

IMPACT OF INDOOR ENVIRONMENTAL QUALITY ON OCCUPANT'S COMFORT & ENERGY USE IN AN OFFICE BUILDING

A Thesis

by

Emine Şen

Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the

Department of Architecture

Özyeğin University

July 2021

Copyright © 2021 by Emine Şen

IMPACT OF INDOOR ENVIRONMENTAL QUALITY ON OCCUPANT'S COMFORT & ENERGY USE IN AN OFFICE BUILDING

Approved by:

Dr. Touraj Ashrafian, Advisor,
Department of Architecture
Özyeğin University

Dr. Neşe Ganiç Sağlam
Department of Architecture
Özyeğin University

Dr. Merve Atmaca,
Department of Architecture
Beykent University

Date Approved: July 2021



To my beloved family.

ABSTRACT

Due to the transitions of technological systems and scientific data related to the building sector and environment under the developing world conditions, the challenges of air pollution and increased energy use have become the main concerns to be urgently and globally acted upon. By its extensive role in occupant's health and energy use, the indoor environmental quality (IEQ) considerations in building design have become a priority with its various parameters examined in a holistic approach. IEQ is highly related to various chemical and physical factors, including subsistence gases, ventilation rates, indoor air temperatures. The increment in time spent indoors with all kinds of work and entertainment activities culminates as more prolonged contact and contingency with the pollutants, pathogens subsistence in the air, also the continuous interactions with indoor air temperatures. While the poor conditions of IEQ are known to have acute and chronic effects on the occupant's health, resulting in adverse outcomes such as Sick Building Syndrome (SBS), it emphasizes the importance of significant determinants of IEQ more profoundly. The Indoor Air Quality (IAQ) and thermal comfort, correspond to the further issues of occupant behavior, ventilation strategies, and energy efficiency.

The thesis aims to investigate the methods to improve IEQ levels in an office building, with enhanced fresh air intake and indoor temperatures to ensure healthy and livable conditions by examining the effects of ventilation strategies, HVAC systems, material selection, and activity scheduling on building energy efficiency and occupant comfort. An office building is used for the analysis and modeled to collect data by simulation using DesignBuilder software. The thesis methodology is followed by the collected data obtained from building modeling variations and their comparisons made by analyzing the levels of indoor air quality parameters as well as the energy use of the building.

ÖZET

Gelişen dünya koşullarında yapı sektörü ve çevre ile ilgili teknolojik sistemler ve bilimsel verilerdeki değişiklikler nedeniyle, hava kirliliği ve artan enerji tüketimi sorunları, küresel olarak acilen harekete geçilmesi gereken temel kaygılar haline gelmiştir. Kullanıcı sağlığı ve enerji kullanımındaki kapsamlı rolüyle, bina tasarımında iç mekân çevre kalitesi, aynı anda incelenmesi gereken çeşitli parametreleriyle bir öncelik haline gelmiştir. IEQ, gaz konsantrasyon, havalandırma oranları, iç hava sıcaklıkları dahil olmak üzere çeşitli kimyasal ve fiziksel faktörlerle yüksek oranda ilişkilidir. Her türlü iş ve eğlence aktiviteleri dahil olmak üzere iç mekanlarda geçirilen zamanın artması, kirleticilerle daha uzun süreli temas ve olasılık, havadaki patojen varlığı, ayrıca iç ortam hava sıcaklıkları ile etkileşimlerin de artması ile sonuçlanmaktadır. İç çevre kalitesinin kötü koşullarının bina kullanıcıları üzerinde Hasta Bina Sendromu (SBS) gibi olumsuz sonuçlara yol açan akut ve kronik etkileri olduğu bilinmektedir. Bu durum, bina sakinlerinin davranışları, havalandırma stratejileri ve enerji verimliliği gibi daha fazla tartışmayı kapsayan iç çevre kalitesinin, iç hava kalitesi ve termal konfor gibi önemli belirleyicilerinin önemini vurgulamaktadır.

Bu tez, bir ofis binasında havalandırma stratejilerinin, HVAC sistemlerinin, malzeme seçiminin ve aktivite planlamasının bina enerji verimliliği ve kullanıcı konforu üzerindeki etkilerini inceleyerek sağlıklı ve yaşanabilir koşulları sağlamak için taze hava girişi ve iç ortam sıcaklıklarını değerlendirerek IEQ seviyelerini iyileştirme yöntemlerini araştırmayı amaçlamaktadır. Analiz için DesignBuilder yazılımı kullanılarak simülasyon oluşturulup, bir ofis binası veri toplamak için modellenmiştir. Tez metodolojisini, bina modelleme varyasyonlarından elde edilen toplanan yazılım verileri ve binanın enerji kullanımının yanı sıra iç hava kalitesi parametrelerinin seviyeleri analiz edilerek yapılan karşılaştırmalar takip etmektedir.

ACKNOWLEDGMENTS

During my studies, I have been supported and encouraged in a great deal by the following people that I would like to thank for,

Firstly, my thesis advisor, Dr. Touraj Ashrafian who gave me his valuable counseling, efficacious and constructive feedback through his expertise on all of the problems I dealt with during my studies and continuously supported me to improve my skills on a higher level in my research field by giving his valuable time and effort.

I would also like to thank my master's tutors, Prof. Dr. Alper Ünlü, Dr. Nevşet Gül Çanakçıoğlu, Dr. Derya Yorgancıoğlu, Dr. Murat Şahin, Dr. Işıl Tekçe, and Dr. Ebru Karahan for sharing their knowledge and influential supervisions where I needed guidance for direction and related tools on different subjects on my research field.

Lastly, I would like to thank my parents, sister, and friends for their never-ending support, love, and care especially during the hardest times of my life journey. The unrequired faith you hold in for me will always be worth it through all.

TABLE OF CONTENTS

DEDICATION	iii
ABSTRACT.....	iv
ÖZET	v
ACKNOWLEDGEMENTS	vi
TABLE OF CONTENTS	vii-ix
LIST OF TABLES	x
LIST OF FIGURES.....	xi-xii
Chapters	
INTRODUCTION	1
1.1 Importance of the Study	1
1.2 Purpose of the Study.....	7
THE REVIEW OF THE LITERATURE.....	9
2.1 Importance of Indoor Environmental Quality on Occupant Health & Productivity..	10
<i>2.1.1 Occupant Health Risks, BRS, and SBS</i>	11
<i>2.1.2 Occupant Productivity</i>	13
2.2 Indoor Environmental Quality and Occupant Comfort.....	16
<i>2.2.1 Indoor Air Quality</i>	16
2.2.1.1 Air Pollution and Indoor Air Pollutants.....	16
Carbon monoxide (CO)	17
Carbon dioxide (CO ₂).....	18
Nitrogen dioxide (NO ₂)	19
<i>Particulate Matter (PM)</i>	19
Volatile Organic Compounds (VOCs).....	19
Other Pollutants	19

TABLE OF CONTENTS

2.2.1.2 Indoor Air Quality Guidelines, and Standards	20
2.2.1.3 Occupant Behavior and Energy Use.....	21
Air Conditioning	25
Ventilation Strategies.....	26
Occupant Activities and Window Operation.....	30
2.1.2 Thermal Comfort	33
2.1.3 Visual and Acoustic Comfort.....	35
2.1.4 Indoor Environmental Quality Improvement Methods.....	35
2.3 Indoor Environmental Quality and Energy Use in Office Buildings	36
2.3.1 Building Systems and Design Strategies.....	36
2.3.2 IEQ in Nearly Zero/Net Zero Energy Buildings	38
2.3.3 Standards and Guidelines on IEQ	39
RESEARCH METHODOLOGY.....	41
3.1 Methodology.....	41
3.2 Case Building	43
3.2.1 Architectural Design and Details	43
3.2.2 Climatic Conditions of Selected Cities	45
3.2.3 Building Modeling Variations and Scenarios	46
3.2.3.1 Variation Groups and Mechanical Systems.....	46
Variation Group 0 (V ₀): ASHRAE 90.1 HVAC Systems	46
Variation Group 1 (V₁) (A1, B1, C1): Proposed HVAC Systems....	48
3.2.3.2 Variation Group 1 Scenarios	49
Scenario A: Insulation Materials by EPS thicknesses	49
Scenario B: Natural Ventilation Scheduling.....	50
Scenario C: Window Layout and Glazing Area	50

