mixing ventilation systems, representing an air age range of 10 to 12 minutes, indicating a slower overall air replacement rate compared to the displacement ventilation systems. With a nominal time constant of approximately 13 minutes, the local air change index is around 100%.

The mixing ventilation systems split the classroom into two main areas, shown by orange and yellow colours. These colours show how old the air is in each area, showing clear differences across the room. This is called a multi-zone effect. This outcome reveals a potential need to pay attention to multi-zone influences when using mixing ventilation systems, with one main supply, as applied in our study.

3.8 Discussion

The following discussion intends to review the results of this study, which based on CFD analysis, has assessed the ventilation effectiveness of classrooms. First, the methodology and measurements are discussed, and further, an in-depth analysis of the results and their potential future focus areas are indicated.

3.8.1 Methodology and measurements

The methodology employed in this research was guided by the performance indicators defined in Chapter 2: Performance indicators (WP1). The primary indicator of ventilation system efficiency, according to Dutch building regulations, is the airflow rate within a room. However, this metric does not accurately reflect the distribution of air throughout the room. Therefore, ventilation effectiveness, a concept first introduced by Sandberg in 1981, was used as a better alternative. This concept includes measures such as Contaminant Removal Effectiveness (CRE) and Air Change Effectiveness (ACE) at the room level. Local indicators can be derived from these room-based indicators. These indicators, along with Computational Fluid Dynamics (CFD) simulations, offer a feasible and practical approach for assessing and enhancing ventilation effectiveness in Dutch schools. This has been elaborated on in Chapter 3.

As no measurement data of the airflow in a typical classroom in the Netherlands was available, the choice was made to select a classroom case from the literature to validate the CFD model that needed to be developed. This classroom model then was applied to perform a parameter study. The initial phase involved setting up a CFD geometry and boundary conditions that represented the classroom based on Awbi's case [34]. After the assessment of the grid sensitivity, the validation was performed. The amount of measurement data available in the article applicable for validation was limited. Nevertheless, based on these outcomes and the simulated flow pattern the conclusion was made that the model was sufficiently validated for performing a parameter study in which the focus is on differences in outcomes instead of absolute values. The scenarios and parameters investigated were agreed on in consultation with the advisory team. As CFD simulations are relatively complex simulations and take time for arriving at a converged solution, the number of cases that can be investigated is limited. The intention was to learn as much as possible from the limited number of cases that have been investigated.

3.8.2 Ventilation efficiency

The results from the CFD model showed that the air change efficiency varied between the different ventilation cases. For the displacement ventilation scenarios, the air change efficiency was 64% for D1 (Displacement ventilation 1) and 61% for D2 (Displacement ventilation 2). For the mixing ventilation scenarios, the air change efficiency was 54% for M1 (Mixing ventilation 1) and 55% for M2 (Mixing ventilation 2). This means that case D1 resulted in a more efficient type of ventilation as compared to the other cases, while case M1 approached a theoretically well mixed situation. In this context, displacement ventilation is found to be a more efficient way of ventilation. This is in line with similar outcomes that can be found in literature. It means that a similar air quality can be achieved with a lower flow rate as compared to mixing ventilation. This can result in lower energy demand.

As the major difference between the case D1 and D2, and M1 and M2 was related to the position of the supply and exhaust, the conclusion can be that the effect of the position on the (room) air change efficiency is limited. This, however, does not mean that locally larger differences in the local mean age of the air can be found .

To visualize the working procedure of displacement ventilation, in Figure 25, a series of data points have been plotted that represent the age of the air at different heights within the room with displacement ventilation.

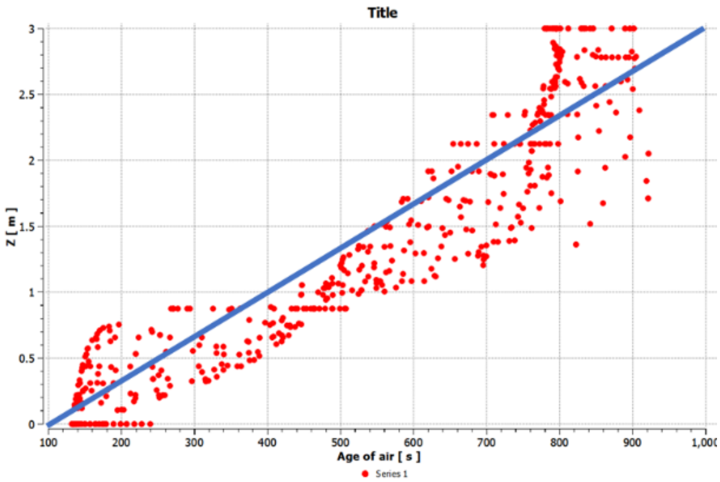


Figure 25: Correlation between height and Age of the Air in Displacement Ventilations.

By analysing the plotted data, it is evident that there is a strong correlation between the age of the air and the height of the room. The flow pattern resembles a plug flow type of ventilation, the most efficient way of ventilation (represented by the blue line) if the air would be supplied at floor level and exhausted at the ceiling.

In contrast, in the mixing ventilation scenarios, no strong correlation was found between height and the ventilation efficiency. However, it was observed that points 1 and 4 had the highest age of the air in the mixing ventilation scenario 1 (M1), which are the closest points to the M1 supply. Similarly, points 4 and 12 had the highest age of the air in the mixing ventilation scenario 2 (M2), which are the closest to the M2 supply. This is illustrated in Table 8.

The parameter studies towards to boundary condition for the window (set temperature instead of adiabatic) indicated a sensitivity of the air change efficiency. These effects can reduce the overall efficiency. In the case of displacement ventilation care should be taken that such effects are avoided by ensuring a good thermal performance of the façade(s).

For mixing ventilation, the supply conditions are critical in assuring that the classroom is ventilated completely. As a result, the throw of the supply can be disturbed easily by direction, supply velocity, temperature differences and obstructions in the supply directions (As a result, the throw of the supply can be disturbed easily by direction, supply velocity, temperature differences and obstructions in the supply directions (which have not been considered in this research).

3.8.3 Multi-Zone effect

Based on the fact that the air quality can be different within a single room, the concept of the classroom division into various zones has been developed. As an example, the quality of air which a student sitting near a window is experiencing, could be different from the one, experienced by a student located at the center or corner of the room.

