YAŞAR UNIVERSITY
GRADUATE SCHOOL

MASTER THESIS

WIND – DRIVEN

CROSS VENTILATION DESIGN AND SIMULATIONS

FOR A NATURALLY VENTILATED CLASSROOM

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INTERIOR ARCHITECTURE

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ABSTRACT

WIND DRIVEN CROSS VENTILATION DESIGN AND SIMULATIONS FOR A NATURALLY VENTILATED CLASSROOM

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Natural ventilation is a well-known ventilation method that can improve indoor air quality and energy efficiency. This study investigates wind driven cross – ventilation effectiveness for an existing classroom. A hypothetical window is placed across the windward windows to enhance the effect of cross – ventilation, and the existing windows' sizes and placement are modified to discern which configuration works best for this classroom. The study is composed of 17 simulations implemented in computer generated simulation program called ANSYS Fluent. The results present that while vertical distance between inlet and outlet openings do not affect airflow rate when the prevailing force is wind, it is definitely affected by inlet – outlet ratio. The hypothetical window not only improves airflow, but it also creates new air paths inside the space. The study also introduces that window sizes and placement can be designed considering occupant comfort and needs.

Key Words: natural ventilation, cross ventilation, wind driven, fenestration, CFD simulation

ÖZ

DOĞAL HAVALANDIRILMIŞ BİR SINIF İÇİN RÜZGAR TAHRİKLİ ÇAPRAZ HAVALANDIRMA TASARIMI VE SİMÜLASYONLARI

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Doğal havalandırma, iç mekan hava kalitesini ve enerji verimliliğini arttıran ve iyi bilinen bir havalandırma yöntemidir. Bu çalışma, mevcut bir sınıf için rüzgar tahrikli çapraz havalandırmanın etkinliğini araştırmaktadır. Çapraz havalandırmanın etkisini arttırmak için rüzgar tarafındaki pencerelerin karşısına varsayımsal bir pencere yerleştirildi ve mevcut pencerelerin boyutları ve yerleri, bu sınıf için hangi yapılandırmanın en iyi sonucu verdiğini görmek için değiştirildi. Çalışma, ANSYS Fluent adı verilen, bilgisayarda çalışan bir simülasyon programında uygulanan 17 simülasyondan oluşmaktadır. Sonuçlar, giriş ve çıkış açıklıkları arasındaki dikey mesafenin hakim kuvvet rüzgar olduğunda hava akış hızını etkilemediğini, ancak giriş açıklığı ve çıkış açıklığı oranından kesinlikle etkilendiğini ortaya koymaktadır. Varsayımsal pencere yalnızca hava akışını iyileştirmekle kalmaz, aynı zamanda sınıf içinde yeni hava yolları da oluşturur. Çalışma ayrıca pencere boyutları ve yerleşiminin bina sakinlerinin konforu ve ihtiyaçları dikkate alınarak tasarlanabileceğini de ortaya koyuyor.

Anahtar Kelimeler: doğal havalandırma, çapraz havalandırma, rüzgar tahrikli, pencere düzeni, CFD simulasyonu

ACKNOWLEDGEMENTS

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I would like to express my enduring love to my parents and my two sisters from the bottom of my heart. I am forever grateful for their support through my seemingly never-ending education.

Lastly, I would like to thank all those people who motivated and supported me to continue. Without them, I would not be able to see the way ahead; all of these impending future prospects have been a great incentive for me to keep trying, and finally achieving.

Elif Gündoğdu

İzmir, 2020

TEXT OF OATH

I declare and honestly confirm that my study, titled "WIND DRIVEN CROSS VENTILATON DESIGN AND SIMULATIONS FOR A NATURALLY VENTILATED CLASSROOM" and presented as a Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Elif Gündoğdu

Signature

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September 25, 2020

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

ACH	Air Change Rate
CO_2	Carbondioxide
DFR	Diluting Flow Rate
IEQ	Indoor Environmental Quality
IAQ	Indoor Air Quality
I/O	Inlet – Outlet Ratio
RMS	Root – Mean – Square
VOC	Volatile Organic Compounds
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
EPA	Environmental Protection Agency
WHO	World Health Organization
TSE	Turkish Standards Institution
REHVA	Representatives of European Heating and Ventilation Associations

SYMBOLS:

V	Control volume
S	Source term
Φ	Dependent variable
ρ	Density
Γ	Diffusion coefficient
A	Cross sectional area
V	Convective velocity
a	Width of model

b	Height of model
q	Airflow rate
m	Meter
m^3	Meter cubes
m/s	Meter per second

CHAPTER 1
INTRODUCTION

1.1. Aims and Objectives of Thesis

Natural ventilation is a passive ventilation method that people have been using for centuries. On the other hand, there are more to it that designers and occupants still do not know about. Natural ventilation design does not only affect indoor airflow, but it subsequently influences indoor air quality, indoor thermal temperature, and indoor environmental quality as well. This is the reason why design is important for the fluctuations in indoor airflow because indoor design is mostly a subject of socio-cultural traditions. Interior design varies from culture to geographical locations, and recent built environment is not usually up to date with human comfort needs.

One of the aims of this thesis is to understand the relation between indoor airflows and design choices through literature surveys and computer-generated simulations. First-hand data are collected from the simulation of the existing space, that the window openings are same as it is. Other first-hand data are devised from hypothetical environments derived from the existing space. These two data sets are analyzed and compared to create a relationship between indoor airflow and interior design, concurrently realizing the comfort of the occupants.

The second aim is to examine the effect of different window configurations to natural ventilation of interior space. This study is also completed in computer generated simulation program as a hypothetical space. The data is acquired from secondary data and are added into the first-hand study. Different window configurations are devised to achieve an optimization for the certain climate and occupant needs.

1.2. Scope and Constraints

The purpose of this study is to understand how natural ventilation is transferred into the interior space, and how it moves around when different window positions and sizes are implemented. The space is a university classroom of 83 m^2. The study derives conclusions from total of sixteen simulation scenarios and one simulation of existing space.

The study examines and expresses natural ventilation aspects, methods, and drivers; also, how natural ventilation is integrated into design in human scale. This study questions how design choices affect our everyday life, also consequently regarding natural ventilation.

The simulations are created on the CFD program called ANSYS Fluent. Additionally, the simulations' boundary conditions, element numbers etc. are derived in compliance with existing second – hand data. The hypothetical window designs are created considering second – hand data.

This study focuses on window dimensions and their vertical placement on the wall that encounter only perpendicular wind force. The space is located geographically in Mediterranean climate; however, due to time constraints, thermal, humidity, solar radiation, and occupant factors are not included in this study.

1.3. Method and Structure of the Thesis

First part of the study explains the aims and objectives, scopes and constraints, and method of the thesis and thesis structure. Second part of the study includes secondary data introducing natural ventilation. The literature survey is conducted through the servers the university library offers. The keywords for the survey include "natural ventilation", "natural ventilation methods", "indoor ventilation", "energy", "Indoor Air Quality" or "IAQ", "natural ventilation and interior design", "interior design and indoor ventilation" and so forth. The guidelines such as ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers), EPA (Environmental Protection Agency), WHO (World Health Organization), TSE (Turkish Standards Institution), and REHVA (Representatives of European Heating and Ventilation Associations) are benefited immensely while developing this study.

Second part of this study covers the definition of interior ventilation, interior ventilation methods and principles, effects of natural ventilation to health and to energy consumption, furthermore, it comprises secondary research conducted on interior design and indoor airflow.

The third part of the study describes the system of the case studies and the building which the case studies took place. The required ventilation rates and wind velocity in indoors through several guidelines are discussed in this chapter.

The fourth part of the study is comprised of the case studies implemented in the CFD program called ANSYS Fluent 2019 R3. Academic. The simulations of each case study are performed for a university classroom of an 83,16 m^2 area, with 64 occupants. First case study is carried out as it is in the realized classroom. The other case studies are conducted with redesigned opening configurations.

Fifth part of the study presents and discusses the results of the simulations in light of the secondary data, considering the certain climate of Mediterranean and occupant comfort. This part presents the results as numerical data and visual data in several tables.

The study is concluded with a sixth part, where all first – hand and second – hand data are discussed. This part also presents several future plans of the author as a researcher.

CHAPTER 2
NATURAL VENTILATION

Second chapter of the study aims to elaborate natural ventilation, the chapter starts with introducing natural ventilation and its objectives. In sub-headings, natural ventilation methods, significance of natural ventilation on Indoor Air Quality, on health and on energy efficiency are explained thoroughly with secondary inputs.

Natural ventilation is a passive ventilation method used to introduce fresh air inside and to remove harmful contaminants away from the interior space (Ji, Tan, Kato, Bu, & Takahashi, 2011). Since it is a passive system, it can lessen energy costs comparing to what mechanical ventilation systems consume, given that natural ventilation ensures acceptable thermal conditions and consistent Indoor Air Quality (IAQ) for occupants (Emmerich, Dols, & Axley, 2001; Nikas, Nikolopoulos, & Nikolopoulos, 2010; Wang, Wang, Zhang, & Battaglia, 2017). Natural ventilation can be defined as the ventilation produced by wind, thermal or diffusion forces or combination of each force through windows, doors, or internal openings of the building (Emmerich et al., 2001). The placement of windows and solar radiation exposure are one of the important factors of correct designed natural ventilation other than the shape of the building and interior design (Cardinale, Micucci, & Ruggiero, 2003).

Natural ventilation objectives could be to:

- Control IAQ by removing harmful contaminants from the interior space to replace it with fresh and uncontaminated outdoor air (Air Quality Control),
- Cool the interior space directly by replacing warm indoor air with cool out-door air provided that the indoor air temperatures are higher than outdoor air temperatures (Direct Advective Cooling),
- Cool the occupants directly by guiding cool outdoor air over occupants through convection and evaporation (Direct Personal Cooling),

- Cool the interior space by cooling thermally convective elements of the building or the thermal storage of the building with cooler air of night (In-direct Night Cooling) (Emmerich et al., 2001; Kleiven, 2003).

Accordingly; air quality control, direct cooling, and indirect cooling are the most often studied subjects in literature (Emmerich et al., 2001).

Natural ventilation occurs in two different ways, namely single-sided and cross-sided ventilation, see Figure 2.1; concurrently the air movement occurs due to the pressure difference caused by the combination of separate or simultaneous wind and buoyancy effects (Dascalaki et al., 1996; Jiang, Alexander, Jenkins, Arthur, & Chen, 2003). Natural ventilation is determined by wind velocity, wind direction and temperature; and these elements can change recurrently (Bangalee, Lin, & Miau, 2012), thus making the calculation of natural ventilation more complex. Aside from these parameters, shape and dimension of the openings can affect the pressure difference, hence the ventilation rate (Evola & Popov, 2006). In literature, the application of natural ventilation is depicted to be affected by external and internal factors. External factors include urban form, building position and orientation, and microclimatic conditions. Internal factors are floor layout, opening configurations (window – wall ratio and window – floor ratio), and louver angles in apertures (Aflaki, Mahyuddin, Awad, & Rizal, 2014; Gao & Lee, 2011). Other than these frequently studied elements, there are also some aspects that are rarely investigated. These elements include different shapes of louvers for the highest ventilation and different shape and form of apertures for the greatest divergence on pressure (Aflaki et al., 2014).

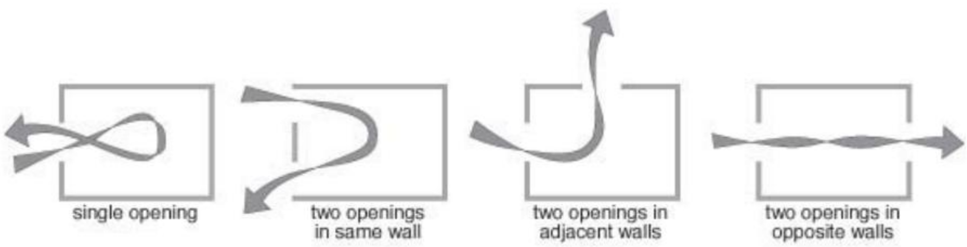


Figure 2.1. Single-sided and cross-sided ventilation methods (Reprinted from "Relevant indoor ventilation by windows and apertures in tropical climate : a review study" by A. Aflaki, N. Mahyuddin, Z. A. M. Awad, and M. Rizal, 2014, *E3S Web of Conferences*, *3*. Copyright by the authors.).

The advantages of implementing natural ventilation into a building can be summed up as decreased operation costs, enhancement in the thermal comfort degree, and acceptable IAQ (Aflaki, Mahyuddin, & Mahmoud, 2015).

2.1. Natural Ventilation Methods

Natural ventilation methods are reviewed under the subtitles of wind driven and buoyancy driven ventilation. Wind driven ventilation occurs from the pressure differences caused by wind forces and buoyancy driven ventilation occurs from the pressure differences caused by the temperature discrepancy between outside and inside environments. In general, these two forces emerge at the same time. Wind driven ventilation involves single – sided ventilation and cross ventilation. Buoyancy driven ventilation can also be named as stack ventilation (Emmerich et al., 2001).

2.1.1. Wind Driven Ventilation

Wind driven ventilation occurs from the pressure differences caused by wind forces between leeward and windward side. Windward side is the face of the façade that encounters wind force, and leeward side is the face that do not exactly happen upon wind force. Wind driven ventilation consists single sided ventilation which is the ventilation that occurs only with the apertures on the same wall and cross ventilation which results in the occasion where two or more apertures are on adjacent or facing walls.

2.1.1.1. Single – Sided Ventilation

In general, simple rooms of buildings have one façade that opens to the outside air, if the room door is not open, which is often the case as shown in Figure 2.2. Single – sided ventilation emerges when the building has only one wall with openings interacting outside air thus providing local ventilation (Dascalaki et al., 1996; Emmerich et al., 2001). In single sided ventilation method, the defiant nature of wind generates fluctuating airflow (Dascalaki et al., 1996), as a result, single – sided ventilation can produce less air flow than cross – ventilation; therefore, the placement and proportions of single-sided openings should be carefully considered (Jiang et al., 2003). The width of the wall that the single sided window(s) are on should be 2.5 times of the floor height; furthermore, the total area of the windows should be 5% of the floor surface (Emmerich et al., 2001).

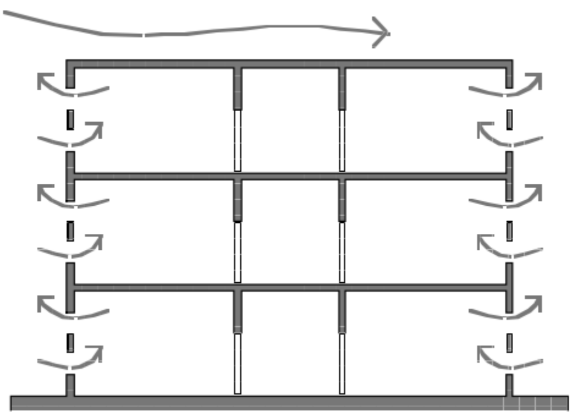


Figure 2.2. Single-sided ventilation within a building (Reprinted from *Natural Ventilation Review and Plan for Design and Analysis Tools* (65), by S. Emmerich, W. S. Dols, J. Axley, 2001, Gaithersburg, Md.: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.).

Single – sided ventilation is generally driven by three forces; wind forces, buoyancy forces and the combination of both forces (Wang et al., 2017). In most cases, rather than a single force, both forces operate concurrently and resolve in an airflow (Wang et al., 2017), since these parameters are irregular, airflow in a single sided ventilation is in a fluctuating manner (Ai & Mak, 2014; Freire, Abadie, & Mendes, 2013). Furthermore, in single sided ventilation method, the opening acts both as an inlet and an outlet for the airflow at the same time (Bangalee et al., 2012), as a result of these occurrences, driving forces for single-sided ventilation are inclined to be small and extremely variable (Emmerich et al., 2001). Additionally, single-sided ventilation is also affected by wind turbulence (Ai & Mak, 2014).

Chu, Chiu, Tsai, and Wu (2015), studied wind-driven natural ventilation for two openings on one façade using tracer gas decay method. Their findings imply that when the wind incidence angle was between 22.5 and 45°, the air change process was directed by pressure difference, and when the angle was 0°, the process was produced by fluctuating pressure. It was also obtained that the air change rates (ACH) were higher for a building with two openings than a single opening on the same façade. Chu et al. also express that ACH is correlated with the opening area and wind speed. In addition to attaining these results, they studied the effect of an internal wall, realizing that for the wind incidence angle of 0-90°, the existence of an internal wall reduced ACH. As for leeward side, the internal wall didn't affect ACH as much as did for the windward side of the wall (Chu, Chiu, Tsai, & Wu, 2015).

Dascalaki et al. (1996) studied single sided ventilation for a single room with a large opening as the size of a door. They studied different wind speed and wind directions in four different experiments. Their study revealed that when the opening is on the windward side, the air change rate is especially higher than of the leeward side (Dascalaki et al., 1996). Contrasting this study, Jiang et al. (2003) expressed in their single-sided ventilation study – conducted in a wind tunnel – that the air change rate was higher for the leeward side opening rather than windward side opening. They explained this as for a wind driven single-sided ventilation the airflow inside fluctuate with wind directions, so the ventilation rates change variably. Correspondingly their wind-tunnel experiment indicated that the air movement in the leeward opening cells were more intense than that windward opening cells. Their laser Doppler anemometer (LDA) measurements also suggested that inside the leeward side opening there were much higher velocities and turbulence (Jiang et al., 2003). Evola and Popov (2006) also justified this circumstance with a grain of salt, they remarked that in their single-sided ventilation study, the airflow in the opening on leeward side were stronger than that windward side opening, resulting in a larger ventilation rate (Evola & Popov, 2006).

Ai, Mak and Cui (2015) studied on on-site measurements of a high-rise building in Hong Kong. Their results revealed that in any orientation of the building and configuration of the opening, the single-sided ventilation supplied the suggested ASHRAE (62-2010) air change rates for a prevailing wind speed of 3.0 – 4.0 m/s (Ai, Mak, & Cui, 2015).

A wind tunnel study that investigated the effects of wind velocity and wind direction on thermal comfort concluded in their CFD simulations and experiments that rather than two centered adjoint openings, single sided ventilation performed better in a situation where the windows placed far left and far right. (Hassan, Guirguis, Shaalan, & El-Shazly, 2007).

Buoyancy forces can be the leading force for single – sided ventilation. In the study of

Tang, Li, Zhu, and Cheng (2016) this circumstance is investigated. They studied single sided ventilation in China for primary school classrooms. According to their research, airflow rates were affected by buoyancy forces rather than wind forces when temperature differences and wind pressure were low at the same time (Tang, Li, Zhu, & Ceng, 2016).

2.1.1.2. Cross Ventilation

This method uses pressure differences between windward and leeward sides more than single – sided ventilation method. Cross – ventilation happens in the case the building has many openings across different façades, whether adjacent or facing walls, and every movement of the wind raises a pressure variance amidst two sides (Jiang et al., 2003; Kleiven, 2003). This way, the air is transferred from windward side to leeward side (Kleiven, 2003), Figure 2.3 illustrates this case in detail drawing. Cross-ventilation is limited to the depth of the building to be effective adequately, therefore it should be regulated to remove pollutants and interior heat (Emmerich et al., 2001; Kleiven, 2003). For wind-driven cross ventilation, depth of the building can be up to 5 times of the ceiling height (Emmerich et al., 2001; Kleiven, 2003). The cross ventilation usually occurs with the existence of open windows (Emmerich et al., 2001)

Cross ventilation moves horizontally and require a wind flow that is created by pressure differences (Wahab, Ismail, Abdullah, Rahmat, & Salam, 2018). Where there are trivial temperature differences between indoor and outdoor environments, cross ventilation is the more effective method to be used; as buoyancy forces would not be as much effective (Aflaki et al., 2015). On the creation of air pressure ventilation, building walls play a great role (Aflaki et al., 2014). Aflaki et al., 2014, express in detail that when the airflow is obstructed by the windward side building walls it creates high pressure, while on the leeward side of the building the pressure is lower than windward side. Therefore when there is an opening on the walls the air streams from positive pressure on the windward side to negative pressure on the leeward side (Aflaki et al., 2014; Li, 2012).

Jiang et al. studied single – sided ventilation and cross ventilation. Their study showed that while a reverse flow was detected along the ground of single -sided ventilation when the opening was on the windward side, there was no such a situation for cross ventilation case when the opening was on the windward side (Jiang et al., 2003).

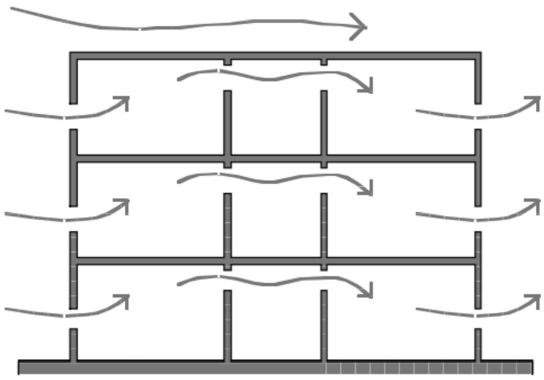


Figure 2.3. Cross ventilation within a building (Reprinted from *Natural Ventilation Review and Plan for Design and Analysis Tools* (65), by S. Emmerich, W. S. Dols, J. Axley, 2001, Gaithersburg, Md.: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.).

Bangalee et al. (2012) studied single sided ventilation of two openings on the same wall and cross ventilation of four openings in two facing walls. They present in their study that air velocity is higher in cross ventilation than single sided ventilation (Bangalee et al., 2012).

In the complex cross-ventilation study of Nikas et al. (2010), it was revealed that when the wind incidence angle arises the inlet flow rate decreases no matter the wind speed level (Nikas et al., 2010), meaning that perpendicular winds have the highest airflow rate.

Gao and Lee (2011) studied natural ventilation of residential units in Hong Kong. They studied 96 window-door configurations. Their study showed that if two adjacent or facing aperture groups were to open, better natural ventilation performance could be attained (Gao & Lee, 2011).

These studies demonstrate that cross ventilation is a great way to naturally ventilate an interior space, whether the openings are adjacent or facing. This circumstance suggests the question: on how the opening size should be designed. Larger openings that encounter wind forces perform more prominently than larger outlets in the leeward side, for cross ventilation, larger inlet performance is better than with a larger outlet; as it provides greater ventilation rate (Tantasavasdi, Srebric, & Chen, 2001). In this study Tantasavasdi et al. (2001), states that when the inlet – outlet ratio (I/O) is two; the ventilation rate is almost 10 m^3/s, and when this ratio is swapped, the ventilation rate drops to 6.5 m^3/s (Tantasavasdi et al., 2001).