TABLE OF CONTENTS

RESULTS AND DISCUSSION.....	52
4.1 Results	53
<i>4.1.1 Energy Use</i>	<i>53</i>
<i>4.1.2 Occupant Comfort.....</i>	<i>58</i>
4.2 Current Situation and Research Gaps.....	64
<i>4.2.1 Covid-19 Pandemic and IAQ.....</i>	<i>64</i>
<i>4.2.2 The Republic of Turkey’s Ministry of Environment and Urbanization Guidelines on nZEB design.....</i>	<i>66</i>
CONCLUSION	68
APPENDIX A: DESIGNBUILDER MODELING DETAILS.....	70
REFERENCES	73
VITA	88

LIST OF TABLES

Table 1: The reviewed papers by year of publication, methodology, source country, occupant behavior relationship, and influential parameters.....	24
Table 2: The reviewed papers related to different ventilation strategies by year of publication, source country, ventilation strategy types, and research methods.....	27
Table 3: The reviewed papers related to window operation by year of publication, source country, and methods.....	32
Table 4: IEQ standards and their scope in detail.....	40
Table 5: The natural ventilation schedules of B ₁ and B ₂ cases.....	50

LIST OF FIGURES

Figure 1:	The topics reviewed in the scope of research.....	9
Figure 2:	The various factors influence indoor environmental quality.....	10
Figure 3:	The factors affecting the occupant health and productivity.....	15
Figure 4:	Building occupants' relationship with building energy use.....	23
Figure 5:	The variations and scenarios that are decided to be analyzed.....	42
Figure 6:	Building modeling.....	44
Figure 7:	Building modeling zones.....	44
Figure 8:	Building modeling floor plan.....	45
Figure 9:	ASHRAE 90.1 HVAC systems set for variation group 0 (V_0).....	47
Figure 10:	Proposed HVAC systems set for variation group 1 (V_1).....	48
Figure 11:	The window layouts of C_1 (left) and C_2 (right) cases.....	51
Figure 12:	The energy uses and the total end uses of V_0 and V_1	53
Figure 13:	The total energy uses in all scenarios (A-B-C) as natural gas, electricity, and water use	56
Figure 14:	The net site and net source energy use of all variations and scenarios...	56
Figure 15:	The heating and cooling end uses in the B scenarios.....	57
Figure 16:	PMV Results of all variations and scenarios.....	60
Figure 17:	The comfort levels including temperature values, and humidity of all variations and scenarios.....	61
Figure 18:	The ventilation rates in all variations and scenarios I.....	62
Figure 19:	The ventilation rates in all variations and scenarios II.....	63

A-1	DesignBuilder HVAC template details of Variation Group 0 (V ₀) with the ASHRAE 90.1 Appendix G preferences.....	70
A-2	DesignBuilder HVAC template details of Variation Group 1 (V ₁) with the Proposed Building Systems preferences.....	71
A-3	DesignBuilder building materials details of walls in A1 (above) and A2 cases (below).....	72



CHAPTER I

INTRODUCTION

1.1 Importance of the Study

The new world conditions drastically changed under various industrialization trends, and strategies which emphasize the human impact on the climate are unequivocal as never before. Rising sea levels, greenhouse gas emissions, melting glaciers, droughts, and rapid changes in the temperatures of the atmosphere and oceans are consequences of human actions that greatly influence the systems of both humans and nature [1].

Climate change, air pollution, and insufficient resources have become the most important future challenges to be addressed worldwide. These challenges require urgent action to become climate adaptive, carbon and energy neutral, and use the world's resources at an optimum level, which ensures these actions are effective and part of the circular economy and sustain efficient living conditions.

The fundamental requisite for human health and comfort is providing enough fresh air. However, one of the significant challenges which have been one of Europe's leading political concerns since the late 1970s is air pollution. [2]. It has become a global and environmental health problem that acts on every human being and each country without considering their socio-economic development indexes.

According to the air quality guidelines by WHO [3], exceeding 2 million premature deaths are inferred from the impacts of both indoor and outdoor pollution. To this extent, it is not a new problem. Yet, it is recently acknowledged as a challenge over the last fifty years since organizations such as the European Union (E.U.), World Health

Organization (WHO) acted upon this concern by raising awareness of prevention and mitigation strategies.

Air pollution can be outlined as a composite that embodies damaging concentrations of particles and gasses which its extremities bring about irrevocable consequences on the environment, as well as human health by diseases of meager air conditions [4]. The recent scientific findings show that the indoor air within residential, commercial, or other buildings is possibly more polluted than the outdoor air in even most developed cities causing health risks due to exposure to pollutants. Additionally, the building occupants such as young, elderly, or others already suffering from chronic diseases who are generally most vulnerable to these health risks spend more of their time indoors [5].

Furthermore, the time spent indoors is about 90 percent, as stated by The U.S. Environmental Protection Agency [6] and the U.S. Consumer Product Safety Commission [7]. People tend to undertake all kinds of activities, including work and entertainment in indoor environments. This increment in time culminates as more prolonged contact and contingency with the pollutants, and pathogens subsistence in the air, and ongoing interaction with temperature changes.

The poor conditions of indoor environments cause risks to human health, decrease work efficiency and productivity, and influence comfort levels. It can emphasize the importance of significant determinants of indoor environmental quality (IEQ), including parameters primarily concerned with these challenges as indoor air quality (IAQ), thermal comfort, along with other comfort levels of acoustic and visual.

To meet an acceptable indoor environmental quality under the concerns of diminishing the indoor air pollutants and immoderate temperatures adverse impacts on building occupants, both outdoor and indoor pollution sources, cooling, and heating

demands should be deliberately inspected. The former concept of sustainability that neglected the other sociological, cultural, or psychological aspects are included in current guidelines and directives [8].

By the standards and regulations such as ASHRAE 55, ISO 7730, and EN15251, designers can follow the drawn pathway to ensure the optimum needed comfort levels for naturally ventilated environments [9]. The ventilation and air contaminant management are included in these standards as stated in the optimum prerequisites and alternative sources to improve IAQ and thermal comfort [10][11].

The IAQ is mainly related to various chemical and physical factors, including the subsistence gases of carbon oxides, tobacco smoke, volatile organic compounds (VOCs), air circulation rates, indoor air temperatures, radiation, etc. Therefore, IAQ assessment is an interdisciplinary task and needs integrated scientists and experts from medicine, chemistry, biology, engineering, architecture, and building sciences [12]. Therewithal, other decision-makers such as owners, builders, or managers rarely consider these parameters due to their fundamental goals: only maintaining low running costs and supplying direct or instantaneous maintenance and operational improvements.

The focus on new or existing buildings is inefficient on IAQ since the methodologies on simple or extensive design decisions and retrofits substantially weighted more on energy efficiency. The cost-effectiveness of these decisions is also not fully assessed concerning IAQ parameters comparing energy efficiency measures while IAQ performs an extensive role on today's concerns. Additionally, while providing energy and cost savings, there are some significant challenges. For example, decreasing active systems usage for ventilation can cause indoor pollutants to increase. Simultaneously, circulating air between indoor and outdoor can raise indoor air pollutants since outdoor air is more polluted in most urban cities [12].

The other parameter of IEQ is thermal comfort, which depends on the heat exchanges between the occupant and its environment. The climate simultaneously regulates these heat transfers since both the occupant and environment are under ongoing exposure to exterior conditions. Therefore several studies take climate as an influencer factor while analyzing thermal comfort parameters and finding correlations between similarities and differences in different climatic zones [9].

As climate conditions differ between locations and environmental conditions, and the evaluation of thermal comfort depends on estimates that are difficult to attain at actual measures, the climate change consequences of rapid and incoherent changes on temperatures make the thermal comfort evaluations much harder to conduct. So obtaining needed levels for occupants requires far more energy consumption and further detailed assessment on the field.