However, the results from the displacement and mixing ventilation systems suggest a different approach. In the displacement ventilation cases, D1 (Displacement ventilation 1) and D2 (Displacement ventilation 2), at breathing height, the classroom naturally divided itself into different zones based on the age of the air. Interestingly, the zones with the oldest air (represented by the colour red) were located in the corners of the room. While these areas might be less critical in a classroom setting as they are often unoccupied, it is still important to consider them in the overall ventilation strategy. Overall, in the living zone, there appears little need to assume a multizone approach.

On the other hand, the mixing ventilation systems showed a clear division of the classroom into two main zones at breathing height. One zone was located near the ventilation units, and the other was on the opposite side of the room, in the direction of the throw of the supply. The zone near the ventilation units had an older air age, indicating a less efficient circulation of fresh air as compared to the other side of the classroom. The differences are limited in terms of time, in the order of 10%, but it still identifies that the room is not well mixed.

These findings suggest that for a mixing type of ventilation, more than one supply would be needed to assure a more even distribution of the air in the classroom. When analysing the age of air for that case, a decision can be made to vary the supply flow rate accordingly to fine-tune distribution. In reality, it will not be straightforward to assess the age of air. In that case, for example, the CO_2-concentration can be applied as indicator for controlling the air flow rate.

Although the initial idea was to divide the classroom into five zones, the results suggest that a division into two zones would be sufficient for the mixing cases investigated (M1 and M2). But this conclusion may differ in case a different design for the supply and exhaust is assumed in the classroom. The CFD approach applied in this work then can be applied to determine the need for a multizone approach in the classroom.

3.8.4 Limitations of this study

This study provides valuable information about the impact of various ventilation systems on the air quality, but there are several limitations to this study that have to be mentioned:

1. **Limitations of Computational Fluid Dynamics (CFD) Simulations**: CFD analysis is a powerful tool to understand the airflow distribution in a classroom. But the quality of the input data has an important impact on the accuracy of the results. These input data can be related to the geometry of the room, the operating conditions of the ventilation system, and the boundary conditions. Simplifications need to be made when modelling. These simplifications will have an effect on the outcomes. The effect of some of these simplifications was investigated but was limited overall. In addition, the complexity of physical phenomena, such as turbulence, heat transfer, etc. can impose an impact on the accuracy of the CFD simulations. In the study, the standard k-ε model was applied as a turbulence model. Better alternatives may be available for the specific case of the classroom. This was not investigated. The study also used different computational grids for grid-sensitivity analysis, which added another layer of complexity to the modelling process. The results of this analysis showed some variation, indicating that the choice of grid can significantly impact the simulation results. Therefore, while CFD simulations provide valuable insights, their limitations should be kept in mind when interpreting the results.
2. **Generalization of Ventilation Types**: The study focused on two specific types of ventilation concepts: displacement ventilation and mixing ventilation. These concepts were chosen because they are the main concepts applied for ventilation of (class)rooms. But it has to be mentioned that there also exist other ventilation concepts, where the findings of the at-hand studies will not be applicable. An example of that is the task ventilation concept, where air is supplied close to the occupant in a room. Each ventilation system possesses unique characteristics and operates at different principles, which can significantly influence its performance. However, the approach developed with the indicators identified and the CFD method as

analysis tool, does allow us to also evaluate these other ventilation concepts. Given the sheer number of variations possible, it is not possible to pre-research all design options.

3. **Simplification of the Classroom Model**: Linked to the limitations of the use of the CFD tool, the simulated classroom model in this study is a simplified version of a real case. It only includes the basic elements, such as the students, one teacher, tables, and lighting sources at the ceiling. However, real-world classrooms are much more complex and can include many other factors that can influence the ventilation performance, such as additional furniture, different classroom layouts, and variations in human behaviour. These factors were not considered in the study, which could limit the applicability of the findings to real-world classrooms. Nevertheless, the approach developed does allow the analysis of such parameters if needed.

4. **Adiabatic Assumption**: The study assumed adiabatic conditions for the walls, which means no heat transfer through the walls. In real-world conditions, walls can absorb or release heat, which can influence the indoor temperature and the performance of the ventilation system. This assumption simplifies the modelling process, but it may not accurately represent real-world conditions. The effect of implementing a temperature boundary condition for the window showed the effect on the performance of the ventilation. However, in modern buildings (classrooms) with good insulation, one may expect that these effects will be limited.

Chapter 4: Conclusion

In this chapter, we summarize the answers to the research and design questions that were presented at the start of the research. They also intend to complete the remaining work packages of the ECoS-IAQ project as shown in Figure 1.

1. **Why is ventilation effectiveness important in assessing classroom environments and how can its best indicators be determined?**

Ventilation effectiveness is crucial in assessing classroom environments because it directly impacts the quality of the indoor air that students breathe. In other words, the only important factor is not the amount of supplied air, but also the quality of the air circulation within the room is an important factor. For instance, traditionally it was conceived that the efficiency of the ventilation system can be determined by the volume at which the air is supplied, but it is obvious now that the distribution efficiency is also an important factor. For example, the sufficient volume of air can be supplied to the room, but it does not guarantee that that air reaches the occupants in the room in an efficient way. As a result of that there may be variation in the air quality throughout a room.

The best indicators for determining ventilation effectiveness are those that can accurately reflect the distribution of air throughout the room. These include the air change efficiency, which quantifies a system's overall ability to replace the air in a room, and the local age of the air which provides an indication of the variation of the quality of the air throughout the room. These indicators provide a more comprehensive understanding of ventilation effectiveness in classroom environments.

2. **How can Computational Fluid Dynamics (CFD) be used to assess ventilation effectiveness in classrooms?**

Computational Fluid Dynamics (CFD) serves as an indispensable tool in assessing ventilation effectiveness in classrooms. It enables the detailed examination of airflow distribution, temperature variations, and air quality within a classroom environment. By simulating different ventilation systems, CFD provides a platform to compare and evaluate their performance in terms of ventilation effectiveness.

In this study, CFD was used to analyse the impact of several factors such as the position of the air exhaust and supplies in both displacement ventilation and mixing ventilation heat generation by students and the temperature differences in different zones. These factors are crucial in optimizing ventilation systems and improving indoor air quality.

Moreover, CFD allows for the exploration of different scenarios and their potential outcomes without the need for physical modifications or installations.

In conclusion, CFD provides a comprehensive, detailed, and efficient approach to assessing and enhancing ventilation effectiveness in classrooms.