2.1.2. Buoyancy Driven Ventilation

Buoyancy is another force used to naturally ventilate interior spaces. The temperature differences between indoor and outdoor air results in a density difference, thus creating thermal buoyancy-driven ventilation (stack ventilation) as airflow (Emmerich et al., 2001; Kleiven, 2003; Wang et al., 2017). The pressure difference created by density variance pulls the warm indoor to discharge it at higher openings, or rather outlets (Emmerich et al., 2001; Kleiven, 2003). Chimneys and atriums are commonly used elements to enhance buoyancy-driven ventilation (Emmerich et al., 2001), Figure 2.4 shows a building illustration that effectively utilizes an atrium.

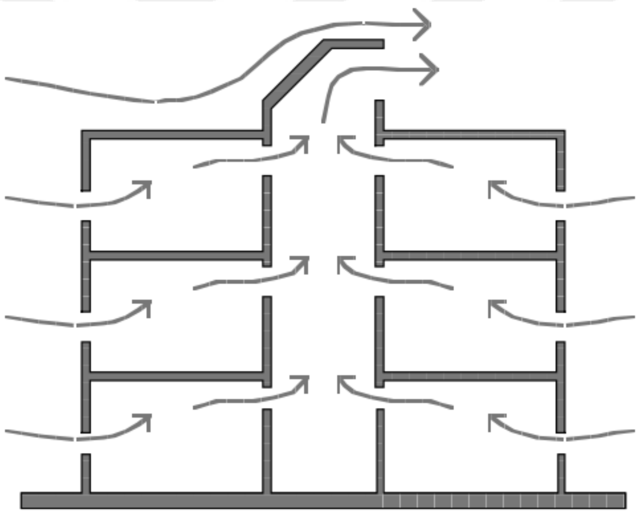


Figure 2.4. Stack ventilation within a building (Reprinted from *Natural Ventilation Review and Plan for Design and Analysis Tools* (65), by S. Emmerich, W. S. Dols, J. Axley, 2001, Gaithersburg, Md.: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.).

Buoyancy driven ventilation moves vertically, depending on air pressure differences between two points at different levels (Wahab et al., 2018). Outdoor air – indoor air temperature difference and height difference between openings are two main essential dynamics for the stack ventilation to be efficient (Aflaki et al., 2015; Hussain & Oosthuizen, 2013). On the other hand, even a negligible amount of wind flow cause air pressure distributions on building envelope that effect the airflow; meaning that wind effect may be more important than buoyancy effect in stack ventilation (Emmerich et al., 2001).

Hussain and Oosthuizen (2013), studied pressure differences caused by thermal differences in a building with an atrium using a validated CFD model. The simulations in the study revealed that in the case of buoyancy-driven ventilation, the outdoor air surges into the indoor space mixing with indoor air. The study revealed that ventilation performance is dependent on ventilation time and indoor-outdoor air temperature difference (Hussain & Oosthuizen, 2013).

2.2. Significance of Natural Ventilation

Natural ventilation is an effective way of ventilating that provides natural and fresh air to indoor environments in a sustainable method. Indoor environmental elements gain greater importance when occupants spent more and more time inside. Air quality is an important element of indoor environment, which can be rather uncomfortable if factors like body odor, CO_2, and VOC (Volatile Organic Compounds) accumulate in the space. Energy efficiency is another matter to manage for more sustainability. This title explains air quality and energy efficiency as a promise of natural ventilation.

2.2.1. Indoor Air Quality (IAQ)

Indoor air quality is the first aspect of natural ventilation that presents itself as a significant benefit. IAQ is an important factor of IEQ that has short and long – term impacts on the health of occupants (Wargocki et al., 2002b; cited by Al horr, 2016). ANSI/ASHRAE (20013) defines acceptable indoor air quality as the “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction” (ANSI/ASHRAE Standard 62.1-2013). In 2006, Fanger presents an alternative to directly define IAQ, using the human sensory response. This definition describes high IAQ as “the perceived air accepted by a large percentage of people” (Fanger, 2006). Moreover, poor indoor environment leads to health problems such as asthma, hypertension, sick building syndrome (SBS), hypertension and even neurodevelopmental abnormalities (Krieger & Higgins, 2002).

2.2.1.1. Indoor Pollutants

Indoor pollutants are certainty in wherever humans inhabit. Indoor environment consists a large amount of pollutants diffused from occupants, outdoor environment, building material, and also office equipment (Al horr et al., 2016; Bakó-Biró, Wargocki, Weschler, & Fanger, 2004; Bluyssen, Fernandes, Clausen, & Roulet, 1996). Also, indoor activities like cooking, smoking and chemical compounds inside building materials are sources of indoor air pollution. The contaminants from building materials (such as wall paints and varnishes) can diffuse into the air in small numbers (Wanner, 1993), and can result in further complications when interacted with temperature and humidity (Jones, 1999). These followings are non-biological pollutants from various sources commonly found in the indoor environment; asbestos, CO_2, carbon monoxide (CO), formaldehyde (HCHO), nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), radon, respirable particles, VOCs, and if it is not a commercial building, tobacco smoke (Jones, 1999). Furthermore, there are pollutants from biological sources such as fungi, bacteria, and viruses (Jones, 1999). As IAQ is an essential issue for schools; molds, bacteria, allergens, particles, volatile organic compounds (VOCs), and formaldehyde may aggravate IAQ (Zhao et al., 2008; cited in Turunen et al., 2013).

Humans are always on move, and breathing is essential to be alive. CO_2 is a colorless gas that humans and animals emit by breathing. For outdoors, CO_2 concentration level is constant and is between 350-450 ppm, while for indoors this level depends on the ventilation of the indoor environment and the number of sources that discharge CO_2. Accordingly, the indoor CO_2 concentration levels are between 500-1500 ppm (Seppänen & Fisk, 2004). In a pamphlet, ASHRAE remark the standards for CO_2 concentration level of indoor air as 700 ppm (ASHRAE, n.d.) and 1000 ppm is the threshold for unacceptable ventilation rates (Blondeau, Spérandio, & Allard, 2002; Madureira et al., 2009). This concentration levels depends on the ventilation rate, number of occupants, the duration of occupants staying in that specific environment and also the room volume (Seppänen & Fisk, 2004).

ASHRAE (2013) states that maintaining a CO_2 concentration level no greater than 700 ppm indicates that majority of occupants in the space will be satisfied regarding body odor; a detailed discussion referring the relationship between CO_2 concentrations and the perception of bio – effluents is contained in the ASTM Standard D6245.C-8;

stating that acceptable outdoor CO_2 concentration levels are between 300 and 500 ppm (ASHRAE, 2013).

2.2.1.2. Controlling IAQ

Indoor air might feel unpleasant; therefore, one may need to change the situation. There are two common strategies to control IAQ, one is to increase the ventilation rate, which consecutively reduces the pollutant rates in the indoor air (Al horr et al., 2016; Daisey, Angell, & Apte, 2003). Table 1 presents the adequate levels for pollutants issued in EPA and WHO guidelines. The second is to reduce the pollution source inside and outside of the environment (Al horr et al., 2016). Therefore, it is possible to say that since natural ventilation can enhance ventilation rate, it can be recognized as a method to amplify IAQ (Reyes, Moya, Morales, & Sierra-Espinosa, 2013).

Table 1. Standard Values for Indoor Air Pollutants (Adapted from Yüksel, 2018; Yurtseven, 2007).

POLLUTANTS	EPA (Environmental Protection Agency)	WHO (World Health Organization)
CO	9 (ppm)	9 (ppm)
CO_2	1000 (ppm)	1000 (ppm)
VOC	3 (ppm)	1-3 (ppm)
Temperature	22,5-25,5 (°C)	22,5-25,5 (°C)
Humidity	≤ 70	≤ 70

Moreover, the standards that establish regulations regarding IAQ usually define acceptable IAQ within the percentages of 15%, 20% or 30% of people being dissatisfied, and therefore designate completory ventilation. Hence, reducing these percentages would require increasing IAQ by a factor of 20, or more; however, if this rate is to be obtained, excessive amount of ventilation is required (Fanger, 2006). Therefore, Fanger (2006), presents these methods to improve IAQ:

- Source control,

• Air cleaning,

• Personalized ventilation, and

• Providing cool and dry air. (Fanger, 2006).

2.2.2. Natural Ventilation and Energy Efficiency

Energy is an imperative necessity to human life. Buildings employ energy both in construction process and during it is inhabited to supply electricity, lighting, and most importantly, ventilation. On the other hand, natural ventilation is a bio – climatic strategy used in both vernacular and modern buildings (Chandel, Sharma, & Marwah, 2016). Natural ventilation is used to cool a building, and this aspect of natural ventilation helps the cost of energy to drop.

The study of Tantasavasdi, Srebric and Chen in 2001 investigating energy savings of natural ventilation showed that in a hot and humid country like Thailand, use of natural ventilation can provide 20% energy saving even in winter, also the indoor air quality can be enhanced immensely (Tantasavasdi et al., 2001).

Cardinale et al. (2003) investigated two semidetached two-story residential buildings in Mediterranean climate, dispatched in three different parts of Italy. They simulated the buildings in a software called AIOLOS, providing size, construction materials, and thermal characteristic data for the software. It was found that for the three sites called Bologna, Ancona and Alghero, an energy saving of 52%, 41% and 46% was found respectively for each site. They concluded that if the designer knows the consequences for each design choice and designs accordingly, natural ventilation can provide a decrease in energy consumption used for cooling and environmental pollution (Cardinale et al., 2003).

2.3. Effects of Interior Design to Ventilation

Interior design is a form of social and cultural manner of life. Therefore, its form and needs change from society to environmental differences. Many people spend their time indoors (Klepeis et al., 2001), this being the case, the interior design is usually a very subjective aspect, however, it does have effects on IEQ and energy demands (Sarkar & Bardhan, 2018). Although interior design is an important feature for an appropriate indoor environment, there is still a downside to it that has to be improved; and it is to optimize interior design layout for natural ventilation conditions (Sarkar & Bardhan, 2019).

Effects of wind and buoyancy forces can be enhanced using architectural elements such as façade elements and apertures (Aflaki et al., 2015). In indoors, the wind speed is affected by outdoor buildings and the interior design which can block the airflow, e.g. misplaced furniture layout and improper indoor design can result wind – channeling effects in indoors, enhancing the unhealthful indoor conditions (Sarkar & Bardhan, 2019). For engineers, indoor layout is not thoroughly considered as a way to heat and cool a building, such as using connected rooms or windows (Stoakes, Passe, & Battaglia, 2011), consequently, the design of interior space that favors natural ventilation is on the shoulders of designers.

IEQ can be improved by modifying the indoor space through scholarly approaches during preconstruction and postconstruction, with optimized interior design and furniture layout, indoor ventilation for appropriate thermal conditions can be maintained (Sarkar & Bardhan, 2019). The air encounters many obstacles like furniture as it flows through indoor space; for instance, taller furniture and indoor partition walls impede the passing wind and downwash it to lower levels, and likewise, furniture create higher and lower micro-level pressure on their facing sides (Sarkar & Bardhan, 2019). On the other hand, some indoor adjustments like raised kitchen floors could improve indoor airflow and occupant comfort (Aflaki et al., 2015). Building corridors are also architectural elements that allow cross ventilation inside the building (Aflaki et al., 2014).

Sarkar and Bardhan (2019) studied optimal indoor layout options for low-income residents in Mumbai, India. The CFD simulations clarified that with proper indoor design, the indoor ventilation, thus thermal comfort can be improved. They proceeded that natural ventilation operations also have positive effects on the occupants' electric bills (Sarkar & Bardhan, 2019).

Stoakes, Passe, and Battaglia (2011) studied the ventilation rates and thermal comfort of the Esherick House by famous architect Louis I. Kahn. The double story house is designed on purpose to operate natural ventilation inside, when the wooden shutters on rear and front side of the house are open, they compatibly modify the flow inside the house. Also, the interior layout does not have many obstructions to block airflow. With the help of open plan of the upper floor, when the shutters on the east side are open, the house cools down in a mere 10 seconds. Higher ceilings, open plan, position of the staircase and proficiently placed shutters improve the natural ventilation, hence the cooling of the house (Stoakes et al., 2011).

In another study, the indoor airflow of two work of Le Corbusier -lower E and upper E Marseilles- is investigated in CFD. The results showed that lower E unit layout provide sufficient cross ventilation. The staircase and height of the units direct the wind flow from lower floor to upper floor while not reducing the velocity of the flow. On the other hand, after 6.5 m into the depth of the lower E unit, the flow is blocked by the partition of the space. Additionally, some occupants changed the original design of the lower E unit by extending the middle floor to the glass curtain wall, cancelling the two storey arrangement of the unit, this situation caused a discontinuity in the internal flow (T. Zhang, Zhu, & Shang, 2011).

The review study of Wahab et al. (2018) of Malaysian houses showed that proper design could improve the internal air flow and enhance the thermal comfort of occupants (Wahab et al., 2018). High ceilings in indoors, apertures below roofs -acting as windcatcher units-, and high windows improve the buoyancy driven ventilation. Some occupants deployed solid fences around the houses for privacy purposes, however they claim that the fences block the wind at some levels that would produce cross ventilation. They concluded that indoor walls could create windward – leeward side of wall concept to occur in the building owing to air pressure differences (Wahab et al., 2018).

Air flow changes direction or is hindered by interior layout, whether furnishing or walls, and every opening redirects the airflow (United States Environmental Protection Agency (EPA), 2009). Occupants generate CO_2 and transports pollutants involuntarily; their activity and behavior change the direction of the flow. Therefore, thinking the corridors, rooms and passages as an air distribution system might be sustainable and energy efficient (EPA), 2009).

CHAPTER 3
SYSTEM DESCRIPTION AND CASE STUDY DESCRIPTION ACCORDING TO VENTILATION TARGETS

This chapter aims to clarify the study through the mediums that are utilized, the classroom, the building that the classroom is in and the university that all study is realized. Later into the chapter, the case studies that this study is composed of are described in detail. In the second chapter ventilation rates were referred briefly, therefore this chapter addresses adequate ventilation rates and elements that influence ventilation rates as supplementary material.

3.1. Yaşar University

Yaşar University was found in 2002, located in the city of İzmir. The university provides bachelor's and graduate level education to over 10,000 students. Yaşar University was also the first university in Turkey to be awarded with a TS EN ISO 50001: 2011 Energy Management System (ENYS) standard certificate in 2016. The university is greatly concerned about the consumption of energy and is focused on to improve energy efficiency for all the university ground.

3.2. Architectural Features of the Building Called 'T'

T building is built in a distance from the main university ground. The building was ready to service in 2017. The building primarily consists classrooms with 26% of the whole building, which is the second largest space in the building and used more frequently than the others, as can be seen from the Table 2. The floor height for the building is 3.50 m, however, with suspended ceiling, the height is lowered down to 2.9 m.

Figure 3.5.The T building has four façades (Image: Yildirim, Gundogdu, & Kahraman, 2019).

Figure 3.6. The building this study takes place in is Yaşar University building T (First image: Yildirim, Gundogdu, & Kahraman, 2019).

Table 2. Utilization of T building (Adapted from Sekerci & Yildirim, 2019).

Building	**T Building**	
Space Name	**Utilization area (m^2)**	**Utilization percentage (%)**
Classrooms	2230.3	25.9
Laboratories	656.3	7.6
Offices	1246.0	14.4
Conference rooms	406.0	4.7

Space Name	Utilization area (m^2)	Utilization percentage (%)
Amenity spaces	284.9	3.3
Restrooms	289.1	3.4
Corridors	2246.0	26.0
Other	1267.0	14.7
Total	**8625.6**	**100.0**

3.3. Ventilation Rates and Ventilation Factors

Ventilation rates are significant to natural ventilation effectiveness. According to the European Norm 15251 (2007), it is possible to create a design for different categories of Indoor Air Quality, that affects required ventilation rates (Catalina & Iordache, 2012; European Standard EN 15251, 2007). The categories of air quality can be expressed in different kinds of ways, such as combination of ventilation for people and building components, ventilation per m^2 floor area, ventilation per person or according to required CO_2 level. Air movement inside a building is affected by the building's façade, form, aperture and orientation; additionally, temperature, humidity, airflow pattern and air velocity affect the flow around and within the building (Aflaki et al., 2015). Window size and window position on the wall are two main prospects that affect ventilation rates.

When a classroom is occupied, outdoor air should be continuously provided to satisfy occupants comfort (United States Environmental Protection Agency (EPA), 2009). 10 m^3/h airflow per person (2.77 L/s) is the minimum requirement (Catalina & Iordache, 2012), nonetheless, in a place where cross ventilation is operated, a small amount of indoor airflow such as 0.04 m/s could also improve the thermal comfort of occupants (Aflaki et al., 2015). An increase above 10 L/s per person in ventilation rates is related to decrease in the sick building syndrome (SBS) occurrence (Calautit & Hughes, 2014). ASHRAE Standard 62.1 (2013) states that ventilation rate for per occupant should be 3.8 L/s at minimum in university lecture halls (ASHRAE, 2013). Table 3 and Table 4 presents the needed area for per person and air mass flow rate for different room types. TS-EN 15251 (2008) states that for classrooms this rate should be between

2,0 and 5,0 L/s (TSE, 2008), another study states similar ventilation rates for classrooms between 2,4 and 6 L/s for a comfortable indoor space (Olesen, 2004).

Table 3. The default occupancy intensity is examples of recommended ventilation rates for non-residential buildings (Adapted from TSE, 2008).

Room Type	Floor Area, m^2/person	L/s, Full Occupancy
Office for one person	10	1,0 – 0,4
Open office	15	0,7 – 0,2
Conference hall	2	5,0 – 2,0
Auditorium	0,75	15 - 6
Classroom	2,0	5,0 – 2,0

A layout providing an air velocity between 0.2 and 1.08 m/sec in indoors could improve thermal comfort of occupants (Dear & Brager, 2002; Nicol & Humphreys, 2002; Sarkar & Bardhan, 2019).

The limits in Table 4 are for designers and engineers to evade draft and provide occupant satisfaction, however or warmer climates these requirements may not be achieved (Arens et al., 1998; Candido, Lamberts, Dear, & Bittencourt, 2011; Khedari, Yamtraipat, Pratintong, & Hirunlabh, 2000; Tanabe & Kimura, 1989; H. Zhang et al., 2007). For operative temperatures of 24 °C – 31 °C, the minimum wind velocity should be between 0.50 m/s and 0.9 m/s to attain 90% of occupant acceptance (Candido et al., 2011).

ASHRAE 62.1 (2013) recommends 0.25 m/s for occupant sitting height, around 1.2 m from floor level (ASHRAE, 2013). Air velocity between 0.76 and 1.014 m/s across the occupants can cool the body of the occupant (ASHRAE, 2015). On the other hand, every person emit CO_2 into the closed space, even with an airflow rate of 7.5 L/s per person, where each person also produce 18 L/h of CO_2, CO_2 concentration would be 650 ppm above outdoor concentration levels, which is very close to ventilation standards (Persily, 2015). Furthermore, as the metabolism of each occupant differs from others, CO_2 generation rates might also vary with age, size, and their level of activity among the occupants (Persily, 2015).

Table 4. Recommended ventilation rates and air velocity for different room types (Adapted from Olesen, 2004).

Room Type	**Occupancy person/m²**	**Maximum average air velocity m/s**		**Ventilation L/s-m²**
		Summer	**Winter**	
Office for one person	0.1	0.18 – 0.25	0.15 – 0.21	2.0 – 08
Open office	0.07	0.18 – 0.25	0.15 – 0.21	1.7 – 0.7
Conference hall	0.5	0.18 – 0.25	0.15 – 0.21	6.0 – 2.4
Auditorium	1.5	0.18 – 0.25	0.15 – 0.21	16 – 6.4
Classroom	0.5	0.18 – 0.25	0.15 – 0.21	6 – 2.4

Window sizes and positions on façade influence the ventilation rates inside. As it is unfeasible to manipulate outdoor conditions (wind, temperature, humidity), designing window opening size and position may be a more practical way to affect indoor airflow (Papakonstantinou, Kiranoudis, & Markatos, 2000).

Usually, sizes and placement of fenestration are set up according to the design requirements rather than scientific studies represent. The study of Papakonstantinou et al. (2000) shows that the smaller the opening is, the exchange rates become lower (Papakonstantinou et al., 2000). Confirming this finding, Ai et al. revealed that smaller openings increase pulsating flow, resulting in a lower air change rate (Ai et al., 2015).

Dascalaki et al. (1996) studied single sided natural ventilation for a room with an opening as large as a common door. They analyzed the airflow using hotwires. They stated that the flow through the large opening is bi – directional, as there are two airflows going one below and one above a neutral level in the opening (Dascalaki et al., 1996).

In a later study, Jiang and Chen (2003) studied buoyancy driven single-sided natural ventilation for a room with a small and a relatively large opening. They measured air velocity using anemometers at different heights. Their study revealed that both for larger and smaller openings the airflow distributions were very similar to each other. On the other hand, temperature difference, the air velocity at the lower part of the opening and the root – mean – square (RMS) velocities at the lower part of the opening were higher for smaller opening compared to the case of larger opening. They expressed that these differences confirm that for the smaller opening instance, the airflow changes were stronger as the result of higher temperature difference (Jiang & Chen, 2003).

In 2011, Ji et al. studied wind driven cross-ventilation in a wind tunnel. They studied on wind speed and opening size combinations, finding that the airflow rate and the diluting flow rate (DFR) were affected by wind speed, wind direction and opening size. For the same wind speed cases, as the opening got larger, the airflow rate arose as well. As for the cases with the same opening size but different wind speeds, as the wind speed arose, the airflow also enhanced significantly (Ji et al., 2011).

Window placement is another factor that affects ventilation rates. Ai and Mak (2014), studied single sided ventilation for a multi – story building in Hong Kong. The study revealed that the rooms located in intermediate levels of the building have smaller air change values. Furthermore, they claimed that the air change values can even differ in the rooms on the same floor. As the most cases, windward rooms' air change value is higher than leeward rooms' air change values. Their study also uncovered that the rooms on different floors experience dissimilar airflow features, such as while a room on the third floor encounter downward airflow, a room on the fifth floor experience an upward airflow. With these findings, they claimed that researches on single rooms cannot be attributed to multi – story buildings (Ai & Mak, 2014).