People perform various tasks to survive and be productive, requiring them to consume different energy forms and sources. From the industrialization era of the world, the primary focus is on energy since it is a crucial sector for the growth and progress of countries to have improved living conditions [14]. Therefore, by the 'world's rapid development trends, energy consumption is rising internationally, linked with prosperity and economic opportunity worldwide.

According to International Energy Agency [15], from 1971 to 2018, the total final energy consumption is approximately doubled and principally increased in the transportation and the residential sectors. This current and steady growth in consumption has only slowed during the world economic crisis around 2009 [16]. It indicates that it is highly related to political and economic aspects and continues to have new challenges and uncertainties since the resources are unevenly divided globally, and unsustainable consumption increases among different countries.

Ensuring energy efficiency and supplement of energy resources are the future issues to be dealt with extended rapid development, deployment, and diffusion of new technologies. These are critical in any energy goal achievement and reduce further emissions and pollution. The challenges have two crucial dimensions. Firstly, the unsustainability of energy use patterns, which rely on fossil fuels threatening to climate and has severe, irreversible consequences on nature and humans. Secondly, a deranged availability of resources among the world population includes a lack of access to electricity, transportation, and essential energy services [17].

All these consequences require energy and cost management in the urban buildings since this sector takes up 40% of the total primary energy use and 36% of greenhouse emissions [18][19]; of which, at the same percentage in the sector is used by commercial buildings [20]. The built environment is also continuously expanding in numbers, and the size which occupied buildings has risen approximately 43% to 34 million in 30 years [21].

Considering energy efficiency or sustainability does not always mean providing occupant comfort levels as the occupant's preferences and behavior vary between user type and attitudes. When the needed conditions for the occupant are not provided, which causes discomfort, there is a behavioral model called adaptive principle in which the occupants react to adapt to physiological, behavioral, or psychological conditions of their environment and behave in different ways to regain their needed comfort conditions [22]. Accordingly, to meet the necessary conditions and improve thermal comfort, and to be able to act on the challenges of energy efficiency and indoor air quality, the relationship between occupants and buildings should be scrutinized, seeing that the mentioned problems are actively tied to the occupant behavior as much as energy-efficient design measures.

The various comfort levels dependent on this relationship are significant fragments of indoor environmental quality (IEQ) and related to occupant satisfaction and wellbeing. Unsatisfactory comfort levels are known to have acute and chronic effects on the health of the occupants resulting in adverse outcomes such as Sick Building Syndrome (SBS) and, accordingly, decreased work efficiency and productivity. The definition of SBS varies since it includes a combination of several symptoms. Still, it is principally related to a specific building in a temporal sense linked with inoperable windows, high temperature and pollutant levels, passive tobacco gasses, sealed and impermeable building envelopes [23].

Ultimately, a critical factor in achieving healthy environments in buildings is providing a high Indoor Environmental Quality (IEQ) level while considering the impact of energy consumption and occupant comfort. The impacts of poor indoor environmental conditions have been studied across various research areas such as health and building sciences. In recent years, the design measures, and strategies around energy efficiency and IEQ evolved and varied since requirements and challenges are expanded as stated. Some recent approaches can be respected as green building design, climate-sensitive house, passive house design, solar house, and nearly or net-zero energy building.

Nearly Zero Energy Building (nZEB) is a common attempt and considerably takes the attention since it has a significant influence on energy efficiency and environmental challenges in the building sector by giving auspicious solutions as reducing carbon emission and energy consumption [24]. As European Commission stated in the Energy Performance of Buildings Directive [25], all new buildings from 2021 (public buildings from 2019) are demanded to be nZEB.

The definition of nZEB varies since climatic conditions, optimum comfort levels, energy demands, and assessment methods change between countries, yet it can be

considered as a building that performs higher at energy [25]. There are also various parameters, which can be defined as physical, design, and scenario factors, to deliberately assess through nZEBs since uncertainties occur in energy generation systems and consumption [26].

Up to now, projects on the related issues are primarily concerned with new urban buildings rather than existing and rural buildings, which have a significant share of energy consumption [27]. Therefore, the overall goal to achieve promising solutions should be considering the different types of buildings in the sector altogether. Also, to reduce the uncertainties of building systems that can be differed as active, passive, and combined; mechanical, natural, and hybrid, the preferences on system types that impact IEQ, and energy parameters should be thoroughly recognized with their advantages and disadvantages.

All in all, the impacts of indoor environmental quality on occupant's comfort and wellbeing and energy consumption are clear and impending. To achieve the goals of energy efficiency and comfort levels, considering future challenges requires action and accordingly research to acquire proficient data from the actual case studies.

1.2 Purpose of the Study

The thesis aims to investigate the methods to provide adequate indoor environment conditions to ensure healthy and livable conditions for building occupants and study the effects of IEQ measures on building energy efficiency. To comply with these objectives, an office building is used to analyze the indoor air quality and thermal comfort measures, evaluate the building conditions under natural ventilation strategies, and observe the energy consumption levels.

The aim is to develop alternative ways of proposing naturally ventilated, healthier, energy-efficient office spaces that will improve its occupants' comfort levels and reduce

energy use relative to existing conditions of the building while bringing insight into the impact of different design considerations and modeling of the indoor environment.

The intended objectives of this thesis include:

1. Establishing a comprehensive literature review on the research subjects including related current problems, IEQ impact on occupant's health and productivity, insight about the reciprocal relationship between occupants and buildings, indoor environmental quality parameters of primarily thermal comfort and indoor air quality, the performance of building ventilation systems, and finally the influencing factors on energy use in office spaces.
2. Analyzing an office building by its energy use of ventilation systems, indoor thermal comfort measures considering the building location's climatic conditions, and design decisions on building HVAC systems and scheduling.
3. Studying fresh air ventilation rates and indoor air temperature rates in office environments by creating different alternatives to compare and highlight the relation of building systems to IEQ.
4. Using building energy modeling to simulate these different variations and to measure levels of fresh air intake and indoor air temperature monitoring the user-side consumption behaviors of the building and building systems by setting different occupant scheduling.
5. Defining the enhanced comfort levels and energy use of the design variations to compose a correlation and modeling results and recommend improved office conditions to compare the impact of IEQ on occupant comfort and energy use.

CHAPTER II

THE REVIEW OF THE LITERATURE

This chapter is constructed as sections that include the outcomes of previous studies to give relevant knowledge and definitions on Indoor Environmental Quality (IEQ). Additionally, its parameters of Indoor Air Quality (IAQ) and thermal comfort, the energy efficiency of building systems, and relationship of indoor environmental quality with occupant comfort and health, and energy use.

The main topics and discussions around the mentioned issues are considered to assist further research and develop a relationship between IEQ parameters with the health and comfort of occupants in nearly zero-energy practices in office building design. The method is followed by reviewing available research topics to demonstrate the state of art literature in the field (Figure 1).

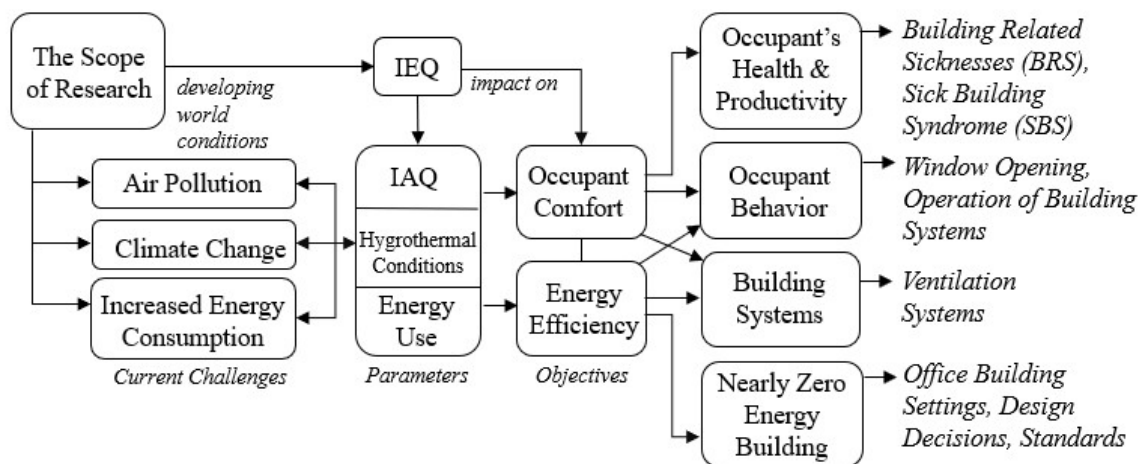


Figure 1: The topics reviewed in the scope of research

2.1 Importance of Indoor Environmental Quality on Occupant Health & Productivity

Indoor environmental quality (IEQ) refers to the internal characteristics of a building, such as indoor air quality (IAQ), temperature conditions, visual (e.g. lighting) and acoustic (e.g. noise) comfort, and related prospective impact on building occupants. Additionally, these parameters are tied up to varied factors: physical, biological, chemical, and exterior, so that they should be inspected all together to obtain optimum levels. (Figure 2).