3. **What are the differences in performance between mixing ventilation and displacement ventilation systems in terms of ventilation effectiveness in Dutch schools?**

Based on the detailed analysis and results presented in this thesis, the differences in performance between mixing ventilation and displacement ventilation in terms of ventilation effectiveness in Dutch schools can be summarized as follows:

1. **Airflow Patterns**: Displacement ventilation (D1 and D2) allows air to move throughout the entire room and then ascend towards the ceiling, a behaviour driven by buoyancy forces. This indicates that displacement ventilation can create relatively uniform conditions across the entire floor area. In contrast, for mixing ventilation (M1 and M2), high-velocity air enters from a wall near the ceiling. The supplied air induces air from the room into the supplied air and with that supports the mixing of the room air. The results show that this mixing is not uniform. Furthermore, the throw of the air is sensitive to several parameters and needs careful attention so that the high velocity air is not penetrating the occupied zone in the classroom where the students are seated. Potentially this can result in draught complaints.
2. **Ventilation Efficiency**: The air change efficiency varied between the different cases. For the displacement ventilation scenarios, the air change efficiency was 64% for D1 and 61% for D2. For the mixing ventilation scenarios, the air change efficiency was 54% for M1 and 55% for M2. The effect of the supply and exhaust position for the cases D1 and D2 and M1 and M2 did show some effect on the air change efficiency, but its effect is limited. Locally, however, differences can be seen as a result of the change in supply and exhaust location.
3. **Advantages and Challenges**: Displacement ventilation offers improved air quality by effectively removing contaminants and delivering better indoor air quality in the occupied zone compared to mixing ventilation at the same flow rate. Due to the low velocities applied, and at some distance from the supply, displacement ventilation is less prone to draught risk problems. As displacement ventilation is more efficient, the concept can be more energy-efficient than mixing ventilation systems.

It's important to note that these findings are specific to the classroom environment and the cases investigated in this study. Different results may be observed in other settings or with other types of ventilation systems

4. What is the need and potential for a multi-zone demand control strategy in classrooms based on the investigated case studies, and how can this be implemented effectively to improve indoor air quality and reduce energy consumption?

Based on the findings from this study, it is not straightforward to determine the need and potential for a multi-zone demand control strategy. The results show that there is a dependency on the ventilation concept applied. The concept of dividing the classroom into different zones is based on the understanding that indoor air quality can significantly vary within the room.

For the displacement ventilation concept, this variation in indoor air quality, represented by the local mean age of the air, is less noticeable. This is due to the working principle of the concept, assuming that sufficient air is supplied into the room. In displacement ventilation, the air is distributed first near the floor over the entire room before it is transported upward along the heat sources present in the room. As a result of that the local mean age of the air is generally evenly distributed in the occupied zone. As a result, the need for a multi-zone control strategy doesn't seem present.

For the mixing ventilation concept, a variation in the local mean age can be found. For the investigated cases, the effect can be assigned to the fact that one supply is used for providing the air into the room. This creates a vortex in the room that results in less optimal mixing and as a result of that gradients in the local mean of the air. This outcome assumes that a better distribution can be achieved by supplying the air at different zones in the room, along with a multi-zone control. The investigated cases would assume that a two-zone approach already could be sufficient, but this needs further evaluation of the updated design solutions for the room. Looking at the absolute differences in the local mean age of the air, one may discuss to what extend there is a need to improve the situation. Nevertheless, from an air quality (and health) perspective it seems fair to strive for an even distribution in the occupied zone of the classroom and a multizone ventilation design strategy (and control) could be considered.

5.How can the ECoS-IAQ project contribute to improving the school ventilation system?

This project is a collaboration of two EngD students: Vinayak Krishnan and Ayda Golahmadi. The ECoS-IAQ project, as explored in this thesis, has made significant strides in understanding the performance of two important ventilation concepts in Dutch classrooms. The project's focus on ventilation effectiveness has provided a new perspective on how to assess and enhance indoor air quality in classrooms. This approach has shifted the focus from merely increasing airflow rates to optimizing the effectiveness of existing ventilation systems.

The use of Computational Fluid Dynamics (CFD) has been instrumental in this project. It has allowed for a detailed analysis of different ventilation concepts, providing insights into how air moves within a classroom and how efficiently it is replaced. This has led to a better understanding of the performance differences between mixing and displacement ventilation systems. The approach developed allows for further analysis of new concepts or other cases.

The project's exploration of a multi-zone demand control strategy has revealed its potential for improving indoor air quality. For the investigated cases, specifically the mixing ventilation concept seems to be supported by a design that supplies air to different zones within a classroom to assure a more even distribution of the air quality in the room.

However, the project's findings are not without limitations. The complexity of the physical phenomena being modelled, the quality of the input data, and the choice of boundary condition significantly limited the range of cases that could be investigated. The results, therefore, are specific to the classrooms and ventilation systems studied and may not be universally applicable. The advice is to apply the approach developed to assess other cases of interest.

Furthermore, the outcomes from Vinayak Krishnan's project have also focused on the design of an optimal Air Handling Unit (AHU) for schools and the performance assessment of low-cost Indoor Air Quality (IAQ) sensor units for classrooms. The design methodology applied has led to the development of new designs to improve current centralized and decentralized school AHUs. The performance assessment of the low-cost sensors has provided detailed insights into the advantages and disadvantages of current low-cost sensor technologies. The project's outcomes included a better understanding of the present ventilation and IAQ scenario in the classroom, an optimized AHU design with optimal filter configuration, and detailed insights into the performance of currently used low-cost IAQ sensors in the market.

In conclusion, the ECoS-IAQ project has made significant contributions to improving school ventilation systems by providing a deeper understanding of ventilation effectiveness and its related indicators, utilizing CFD for detailed assessments, exploring the potential of a multi-zone demand control strategy, and optimizing the design of AHUs and assessing low-cost sensor in classroom and improving and finding optimal filters for classroom. The findings from the two projects have important implications for the design and operation of ventilation systems in schools, with the potential to improve indoor air quality, and with that enhance student health and comfort.

Chapter 5: Design Guidance

5.1 Overview

As the final part of the work, the outcomes from the analyses described earlier in this report have been applied to provide design guidance for the design of the ventilation in a classroom. It covers the main outcomes as obtained from the analyses.