An important output of the study of Gao et al. (2011) is that natural ventilation was very sensitive to window position changes, subsequently, it is affected by building orientation and door positions (Gao & Lee, 2011).

3.4. The Case Study: Classroom 214

The classroom selected for the case study is in the T building. The building has seven floors and has four façades. All cases for this studied were calculated and simulated for the classroom on the second floor of the building. The classroom is 8.8 meters from the ground. Dimensions of the room are 7.70 meters to 10.80 meters, see Figure 3.10.

Figure 3.7. The windows on South East façade, only two of these windows are operable.

Figure 3.8. The windows on both façades in the classroom.

There are 3 operable windows in the classroom, one on the north façade and two are on the east side of the building; they are top hung type and opens only to a degree of 5%. Windows are 180 cm in height and 110 cm in width, and the door to the classroom is double winged, with 140 cm width and 210 cm height, Figure 3.9. The section views of the classroom are given in Figure 3.11 and Figure 3.12.

(a) (b)

Figure 3.9. (a) The windows open only up to a small degree. **(b)** The doors of the classroom are double winged.

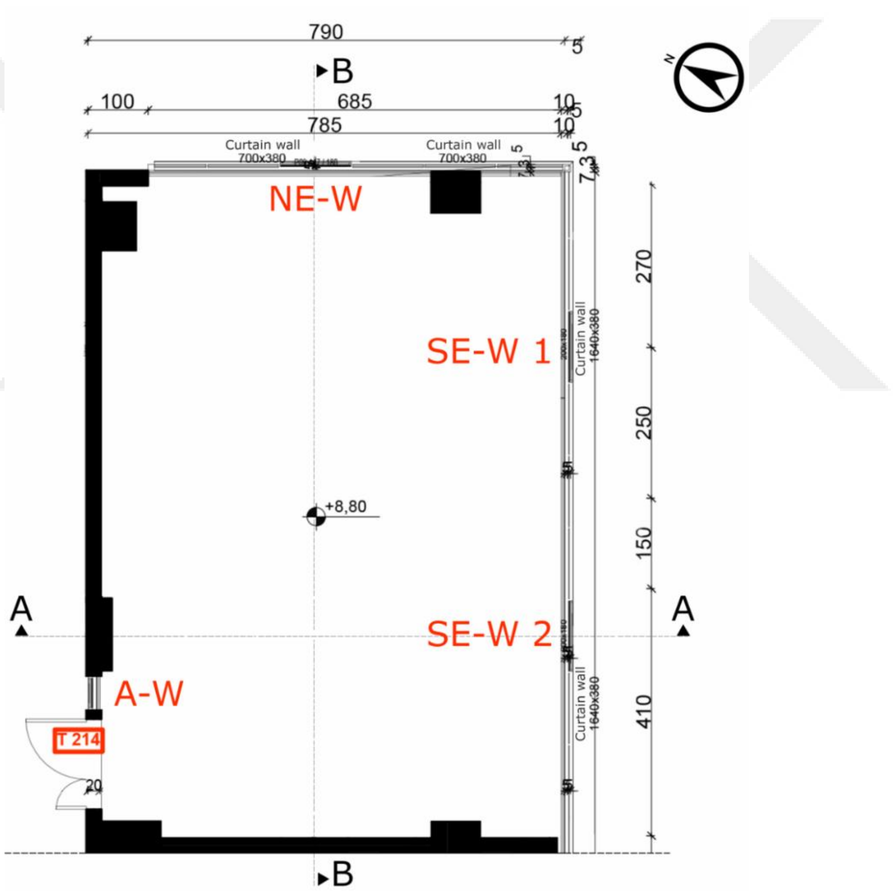


Figure 3.10. The dimensions of the classroom are 7.9 m and 10.8 m. Window names and placements in this study are also given in the figure. Aisle window (A-W) is added as a proposal.

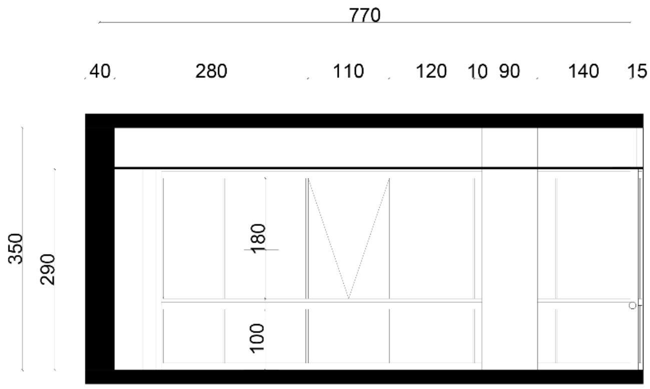


Figure 3.11 Section A of the classroom faces the North East window.

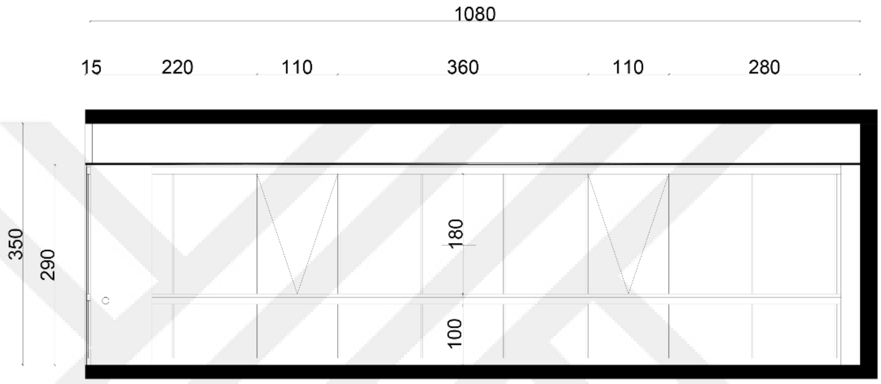


Figure 3.12. Section B of the classroom, looking toward two South East windows.

3.5. Case Studies

For case studies, other than the realized situation, there are some concocted situations. It was believed that the windows of the classroom were open according to the students' needs, and the doors of the classroom shall be closed during lectures. Therefore, a small window near the door wings was assumed to ensure some cross-ventilation flow effects for this room. The names of the windows as they are named in this study are given in Figure 3.10. The details for the concocted window configurations are to be given in this section.

3.5.1. The Geometry of the Case Studies

The geometry and dimensions for the case studies are presented in Figure 4.15. Since only the interior flow is considered in this study, to save calculation time; the height of the geometry is limited to the real size of the classroom; as the geometry gets larger, greater mesh cell numbers (pg. 33) are calculated each time. The bodies leading to inlet are fragmented to three parts to enable mesh component to create lesser mesh cell numbers, see Figure 4.15.

For this study, there are 16 configurations of window size and placement ranging from 45 cm, 90 cm, and 120 cm. The size and placement of the door is not changed for all the case studies. All details of the window sizes and placements are given in the Table 7 before the simulation results of the case studies are introduced.

The base case was designed without the A-W, and as if the doors were closed. The sizes of the windows are as following, for NE-W, SE-W 1 and SE-W 2, 110 x 12,25 cm. Case number 1 is the case with the A-W (aisle window) integrated into the Base Case study, the aisle window size is 45 x 120 cm and 100 cm above floor. For cases 3, 5, and 7-10, the size and the placement of the aisle window stays unchanged. Case 11, 12, and 13 have the aisle window at the height of 10 cm from floor with the size of 45 x 120 cm. The aisle window size is 45 x 200 cm and it is 10 cm from floor for the case studies 14, 15, and 16. The cases numbered 2, 4, 6, and 10 do not have an aisle window just as the Base Case.

For the case studies 2,3, 4, 5, 12, and 16; the sizes of windows NE-W, SE-W 1 and SE-W 2, are 110 x 120 cm. This windows' sizes change to 110 x 45 cm for the case studies 6,7, 8,13 and 14. And finally the window size is 110 x 90 cm for the 9,10,11 and 15 numbered case studies.

The positions of the NE-W, SE-W 1 and SE-W 2 named windows for each case study are as following; for case studies 2 -8, 12-14, and 16, 100 cm above floor level, and case studies 9-11, and 15, 190 cm from the floor level.

These configurations are examined with the composition of open-close situations. In Base Case and Case 1, the doors are closed, however in Case 1 the aisle window is open. In cases numbered 3, 5, 7-9, and 11-16 the aisle window is open. There are also cases where only the doors are closed, which are case 2, 8, 9, 11-16. Case 5 and Case 7 are the only cases which NE-W is closed. In cases 2, 6, and 10 both aisle window and doors are closed. Case 4 is the only case with aisle window closed and doors open.

CHAPTER 4
METHODOLOGY OF SIMULATIONS

In this section, the method for the simulations are explained in detail. First, for easy understanding of the process, the simulation software and its usages are described shortly. Afterwards, the method for the simulations of this study are explained step by step; from crafting the geometry to evaluating the results of the simulations. All of the simulations are created similar to each other. ANSYS Fluent involves many more execution possibilities; however, since explaining all aspects would be lengthy, also, for the purpose of this study, only of those that are employed in the study are described extensively.

4.1. Assumptions and Constant Parameters

- On the second floor of the T building, the corridor the classroom opens up to is 30 m long, and other than the case classroom, there are 10 more classrooms. Since the model contains almost 3 million meshes, it was settled on that only the classroom and half of the corridor were to be modelled and meshed, hence utilizing only four classroom doors on the aforementioned corridor, see Figure 4.13.

- CFD program do not allow the users to employ infiltration. Therefore, there is a 5 cm of gap under each door to provide the airflow proceed without any obstruction and unprecedented turbulence, see Figure 4.13.

- Meteorological circumstances are not considered in this study.

- For all the case studies, effects of any human existence were disregarded.

- For all case studies, steady flow was utilized.

- For all case studies, the wind flow occurred at a 15 m distance from the main calculation zone, namely classroom.

- In discussing the results of the simulations, the air mass flow rate is converted into m^3/h from kg/s which is the default data Fluent provide in results component. The data is converted to m^3/h by adopting the air density ρ as 1,225 kg/ m^3.

- For all case studies, the wind flow occurred from South-East side of the T building with an incidence angle of 90°.

- The literature on CFD calculations dictate that the dimensions of ambient air should be 5X of the main calculation zone. However, since this study is only interested in the interior flow, also to save time, the ambient air was limited to 2.5X of main calculation zone, deeming that the measurements differed only slightly.

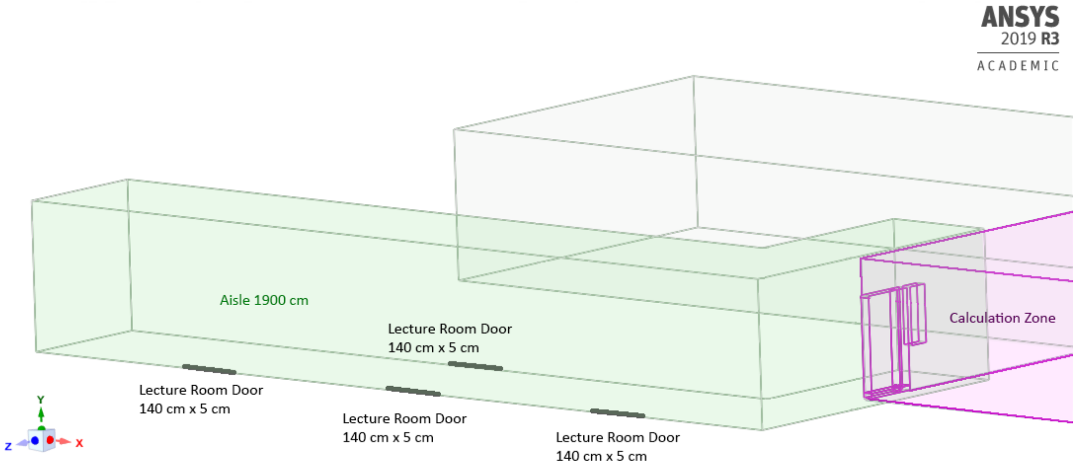


Figure 4.13. Figure shows the aisle and filtration outlets under classroom doors in the aisle (140 cm x 5 cm).

4.2. Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) predicts fluid flow, heat and mass transfer, chemical reactions etc. with the physical properties like momentum, pressure, temperature, density and mass etc. (ANSYS, 2016a; SIMSCALE, n.d.). It generates a virtual solution without any expense for the user (SIMSCALE, n.d.).

ANSYS CFD Fluent solver is based on finite volume method; which's equations is shown in Eq.1.

- Domain is discretized into a finite set of control volumes

- General conservation (transport) equations for mass, momentum, energy, species, etc. are solved on this set of control volumes
- Partial differential equations are discretized into a system of algebraic equations
- All algebraic equations are then solved numerically to render the solution field (ANSYS, 2016a).

Unsteady Convection Diffusion Generation

$$\frac{\partial}{\partial t}\int_V \rho\phi dV + \oint_A \rho\phi \mathbf{V}\cdot d\mathbf{A} = \oint_A \Gamma_\phi \nabla\phi \cdot d\mathbf{A} + \int_V S_\phi dV$$

Eq.1. Finite volume method equation (Adapted from ANSYS, 2016a; De Biase, Feraudi, & Pennati, 1996).

Eq. 1 is the finite volume method equation where V is the control volume, S is the source term, ϕ is the dependent variable, ρ is the density, Γ is the diffusion coefficient, **A** is cross sectional area, and **V** is the convective velocity (De Biase et al., 1996).

4.3. Ansys Fluent

For this study, ANSYS Fluent 2019 R3 Academic (ANSYS, 2019) that is provided by Yaşar University is utilized for the simulations. ANSYS is the producer of simulation programs in engineering simulations. Their software offers solutions for many industries such as aerospace, energy, healthcare, material, and construction. Fluent software provides users to model turbulence, flow, heat transfer and reaction for industrial applications (ANSYS, n.d.). The simulations start from the ANSYS interface called Workbench.

Workbench is the main platform that stores modeling, meshing and simulation setup and result. The Workbench application window contain Toolbox and Project Schematic. In the Toolbox, peculiar simulation analyses are listed, and Project Schematic displays the components of the chosen analysis. For this study, for an easier management, the author used component analysis. Using component analysis is more useful, as components of Mesh and Fluent components can be drag-dropped to Geometry and Mesh components, respectively. This way, one geometry can be used for different mesh types and one mesh type can be used for different Fluent solutions, see Figure 4.14. All analyses are named after the peculiar case names and numbers.

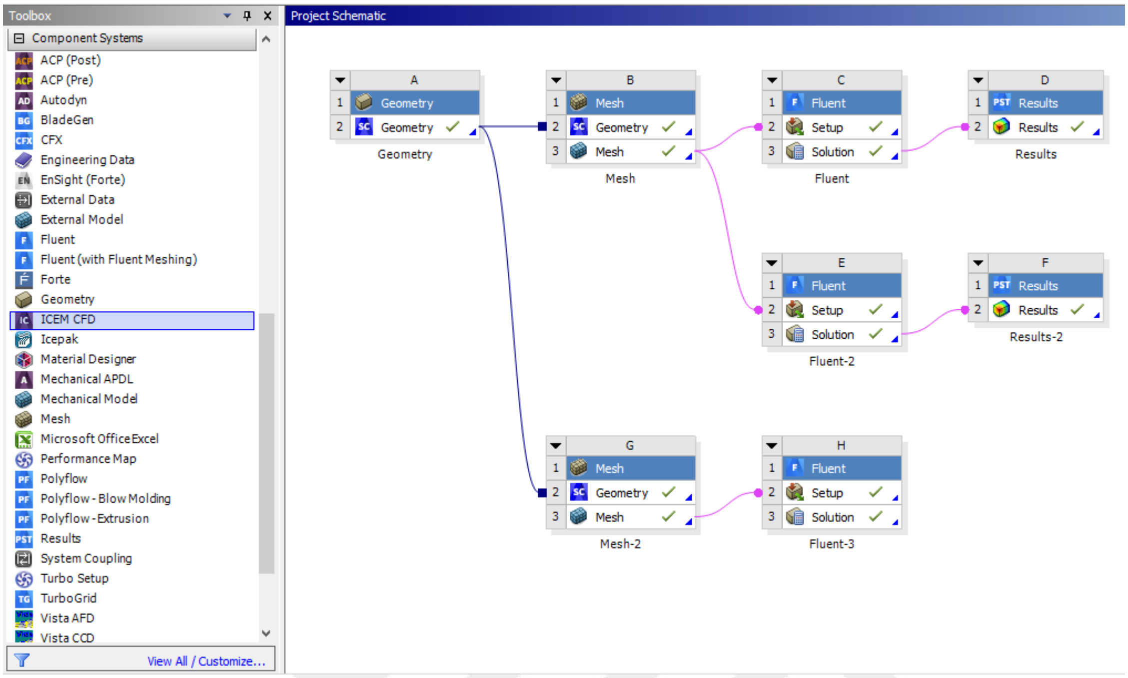


Figure 4.14. Workbench interface is composed of Project Schematic and Task Bar. The workflow of this study is proceeded as dragging each component from Component Systems and connecting them to each preceding one, as seen in the figure.

4.3.1. Geometry Component

Geometry could be imported from other drawing and modeling software, however for this study, SpaceClaim which is launched within Workbench is broadly employed to create the geometry in Figure 4.15. All geometries for all case studies were created in SpaceClaim Tool which comes with the installation of Fluent. All geometries that are modeled here are innately assumed as fluid region in Fluent simulation unless specified otherwise (See Appendix 1 for more information).

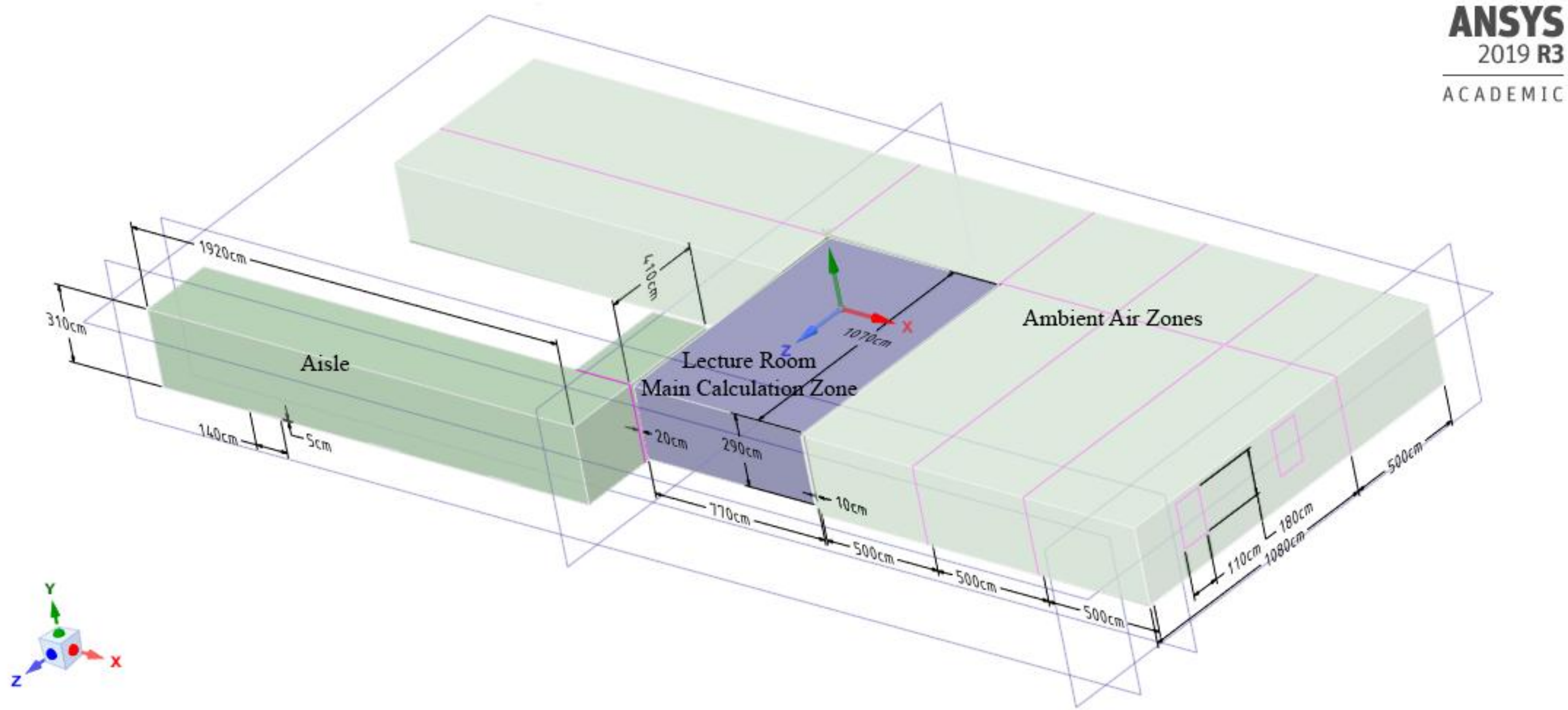


Figure 4.15. Dimensions are given for the geometry of Case studies. The window bodies were remodeled according to the case studies. The dimensions and placements of each window is given in Table 7.

4.3.2. Mesh Component

Fluent simulations are solved by equations of preferred analysis system. These equations are solved at cell locations; therefore, the bodies must be divided into separate cells, and this process is named as meshing.

For efficient meshing, smaller cells (refine meshing) are defined where the high solution is required and larger cells (coarse meshing) are created elsewhere. Mesh quality, in other names, solution precision and stability are profoundly influenced by mesh cell shape and mesh size.

Mesh component can be drag dropped from Component Systems to Project Schematic in Workbench. Outline in Mesh Tool involves a tree system. There are three default sections in the tree, geometry section where the bodies from Geometry component is imported, coordinate systems where the global and user defined systems are listed and lastly mesh section where all meshing operations (global and user defined controls and methods) take place (See Appendix 2 for more detail).

For this study, tetrahedral and hexahedral cell meshes are used. Afterwards, while tetrahedral meshes are converted to polyhedral meshing, hexahedral meshes remained unchanging. This is because it was strived for lesser elements, as 12 tetrahedral cells can be converted into 1 hexahedral cell. ANSYS recommends less elements contribute to faster solution time with better accuracy (ANSYS, 2018a).

Moreover, patch conforming method is used in this study to create denser mesh cells for main calculation zones, such as the classroom and windows.