The poor conditions of IEQ and the characteristics of the building can have adverse effects on the occupant's health and productivity so that maintaining and improving IEQ measures in buildings is a vital concern [28]. If any discomfort or negative impact on occupants creates sicknesses, then the building design and technical conditions should be inspected through building systems.

IEQ measures are also tied up to its occupants since they are affected by the building occupants' perception and satisfaction, which makes the relationship between the building and its occupants another critical factor for consideration.

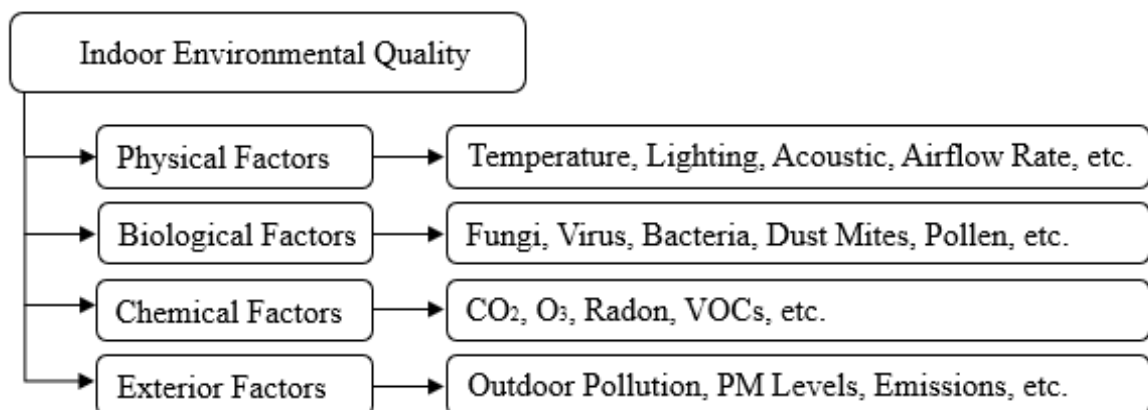


Figure 2: The various factors influence indoor environmental quality

Furthermore, people tend to spend approximately 90% of their time indoors [29] that makes this consideration even more significant since the contact between occupants and the characteristics of the building are lengthened. Some studies show a link between symptoms of the discomfort of IEQ and the working productivity of occupants [30][31].

The available studies have constituted the strong relation of IEQ related problems have a direct impact on comfort, health, the efficiency of building occupants so that the research on the IEQ measures have been increasing under the discussions of building design, energy use, CO₂ emissions, and occupant comfort [32][33]. This relationship is not simple and easy to analyze since there are various parameters of IEQ as thermal, visual, acoustic, and chemical [34][35].

Besides, the impacts can be interim or continuing; if not, the main causes cannot be analyzed and solved [36][37][38]. The psychological or chronic impacts on occupants are complicated to identify at first sight. Yet, they can be potent and abiding in the long-term as symptoms of chronic diseases such as Sick Building Syndrome (SBS), cardiovascular, asthma, depression, obesity, etc. [39][40][41].

2.1.1 Occupant Health Risks, BRS, and SBS

The health problems related to the building environment can be broken down into two. Firstly, building-related sicknesses can be defined as infectious diseases caused by building services to occupants such as fungal spreads [42], or occupant to occupant transmissions such as virus infections [43], or toxic reactions to chemicals. Secondly, Sick building syndrome (SBS) is a set of symptoms, does not cause specific exposure or disease [44].

SBS can be defined as a compound series of detrimental and discomfort symptoms of building occupants, including irritations, asthma, sensitivity reactions, allergies, etc. They occur concerning the time that occupant spent indoors and ease in the absence,

especially in highly occupied office spaces [45]. Those symptoms can be caused by regional or systematical dysfunctionality of the human body, such as respiratory symptoms as itchiness, irritations, dryness of eyes, sinus, nose, skin, or throat, along with distressing as tightness, wheezing, or difficulty breathing in the chest, and as neurophysiological symptoms including headache, tiredness, mental fatigue, or dizziness, etc. [46].

The risk factors of SBS on occupants are researched through psychological, somatic, and environmental determinants. It showed that SBS should be separated from building-related sickness, which means that the occurrence of a specific medical condition is directly linked with building characteristics of ventilation, construction, design, etc. [47][48][49] [50]. The building factors include poor cleaning, lighting, building service maintenance, water damage, low fresh air intake, high temperatures indoors, etc. [51][52][53][54].

By the review of studies about Building-Related Sickness considering productivity and sick leave, the results showed a link between BRS and sick leave of occupants, which also impacts the productivity of office workers depending on the intensity of poor conditions indoors [55].

A recent study by Shan et al. [56] concluded that physiological measures still stay higher than optimum comfort level even in the worst-case scenario. Yet, enhancements in an indoor environment can also improve SBS by considering essential occupant's receptor sensations as head, breath, and eye from its environment. The results of this study on ventilation types as analyzing different scenarios as mixed and displaced showed that by lowering CO₂ concentration in the work environment, the occupant productivity could be improved; also eye irritations have lessened, which resulted in occupants performing better on the tasks.

These health risks are also followed by today's considerations on building design which requires attentive and collaborative strategies, both architectural and mechanical, since the extreme circumstances of recent pandemics or any infectious diseases are rising more than ever. By the latest Covid-19 global pandemic, which has unexpected effects on humans in a short time by increasing the fatality approximately to 2-3% [57], the convergence of particles in an enclosed space that depends on indoor air quality becomes a major topic to be discussed in the health and related fields. Alongside the other measures such as social distancing, hand washing, sanitization, face-masks, and designated lockdowns, the control of fresh air intake by improved ventilation strategies are required to decrease the particles affecting human health [58].

2.1.2 Occupant Productivity

As Guzzo and Bondy [59] stated, even there is no certain definition for productivity, it simply is 'the ratio of output to input' and depended on the transformation of technology from input to output along with office workers' performance; accordingly, there is no defined methodology to follow for measuring the increment or decrease of work productivity. The workers' performance cannot be assessed directly, yet criteria and productivity indicators provide approximate outcomes [60].

The pioneering research on occupant productivity related to the building environment dates back to the early 20th century, including the educational and work environments and their relation to the occupant's comfort [61][62].

As Herzberg discussed in his books, the occupants' behavior, motivation, and understanding of the work are affected by several factors. The working conditions as a first-level factor that defines the accessibility of facilities and tools, acceptable levels of ventilation, lighting, and other physical environmental qualities such as the functionality of spaces are some of the related factors [63][64].

The initial studies on the relationship between IEQ and occupant productivity have focused on enhancing occupants' cognitive and physical performance [65]. Accordingly, the economic alteration toward service and research-based operations globally follows indoor office environments [66].

Enhancing the physical conditions of office environments result in a 15% increase in productivity [67]. The results of studies undertaken in work productivity considering only the air quality demonstrated that decreasing 10% of dissatisfied occupants portion with the indoor air quality concludes as 1% enhancement in overall office work performance of occupants [68].

Wilkins et al. [69] established a questionnaire on 42 office occupants who work under non-fluctuating light as intense. He found that the occurrence of headaches can be reduced down to half by changing the lighting type.