5.1 Designing Mixing Ventilation Systems

Location of the supply and effect on ventilation effectiveness: The placement of the supply does not significantly affect the effectiveness of ventilation overall, whether it is located in either of the side wall of the classroom. For an improved distribution of the air, it is advised to supply the air at more the one position in the room.

Air supply velocity and direction: The magnitude and direction of the air supply can cause significant differences in the distribution of the air flow pattern in the room. If the throw of the supplied air ends in the occupied zone this may result in draught complaints. Therefore, careful consideration should be given to these parameters during the design phase. The effect on the air change efficiency was not investigated in this case, but it is to be expected that it will result in larger gradients in the room when compared to a well-functioning mixing ventilation design.

Concept of Multizone: As single supply solutions do not appear to generate an even distribution of the air quality in the classroom, the concept of multizone can be considered and applied in classrooms with mixing ventilation. This involves identifying different zones in the classroom for which the supply devices can be designed accordingly. Based on the outcomes investigated, a minimum of two zones may already be sufficient to cover the major variation in a classroom. Different ventilation rates could be applied in the two zones identified. The need for that may be determined on air quality measurements, such as the CO_2 concentration. As a result, a more uniform distribution of fresh air throughout the classroom can be realized. Specifically for larger spaces such an approach will be beneficial. By strategically positioning multiple air supplies, it's possible to reduce areas of stagnant air and improve the overall effectiveness of the ventilation system. This approach requires careful planning and design to ensure that the additional air supplies do not create conflicting airflows or increase the risk of draughts. The use of CFD may support this design process.

5.2 Design of Displacement ventilation

Location of the supply and effect on ventilation effectiveness: Similar as for mixing ventilation, the location of the supply (and exhaust) does not appear to significantly affect the air change efficiency at room level. An important consideration, however, is that the supply needs to be positioned near floor level, while the exhaust is positioned near ceiling level. Additionally, there is a requirement for displacement ventilation, in order to function correctly, that the supplied air has a lower temperature than the room temperature. If the system is used for heating than the air change efficiency will be drastically reduced.

Air supply velocity and direction: The performance of displacement ventilation is less affected by the supply conditions. Generally, the supply velocity is low when compared to a mixing ventilation solution. This assures that the supplied air is not mixed. As indicated above, the single main requirement is that the supply temperature is colder than the average room temperature. In that context draught risk may pose an issue of concern as the colder air is supplied near the occupied zone.

Sufficient distance between supply and the position of students (and teacher) should be allowed to limit the draught risk. One potential solution is to position the supply in the floor rather than the side wall.

Concept of Multizone: From the CFD-results for the displacement ventilation concept and its working principle, it can be derived that there is no actual need to divide the classroom into separate zones. Within the occupied zone a uniform distribution of the age of air is found. The location with reduced local air change efficiency is found in zones that generally are less critical in a classroom setting as they are often unoccupied.

Figure 26 presents a flow diagram that encapsulates the key findings and considerations derived from the ECoS-IAQ project, specifically tailored for ventilation design engineers. This diagram serves as a visual guide, summarizing the critical steps and considerations in designing and implementing effective ventilation systems in classrooms.

The flow diagram starts with the selection of the ventilation system's main purpose - cooling, heating, or both. For cooling, displacement ventilation is recommended, while for heating or combined heating and cooling, mixing ventilation is suggested.

The diagram then guides through specific considerations for each system. These include the positioning of supplies and exhausts, the assessment of draught risk, and the application of a multizone demand control approach. Each of these elements support the design of an efficient and effective ventilation system.