4.3.3. Fluent Setup and Solution Component

- **Polyhedral Meshing**

Polyhedral meshing is accessible to only CFD / Fluent users. Polyhedral meshing is only available in Fluent or Fluent with meshing component, it is not available in Workbench meshing component (ANSYS, 2018d). Polyhedral mesh is produced by simply clipping to ‘Make Polyhedra’ in Fluent component ribbon.

To make Polyhedral mesh, the Fluent user must use tetrahedral mesh in Workbench meshing component. Fluent creates prism-tetrahedral mesh from triangular surface meshes, which are converted into high quality polyhedral mesh which also supports the inflation layers created in Workbench mesh component (ANSYS, 2018d), see Figure 4.16.

For polyhedral mesh, skewness mesh quality of 1 is accepted (ANSYS, 2018d). For this study, the mesh metrics are as it follows; lowest value of orthogonal quality is 0,19 for orthogonal quality and highest value is 0.89 for skewness; which are acceptable (See Figure A2.37 and Figure A2.38).

There are several advantages of converting tetrahedral mesh cells into polyhedral mesh cells:

- Improved quality,
- Significantly reduced cell count, and
- User control over the process (ANSYS, 2016b).

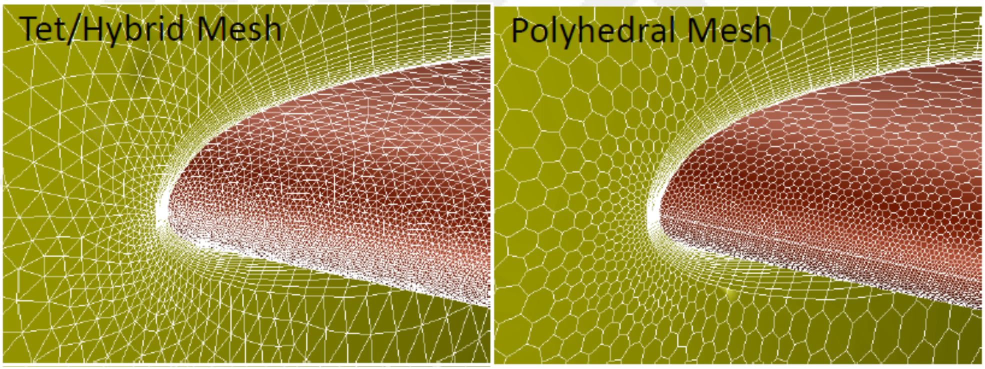


Figure 4.16. Tetrahedral mesh and polyhedral mesh (Image adapted from: ANSYS, 2016b).

For this study, a mix of tetrahedral and hexahedral meshing is employed. In Fluent, while the tetrahedral mesh cells are converted into Polyhedral mesh cells, hexahedral mesh calls remain unchanged. Tetrahedral mesh cells are created in more important calculation zones, such as in the classroom itself, while the ambient air around the room is meshed with hexahedral mesh cells as much as possible, see Figure 4.17.

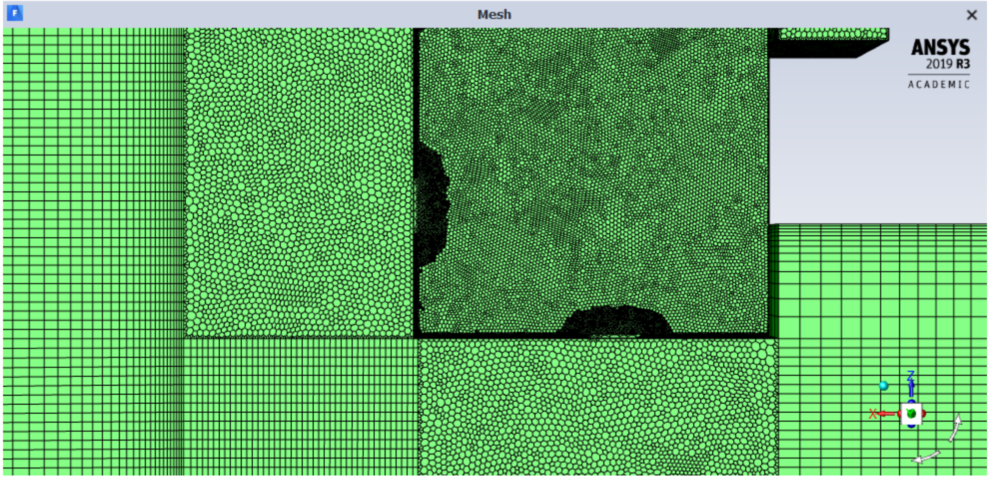


Figure 4.17. Polyhedral mesh cells are created in the Fluent component. The classroom and immediate bodies are polyhedral mesh cells, while other ambient bodies remain hexagonal mesh cells. The dense mesh cells around the windows can be seen from this figure.

4.3.3.1. Fluent Workflow

Basic workflow for this study is as following:

- Setting the domain:
  - Read and check domain (done by Fluent solver)
  - Convert mesh to Polyhedral
  - Set Units
- Setting up the physics:
  - Solver: Setup of basic options
  - Models: Setup energy, viscous (turbulence), heat transfer etc.
  - Materials: Create and edit materials and their properties (solid and fluid materials)
  - Zones: Cell zone and boundary conditions (Changing the type of cell zones accordingly from fluid to solid for each case, and inlet and outlet boundary conditions)
- Solving:
  - Choosing solution Methods and its controls
  - Define reports for convergence checking (0.001 as default)
  - Initialization

- Running the calculation
    - Postprocessing
  - Graphics and plots: Visualization of solution data
  - Reports: Quantitative solutions analyses (ANSYS, 2016b).

- **Setting Up Physics**
  1. Solver Models

There are a couple of models that are used in simulations, energy, radiation, viscous, etc. To proceed a CFD Fluent simulation, the solver model must be viscous (turbulence) model. For an extensive simulation, energy model (for heat transfers) can be added to viscous model.

ANSYS Fluent offers many turbulence models such as laminar, transition, RANS (Reynolds Averaged Navier-Stokes Simulation) based, etc. RANS based models are two-equation models that are widely used for industrial flows (ANSYS, 2016d).

RANS based models are comprised of $k - \varepsilon$ family (Standard, RNG, Realizable) and $k - \omega$ family (Standard, BSL, SST). For standard cases, Realizable $k - \varepsilon$ and SST $k - \omega$ are recommended (ANSYS, 2016d). Realizable $k - \varepsilon$ model is the variant of Standard $k - \varepsilon$ model. The realizability is derived from the changes permitting specific mathematical limitations to be conformed to decisively improving the implementation of the calculation (ANSYS, 2016d). Compared to Realizable model that predicts the size precisely, Standard model underpredicts the size of separation bubble (ANSYS, 2016d), which is the volume enclosed by the regions of separated laminar flow and turbulent flow (Hepperle, 2018).

The solution gradients in near-wall region are very high; therefore, to achieve precise solutions for the aforementioned region, the user can use Near-Wall Treatments (ANSYS, 2016d). For this study, as the viscous sublayer is resolved, Enhanced Wall Treatment is employed, see Figure 4.18.

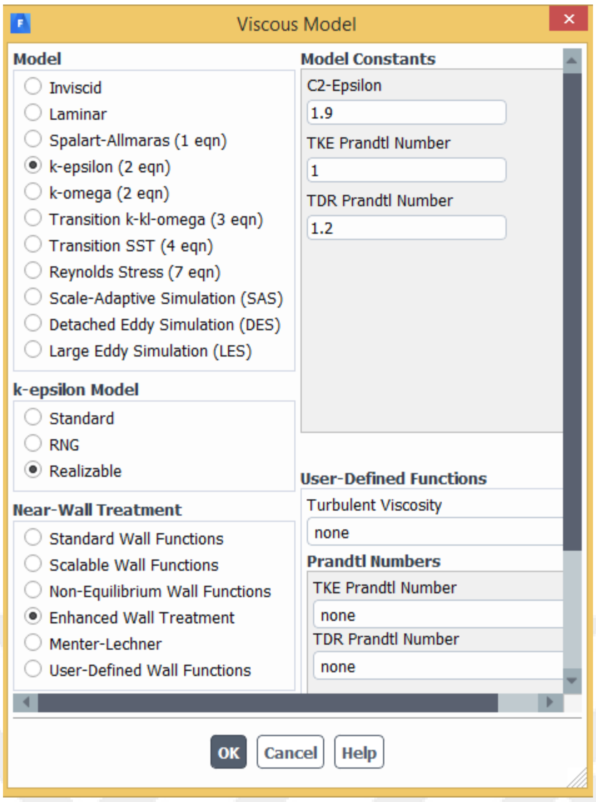


Figure 4.18. Settings for the viscous model – *laminar flow* – for all cases are given as in the figure.

2. Cell Zones

There are two different types of cell zones, fluid and solid. Fluent equations are calculated in fluid bodies. Solid bodies are where no air transmittance occurs. The type of a cell zone can be changed by clicking right and choosing either fluid or solid type for that specific cell zone, as seen in Figure 4.19. For this study, there were only solid bodies when the certain windows or doors were assumed to be closed, to assure that there was no air flow in those zones. The apertures are modeled unattached from the main calculation zones to perform type change. Following are the types of each cell zone that were turned into solid for each case, also refer to Table 7,

Base case: Doors and Aisle Window (A-W) are turned to solid.

Case 1: Doors are turned to solid.

Case 2: Doors and Aisle Window (A-W) are turned to solid.

Case 3: Doors are turned to solid.

Case 4: A-W is turned to solid.

Case 5: NE-W is turned to solid.

Case 6: Doors and A-W are turned to solid.

Case 7: NE-W is turned to solid.

Case 8: Doors are turned to solid.

Case 9: Doors are turned to solid.

Case 10: Doors and A-W are turned to solid.

Case 11 – 16: Doors are turned to solid.

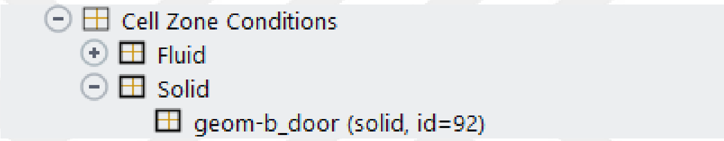


Figure 4.19. Cell zones are turned into solid by clicking right. In the figure, the door body is turned into "solid" to prevent Fluent calculate the equations for this body.

3. Boundary Zones and Conditions

Naming faces in Mesh Component comes in handy for this section. Inlet, outlet, wall, symmetry, etc. are boundary zone types. These zones allow user the set boundary conditions for each zone. There are several types of boundary conditions for boundary zones:

- For inlets: Velocity inlet, pressure inlet, mass flow, etc.
- For outlets: Pressure outlet, outflow, outlet vent, etc.
- For walls: Stationary or moving walls
- For symmetry: Equations are mirrored with the symmetry face

For this study, velocity inlet for inlet zone, pressure outlet for outlet zones, walls and symmetry zones are used excessively. The conditions for inlets and outlets are given in the next passage.

- *Boundary Conditions*

- Flow Inlet

Inlet boundary condition is defined to specify the value of wind speed. For the case studies, velocity inlet is used as the air deemed as incompressible. Velocity inlet boundary condition defines velocity vector and scalar properties of flow at inlet boundaries (Bakker, 2006). Velocity inlet is intended for incompressible flows, it is not recommended to use velocity inlet for compressible flows (ANSYS, 2016c). Placing a velocity inlet too close to a solid obstruction can force the solution to be non-physical (Bakker, 2006), therefore, for this study; velocity inlet was placed 15m before a solid obstruction, which was the classroom in this study. Figure 4.20 shows the velocity inlet setup for the face of inlet.

For all cases, the settings for velocity inlet boundary condition is as following:

- Velocity: 1 m/s
- Pressure: 0 Pa
- Turbulent Intensity: 5%
- Hydraulic diameter: 5.193 m

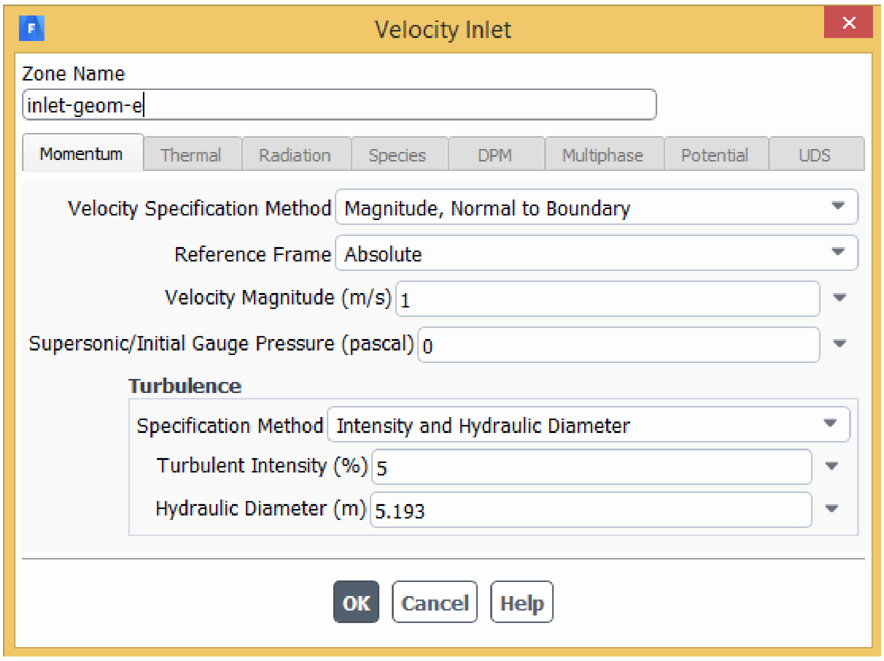


Figure 4.20. Velocity inlet settings in the case studies, for the inlet face.

- Flow Outlet

Flow outlet is the surface the outlet boundary conditions are defined. For all the case studies, pressure outlet is employed for outlet boundary conditions. Pressure outlet is used for both incompressible and compressible flows (ANSYS, 2016c). For the type of pressure outlet boundary condition, static/gauge pressure is defined as the static pressure of the environment the flow exhausts. Backflow quantities are used as inlet conditions if any backflow occurs, outlet acts like an inlet (ANSYS, 2016c), see Figure 4.21 for backflow turbulence intensity and hydraulic diameter and pressure outlet setup for this study.

For all cases, the settings for velocity inlet boundary condition is as following:

- Pressure:0 Pa
- Hydraulic diameter for main outlet: 4.386 m
- Hydraulic diameter for door infiltration outlets: 0.096 m

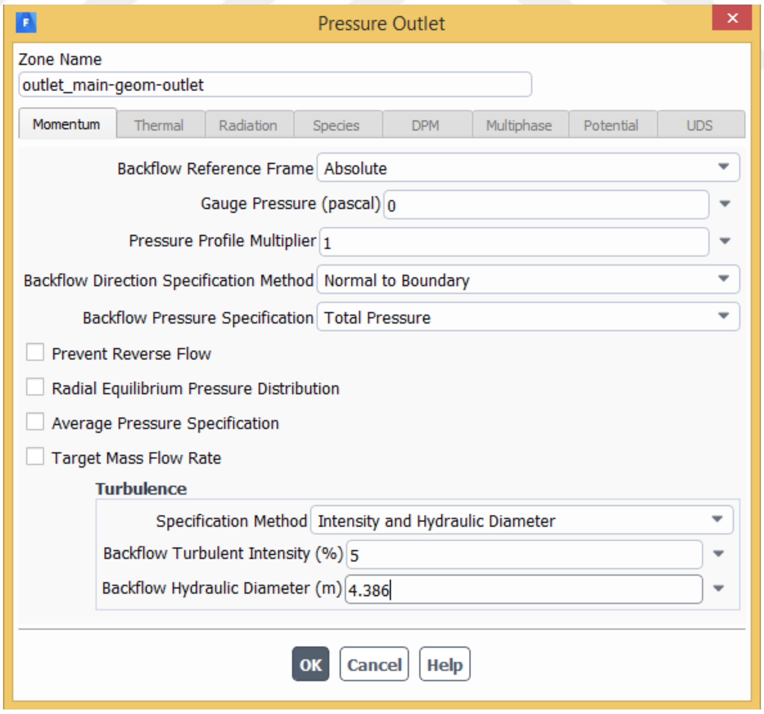


Figure 4.21. Pressure outlet settings in the case studies, for the main outlet face.

- Specifying Turbulence Parameters

Boundary conditions must be arranged for turbulence models when the turbulent flow enters the fluid domain at the inlets or outlets. There are four methods to provide these conditions:

- Turbulent intensity and viscosity ratio (default)
- Turbulent intensity and length scale
- Turbulent intensity and hydraulic diameter
- Explicitly input k, e, w

For this study, turbulent intensity and hydraulic diameter which is mainly used for internal models is used for the turbulence models of both inlet and outlet boundary conditions, the diameter was obtained using 2ab / *a + b*

Eq.2.

Hydraulic diameter for rectangular diameter is:

$2ab / a + b$ Eq.2

where a is the width and b is the height of the model.

- Wall Boundaries

Wall boundary conditions are used to conjoin solid and fluid bodies. Stationary wall is chosen as the wall motion type. For wall roughness, no-slip wall condition is selected for all wall boundaries.

- Symmetry

For symmetry faces, the equations are solved equally for each side of the face, the flow is mirrored. Therefore, only such zones were named as symmetry, nothing more was employed.

- **Solving**

Solving procedure for Fluent proceed as following:

- Setting solution parameters,

- Initializing the solution,
- Calculating the solution,
- Checking for convergence,
- Checking for accuracy (ANSYS, 2016e).

Fluent Solver setup for physics include options for time and type. For this study, solver time and type are set as default, steady and pressure based, respectively.

There are a couple of solution methods for CFD Fluent, such as SIMPLE, PISO, Coupled, etc. The default is SIMPLE method which is good for the most of flow calculations. Coupled method is preferred both with incompressible and compressible flow calculations. Coupled method is used in place of SIMPLE method in case of convergence problems (ANSYS, 2016e).

For this study Coupled method is used with default settings of solution controls, as ANSYS informs the users that the default settings are suitable for the majority of the problems (ANSYS, 2016e), so long Coupled method solved all case studies without any hindrance.

After setting methods, the Fluent solver requires all variables to be initialized before starting calculation, meaning that "… in every individual cell in the mesh a value must be assigned for every solution variable to serve as an initial guess for the solution" (ANSYS, 2016e). There are five different types of initializing, however, for this study, the default initialization type which is Hybrid initialization is employed. If the initialization is successful, the user can proceed to calculate the problem. For Steady State calculation, only iteration number is required. For Transient calculations, time step size and number of time steps replace the iteration number. As this study do not calculate any case for a period of time, it is rather suitable to choose Steady State and setting the number of iteration higher than 500.

- **Post-Processing**

In Reports, Surface Integrals is used to present data for various report types. Mass – Weighted Average and Mass Flow Rate report types compute the generated data from the solving process. Airflow velocity is generated by selecting the Mass – Weighted Average as the report type and velocity as the field variable, Figure 4.22 demonstrates the surfaces that are created for this study. The mass airflow rates are generated by choosing Mass-Flow Rate in reports type.

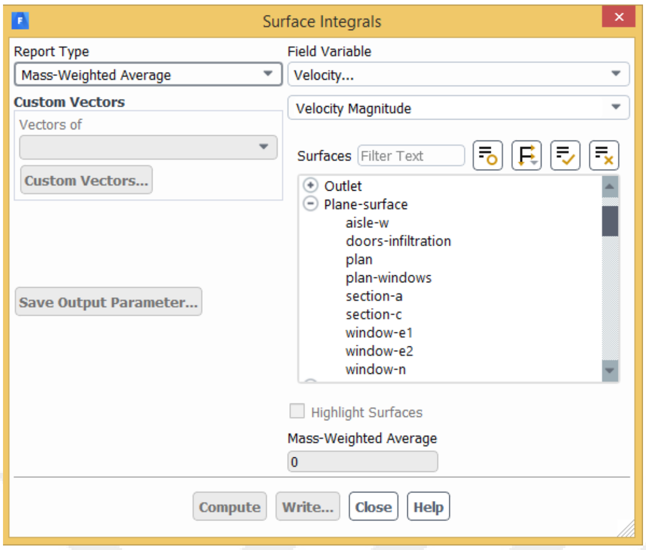


Figure 4.22. Surface integrals present mass airflow rate and airflow velocity for named surfaces.

Images generated for this study is produced by Graphics section in Fluent component. Vectors and contours, vectors, and pathlines produce plots of the geometry. Vectors present the generated data for selected surfaces. For this study, vectors of velocity are used to create 2D images, see the setup in Figure 4.23.

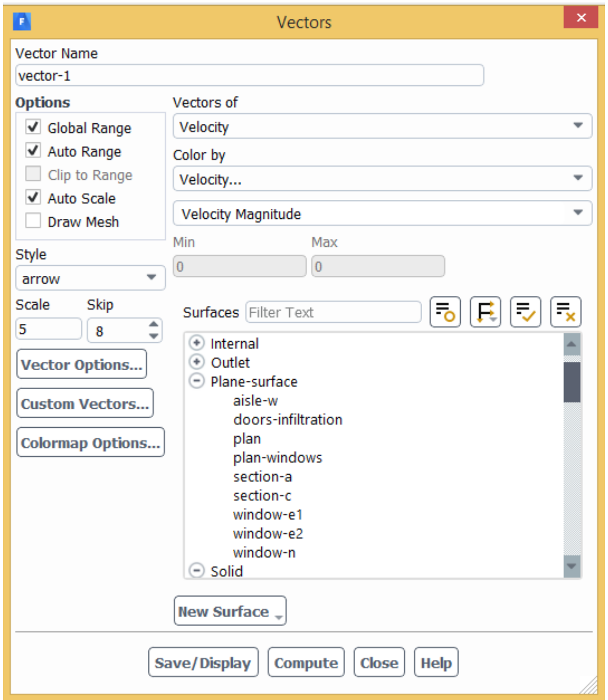


Figure 4.23. 2D images in the results and discussion chapter is produced by selecting the named surfaces and computing the data as vectors of velocity.

4.4. Verification of CFD Model

Verification of the model that the case studies were studied on was realized through mesh independency. Mesh independency is comparing the measurements of different numbered mesh cell solutions and deciding that all measurements are similar to each other. In this case study, this method was utilized as comparing the results of 2.8 million, 6.3 million, and 9.8 million mesh cells, Table 5 presents the aforementioned results for different mesh cell numbers. After running solutions for each mesh number, as the solutions do not differ greatly, it was decided to use the least mesh number to save time, which is 2.8 million mesh cells.

Table 5. Mesh independency can be declared according to the results.