In a more recent study done by Kang et al. [70], the office lighting combining artificial and natural lighting conditions have advantageous effects on office lighting quality and occupant productivity, even if the natural lighting has much lower satisfaction levels than artificial lighting. It indicates the improvement in natural lighting is needed to ensure satisfaction and productivity of office occupants during work hours.

A study done by Huang et al. [71] studied various IEQ parameters as indoor air quality, thermal comfort, and acoustic and visual environment in a controlled office environment assessment. By surveying 120 subjects, half female half male students, under 8 different temperatures, and five different noise levels, they found out that even in controlled or air-conditioned office spaces, there are a set of demanded temperatures by the occupants, which shows the variety occurs by occupant's perception and satisfaction.

Their result on acoustical comfort shows a threshold of discomfort level, which is 49.6 dB. If it drops below that level, the occupants' performance is also highly influenced.

Some authors have further discussed the indoor air quality aspect, which recognized the improvement on office work when IAQ increases [72][73][74]. For example, recent research has provided evidence for this aspect of IAQ by conducting an observational analysis on six office buildings in China. They correlate the outdoor pollution with indoor pollution measures as PM concentrations based on modeling results, showing a 15% decrease in cognitive performance scores when poor conditions of IAQ build-up over inadequate ventilation [75].

Although studies have been addressed the strong correlation between IAQ measures with occupant's health and productivity, it is a two-sided relationship in which IAQ levels are also influenced by occupant behavior, including occupant preferences and personalized demands (Figure 3).

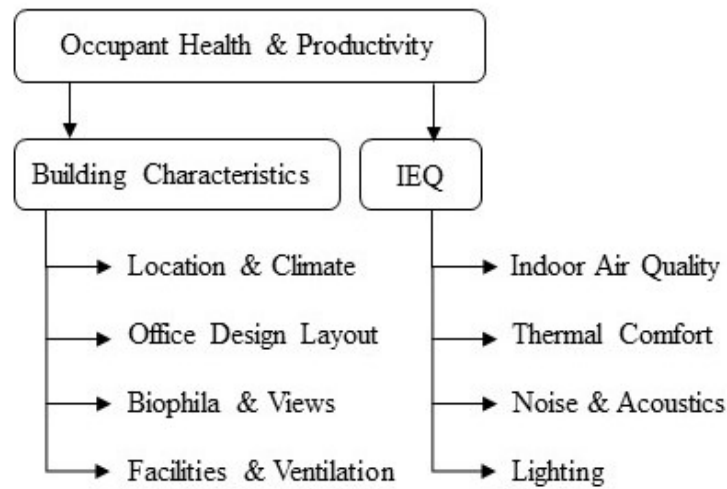


Figure 3: The factors affecting the occupant health and productivity

Moreover, the reciprocal relationship between IEQ parameters and building occupants impacts energy use as well due to the utilization of building systems. It was reported in the literature that the occupant behavior-related interactions with building systems of HVAC, lighting, plug loads, and windows has an impact on overall energy use in a non-rated building with an almost 25% higher use than in a green-rated building [76].

2.2 Indoor Environmental Quality and Occupant Comfort

2.2.1 Indoor Air Quality

2.2.1.1 Air Pollution and Indoor Air Pollutants

Indoor air quality (IAQ), one of the main parameters of IEQ, has become an international issue of broadening environmental and health concerns. These issues are eminently brought out to the subject by the world's challenges of accelerating air pollution and energy use. The Environmental Protection Agency (EPA) drawn attention to IAQ as an urgent environmental issue and established the clean air and air pollution acts. The aim is to overcome emerging pollution threads, control emissions while maintaining reductions, guide the participation and implementation of air quality standards by responsible authorities, and motivate innovation in clearer technologies [77][78].

Indoor air pollution escalated by the energy conservation attempt in the late 20th century as increment in thermal insulation practices in buildings to preserve the heat during the energy crisis period. The first investigations into air pollution and strategies of most countries are weighted more on the ambient air pollution with just some of the common air pollutants, including evaluations of black smoke (BS) and SO₂ rather than comprehensive evaluations of several contaminants [78].

The main shortfall of these early investigations is that they conducted the evaluations only for short periods; they did not consider integrated or reflective measures in their inquiry on the impact of air pollution on indoor air quality and occupant health. Researchers found that poor indoor air quality is a severe and pervasive concern across several developing nations. Still, knowledge and resources regarding indoor air quality are frequently inadequate.

Air pollutants differ between indoor and outdoor air in terms of category and density. The EPA underlines that the indoor air can be more polluted than the outdoor air within

the homes, offices, schools, which leads to or aggravates all health problems up to almost 50% due to indoor air pollution [79]. A challenging problem in this domain is that these health problems can entail acute and chronic long-term and short-term effects on building occupants commonly affiliated with the intensity of SBS symptoms, building-related illnesses.

Furthermore, specifying and overcoming their cause cannot be accomplished with a single strategy. The building occupants interact with their environment while they perform different diurnal activities. The concentrations of pollutants in the breathing zones differ drastically over navigation between the building's respective zones, influenced by varying absorbance indices and degrees from indoor air pollutants sources. So, assessing IAQ parameters by knowing each pollutants' type, densities related to each building zone will still be neglected to explain occupants' physiological and medical reactions to exposures [28]

Given that IAQ is an international multidisciplinary attempt to accomplish, and it covers different aspects and sources to be investigated, such as the preference of building materials and products, used appliances, and system elements covering their operation and maintenance strategies. Whereas in closed spaces of buildings, both chemical and physical determinants are affecting IAQ, which is composed of varied chemicals such as carbon monoxide (CO), carbon dioxide (CO₂), nitrogen dioxide (NO₂), particular matter (PM), asbestos, radon, volatile organic compounds (VOCs) such as formaldehyde, respirable particles, tobacco smoke, and biological pollutants such as micro-organisms, bacteria, fungi, and allergens [78][80][81][82][83][84].

Carbon monoxide (CO)

CO gases, as one of the indoor chemical pollutants, cause several symptoms such as nausea and fatigue due to reducing the capability of red blood cells to transmit O₂ even

causing deaths in extreme conditions [85], which depends on its density, exposure time, and particular occupant's physiological characteristics.

The standards set value for CO is differs between countries but generally around 10 mg/ m³ as 8-h average, which is decided as the same by worldwide organizations [86][87][88]. The primary source of the CO is where fuels are emitted by vehicles such as enclosed parking lots, tunnels, and the building zones near the building mechanical systems are operated with deficient ventilation.

Carbon dioxide (CO₂)

The density of CO₂ gases is generally dependent on the ratio of occupants to the building zone's area and the rates of ambient air transmission to indoors. Therefore, evaluation related to its concentrations in the indoor environment can give insight into the occupant numbers and ventilation rates.

The primary source of CO₂ is not easy to detect because it is not unique to one indicator of IAQ. It is more related to outdoor sources. The ventilation strategies are essential in their effects on occupant's health since reducing it can decrease energy use, but its increased concentrations can augment the health symptoms and risks.

A study on the association of CO₂ with occupants' health in commercial and institutional buildings of 30,000 occupants in about 400 buildings indicated the prevalence of SBS symptoms [89]. Satish et al. [90] reported that the levels of CO₂ concentrations significantly impact the occupant's decision-making performance in the work environment. Even if the office buildings are less polluted by CO₂ than educational or residential buildings since the decision-making zones such as meeting rooms can have higher CO₂ concentrations than the other zones, the economic aspect of the IAQ impact should be considered.

Nitrogen dioxide (NO₂)

The health effects of NO₂ gasses are asthma, damaged lung functioning, or related respiratory illnesses affecting the tissues of breathing as swelling and blocking (Rao et al. 2014). The set value for NO₂ internationally by ASHRAE [92] is 0.02 ppm (40 µg/m³) in one year. The sources of NO₂ gasses differ as vehicles as fossil fuel-burning such as gas stoves, heaters, etc. [93].