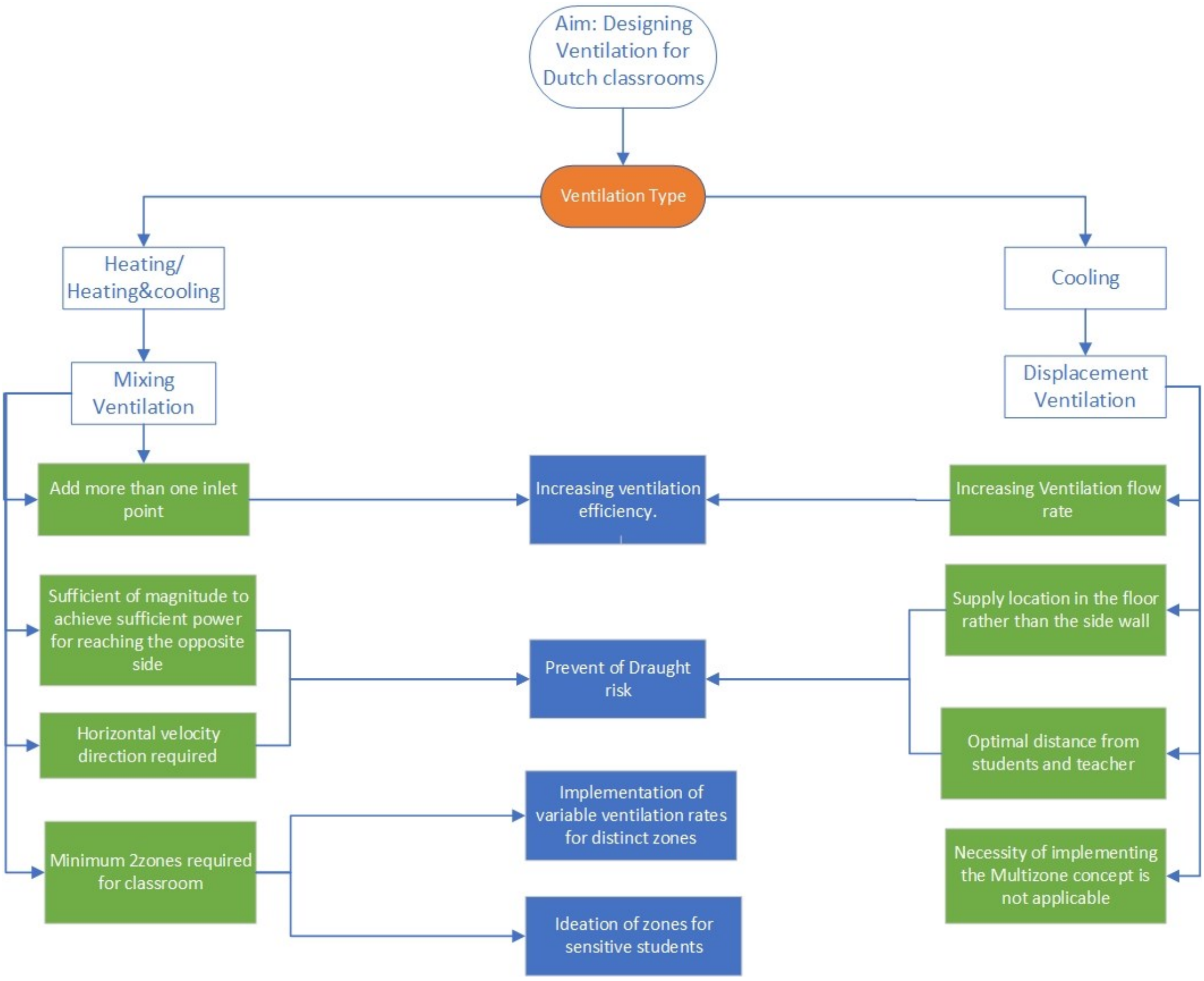


Figure 26: Flow Diagram for Designing Ventilation Systems: Highlighting Key Considerations and Solutions for Mixing and Displacement Ventilation Systems.

Important notes for designing displacement ventilation:

•The impact of exhaust location on ventilation effectiveness is around 4 percent

•Air change efficiency is lower in winter because of temperature differences, and it can be solved by enhancing air flow in classroom

•The location of the supply in the classroom does not affect ventilation efficiency.

Important notes for designing mixing ventilation:

•Importance of supply height from the ceiling in preventing air falls in the middle of a classroom.

•The location of the supply in the classroom does not affect ventilation efficiency

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Appendix A. Natural Ventilation and Mechanical Ventilation

1.1 Natural Ventilation

Natural ventilation is a passive approach that relies on wind pressure and temperature differences to drive airflow through openings such as windows, doors, and vents [33]. This ventilation method is particularly attractive for school buildings due to its energy-efficient nature, low operating costs, and smaller environmental footprint [33]–[35].

1.1.2 Challenges of natural ventilation

- Variable airflow: The driving forces behind natural ventilation, wind pressure, and temperature differences, are inherently variable and can lead to inconsistent airflow rates and difficulty in maintaining optimal indoor conditions [33].
- Climatic limitations: In extreme climatic conditions, such as very cold or hot environments, natural ventilation may not provide sufficient thermal comfort without supplementary heating or cooling systems [33], [35].
- Noise and security concerns: Openings required for natural ventilation, such as windows, may introduce outdoor noise and present security risks, particularly in urban settings or ground-floor classrooms [33].
- Limitations in air distribution: Achieving even air distribution and maintaining the desired indoor conditions can be challenging, particularly in large or complex spaces, with natural ventilation systems [33].

1.1.3 Advantages of natural ventilation

- Energy efficiency: Natural ventilation systems have minimal energy requirements, as they do not rely on mechanical equipment such as fans or pumps [33]–[35]. This results in lower energy consumption and associated greenhouse gas emissions, contributing to a smaller environmental footprint.
- Cost-effectiveness: Reduced energy consumption and the absence of complex mechanical systems lead to lower operating and maintenance costs for natural ventilation systems, making them an economically attractive option [34], [35].
- Improved indoor air quality: By providing a continuous supply of fresh outdoor air, natural ventilation helps dilute indoor pollutants, contributing to a healthier indoor environment for building occupants [33].

Despite the numerous advantages of natural ventilation, there are limitations, particularly in regions such as the Netherlands. Due to the unique climatic conditions and other factors, natural ventilation may not always provide optimal indoor air quality and thermal comfort for occupants. In addition to that, in case of heating, there is no option to recover heat that is removed by the natural ventilation.

1.2 Mechanical ventilation

A mechanical ventilation system is an engineered solution designed to control indoor air quality and maintain thermal comfort by actively regulating the flow of air within a building or enclosed space. It comprises various components, including fans, ductwork, air handling units, filters, and control systems, that work in together to ensure the efficient circulation, distribution, and exhaust of air [33]–[35].

Mechanical ventilation systems can be categorized into two primary types: supply (or positive pressure) systems and exhaust (or negative pressure) systems. Supply systems introduce fresh, filtered outdoor air into the space, while exhaust systems remove stale, contaminated indoor air [33], [36]. In many cases, these systems are combined to form a balanced mechanical ventilation system, where the inflow of fresh air is equal to the outflow of stale air, maintaining consistent air pressure within the space [36].

The performance and efficiency of a mechanical ventilation system are contingent upon several factors, such as the design of the air distribution system, fan types and sizes, filtration efficiency, and the control mechanisms implemented.

1.2.1 Advantages

- Precision control: Mechanical ventilation allows for precise control over indoor conditions, such as air quality, temperature, and humidity, resulting in improved thermal comfort and a healthier environment for building occupants [34], [35].
- Integration with other building systems: Mechanical ventilation can be seamlessly integrated with other building systems, such as heating, cooling, and air filtration, to enhance overall energy efficiency, indoor air quality, and occupant comfort [34].
- Consistent performance: Unlike natural ventilation, which relies on variable driving forces, mechanical ventilation systems can provide consistent and reliable performance, ensuring a stable and comfortable indoor environment [34].

1.2.2 Challenges

- Energy consumption: Mechanical ventilation systems typically have higher energy consumption compared to natural ventilation, which may increase operational costs and contribute to a larger environmental footprint [33]. However, in case of a balanced ventilation solution, heat recovery may be applied, reducing the need for heating.
- Maintenance requirements: Regular maintenance, such as filter replacement and duct cleaning, is necessary to ensure optimal performance and prevent potential issues related to mechanical ventilation systems [33].

Appendix B. Mixing Ventilation and Displacement Ventilation

2.1 Mixing Ventilation Overview

Mixing ventilation is a widely used mechanical ventilation system that functions by introducing conditioned air into the space at a high velocity, typically near the ceiling. This method ensures effective mixing of the conditioned air with the existing room air, providing consistent and uniform indoor conditions. By maintaining a high level of thermal comfort and air quality, mixing ventilation systems can cater to the needs of diverse applications, including schools and offices [36].

2.2.2 Advantages and Challenges of Mixing Ventilation

One of the key advantages of mixing ventilation is its, assumed, ability to create consistent and uniform indoor conditions. By mixing conditioned air with the existing room air, it intends to ensure a high level of thermal comfort and air quality for occupants [36]. Furthermore, mixing ventilation systems offer flexibility, as they can be easily adopted to various building types and layouts. This versatility makes them a popular choice for diverse applications, including schools [36], [37]. Another advantage is the integration with other building systems. Mixing ventilation can be effectively combined with heating and cooling systems [36], [37].