Mesh cell numbers	Calculation Face Names	Mass Airflow Rate (m^3/s)	Average Air Velocity (m/s)
2.8 million cells	A-W	0,213	0.606
	Doors / I.S.	1,367	0.688
	SE-W 1	0,377	1.122
	SE-W 2	1,209	1.075
	NE-W	0,000	0
6.3 million cells	A-W	0,214	0.657
	Doors / I.S.	1,384	0.718
	SE-W 1	0,409	1.147
	SE-W 2	1,205	1.077
	NE-W	0,000	0
9.8 million cells	A-W	0,211	0.617
	Doors / I.S.	1,391	0.703
	SE-W 1	0,413	1.158
	SE-W 2	1,206	1.082
	NE-W	0,000	0

- Anemometer

The adapted results of the study that investigated wind velocity rates inside the classrooms in Yaşar University is given in Table 6. These values are compared with the results of the Base Case simulation in this study.

Table 6. The wind speed values (m/s) for the classroom T214 (Adapted from Ongun, 2020).

1 window open		**2 windows open**		**1 window and doors open**	**2 windows and doors open**
Window	**Window 2**	**Window**	**Window 2**	**Door**	**Door**
–	1.96	1.7	4	0.51	0.95
–	1.44	2.1	3.3	0.48	1.16
–	1.79	2.3	1	0.45	1.61
				0.67	1.03
				0.73	1.02
				0.62	0.88
				0.45	0.39
				0.43	0.35
				0.38	1

CHAPTER 5
RESULTS AND DISCUSSIONS

The results of the case studies are presented and discussed in this chapter. First, the window configurations for each study are shown in Table 7. The results are provided as mass airflow rate (m^3/s) and average air velocity (m/s) in Table 8 and Table 9. The tables gives the plan views and the section views for a better understanding of the airflow.

In the Base Case, the window diameter that opens to outside air is 0,20 cm^2 and for other case studies this value is 0,53 cm^2 for 110 x 45 cm windows, 0,99 cm^2 for 110 x 90 cm windows and 1,15 cm^2 for 110 x 120 cm windows. Therefore, it can be said that, the air velocity arises because the diameter decreases. First presented case is the Base Case which the windows' diameters are as similar as to the existed one. The doors are closed, creating a situation that happens during lecture times. The Case 1 is similar to Base Case, however, in this case a small window called A-W is placed near the doors to create cross – ventilation effect. The results indicate that the mass airflow rate passing through the windows of Base Case is lower than the conducted studies, even though the average air velocity that channels into the classroom from windward windows is higher than Case 1.

In Base Case and Case 1, the NE-W, SE-W 1 and SE-W 2 windows of the classroom are open, and the doors are closed while infiltration under the doors exists. In Case 1, the hypothetical window A-W is placed near the doors with the dimensions of 45 x120 cm and is 100 cm from floor level. The wind velocity for NE-W is lowered to 2,68 m/s from 3,08 m/s, and mass flow rate is lowered down as well, from 0,33 m^3/s to 0,29 m^3/s for Case 1 and Base Case, respectively. These rates are for the NE-W window that is on the leeward side and conducts as an outlet. Total mass flow rate into the room – total flow rate through windward windows SE-W 1 and SE-W 2 – is 0,58 m^3/s for Base Case and 0,68 m^3/s for Case 1. Wind velocity of Base Case for these prementioned windows are 2,58 m/s and 2,59 m/s respectively. This value goes up to 2,96 m/s and 2, 98 m/s for Case 1, indicating that there is a channeling effect which is initiated by A-W, creating cross – ventilation. Therefore, it can be said that adding A-W leads to more air flow rate into the room, however creating faster air velocity at occupant level.

For Case 2,3,4, and 5; the size of NE-W, SE-W 1 and SE-W 2 is 110 cm x 120 cm. There is no A-W for Case 2 and Case 4, however while doors are open in Case 4, it is closed in Case 2. Nevertheless, total air mass flow rate for Case 2 is 3,6 m^3/s and 4,22 m^3/s for Case 4; meaning that opening the doors creates the same effect - if not more - as adding the A-W does for Case 1. While in Case 2 the velocity of air is dispatched almost equally for windward side windows, 1,79 m/s and 1,78 m/s, respectively for SE-W 1 and SE-W 2; it is relatively unequal for Case 4 with values of 2,06 m/s and 1,96 m/s for each window. The air velocity and mass airflow rate of air changes drastically for the air that passes through the doors; when the doors are open in Case 4, the average air velocity is 0,68 m/s and 0,99 m^3/s of mass airflow rate exists; in Case 2, these numbers are 2,37 m/s and 0,26 m^3/s, respectively.

Case 3 is a case with A-W window, and the doors are closed, contrasting Case 5, where the doors are open, however the NE-W window is closed in Case 5. For Case 3 and Case 5, the mass air flow rate and average air velocity that passes through A-W respectively is 0,67 m^3/s and 1,43 m/s; and 0,21 m^3/s and 0,61 m/s. The total mass flow rate that the classroom holds for Case 3 is 4,1 m^3/s and 1,59 m^3/s for Case 5. On the other hand, as expected, through the doors, the air mass flow rate increases, and average air velocity for all openings is decreased for Case 5. It is discernable that the opening NE-W window enhances both the air mass flow rate and average air velocity in the classroom. Table 9 shows that airflow velocity rates are more densified in Case 3 rather than Case 5.

Case 6 and Case 2 have the similar window configurations except the sizes of the windows NE-W, SE-W 1 and SE-W 2. In Case 6 the sizes of these windows are 110 x 45 cm instead of 110 x 120 cm which was for Case 2; the I/O is 1,9 for Case 2 and 1,75 for Case 6. The positions of the windows for each case are 100 cm from floor level. The doors are closed, and A-W window do not exist. The flow that passes underneath the doors are similar in each case, both for mass airflow rate and average air velocity. However, the total airflow that goes into the classroom decreases from 3,61 m^3/s in Case 2 to 1,86 m^3/s in Case 6 when the window diameters decreases. The average air velocity around occupant height just before the windward windows are increased with the decrease of window diameter. While the I/O ratio is almost similar in both cases, the mass flow rate through windward windows is doubled, because the window diameter is smaller.

The window dimensions and positions for Case 6, 7 and 8 are same, with 110 x 45 cm of size and 100 cm from floor level. However, while in Case 6 there is no A-W window and the doors are closed; in Case 7 both A-W window and doors are open, although, NE-W window is closed. The total mass airflow rate that enters the room through windward windows is lesser in Case 7 compared to Case 6, with rates of 1,21 m^3/s and 1,86 m^3/s, respectively. The average air velocity subsides as well in number, 2,11 m/s for S-E W 1 window and 2,05 m/s for S-E W 2 window in Case 6, and 1,56 m/s for S-E W 1 window and 1,49 m/s for S-E W 2 window in Case 7.

In Case 8, the NE-W window is open, the air mass that flows through windward windows S-E W 1 (0,99 m^3/s) and S-E W 2 (1,14 m^3/s) is higher even when the doors are closed. The existence of A-W window increases both mass airflow rate and average air velocity through the windward windows. The flow that passes through A-W window decreases these values an iota for NE-W window, because the air that originally traverses NE-W window is pulled by A-W window, creating a stronger flow through the classroom.

In Case 8 and in Case 9, the doors are closed, and A-W window exists, however the window diameter for Case 9 doubles in size to 100 x 90 cm. Also, the windows in Case 9 are positioned in 190 cm from floor level. The total mass airflow rate enhances to 3,53 m^3/s when the window diameter rises in Case 9, and average air velocity drops. This case is a lot more understandable with the sections of the solution, in Figure 5.24, where the wind force is located near the ceiling, not at the level of seated occupants**.**

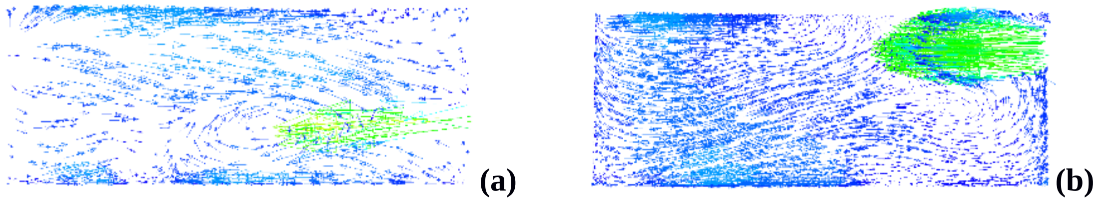


Figure 5.24. (a) Section A from Case 8 **(b)** Section A from Case 9 presents the direction of airflow when the window heights from ground change.

Table 7. Window configurations for each case are given in the table.

Case No	NE-W			SE-W 1			SE-W 2			Doors			A-W			
	S	**D**	**h**	**S**	**D**	**h**	**S**	**D**	**h**	**S**	**D**	**h**	**S**	**D**	**h**	**I.S.**
Base Case	O	110 x 11.25	100	O	110 x 11.25	100	O	110 x 11.25	100	C	140 x 210	0	N/A	N/A	N/A	140x5
1	O	110 x 11.25	100	O	110 x 11.25	100	O	110 x 11.25	100	C	140 x 210	0	O	45 x 120	100	140x5
2	O	110 x 120	100	O	110 x 120	100	O	110 x 120	100	C	140 x 210	0	C	45 x 120	100	140x5
3	O	110 x 120	100	O	110 x 120	100	O	110 x 120	100	C	140 x 210	0	O	45 x 120	100	140x5
4	O	110 x 120	100	O	110 x 120	100	O	110 x 120	100	O	140 x 210	0	C	45 x 120	100	140x5
5	C	110 x 120	100	O	110 x 120	100	O	110 x 120	100	O	140 x 210	0	O	45 x 120	100	140x5
6	O	110 x 45	100	O	110 x 45	100	O	110 x 45	100	C	140 x 210	0	C	45 x 120	100	140x5
7	C	110 x 45	100	O	110 x 45	100	O	110 x 45	100	O	140 x 210	0	O	45 x 120	100	140x5
8	O	110 x 45	100	O	110 x 45	100	O	110 x 45	100	C	140 x 210	0	O	45 x 120	100	140x5
9	O	110 x 90	190	O	110 x 90	190	O	110 x 90	190	C	140 x 210	0	O	45 x 120	100	140x5
10	O	110 x 90	190	O	110 x 90	190	O	110 x 90	190	C	140 x 210	0	C	45 x 120	100	140x5
11	O	110 x 90	190	O	110 x 90	190	O	110 x 90	190	C	140 x 210	0	O	45 x 120	10	140x5
12	O	110 x 120	100	O	110 x 120	100	O	110 x 120	100	C	140 x 210	0	O	45 x 120	10	140x5
13	O	110 x 45	100	O	110 x 45	100	O	110 x 45	100	C	140 x 210	0	O	45 x 120	10	140x5
14	O	110 x 45	100	O	110 x 45	100	O	110 x 45	100	C	140 x 210	0	O	45 x 200	10	140x5
15	O	110 x 90	190	O	110 x 90	190	O	110 x 90	190	C	140 x 210	0	O	45 x 200	10	140x5
16	O	110 x 120	100	O	110 x 120	100	O	110 x 120	100	C	140 x 210	0	O	45 x 200	10	140x5

NE-W: North-East Window, SE-W 1: South-East Window 1, SE-W 2: South-East Window 2, A-W: Aisle Window, I.S.: Infiltration Space under the doors, S: Situation of windows, D: Dimensions of windows, h: Height of the windows above ground level

Case 9, 10 and 11 have the same sizes and positions for all the window openings. From the section-b in the Table 9, it is comprehensible that the existence of A-W window increases the airflow speed around the door, see Case 9 and Case 11. Even so, for these three cases, the fastest ventilation speed happens closer to ceiling floor, since NE-W, SE-W 1 and SE-W 2 are placed at 190 cm height.

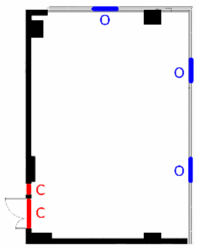
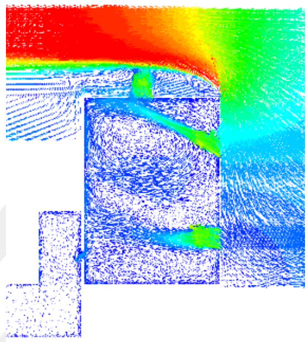
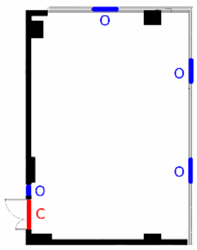
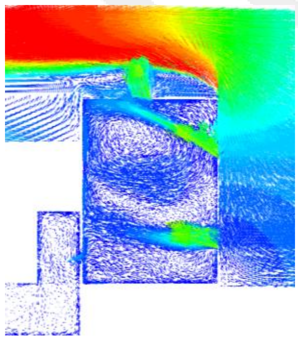
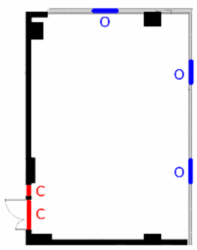
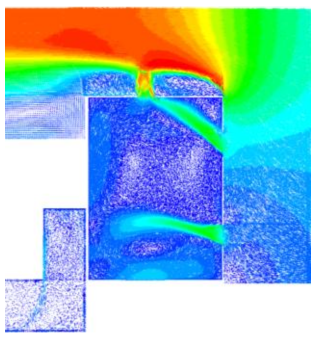
Even though the opening dimensions are same for cases 9, 10 and 11; in Case 11 the A-W window is 10 cm from floor level, the effect of this window's placement is apparent from the section-b in Table 9 when compared to Case 10. The airflow changes direction towards the new place of the outlet, which, in this case is the A-W, the flow is an iota faster than in Case 9, where the A-W is 100 cm from floor level. Since the placement of the window do not change the inlet – outlet ratio, this outcome is understandable. On the other hand, even so human eye cannot see the difference, human body can feel the draft of the airflow around the door and the wall the door is located.

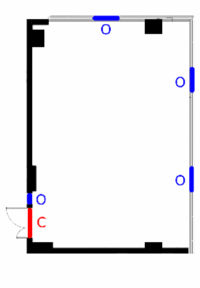
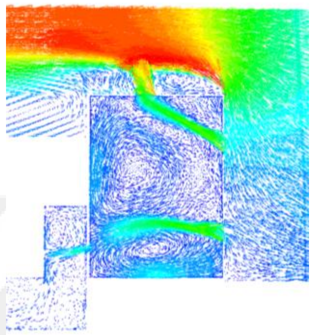
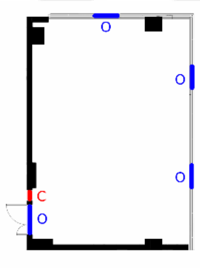
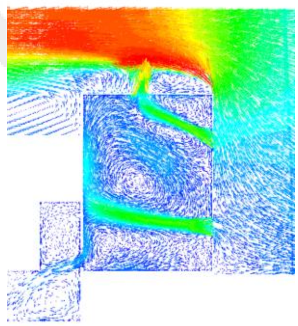
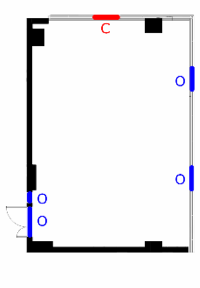
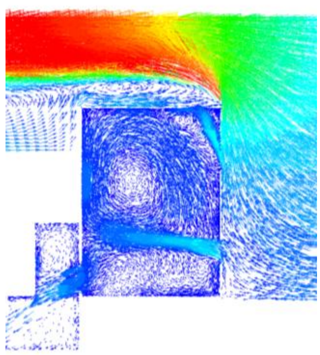
Total mass airflow through windward windows is 3,53 m^3/s in Case 9. In Case 10 the total mass airflow rate through these windows is 3,11 m^3/s and for Case 11, it is 3,56 m^3/s. The average wind velocity in these windows arises slightly in Case 11, presenting the effect of outlet opening placement. Therefore, it can be said that, inlet – outlet placement plays a great role in the motion of airflow.

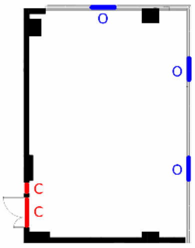
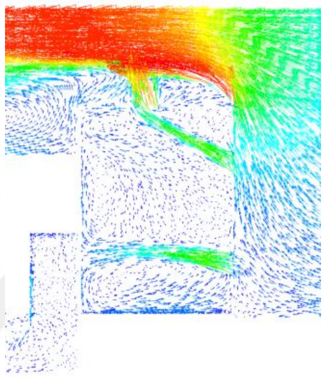
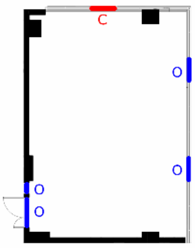
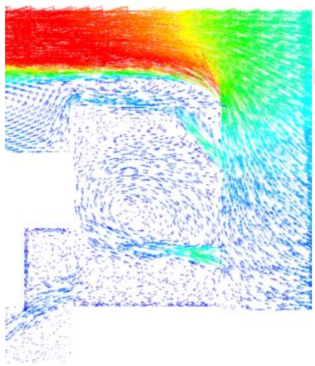
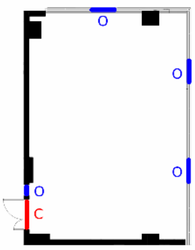
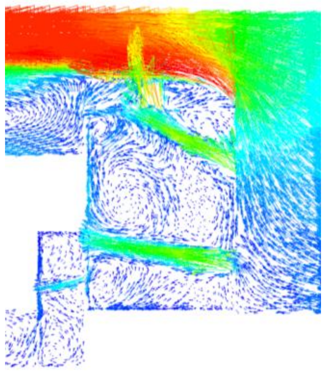
In Case 12, the NE-W, SE-W 1, and SE-W 2 windows' dimensions are 110 cm in height and 120 cm in width, and they are placed 100 cm from floor level. The A-W window is placed as the same as in Case 11, at 10 cm height from ground. The total mass airflow rate is 4,1 m^3/s.

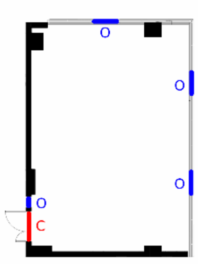
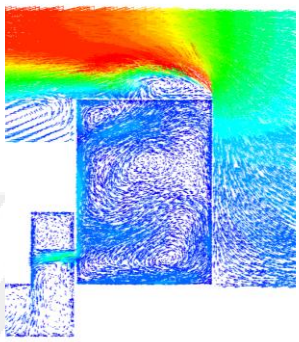
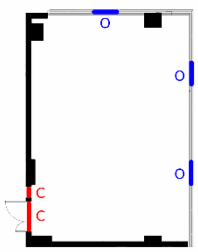
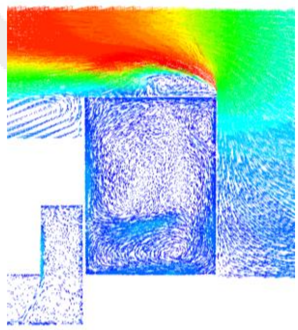
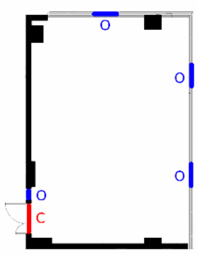
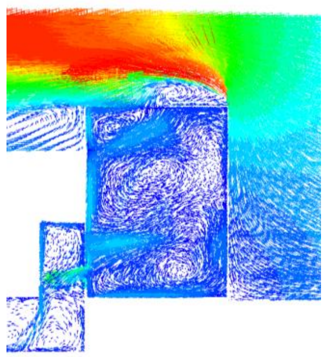
Case 13 has the NE-W, SE-W 1, and SE-W 2 windows at the height of 100 cm, and A-W window at 10 cm from floor level. Although, the NE-W, SE-W 1, SE-W 2 windows have 45 cm height and 110 cm width. In this case, the average air velocity is slightly higher compared to the other cases where the A-W window is placed 10 cm from floor level. However, the total rates of mass airflow decrease to 2,13 m^3/s when compared to Case 11, where the NE-W, SE-W 1, and SE-W 2 windows' dimensions are 110 x 120 cm. Also, most of the airflow intensifies at occupant level in Case 13.

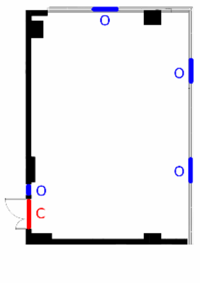
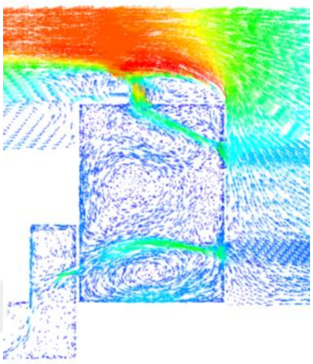
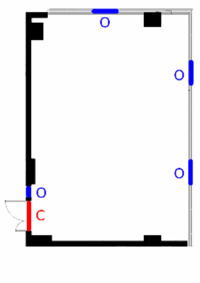
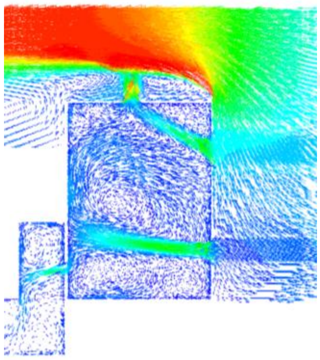
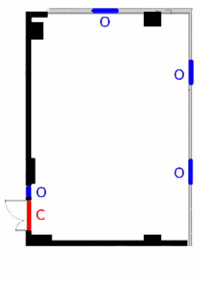
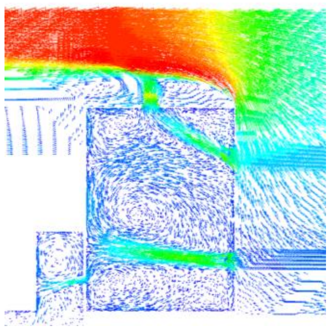
Table 8. Mass airflow and average air velocity rates for each case are given with a plan of window configuration and a plan view of calculation zone, the classroom.