Particulate Matter (PM)

Particulate Matters are differed by their types, concentrations, and sources, but it is the pollutant that has been examined and evaluated at most in the literature. The types of PM_{2.5} and PM₁₀ effects are the same as other pollutants, including asthma, chronic cardiovascular and illnesses related to the respiratory system such as lung cancer.

WHO's set value is 10 µg/m³ for PM_{2.5} and 20 µg/m³ for PM₁₀ in one year [94]. Its primary sources are rather natural such as vegetation or disasters such as dust storms, or human sources such as manufacturing or transportation emissions [95].

Volatile Organic Compounds (VOCs)

A variety of substances such as building materials and equipment or fluids release VOCs as gas emissions. Their impact on occupant health can be extended or short-term, including respiratory, immune system illnesses, damaged lung functioning, overnight asphyxia, and allergic reactions [96][97].

Other Pollutants

The other indoor pollutants are sulfur dioxide (SO₂), asbestos, radon, ozone, tobacco smoke, and biological contaminants, which also have similar health risks, including asthma, acute lung diseases, allergic reactions, or airway inflammations [98][99]. Their sources generally include chemical industrial sources or fuels used in heating systems.

2.2.1.2 Indoor Air Quality Guidelines and Standards

While having health-related standards for ambient outdoor air, it appears understandable to have indoor air standards applied to the building environments [100]. International agencies and national organizations set various approaches to solve the air pollution issue [101]. By international initial policy working group, WHO [102], identified the current situation of the health impact of air pollution in numbers as more than 6 million deaths yearly as a result of exposure to outdoor and indoor air pollution, and 91% of the world's population is under the air quality limits [103].

The varied guidelines were consequently set at the primary issues on pollutants, dampness, and mold, household fuel combustion and reflected that the characteristics and clusters of indoor air pollutants altered from the outdoor pollution [104][105][106]. To reduce energy use, ASHRAE defines established practices for HVAC and refrigeration systems worldwide along with energy effect building design for standards that promote common methods and certifying technology to provide fresh air.

At the national level, the socioeconomic and geographical conditions, as well as feasibility and access control technologies, are significant determining factors on IAQ considerations on indoor air pollution. There is still considerable ambiguity with regard to law and legislation due to the lack of pivotal data about contingency with the pollutants in their own country, which results in the acceptance of WHO guidelines as a base to constitute IAQ standards. Yet, existing data on controlling pollutant sources, dangerous tools, consumer product, and fuel quality standards, regulations on construction materials, chemicals, and building ventilation is already at hand in most countries.

The Australian Commonwealth Scientific and Industrial Research Organization (1995) reported on “National State of the Environment Report – Indoor Air Quality”, to control indoor air pollutants by identification of comfort, ventilation, and source

parameters such CO₂ concentrations, VOCs, optimum relative humidity levels to maintain a systematic process on cope with the problem [99]. Some of the other countries, France, Canada, Finland, developed similar methods for IAQ parameters and concluded their main aim as specifying pollutants which is at higher concentrations indoors and set a value for each to not threaten the health of the occupants and ensures the optimum comfort levels [107][108][109].

In Turkey, a report on air pollution and health by the Health and Environment Alliance [110], the air quality rates are higher than regulated values by WHO, where PM_{2.5} concentration EU annual limit value of 25 µg/m³ exceeded by a value of 39 µg/m³, PM₁₀ concentration value of 40 µg/m³ exceed by the value of 58 µg/m³. By the role of coal usage on the energy sector, the exhaust discharged by the power plants is the most distressing factor, amplifying two significant pollutants, particulate matter (PM) and ozone, by emissions of VOCs, SO₂, and NO_x.

As European Environment Agency [111] reported data on air pollution country fact sheet for Turkey, the emissions by sector show that residential, commercial & institutional sectors taking the lead after agriculture and energy supply sectors. The steps to be taken by health professionals to prevent threatening effects on public health are established at acknowledging public on risks due to air pollution, involving in policymakers, and checking the air quality situation by local monitoring system (www.havaizleme.gov.tr) along with following WHO Air Quality Guidelines for the needed improvements.

2.2.1.3 Occupant Behavior and Energy Use

As stating in Corgnati et al. [112], the definitions of IAQ are respective, yet it can be primarily referred to as the optimum levels of air temperature, odor, humidity, rates of indoor pollutants, and fresh air which their measures differ according to the building

occupants, selected materials, and activity types in enclosed spaces.

The building occupants' understanding of the environment is highly correlated with IAQ. The occupant satisfaction levels demand adequate levels of different parameters such as indoor air temperature, fresh air rate, and concentrations of indoor pollutants to ensure healthy conditions and comfort. Meanwhile, occupants tend to control their environments to achieve thermal, visual, acoustic comfort and IAQ by adjusting the systems in the building so that they influence their indoor environment by their habitation and actions. So, occupant behavior is a significant determinant of IAQ levels by their actions and presence.

The reciprocal interaction between IEQ parameters and building occupants can also influence the energy consumption of the building systems due mainly to the utilization of technical and mechanical systems, particularly the air circulation or the fresh air exchange levels in indoor spaces. Furthermore, designing, controlling, and operating both the building systems and occupant behavior simultaneously in order to achieve IAQ and energy efficiency is essential.

As Leaman [113] draws attention to the preference of instant advantage by using the easiest and fastest way, the occupants generally cannot wholly acknowledge how to operate building systems and appliances in an energy-efficient manner. Along with that, Haymore and Odom [114] reported that improving IEQ will not result in enhanced or lower costs unless workers working in those circumstances demand it.

In his simulation study on occupant behavior's impact on office building consumption, Karjalainen [115] questions the application of design solutions' effect on energy use. He compares different design solution effects and types of behavior resulting as those robust design solutions, which means buildings with lesser sensitivity to occupant behavior, are the most effective way by consuming around 75% less energy than

the ordinary solutions. The occupants engage with control systems and building elements in many different ways to achieve their optimal comfort level: operation of windows, controlling artificial and natural lighting systems, and regulating solar shading (e.g. adjusting blinds), HVAC systems (e.g. turning air conditioners on or off and adjusting heating system temperature), water heating and electrical appliances (Figure 4).

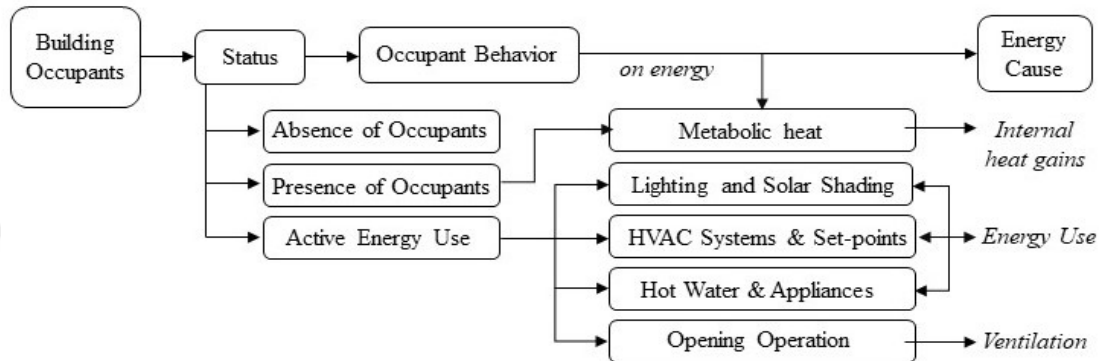


Figure 4: Building occupants' relationship with building energy use
(Adapted from Delzendeh, 2017) [116]

In this manner, IAQ strategies are mainly based on air conditioning and ventilation systems and various occupant behavior determinants. It is concerned with physical factors in ventilated and conditioned environments such as shaft use, window, and facade arrangements. A growing body of literature has examined the mentioned focus topics documented predominantly on ventilation strategies. They vary as natural, personalized, or air-conditioned, as window operation that contains closing and opening window patterns. Some other studies consider standards, occupant behavior, and comfort levels. Most of the available research examined the occupant behavior relationship on these systems by varied methodologies due to the considerable number of different parameters affecting IAQ levels (Table 1). The qualitative methods such as using questionnaires, field, or online surveys, and quantitative methods such as dynamic estimation of occupancy loads and rate with simulation and modeling, evaluating sensor data and calculations are some of the approaches that have been performed and sometimes combined by researchers.