However, there are also challenges associated with mixing ventilation systems. One such challenge is the distribution of airborne pollutants. Since the system relies on diluting the contamination, rather than directly removing them, it may not be as effective in addressing localized sources of airborne contaminants [36]–[38]. Additionally, energy consumption can be an issue, as mixing ventilation systems often require more energy to maintain uniform conditions compared to displacement ventilation, particularly in large or complex spaces. Lastly, the potential for drafts or uncomfortable air movement exists due to the high-velocity air jets generated by the diffusers. Proper design and positioning of the diffusers are essential to minimize this issue [36]–[38].

2.2 Displacement Ventilation Overview

Displacement ventilation is a specific approach to mechanical ventilation characterized by distinct operational principles and features. The system is engineered to introduce conditioned air into the space at a relatively low velocity, typically from diffusers situated at or near floor level. The low-velocity supply air gradually ascends as it absorbs heat from interior sources such as occupants, electrical equipment, or incident solar radiation. The resulting airflow pattern is one of vertical stratification, with air temperatures increasing with elevation within the room. Furthermore, the ventilation strategy makes use of the natural buoyancy of heated air to transport airborne contaminants upward and away from the occupied zone, eventually being exhausted through high-level exhausts [34], [36]–[38].

2.2.1 Advantages and Challenges of Displacement Ventilation

One of the most significant advantages of displacement ventilation is the improved air quality it offers. By introducing conditioned air at a low velocity near the floor level and allowing warm, contaminated air to rise and be exhausted through high-level exhausts, this system effectively removes contaminants and delivers better indoor air quality in the occupied zone compared to mixing ventilation [36]–[38]. In addition to these benefits, displacement ventilation systems can be more energy-efficient than mixing ventilation systems, especially in spaces with high heat loads or large internal volumes [36]–[38].

On the other hand, displacement ventilation also encounters some challenges. In colder climates, displacement ventilation systems are not able to provide sufficient heating, as the warm air tends to rise and will then be exhausted near the ceiling. As a result, the occupied zone will stay cooler [36]–[38].

Appendix C. Modelling and Simulation of 2D Fluid Flow Using CFD

3.1 Methodology and Results

The geometry of the space being modelled, including any boundaries or structures that affect airflow, was defined using Design Modeler applications to create and manipulate geometric shapes.

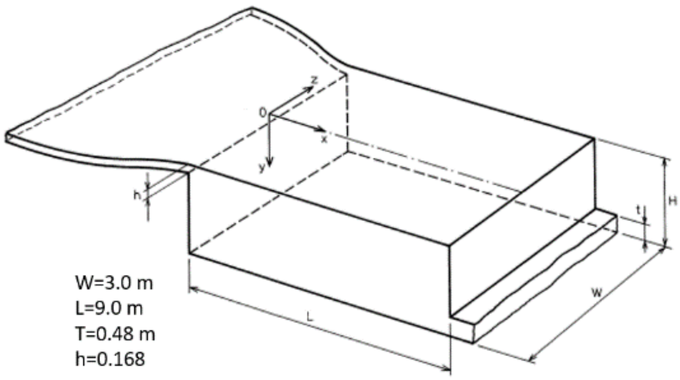

Figure 27: Schematic Representation of the 2D Model [39].

To ensure accuracy in representing the specific scenario being investigated, a 2D model was developed and validated using real experimental data provided by Nielson in 1990 [39]. The model assumed an isothermal case with two sensor locations, where the temperature of the fluid was kept constant throughout the simulation. This simplification enabled easy analysis and comprehension of the model [39]. Specification of a two-dimensional test case. Additionally, the geometry and grid for the simulation were set up by defining the boundaries, fluid properties, and other parameters essential for the simulation. Figure 28 displays the two sensor locations, x_1 and x_2, along with their corresponding points for reference.

Figure 28: Schematic Cross-Section of the Demonstration Room Highlighting the Positions of Two Sensors, Indicated as X1 and X2

Once the geometry has been defined, the next step is to create a mesh. Meshing involves dividing the geometry into discrete cells, which enable the software to calculate airflow through the space and also grid sensitivity is also done to understand best grid in 2D model. The left image shows coarse mesh, and the middle image is reference mesh and the right image show fine mesh.

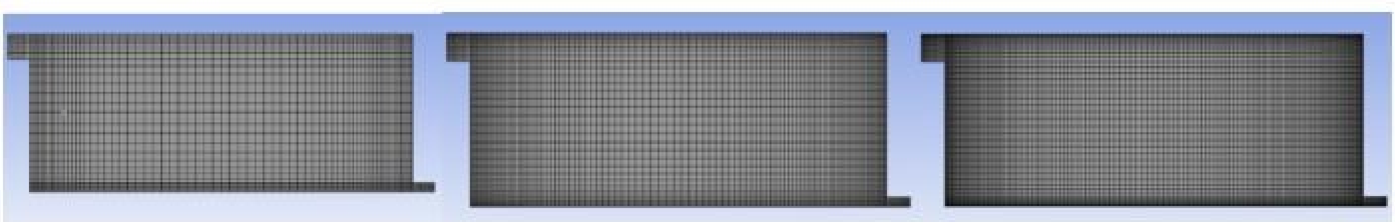

Figure 29: three structured mesh model. left image (a) shows the coarse mesh and middle image is reference mesh and the right image (b) shows the fine mesh

Figure 30 illustrates the difference in velocity between two types of mesh, as well as the corresponding experimental data. This figure provides a visual representation of how the velocity changes when different mesh types are used, based on the experimental data collected at points x_1 and x_2.