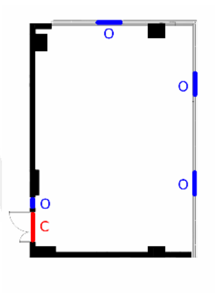
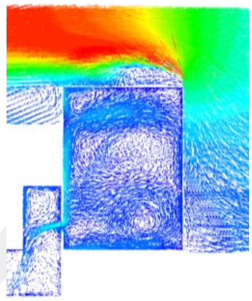
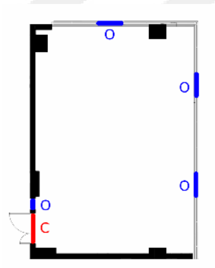
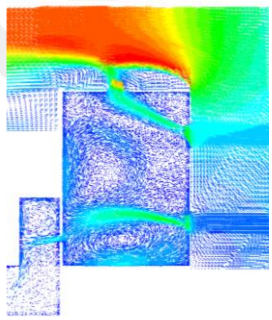
Case Numbers	**Calculation Face Names**	**Mass Air flow Rate (m^3/s)**	**Av. Air Velocity (m/s)**	**Plan**
Base Case 	AW	N/A	N/A	
	Doors / I.S.	0,241	2.227	
	S-E W – 1	0,272	2.580	
	S-E W – 2	0,309	2.592	
	N-E W	0,330	3.082	
Case 1 	AW	0,311	0.788	
	Doors / I.S.	0,072	0.793	
	S-E W – 1	0,323	2.966	
	S-E W – 2	0,358	2.986	
	N-E W	0,286	2.688	
Case 2 	AW	0,000	N/A	
	Doors / I.S.	0,263	2.378	
	S-E W – 1	1,572	1.790	
	S-E W – 2	2,034	1.781	
	N-E W	3,345	3.274	

Case Numbers	Calculation Face Names	Mass Air flow Rate (m^3/s)	Av. Air Velocity (m/s)	Plan
Case 3 	AW	0,673	1.443	
	Doors / I.S.	0,158	1.454	
	S-E W – 1	1,854	1.982	
	S-E W – 2	2,249	1.965	
	N-E W	3,258	3.239	
Case 4 	AW	0,000	N/A	
	Doors / I.S.	0,990	0.680	
	S-E W – 1	1,970	2.064	
	S-E W – 2	2,247	1.968	
	N-E W	3,217	3.155	
Case 5 	AW	0,213	0.606	
	Doors / I.S.	1,367	0.688	
	S-E W – 1	0,377	1.122	
	S-E W – 2	1,209	1.075	
	N-E W	0,000	0	

Case Numbers	Calculation Face Names	Mass Air flow Rate (m^3/s)	Av. Air Velocity (m/s)	Plan
Case 6 	AW	0,000	N/A	
	Doors / I.S.	0,259	2.317	
	S-E W – 1	0,847	2.114	
	S-E W – 2	1,012	2.049	
	N-E W	1,672	3.370	
Case 7 	AW	0,169	0.459	
	Doors / I.S.	1,048	0.503	
	S-E W – 1	0,483	1.562	
	S-E W – 2	0,727	1.491	
	N-E W	0,000	0	
Case 8 	AW	0,535	1.235	
	Doors / I.S.	0,122	1.334	
	S-E W – 1	0,990	2.355	
	S-E W – 2	1,137	2.290	
	N-E W	1,534	3.076	

Case Numbers	Calculation Face Names	Mass Air flow Rate (m^3/s)	Av. Air Velocity (m/s)	Plan
Case 9 	AW	0,596	1.496	
	Doors / I.S.	0,147	1.424	
	S-E W – 1	1,600	2.0559	
	S-E W – 2	1,929	2.0293	
	N-E W	2,793	3.387	
Case 10 	AW	0,000	N/A	
	Doors / I.S.	0,252	2.2462	
	S-E W – 1	1,364	1.855	
	S-E W – 2	1,750	1.842	
	N-E W	2,868	3.522	
Case 11 	AW	0,583	1.502	
	Doors / I.S.	0,144	1.447	
	S-E W – 1	1,611	2.073	
	S-E W – 2	1,927	2.065	
	N-E W	2,798	3.390	

Case Numbers	**Calculation Face Names**	**Mass Air flow Rate (m^3/s)**	**Av. Air Velocity (m/s)**	**Plan**
Case 12 	AW	0,644	1.436	
	Doors / I.S.	0,143	1.328	
	S-E W – 1	1,846	1.981	
	S-E W – 2	2,256	1.986	
	N-E W	3,299	3.336	
Case 13 	AW	0,578	1.431	
	Doors / I.S.	0,141	1.381	
	S-E W – 1	1,007	2.424	
	S-E W – 2	1,122	2.358	
	N-E W	1,369	3.125	
Case 14 	AW	0,948	1.353	
	Doors / I.S.	0,144	1.370	
	S-E W – 1	1,124	2.626	
	S-E W – 2	1,222	2.557	
	N-E W	1,287	2.951	

Case Numbers	Calculation Face Names	Mass Air flow Rate (m^3/s)	Av. Air Velocity (m/s)	Plan
Case 15 	AW	0,694	1.192	
	Doors / I.S.	0,117	1.130	
	S-E W – 1	1,647	2.102	
	S-E W – 2	1,921	2.059	
	N-E W	2,741	3.324	
Case 16 	AW	0,783	1.078	
	Doors / I.S.	0,109	1.016	
	S-E W – 1	1,902	2.022	
	S-E W – 2	2,276	1.998	
	N-E W	3,273	3.256	

In cases 14, 15 and 16; the position of the A-W window is 10 cm from floor level; however, it is as tall as the doors, 45 cm in width and 200 cm at height. In Case 14, the NE-W, SE-W 1, SE-W 2 windows are 45 cm in height, similar to Case 13. The total mass airflow through windward openings is 2,35 m^3/s, marginally higher than Case 13 where the total airflow entering the zone is 2,13 m^3/s. On the other hand, the mass airflow going out from the A-W window doubles in rate. The wind speeds at the occupant level increase only by little.

In Case 15 the window width is doubled with width of 90 cm, and they are placed at 190 cm from floor level. A-W window is 200 cm in height; however, the mass airflow rate of A-W window drops to 0,7 m^3/ from the Case 14's mass airflow rate of 0,95 m^3/s. This situation occurs even though the diameters of the inlet windows enhances, and the total mass airflow through windward windows rises to 3,57 m^3/s. In this case, most of the flow exists the building through NE-W window, creating an air motion even at the occupant level in front of NE-W window.

The last case study is Case 16, the NE-W, SE-W 1, SE-W 2 windows are placed at 100 cm from ground, and their size is 110 x 120 cm, and the A-W window is 200 cm in height. Since the window diameter is bigger, it is understandable that the mass airflow rate rises to 4,2 m^3/s. The flow through A-W window rises only 0,09 m^3/s to 0,78 m^3/s, and the wind velocity factors are very similar to Case 15. The air movement at occupant level densifies as well, since the inlet windows are placed at the occupant level, it is understandable.

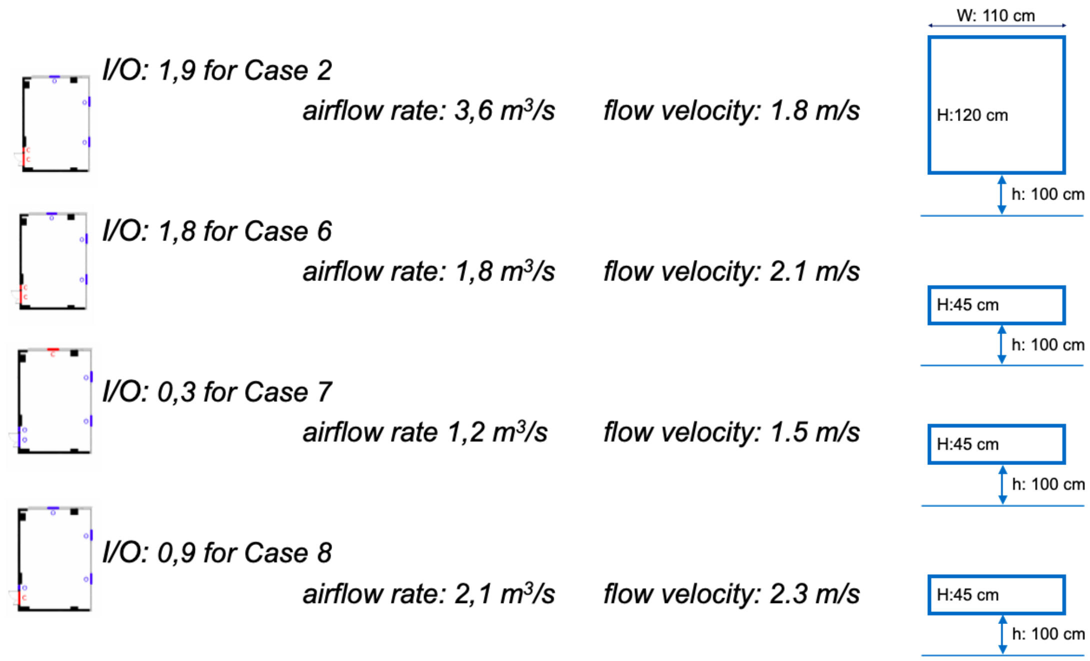


Figure 5.25. Figure presents the airflow rates and flow velocity for cases 2, 6, 7 and 8. The aisle window dimensions for these cases are 45 cm and 120 cm. The dimensions and positions of the windows NE-W, SE-W 1 and SE-W 2 are given in the figure.

To summarize the results, the next paragraphs discuss the results of the simulations. In this thesis, the situations where the window dimensions and their placement are changed vertically are also investigated. As can be seen in Figure 5.25, in Case 2, the NE-W, SE-W 1 and SE-W 2 windows' dimensions are 120 cm in height, and they are

100 cm above ground level. In the cases 6,7 and 8, these windows' dimensions are 45 cm in height, and they are also 100 cm above ground. The inlet-outlet ratio of these cases differs from each other. It is 1,9 in Case 2 and 1,8 in Case 6. In both cases, the aisle window and the doors are closed. While the inlet - outlet ratio is same in these both cases, the airflow rate is reduced by half. The flow velocity rises because the window diameter decreases in number. On the other hand, in Case 8, while the window diameter is same as in Case 6 and the inlet outlet ratio is reduced, the airflow rate and flow velocity increases. We can say that the aisle window that is facing the windward windows generates more airflow when open. In Case 7 as well, the airflow rate drops as the inlet outlet ratio decreases.

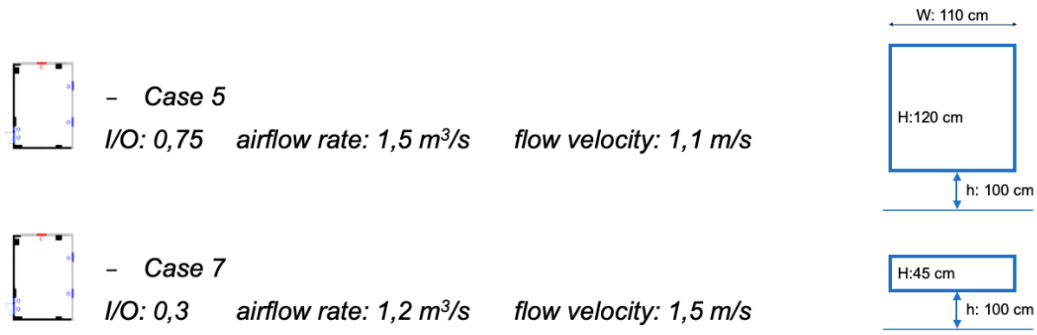


Figure 5.26. Comparison of the cases when the NE-W window is closed. NE-W, SE-W 1 and SE-W 2 windows' dimensions and positions are given in figure.

In cases 5 and 7, the NE-W window is closed while the aisle window and the doors are open. The inlet outlet ratio drops because the inlet windows' diameters is decreased. Therefore, the airflow rate decreases, and the flow velocity increases, see Figure 5.26.

In cases 9, 10 and 11; the NE-W, SE-W 1 and SE-W 2 windows' height is 90 cm and they are 190 cm above ground level. In cases 9 and 11, the aisle window is open, although their place is changed vertically; in Case 9 it is 100 cm above ground level, and it is 10 cm in case 11, see Figure 5.27. Here we can see that while changing the place of the aisle window vertically did not improve ventilation, and their I/O ratios is same, you can see that airflow rate and flow velocity of both cases are same. In case 10, however, the aisle window is closed. While the I/O ratio rises, the airflow rate drops, Figure 5.27 demonstrates the airflow rates. This means that in cross ventilation, openings on opposite walls are more effective than openings on adjacent walls.

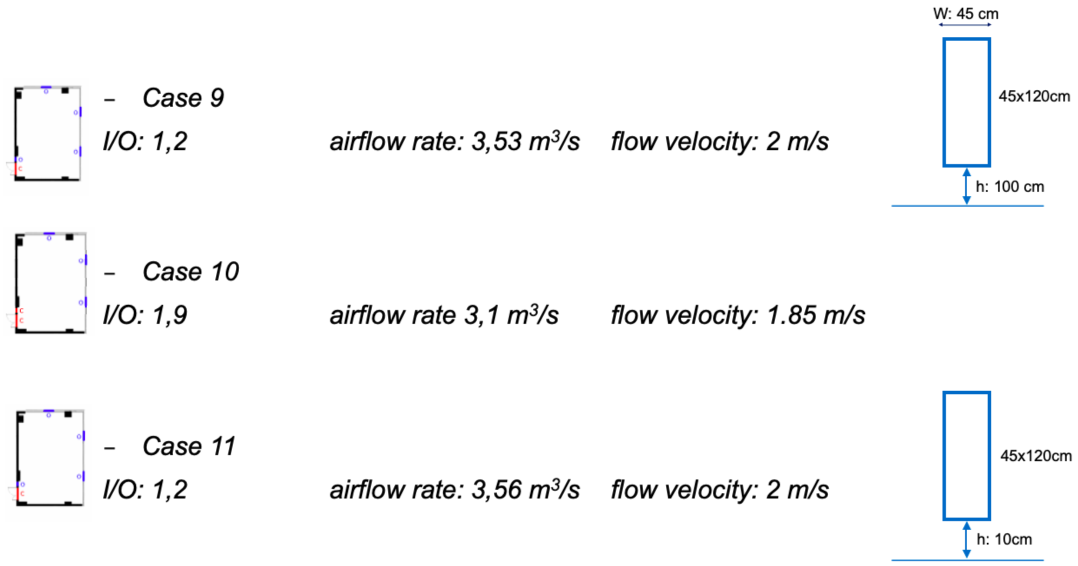


Figure 5.27. The ventilation rates for cases 9, 10 and 11 are given in the figure. Aisle window dimensions for the cases are also presented.

In cases 13 and 14, the windward windows' diameter is same, and aisle windows are open while the doors are closed. In Case 13, the I/O ratio is higher than Case 14, but the airflow rate is lower. It is comprehensible that an increase in aisle window size can result a bit higher airflow rates and flow velocity, see Figure 5.28.

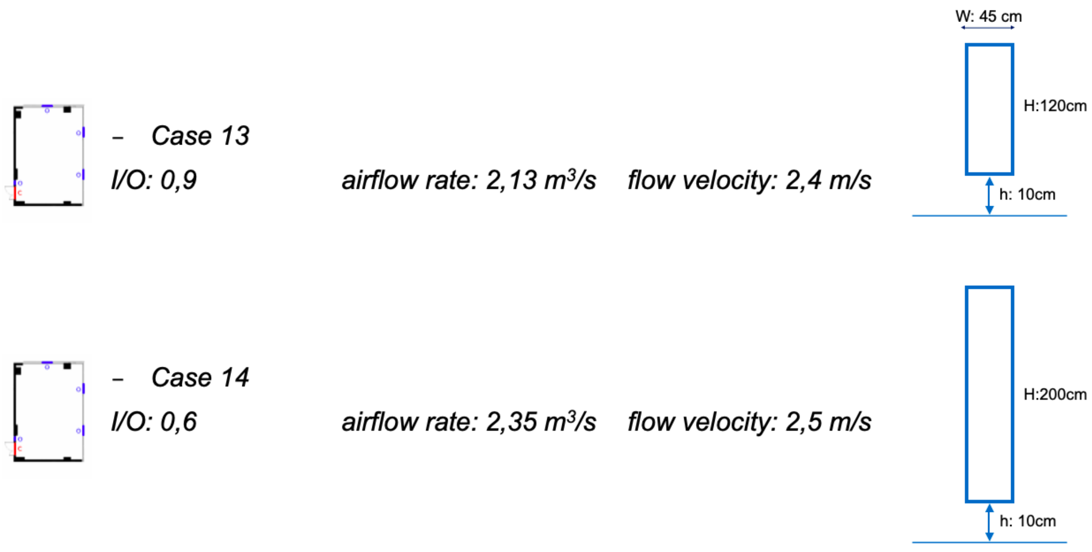


Figure 5.28. The airflow rates increase only by little when aisle window dimension gets larger, from 120 cm to 200 cm.

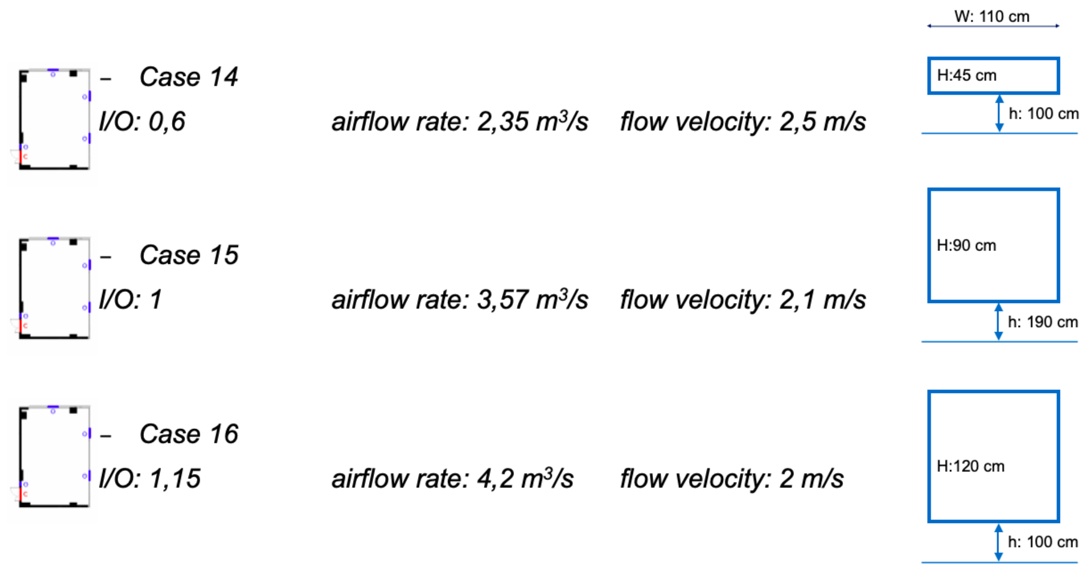


Figure 5.29. The airflow rates and flow velocities are given for cases 14, 15, and 16. The NE-W, SE-W 1 and SE-W 2 windows' sizes for each case are presented in the figure.

In cases 14, 15 and 16; the NE-W, SE-W 1 and SE-W 2 windows are in different sizes. While in Case 15, the windows are 90 cm in height and 190 cm above ground level, in Case 14 the windows are 45 cm in height, and in Case 16, they are 120 cm in height. In cases 14 and 16, the windows are 100 cm above ground level. The size of the aisle window changes for these three cases. It is width is 45 cm as the cases before, however its height is almost as tall as the doors, in 200 cm and it is 10 cm above ground. In all these three cases the aisle window is open, and the doors are closed, the outlet diameter do not change; therefore, as the windward windows' diameters increase, I/O ratio rises as well. Accordingly, the airflow rate rises as well, see Figure 5.29. As the I/O ratio rises, the flow rate rises, and the average air velocity drops. When the A-W window is bigger, the flow path gets stronger around this window, changing the airflow path; even in case 15, when the NE-W, SE-W 1 and SE-W 2 windows are placed at 190 cm height, the airflow follows the wall A-W window is placed at the seated occupant height, probably affecting the air motion when the lecturer is standing in front of the board or when seated in their seat in front of this wall.

For cases 3, 4, and 12, the windward windows size and placement are same, and for cases 3 and 12, the I/O ratio is same as well. The only difference is that in Case 4, the aisle window is closed and instead the doors are open. In cases 3 and 12, the I/O ratios are same, however, changing the position of the aisle window in vertical plane do not affect airflow rate and flow velocity rate. The distance between inlet and outlet in Case 3 is zero, and it is 90 cm for Case 12. The total mass airflow from windward windows – SE-W 1 and SE-W 2 – is 4,1 m^3/s for both Case 3 and Case 12; it seems that the value of the mass airflow do not change when the outlet is placed lower. On the other hand, the flow rate through A-W window decrease 0,03 m^3/s when the outlet is 90 cm lower than inlet. The average airflow velocities as well do not significantly enhance when the inlet – outlet distance is 90 cm rather than zero. In Case 4, however, the aisle window is closed and instead the doors are open; therefore, I/O ratio drops. Nonetheless, it is cognizable that while the I/O ratio decreases, the airflow rate and flow velocity do no not differ, as seen in Figure 5.30. Therefore, it can be said that when the classroom is occupied, the students may not be able to open the doors as there can be visual and vocalic discomfort, they can open the aisle window that can provide the same airflow rate as the doors.

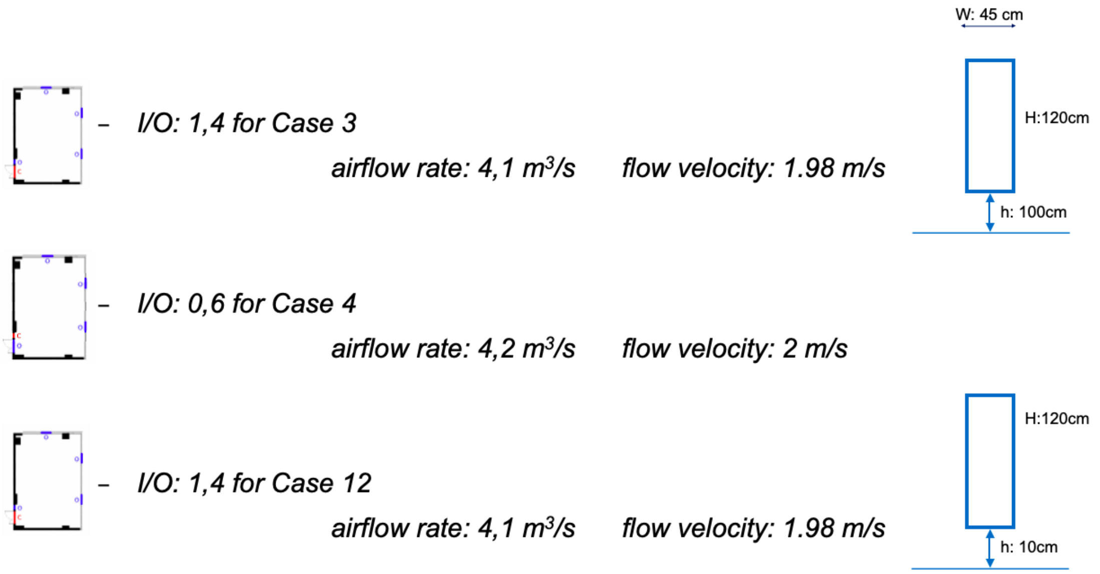


Figure 5.30. Comparison of the airflow rates and flow velocity of cases 3, 4 and 12 are given. The aisle window dimensions for both cases do not change, but its height from ground is 100 cm in Case 3 and 10 cm in Case 12.