Table 1: The reviewed papers by year of publication, methodology, source country, occupant behavior relationship, and influential parameters.

Reference	Paper Title	Methodology	Source Country	Occupant Behavior Relationship	Parameters
Kim et al. (2019)[118]	Thermal comfort in a mixed-mode building: Are occupants more adaptive?	Occupant Comfort Surveys, Existing Survey Data, a PMV-PPD model	Australia	Occupant Perception of Comfort with Ventilation	Indoor and Outdoor Temperatures, PMV, and CO ₂ concentrations
Kim et al. (2018)[119]	Case study of an advanced integrated comfort control algorithm with cooling, ventilation, and humidification systems based on occupancy status.	Building-integrated control testbed (BICT),	South Korea	Occupancy Status	CO ₂ concentrations, PMV value
Meclarova et al. (2016)[120]	Examining The Impact of Indoor Air on Office Rooms Occupants - Case Study	A questionnaire, Case Study Building, Experimental Measurement	Sofia	Occupant Pulse Monitoring Feedback	CO ₂ concentrations
Hailemariam et al. (2011, April)[121]	Real-Time Occupancy Detection using Decision Trees with Multiple Sensor Types	Existing Survey Data, Sensor Data, Decision Tree Method	Boston, USA	Occupancy Detection	Several IEQ parameters
K.P. Lam et al. (2009)[122]	Occupancy detection through an extensive environmental sensor network in an open-plan office building	Sensor data, Existing Survey Data, Calculations	PA, USA	Occupancy Number Detection	CO ₂ concentrations
Rijal et al. (2008)[123]	Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use, and overheating in buildings	A questionnaire, Existing Survey Data, Simulation and Modeling	UK	Window Opening and Closing Patterns	The values of globe temperature (T_g) and outdoor air temperature (T_{aoi})
Rubin et al. (1978)[124]	Window Blinds as a Potential Energy Saver-A Case Study	Experimental Design Data, Case Study Building, Treatment Group	USA	Occupant Behavior on Window Operation	View, Heat Transfer, Lighting, and Windows

Percentage Dissatisfied (PD) is one of the discretionary ways for estimating IAQ levels. The European Committee for Standardization [117] presented EN 15251 and EN CR 1752, which classified IAQ in groups depending on a graph describing the relationship in both outdoor fresh air flowrate per occupant and the PD, with increased

outdoor flowrates resulting in better IAQ and a lesser number of unsatisfied occupants. The available information on ventilation rates and occupant wellbeing or perception consequences and numerous contributing indicators have been obtained through various buildings among cross-sectional research with different methodologies including observational, statistical models, or experimental and intervention studies.

Air Conditioning

As an active strategy for ventilation, air conditioning (AC) is one of the main focus areas since AC systems are preferred systems for heating and cooling primarily in office spaces. Furthermore, it impacts indoor air exchange by controlling and removing humidity and fresh air indoors. When most of the research comprehensively executes their analysis on considering other comfort parameters of Indoor Environment Quality (IEQ), available literature on AC is much more related to thermal comfort levels than IAQ parameters which are only pollutant contamination, allergens, or VOCs, etc.

Even if some of the studies indirectly examine the IAQ parameters, the effects of filtration and humidity levels are included in most of them. Also, in this focus area, results are highly related to electricity usage and generally with energy use rather than any other focus topic since the operation of AC systems demands active energy use.

In their analysis of the relationship between office occupancy and air-conditioner use through field monitoring of an open-plan office building in South Korea, Yun et al. [125] examined CO₂ concentrations. Their findings showed that CO₂ levels had reached peak levels before lunchtime. They concluded that CO₂ concentrations are linked with occupancy and the density of the occupants. Their research argues that air-conditioners are operated for ventilation by occupants not according to the designated optimum levels of comfort temperatures and fresh air demands but more by the occupant's will and spontaneous decisions. Even if normalized indoor temperatures of 26-28°C are met, they

continued to use air conditioners at night. It shows that the frequency of AC usage does not always mean ensuring comfortable indoor conditions.

Another research done by Ahadzie et al. [126] provides the effects of alternative strategies on AC usage, including fan operation, natural ventilation as window operation, clothing preferences. They trace the advances of these strategies as reduced AC usage in public buildings, which show that the energy predictions are highly tied up to occupant behavior. In an investigation into AC use behavior in the summer period by conducting 3083 questionnaires among 34 cities of China, Meng et al. [127] show that most of the AC use is not continuously operated. But in intermittent periods, which outline the fact that the current standards based on assumed AC use with continuous periods are not thoroughly evaluated and fail to adopt energy-efficiency measures.

Ventilation Strategies

The field of ventilations includes strategies that can be categorized primarily as combined ventilation systems, particularly as personalized ventilation, and natural ventilation, differing by their research focus topics, aims, and methodologies under considerations of occupant activities and comfort levels (Table 2). While the combined ventilation systems are comprehensively assessed through mechanical, natural, and hybrid systems, the personalized ventilation findings have generally been examined for related other building appliances and their interaction with the occupants.

Natural ventilation findings are directly related to airflow through window operation or any other openings of buildings that allow air transmission from outdoor to indoor. Research related to this ventilation system includes climate considerations and precautions and focuses primarily on occupants, building systems, and ventilation rates [128]. Natural ventilation strategies can be preferred when the airflow rates are controllable and climatic conditions are suitable as an energy-efficient strategy.

Table 2: The reviewed papers related to different ventilation strategies by year of publication, source country, ventilation strategy types, and research methods.

Reference	Paper Title	Source Country	Ventilation Strategies	Research Methods
Boonyayothin et al. (2011) [130]	Ventilation Control Approach for Acceptable Indoor Air Quality and Enhancing Energy Saving in Thailand	Thailand	Combined Ventilation	Field Survey, An occupant questionnaire
Zhang et al. (2015) [131]	Airflow utilization in buildings in hot and humid areas of China	China		Field Survey, An occupant questionnaire
Chenari et al. (2016) [132]	Towards sustainable, energy-efficient, and healthy ventilation strategies in buildings: A review	Portugal		Literature Review on Ventilation Methods, Regulations and Standards
Kim et al. (2019) [133]	Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model	South Korea		Real-time collection of data, curve analysis, logistic regression
Kim et al. (2019) [134]	Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation	South Korea		Real-time collection of data, Assessment of IEQ parameters, and score
Stamp et al. (2020) [135]	Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings	England		Case study building, monitoring, Sampling
Yang et al. (2014) [136]	Interaction of dynamic indoor environment with moving person and performance of ceiling mounted personalized ventilation system	China	Personalized Ventilation	Case study building, CFD simulation, Assessment of system performances
Habchi et al. (2016) [137]	Effect of shifts from occupant design position on performance of ceiling personalized ventilation assisted with desk fan or chair fans	China		CFD simulation, Particle Transport Modeling, Experimental modeling
Habchi et al. (2016) [138]	Ceiling personalized ventilation combined with desk fans for reduced direct and indirect cross-contamination and efficient use of office space	Lebanon		CFD simulation, Particle Cross-infection evaluation, Experimental modeling
Al Assaad et al. (2017) [139]	Mixing ventilation coupled with personalized sinusoidal ventilation: Optimal frequency and flow rate for acceptable air quality	Lebanon		CFD simulation, Airflow, and air quality modeling, Experimental modeling
He et al. (2017) [140]	The influence of personally controlled desk fans on comfort and energy consumption in hot and humid environments	China		Experimental modeling and testing, A questionnaire, Statistical Analysis

Table 2 continues on the next page.

Table 2: The reviewed papers related to different ventilation strategies by year of publication, source country, ventilation strategy types, and research methods.