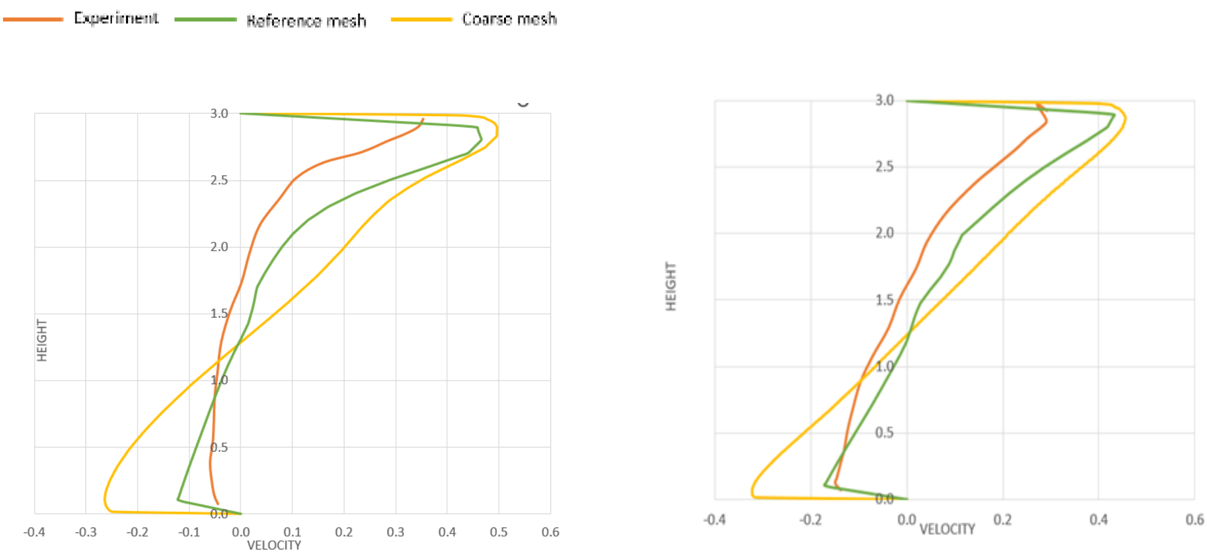

Figure 30: Comparison of Experimental Results and Computational Predictions from Coarse and Reference Meshes for the Velocity.

In Figure 31, there is a velocity diagram that represents the movement of air in the room. The diagram shows that the velocity of the air is highest near the supply. This means that the air is entering the room at a high speed, which can help to distribute it more evenly throughout the space. As the air moves away from the supply, the velocity decreases, which can cause the air to stagnate in certain areas of the room.

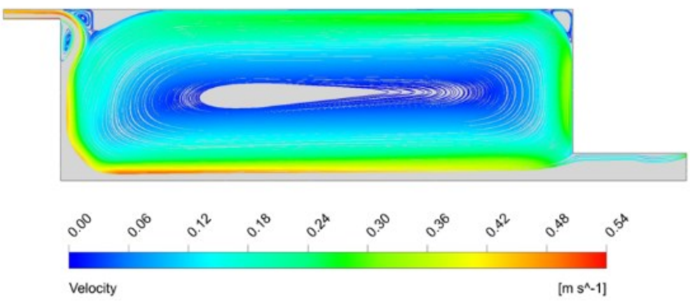

Figure 31: Diagram Depicting the Velocity Distribution of Airflow within the Room

3.2. Modeling and Simulation of 3D Fluid Flow Using CFD: Methodology and Results

The second step in the process is to create a 3D model of the room, in order to make a prediction of the temperature stratification within the room when it is equipped with one heat source and displacement ventilation. The paper "CFD simulation of stratified indoor environment in displacement ventilation by Gilani [40]: Validation and sensitivity analysis" presents a computational fluid dynamics (CFD) simulation study of the temperature stratification within a room with displacement ventilation. The goal of the study is to validate the simulation results with reference data and to analyse the sensitivity of the results to different parameters such as the position of the heat source and ventilation openings [40].

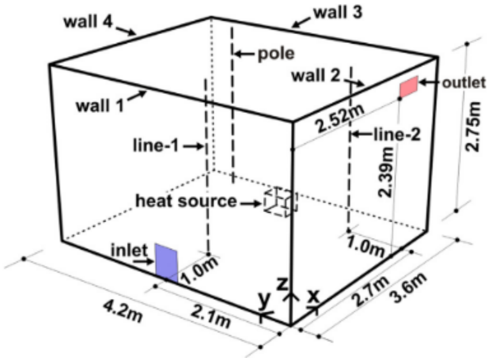

Figure 32: Geometry of the test room: position of the supply and exhaust openings, heat source and line-1, line-2, and line-3 [40]

The study aims to improve the understanding of the thermal dynamics of rooms with displacement ventilation and to inform the design and operation of such spaces. In order to assess the impact of the computational grid resolution on the results, a grid-sensitivity analysis was conducted. Two additional grids were created by refining and coarsening the original grid with an overall linear factor of √2. The finer grid contained 1,348,853 cells, while the coarser grid had 178,054 cells.

The profiles of the age of air were obtained for the three grids along the pole and two other vertical lines. For the age of air, the deviations were about 3.5% and 2.4%, respectively. The average age of air for the three grids was found to be about 32.5, 32.6, and 32.0 minutes, respectively, with a deviation of about 1.2% for both the coarse and fine grid from the reference grid. To ensure uniform reporting of this grid convergence study, the Grid-Convergence Index (GCI) by Roache was used [31], [32], as illustrated in Figure 33. The results revealed that the deviation was more pronounced for the lower parts of the pole, line-1, and line-2, while for other parts of these lines, the deviation was negligible. Therefore, the reference grid was retained for further analysis.