This is the same situation when the inlet – outlet distance is 25 cm in Case 8 and 85 cm in Case 13. The total mass airflow rate is 2,12 m^3/s for both cases. In addition, when inlet – outlet distance is 60 cm in Case 9 and 150 cm in Case 11, the total mass airflow rate is 3,53 m^3/s and 3,56 m^3/s for each case, respectively. This can be discussed that when the main force is wind, the distance between inlet and outlet openings do not drastically change the total mass airflow rate as much as the inlet – outlet ratio. On the other hand, the airflow path changes as the inlets and outlets placed at different heights, see Figure 5.31.

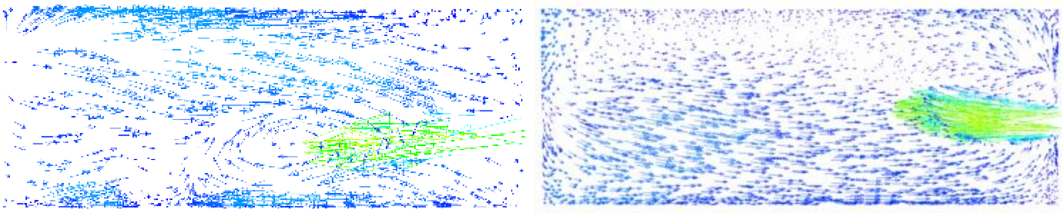


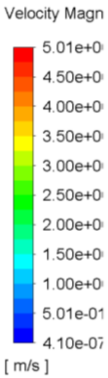
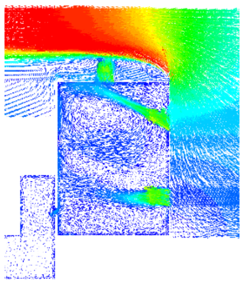
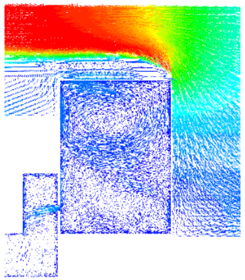
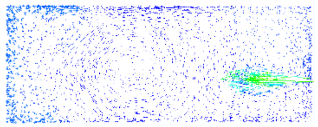
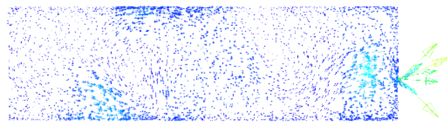
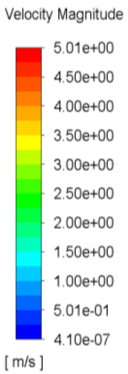
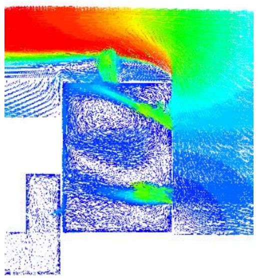
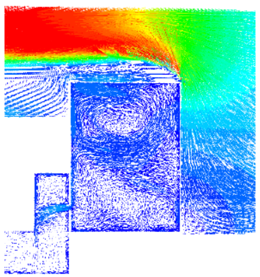
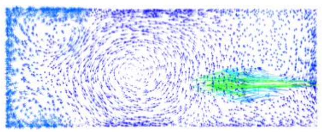
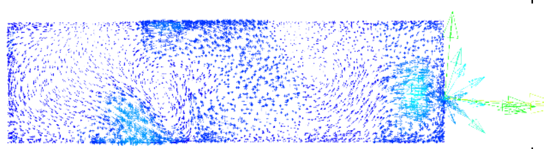
Figure 5.31. Section A views for Case 8 (left) and Case 13 (right) shows that even if the changing positions of openings do not change airflow rates, it affects the path air follows inside the space.

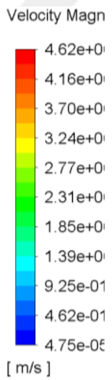
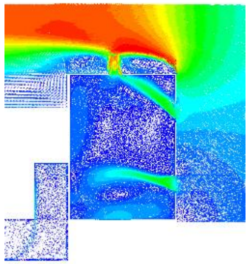
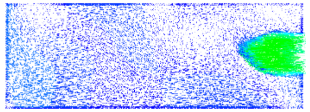
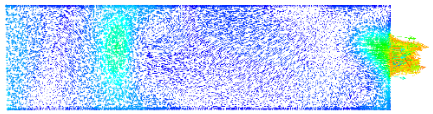
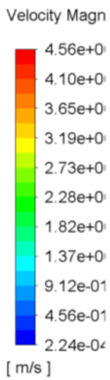
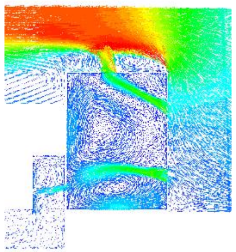
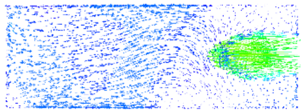
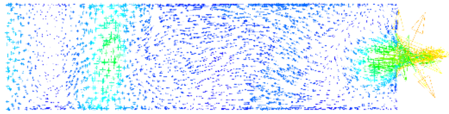
Opening an aisle window increase airflow rates by 15%. Furthermore, opening doors instead of aisle window only enhances airflow rates by 2%. When inlet openings diameter increases 2.5 times, the airflow rates increase 65% when the aisle window is open and 22% when the aisle window and doors are open. While opening the doors only increases airflow rates by 17%. Bigger aisle window enhances airflow rates by just 9%.

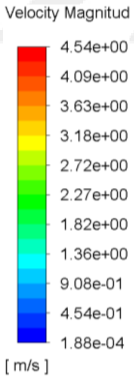
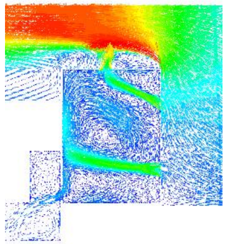
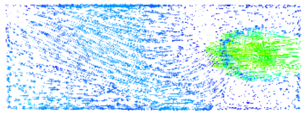
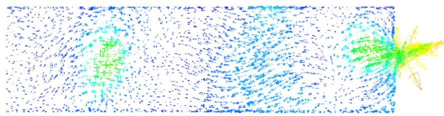
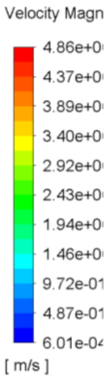
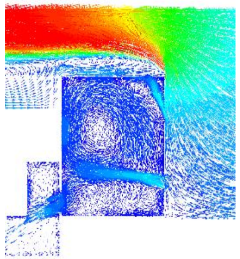
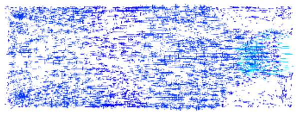
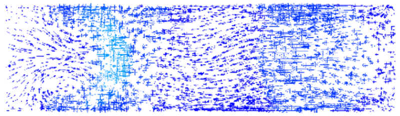
It can be concluded that not only the mass airflow rate, but how the air movement inside the space is significant to occupant comfort as well. When the wind force dominates the airflow, the placement of openings only matters just because of the airflow path, the total mass airflow rate does not change if the inlet – outlet ratio stays same. Airflow velocity in occupant height is higher in cases where the windows are leveled with the occupant sitting positions, however when the windows are placed in higher position, the velocity decreases at that height, instead the high velocity airflow flows through the ceiling, and cooling the stagnant air just beneath the ceiling floor.

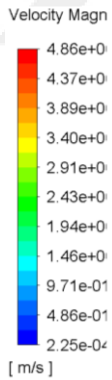
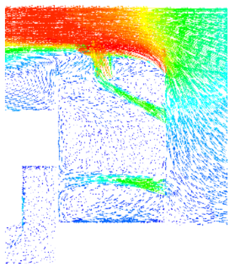
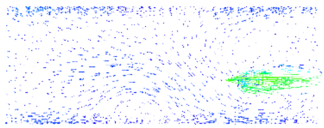
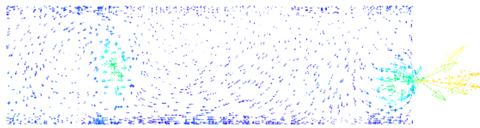
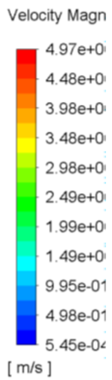
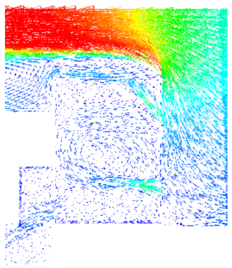
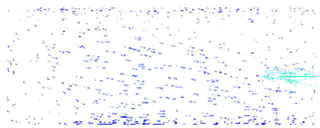
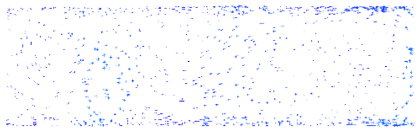
On the other hand, this study confirms the study of Papakonstantinou et al. (2000) and Ai et al. (2015), that smaller openings lower the air change rates. Moreover, it is understandable from this study that larger inlets supply more airflow than larger outlets. Furthermore, openings on opposite walls provide airflow ventilation more that the openings on adjacent walls. While changing the position of windows do not necessarily change ventilation rates, it makes it possible to create new airpaths that can improve occupant comfort. While opening doors provide great amount of air ventilation, it can cause visual and audio discomfort, therefore, opening a smaller window created as much as the airflow rate as opening the doors.

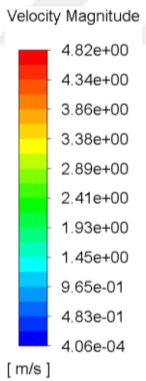
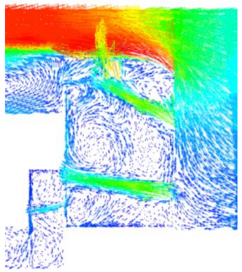
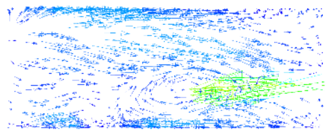
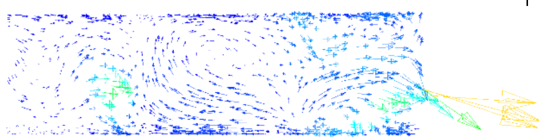
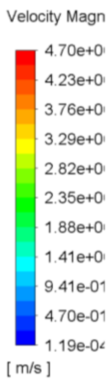
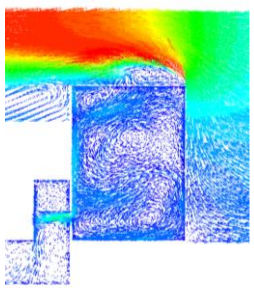
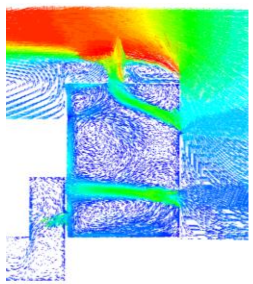
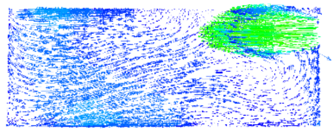
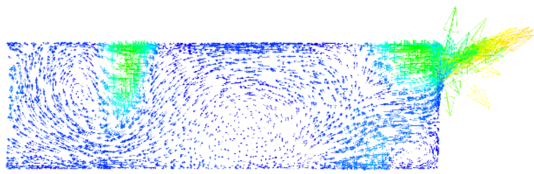
Table 9. Plan and section views with velocity legend are given for each case study, there are two plan views for certain cases.

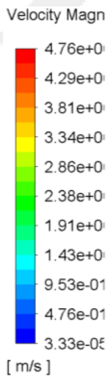
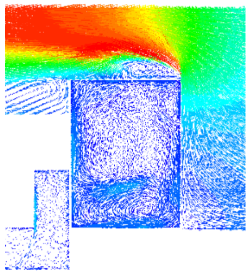
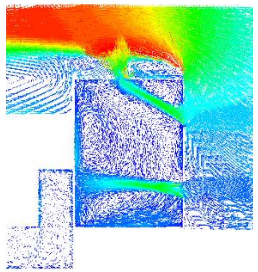
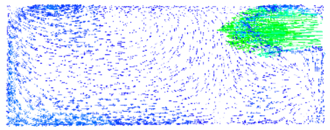
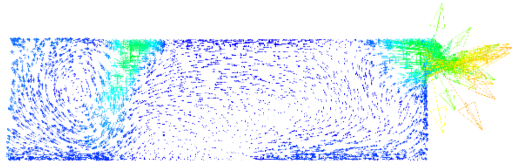
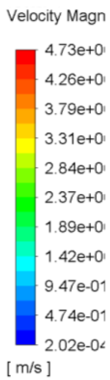
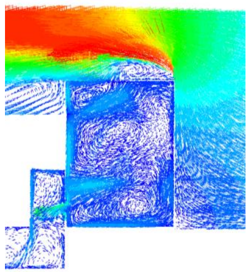
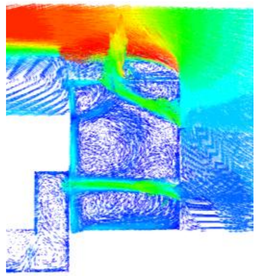
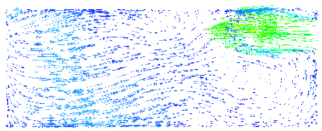
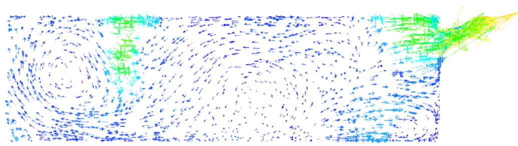
Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Base Case					
Case 1					

Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 2			–		
Case 3			–		

Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 4			–		
Case 5			–		

Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 6			–		
Case 7			–		

Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 8			–		
Case 9					

Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 10					
Case 11					

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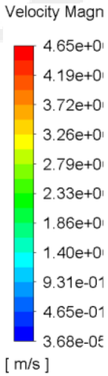
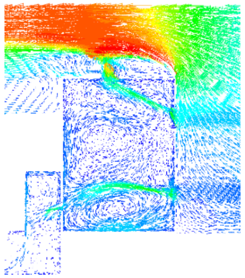
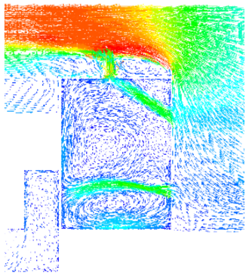
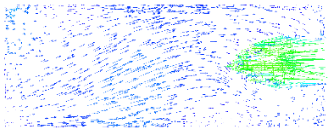
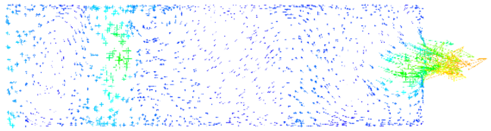
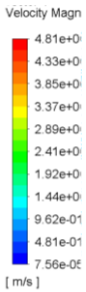
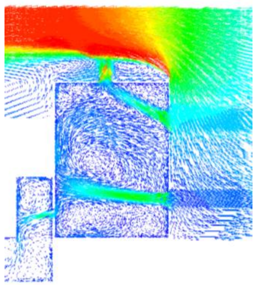
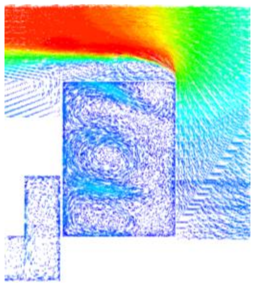
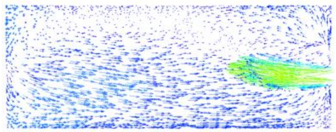
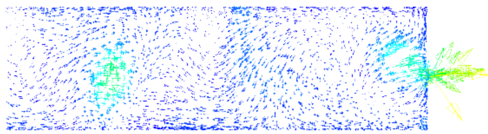
<tr><th>Case name</th><th>Velocity Legend</th><th>Plan at 1.2 m</th><th>Plan at 2 m</th><th>Section-a</th><th>Section-b</th></tr>
<tr><td>Case 12</td><td>
</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Case 13</td><td>
</td><td></td><td></td><td></td><td></td></tr>
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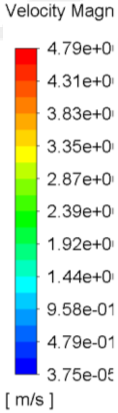
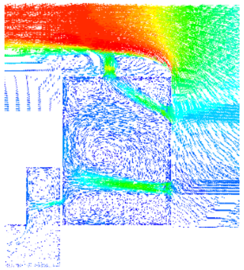
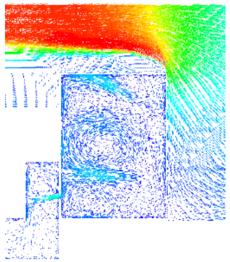
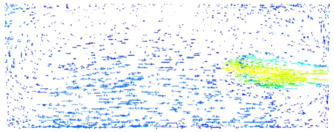
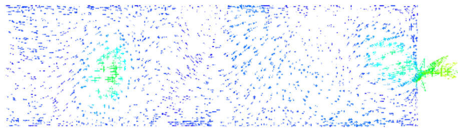
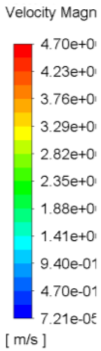
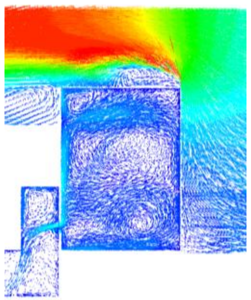
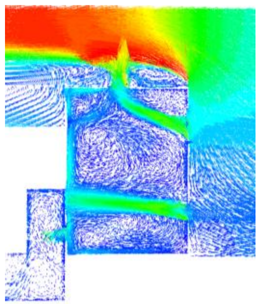
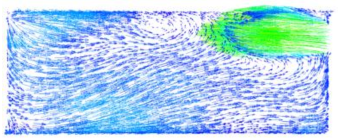
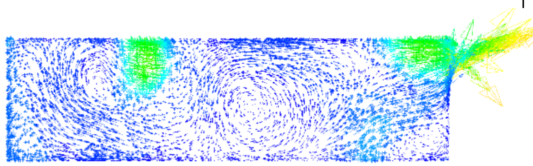
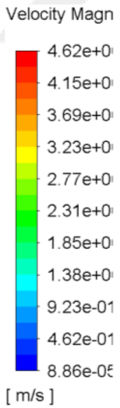
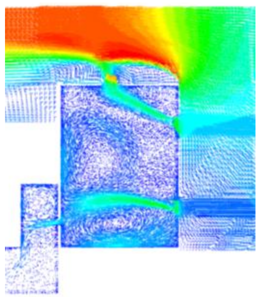
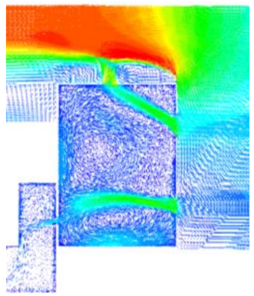
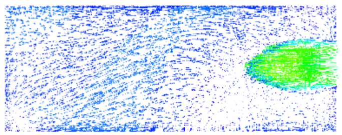
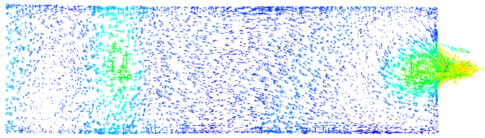
Case name	Velocity Legend	Plan at 1.2 m	Plan at 2 m	Section-a	Section-b
Case 14					
Case 15					

Case name	**Velocity Legend**	**Plan at 1.2 m**	**Plan at 2 m**	**Section-a**	**Section-b**
Case 16					

CHAPTER 6
CONCLUSION

The purpose of this thesis is to understand the relation between indoor airflow and design choices regarding literature surveys, and also to investigate the effects of window opening configurations to natural ventilation design by generating computer simulations. Oriented around these aspects, the aims, scopes, and methods are explained in Chapter 1. In Chapter 2, the secondary data that describes natural ventilation and its methods, drivers, principles, effects of natural ventilation to health, energy consumption and secondary research on the relation between interior design and airflow are explained. Chapter 3 describes the system of the case studies and the building the case study classroom is located. Several guidelines regarding natural ventilation are provided in Chapter 2 and Chapter 3. In Chapter 4, the method for the computer – generated simulations are explained. Chapter 5 presents the results of these simulation studies as numerical and visual data, and Chapter 6 concludes the study including suggestions from the author.

In the T building of Yaşar University in İzmir, natural ventilation aspects were investigated. 17 different case studies that were generated in a CFD (Computational Fluid Dynamics) program were analyzed, and their results were evaluated. This paper studies the ventilation rates and ventilation velocities for a specific classroom in this building has three windows on adjacent walls. It is assumed that the doors of the classroom are closed, therefore leaving only a window on adjacent wall as the outlet. A hypothetical window is placed near the doors and its dimension and location on wall is changed in different simulations, along with other three existing windows.

Based upon the outcomes that were explained in Chapter 5, it is possible to arrange the obtained results as following:

- Adding an extra window facing the windward windows improves the airflow rates and flow velocity.
- Larger inlets provide more ventilation rates than smaller inlets, even if the I/O

ratio is almost same.

- When the inlet and outlet openings are on opposite walls, they provide more ventilation than in the case they are on adjacent walls.
- As the I/O ratio rises, the ventilation rate increase as well; ventilation rate increases a lot more when the openings face each other.
- Bigger aisle window (as the outlet opening) improves ventilation rates only an iota.
- When the wind force is the main driver for natural ventilation, changing the place of the aisle window vertically do not improve ventilation rates significantly, if not zero.
- On the other hand, changing the position of windows can make a difference for occupant comfort; when the windows are placed high, the air follows a path in higher levels as well, preventing the discomfort of draft.
- While opening the doors create great amount of ventilation rate, these values can be achieved by opening a window right beside the door. Even more, opening the doors may cause discomfort for the occupants, so it is feasible to open a smaller window that can result in same ventilation rates.
- This hypothetical window not only improves air ventilation rates; it also creates alternative air paths in the indoor space.
- Even if the I/O ratio stays same, it is understandable that the height difference between inlet and outlet openings change the air path inside the space.