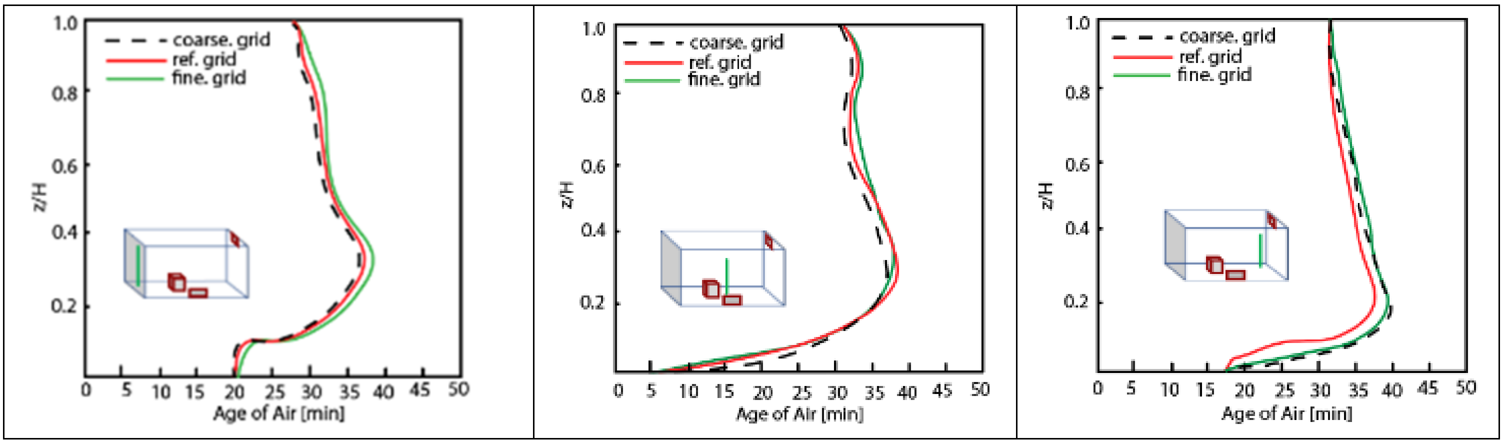

Figure 33: Impact of grid resolution on age of air, along three vertical lines

Compared to the reference data, the CFD simulation results are close to experiment data. As a result, it was concluded that the location of the heat source, as well as the ventilation openings in the room, can play an important role in determining temperature stratification in the room, and a properly designed room can result in better thermal comfort by improving thermal stratification in the room.

Appendix D. Calculation age of air in Ansys CFX

Ansys CFX does not automatically include the mean age of air as a predefined variable. The following methods can be used to define it as an additional variable during the pre-processing stage: The following section provides some background and additional information. [41].

T_{mean} is the mean age of air determined by solving the advection equation:

$$\frac{DTmean}{Dt} = 1$$

The derivative of the source with respect to time is 1, implying that the integral is equivalent to time. Therefore, upon integration, the age scalar will reflect the residence time [41].

In the context of Ansys CFD solvers, scalar quantities are incorporated into the transport equations by multiplying them with the density symbol, denoted as rho (ρ) [41]. Hence, in this specific scenario, the appropriate equation to apply would be:

$$\frac{D(\rho T_{mean})}{Dt} = \rho$$

To compute the 'Age of Air' within Ansys CFX, it is essential to first establish a new variable within the 'Expression, Functions, and Variables' tree, as found in the CFX-Pre module. For our purposes, this novel variable will be designated as 'Age of Air' and will be measured in units of seconds[41].

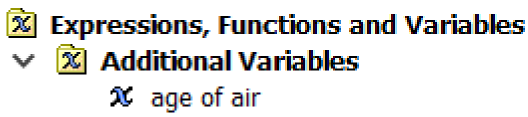

Figure 34: Representing expressions in CFX.

In CFX-Pre, an additional variable is added.

Figure 35: Step-by-step process for calculating 'Age of Air' within Ansys CFX using the CFX-Pre-module.

A transport equation is solved within Ansys CFX for the newly introduced variable 'Age of Air'. A description of this process can be found under 'Fluid Models', specifically under 'Additional Variable Models'. Given that the age of air doesn't undergo diffusion, it's not required to define a 'Kinematic Diffusivity' for it. It's important to note that Ansys CFX includes turbulent diffusion as a default setting [41].

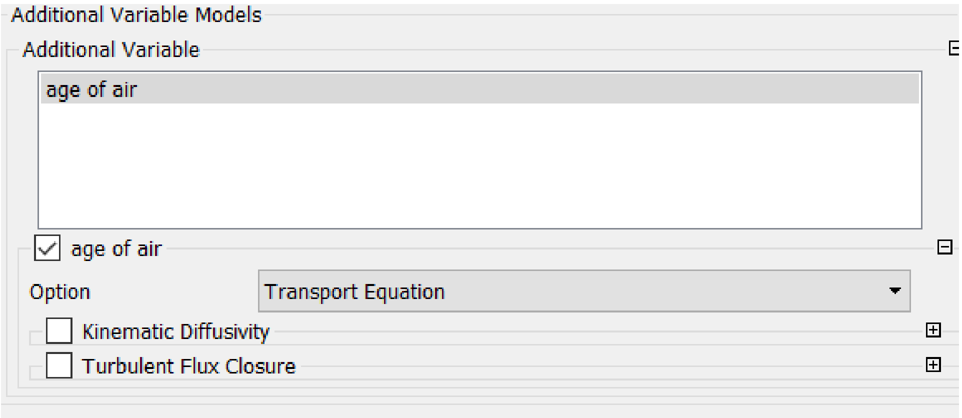

Figure 36: The 'age of air' variable within Ansys CFX, with a focus on transport Equation solution

By defining the 'Source' to be 1, we create a subdomain under the Default Domain.

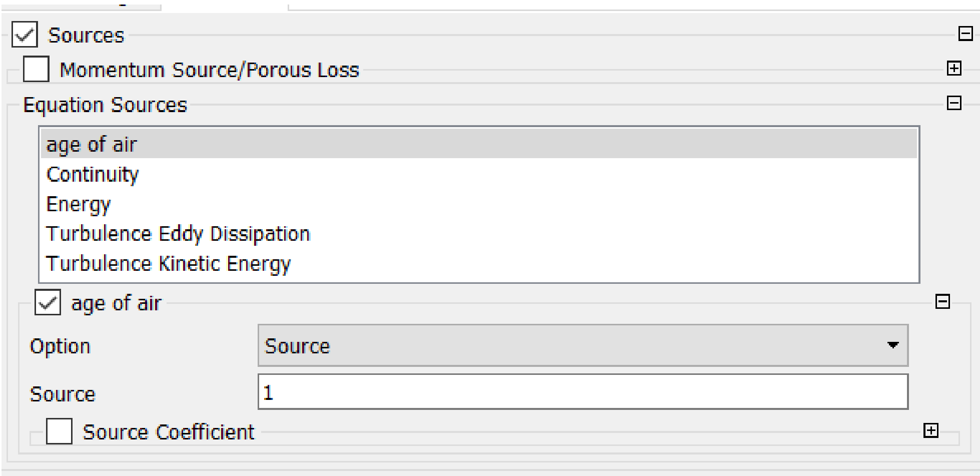

Figure 37: Creation of subdomain with 'source' defined as 1 in Ansys CFX.

In Ansys CFX, the final step is to set the Age of Air at any boundary conditions where air can enter the domain. For this example, the age of air at the diffuser and exhaust (for any return flow) is set to 0 [s] [41].