The results present that window position and dimension affect ventilation rates and air velocity rates in an enclosed room. A hypothetical window not only improves air ventilation rates, but also creates alternative air paths in the space. Even if inlet – outlet distance does not change the airflow rates when the main force is the wind force, it helps to create a path that grants occupant comfort. Therefore, it can be suggested to the designers that, since mass airflow rate is not affected by inlet – outlet distance, but it is influenced greatly by inlet – outlet ratio, they are not limited to design same height windows, they can place the inlet and outlet openings at different heights to improve occupant comfort.

Based upon the results of this study, it can be recommended for designers to understand the wind forces and the path the airflow follows inside the space. IEQ and

IAQ put occupant comfort before many aspects, therefore, conducting simulations before a space is constructed can help to improve the comfort level.

This study does not present the effects of temperature, humidity, and different wind incident angles on ventilation rates for the same space. Furthermore, airflow rate, ACH, and airflow velocity is affected by wind speed and wind direction, which this study is absent of. As a future work, including these parameters into the study will be attainable.

Interior layout and furnishing are other subjects that natural ventilation studies overlook, as a future work, the effects of different kinds of masses on natural ventilation inside a space can be studied, even more, there can be guidelines that includes design principles to improve occupant comfort. Occupants generate CO_2 and transports pollutants involuntarily; every window opening behavior and their activity levels change the direction of the flow. Therefore, thinking the corridors, rooms and passages as an air distribution system would be a bio-climatic method and even energy efficient.

Window opening is an occupant behavior, and in some buildings, there are not even operable windows. It can be suggested as a future work that with a sensor that can detect the wind velocity, the window can close before the airflow becomes uncomfortable, for this purpose, IoT (Internet of Things) might be utilized.

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APPENDIX 1 – Geometry Component

SpaceClaim Tool

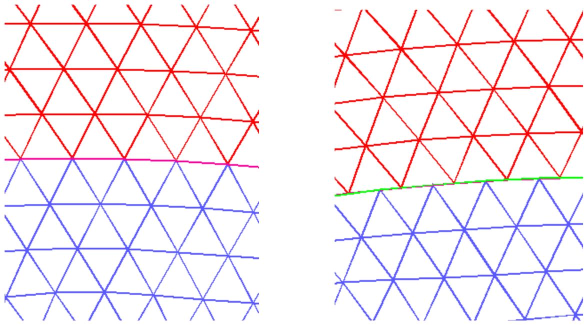
SpaceClaim is a tool for sketching and modeling. All modeled geometry are innately assumed as fluid region in Fluent simulation unless specified otherwise. There can be need to split bodies to create simpler fluid regions. Pull, move, combine, and split body tools are employed to create the models for the cases assembled for this study, see the Figure A1.32 for the tools in the geometry component.

- **Pull Tool** Pull tool creates 3D models out of sketched 2D shapes.
- **Move tool** Move tool enables user to move the sketches, solids, and components.
- **Combine Tool** Combine tool performs Boolean operations, this tool adds or subtracts solids. Combine tool is used to create extensions of windows in this study; meshing for these extensions is denser than other solid bodies, this process is be explained in Appendix 2.
- **Split body tool** Split body tool is used to create two or more solid bodies out of one single body. This tool was employed to create identical bodies for ambient air meshing.

Figure A1.32. Figure represents the geometry tools used in this study; pull, move, combine, and split body tools.

Share Topology

SpaceClaim can share topology between bodies (volume and surface bodies included) and surfaces that are in contact. Shared Topology is the only way to achieve a conformal mesh, which is more preferred if there are more than one bodies in contact, see Figure A1.33. In Fluent solver, non-conformal mesh is treated as 'wall', meaning that the equations are not solved for that mesh (ANSYS, 2016c).



Conformal Mesh Non-conformal Mesh

Figure A1.33. Conformal mesh and non-conformal mesh comparison is shown. The nodes of mesh cells meet each other in conformal mesh (ANSYS, 2016c).

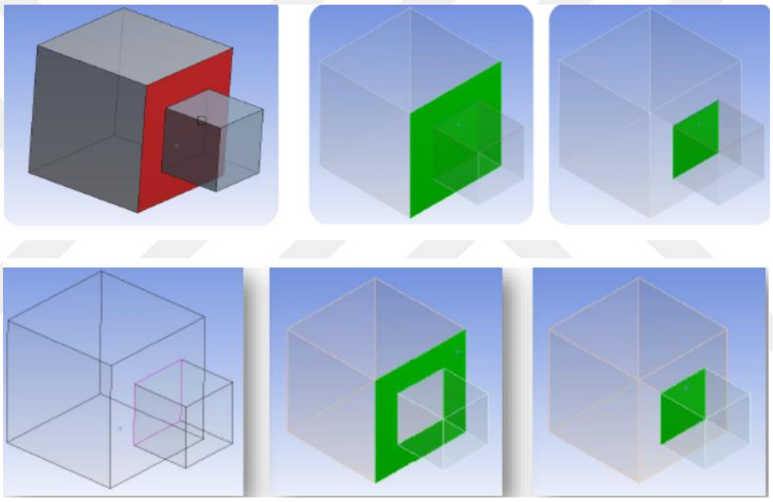
If the parent Component in Geometry model is set to ‘Share’, Shared Topology is passed from SpaceClaim to Workbench, see Figure A1.34. All solids and surfaces under the parent component are considered as a multi body and they share the topology.

Figure A1.34. Share topology in geometry component is simply processed by 'Share' button on the ribbon.

APPENDIX 2 – Mesh Component

Contact Region

Contact region is listed under Coordinate systems – Connections. Contact regions occur automatically between two faces. If these two faces share no connection (no face sharing, as it was explained in 4.2.1.1.1. Share Topology), each face are meshed independently, and creating non-conformal mesh where meshes do not match and the cell nodes are not connected, see Figure A2.35 a. On the other hand, if the geometry is topology shared, as it is done in this study, the contacting faces fuse and create an interior face which is shared by the bodies, Figure A2.35 b.



(a)

(b)

Figure A2.35. a) The two bodies do not share topology; therefore, the two faces are meshed independently, creating non-conformal mesh. **b)** Two bodies are sharing topology, in conclusion to that, two contacted faces fuse together to create a common face which is named as 'interior'. This process results in conformal mesh. Imagery:

Meshing 3D Bodies

The Mesher disintegrates the bodies to four different mesh cells, tetrahedral, pyramidal, prismatic, and hexahedral; see Figure A2.36 for imagery. The meshing methods used in this study are:

- Tetrahedrons (tetras only),
- Sweep (hexahedrons and prisms),
- Automatic (patch controlled tetrahedrons).

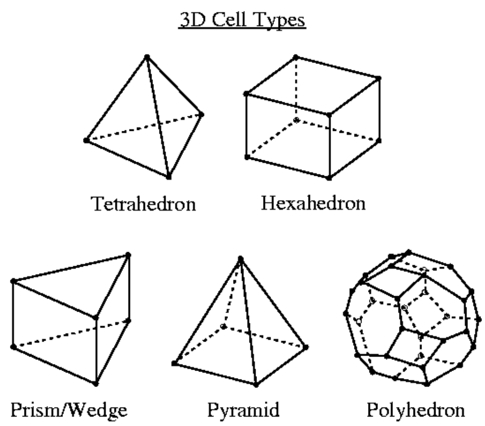


Figure A2.36. Four main mesh cell types; tetrahedral, pyramidal, prismatic, and hexahedral are used to disintegrate bodies, polyhedron mesh cell type can only be obtained through tetrahedral mesh cells. Image: (ANSYS, 2010).

Mesh Metrics

Mesh metrics display mesh quality. For the meshes of this study, two of quality criteria which are skewness and orthogonal quality are considered. High orthogonal values and low skewness values are recommended for a better mesh quality (ANSYS, 2018d). Figure A2.37 and Figure A2.38 displays the mesh metric spectrum values for skewness and orthogonal quality, respectively. The mesh metrics respectively for this study are as follows; lowest value of orthogonal quality is 0,19 for orthogonal quality and highest value is 0.89 for skewness; which are acceptable.

Excellent	Very good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

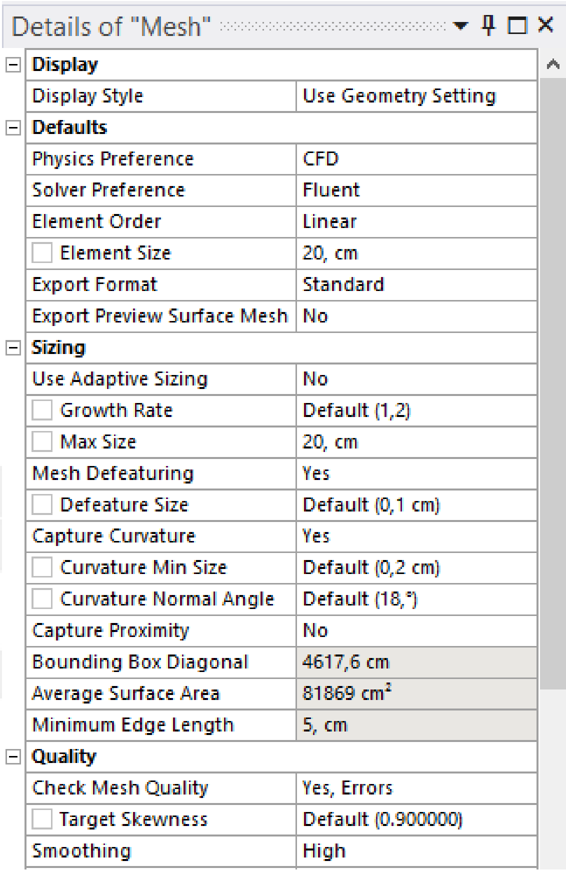
Figure A2.37. Skewness mesh metric spectrum (ANSYS, 2018d).

Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

Figure A2.38. Orthogonal quality mesh metric spectrum (ANSYS, 2018d).

Global Mesh Controls

Global mesh controls are used to make global adjustments in the meshing, such as sizing, inflation, etc. (ANSYS, 2018b). The following describes the procedure for global mesh controls of this specific study. REHVA Guidebook no:10 expresses that for a room of 50 m3 the number of mesh cells generates 200 000 cells; and for a room of 4500 m3 yields 2.6 million cells (Nielsen & Francis, 2007). The grid distance, or element size, for the mesh cells should be 30 cm at most for a room of size 20 m (Nielsen & Francis, 2007). The global mesh details are given in Figure A2.39.



Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	20, cm
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1,2)
Max Size	20, cm
Mesh Defeaturing	Yes
Defeature Size	Default (0,1 cm)
Capture Curvature	Yes
Curvature Min Size	Default (0,2 cm)
Curvature Normal Angle	Default (18,°)
Capture Proximity	No
Bounding Box Diagonal	4617,6 cm
Average Surface Area	81869 cm²
Minimum Edge Length	5, cm
Quality	
Check Mesh Quality	Yes, Errors
Target Skewness	Default (0.900000)
Smoothing	High

Figure A2.39. Global mesh controls for all case studies. Maximum element size is chosen as 20 cm.

- **Defaults**

In defaults section, physics and solver preferences are chosen. For CFD simulations, physics preference must be chosen as CFD and for solver, Fluent must be chosen. Default mesh settings are consequentially attuned when the preferences are decided (ANSYS, 2018b).

- **Sizing**

Size function manages the distribution and growth of mesh cells (ANSYS, 2018b). For this study, adaptive sizing is not used, transitions (controls the rate at which elements grow) is set to Slow and Span Angle Center is set to Fine. Maximum element size is

20 cm for finer meshing.

- **Quality**

For Quality setting, other than smoothing, all other options are left to be default. Smoothing is set to High for better mesh quality.

- **Inflation**

Inflation is used to create thin mesh cells nearby the boundaries (ANSYS, 2018b). For this study, instead of global inflation settings, inflation is applied to the bodies for independently for higher accuracy for the main calculation zones. This application is explained in Local Mesh Controls.

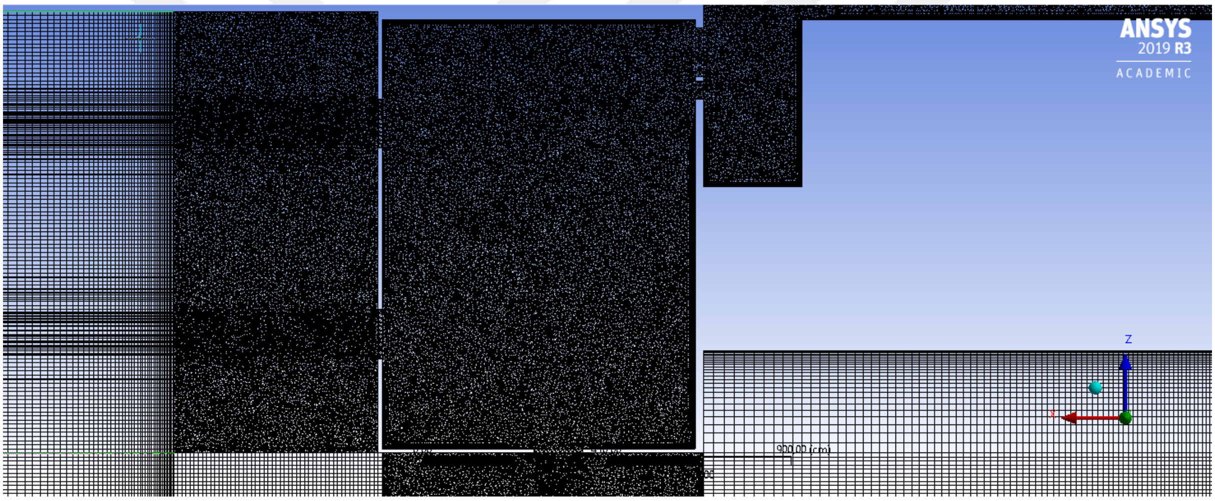


Figure A2.40. Mesh elements for all case studies include hexagonal cells around the main calculation zone and tetrahedral cells for the main calculation zone and immediate bodies around it.

Local Mesh Controls

Unlike global mesh controls, local mesh controls manages the mesh locally depending on the mesh method used (ANSYS, 2018c). Local mesh controls are added after selecting the desired body and clicking right. The listed controls are used in this study:

- Method for body (Sweep and Automatic),
- Sizing for face and body (Smaller element sizes for finer meshing),
- Refinement for face,

- Inflation for face (Only for main calculation zones such as the classroom) (ANSYS, 2018c). The detailed controls are listed in Figure A2.41.

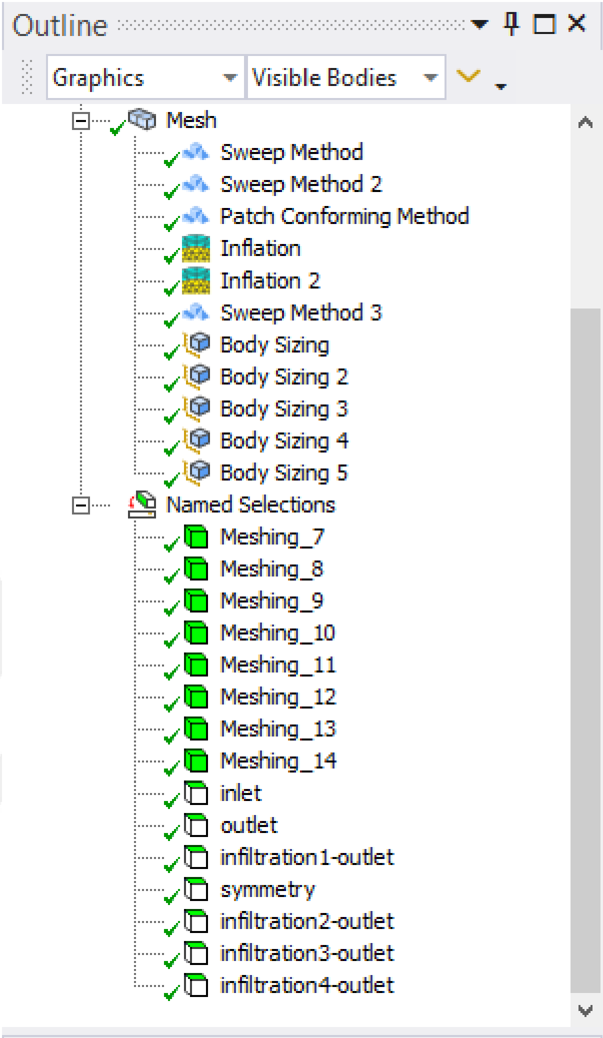


Figure A2.41. Different kind of methods, inflation and body sizing are used for the case studies. Under the named selections, the list of the face names and meshing order is listed.

- **Methods**

Sweep method can only be used with the bodies Meshing deems as sweepable bodies. Only “ambient air” bodies were meshed with sweep method for this study. Patch conformal method is used to create tetrahedral mesh cells for windows, because these bodies are transformed into polyhedral mesh cells later on.

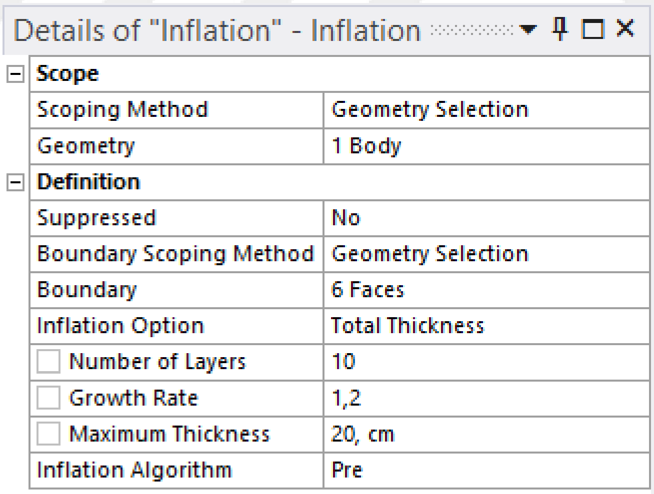
- **Sizing**

There are four different types of sizing option, element size, number of divisions, body of influence and sphere of influence. For this study, only element size is employed. Element size on a body defines the maximum cell size on the body, overriding the global settings (ANSYS, 2018c).

- **Inflation**

Inflation is used to generate thinner mesh cells adjacent to boundaries. Inflation layer can be added bodies using faces as the boundary (ANSYS, 2018c). The inflation option used for this study is Total Thickness which maintains constant total height of inflation layer throughout the boundary (ANSYS, 2018b).

The inflations were added to bodies. Boundaries were chosen as the faces of the respective bodies. The number of layers, maximum thickness and growth rate were set as 10, 20 cm, and 1.2, respectively, see Figure A2.42. Inflation Algorithm was chosen as Pre. Pre is the default algorithm and the best suited for Patch Conforming. In Pre algorithm, “the surface mesh is inflated first, then the rest of volume mesh grows” (ANSYS, 2018b).


Details of "Inflation" - Inflation

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Suppressed	No
Boundary Scoping Method	Geometry Selection
Boundary	6 Faces
Inflation Option	Total Thickness
Number of Layers	10
Growth Rate	1,2
Maximum Thickness	20, cm
Inflation Algorithm	Pre

Figure A2.42. Details of the inflation utilized on all bodies.

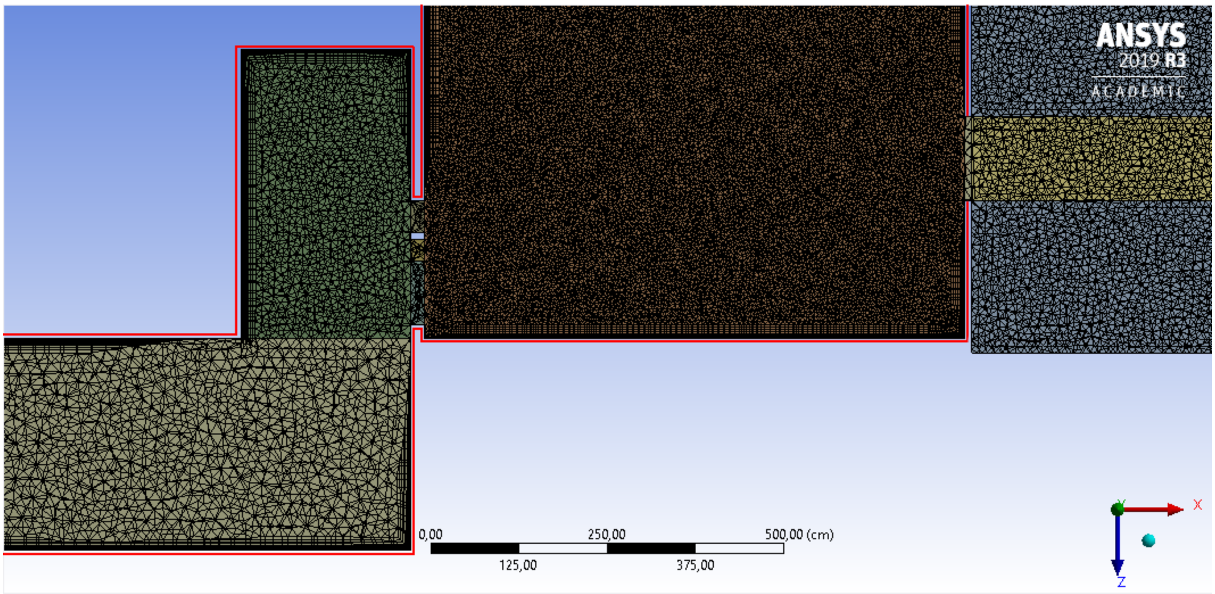


Figure A2.43. Inflation layer is framed in red; the layer is inside the main calculation zone and immediate body of interior space (aisle zone) as a thick layer of mesh cells.

- **Name Selection**

Name selection is a useful tool to name faces or bodies for later convenience. Inlet, outlet, wall, and symmetry faces are named in this section, see Figure A2.41. After clicking right while the face is selected, a bar opens to user to name the selection. The named selections for this study are: Inlet, outlet, infiltration outlets and symmetry faces. There is no need to name a face as wall unless required otherwise, since Fluent component treats all unnamed faces as walls.