Reference	Paper Title	Source Country	Ventilation Strategies	Research Methods
Schiavon et al. (2017) [141]	Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons	Sweden	Personalized Ventilation	Experimental modeling and cognitive testing, A questionnaire, Statistical Analysis
Al Assaad et al. (2018) [142]	Effectiveness of intermittent personalized ventilation assisting a chilled ceiling for enhanced thermal comfort and acceptable indoor air quality	Lebanon		CFD simulation, Airflow, and air quality modeling, Experimental modeling
Al Assaad et al. (2018) [143]	Simplified model for thermal comfort, IAQ, and energy savings in rooms conditioned by displacement ventilation aided with transient personalized ventilation	Lebanon		Temperature and species distribution modeling, Mathematical formulations, Air Quality Assessment Experimental Modeling
Sekhar et al. (2018) [144]	Study of integrated personalized ventilation and local fan-induced active chilled beam air conditioning system in hot and humid climate	Singapore		IES and ANSYS Fluent software and CFD simulation,
Khalil et al. (2020) [145]	Hybrid mixed ventilation system aided with personalized ventilation to attain comfort and save energy	Lebanon		IES and VE software, PV model, bio-heat model
Gao et al. (2020) [146]	Research on a personalized targeted air supply device based on body movement capture	China		CFD simulation, Experimental modeling
Liu et al. (2013) [147]	Feedback from human adaptive behavior to neutral temperature in naturally ventilated buildings: Physical and psychological paths	China	Natural Ventilation	Case Study Building, Survey and Monitoring, A questionnaire, ABF model, Statistical analysis
Wang et al. (2013) [148]	Human-Behavior Oriented Control Strategies for Natural Ventilation in office buildings	China		Simulation and Ventilation rate calculations
Bourikas et al. (2018) [149]	Camera-based window-opening estimation in a naturally ventilated office	England		Optical camera-based and window-opening assessment, Case study building
Ornaghi et al. (2018) [150]	The effect of behavioral interventions on energy conservation in naturally ventilated offices	England		Real-time monitoring, behavioral intervention, econometric specification
Kim et al. (2019) [151]	The effects of filters for an intelligent air pollutant control system considering natural ventilation and the occupants	South Korea		Real-time monitoring, Experimental modeling
Zhai et al. (2019) [152]	Use of adaptive control and its effects on human comfort in a naturally ventilated office in Alameda, California	USA		Real-time monitoring, Field test, and occupancy survey

The recent literature review on natural ventilation topic analyzed monitorization and automation of building systems since development technology is rapidly changing in the related industry. This area is highly correlated to building energy efficiency. Natural ventilation can be used as passive ventilation, heating, and cooling system rather than mixed strategies such as automated or air-conditioning that use active energy consumption. As a passive strategy, natural ventilation is where the literature findings include all occupant comfort levels, IAQ parameters, and energy consumption measures and results at the most.

However, previous research on window operation patterns focuses on the state of the window rather than the shift through one state to another (opening and closing) and levels of parameters in office spaces inspected independently from the window operation of occupants or considerations on other building openings, doors or existing crack ratios are some of the current research limitations. In this manner, Al-Hemoud et al. [129] a developed analysis on standardizing IAQ regulations and evaluating the influence of door operation on VOCs, formaldehyde, and NO₂ concentrations in office buildings. Air circulation and air movement are the critical research determinants assessed and used to obtain data through building modeling and simulation.

Other research focuses on all IAQ, occupant behavior, and energy use combined, rather than a particular ventilation strategy, personalized ventilation. This method includes all kinds of cognitive, personal preferences, desk or chair fans, or the ceiling fans that left control to the occupants themselves. The available literature's methods are varied as combinations of CFD fluid dynamics, simplified models, energy simulations, field surveys, or questionnaires supported generally with experimental modeling data to compare real-time assessment results. The IAQ parameters are chosen as the main determinants of occupant behavior as activities and preferences. At the same time, the

research focused on both climatic conditions and occupant's physiological characteristics and psychological factors.

Occupant Activities and Window Operation

IAQ's relationship with occupant behavior and energy use is associated with occupant activities which mainly consist of window operation patterns, other operation of appliances, and occupancy densities according to the scheduling and presence of occupants when IAQ parameters of fresh air ventilation rates and air temperatures are investigated through the building spaces.

To ensure comfort levels, the research area analyses occupant activities, where they considered occupant preferences with several determinants such as behavioral, physiological, psychological, and exterior. However, the results are open to discussion considering most of the findings were established the activities separately as window operation or AC usage, not in a whole integrated manner.

The operation includes window opening and closing patterns of occupants related to the work scheduling in office environments where it is also an occupant behavior outcome related to ventilation strategies. Yet, this area is directly occupant behavior-based, including patterns of both timewise and action-wise. The influence of operation patterns on energy use levels is evident in these findings since window operation is related to natural ventilation strategies. The methodologies differ in building modeling, simulation, and real-time analysis of office users (Table 3).

The related research was conducted to measure window operation impact on energy use under occupant behavior influence. Their methodology focused more on standardization of selected parameters to ensure optimum comfort levels by using various behavioral, logistic regression, deterministic, and stochastic models rather than just analyzing specifically the occupant activity itself. So, it can be categorized separately

from previous research focus areas of ventilation systems, AC, comfort levels. Additionally, assessments related to IAQ in this research area cover the comfort levels comprehensively, covering thermal comfort measures such as air temperatures rather than just focusing on parameters of IAQ as air circulation or fresh air intake.

Few studies used sensor technology to monitor occupants for thermal comfort parameters in their building modeling. However, they are considerably limited to other focus areas where they only included CO₂ levels and other IAQ parameters separately by output data on their sensor technologies' analysis. They are advisory and open to further research and discussion since the control algorithms and sensor assessment criteria are not broadly evaluated and fail to offer comparable information about real usages and conditions. Yet, as the results mentioned by Kim et al. [153], the data-driven models are adequately suitable to predict occupancy state as active or static by using CO₂ sensors. The validity of the state prediction model has been found as 94.9 % based on the terms between the measured and estimated values.

In conclusion, the occupant behavior effect on both IAQ and energy use has a binding and strong relationship since their parameters are interrelated when it comes to ventilation strategies, both active, passive, or mixed, or occupant activities as window operation, occupancy schedule, and comfort levels.

To be able to research that compasses on all three concerns, there are feasible gaps on various areas such as consideration of different influences simultaneously along with considerations on several occupant activities, methods to obtain data or the types and impact of building elements and technologies with advantages and disadvantages. Also, further regional studies can be conducted in the future since IAQ and occupant behavior becomes more diverse between climatic regions by climate change and air pollution densities.

Table 3: The reviewed papers related to window operation by year of publication, source country, and methods.

<i>Reference</i>	<i>Paper Title</i>	<i>Source Country</i>	<i>Research Methods</i>
Fabi et al. (2012)[154]	Occupants' window opening behavior: A literature review of factors influencing occupant behavior and models	Italy	Identifying driving forces both interior and exterior
D'Oca et al. (2014)[155]	A data-mining approach to discover patterns of window opening and closing behavior in offices	USA	Statistical analysis and data-mining techniques, real-time survey and monitoring
Li et al. (2015)[156]	Probability of occupant operation of windows during transition seasons in office buildings	China	Monte Carlo simulation,
Wang et al. (2015)[157]	Window operation and impacts on building energy consumption	USA	Case Study Building, Experimental modeling, Behavior model, Logistic regression model
Fabbri (2016)[158]	How to use online surveys to understand human behavior concerning window opening in terms of building energy performance	Italy	Adaptive Occupant Behavior Model, an occupant questionnaire, Building Energy Modeling
Tahmasebi et al. (2016)[159]	An inquiry into the reliability of window operation models in building performance simulation	Austria	Stochastic model, calibrated building model, and long-term monitored data
Markovic et al. (2017)[160]	Comparison of Different Classification Algorithms for the Detection of User's Interaction with Windows in Office Buildings	Germany	Case study building, data sets, SVMs, Dynamic Bayesian Network
Stazi et al. (2017)[161]	Comparing real and predicted window use in offices. A POE-based assessment	Italy	Deterministic And Stochastic Models, Post-Occupancy Evaluation (POE), Experimental data
Markovic et al. (2018)[162]	Window opening model using deep learning methods	Germany	Co-simulation of deep learning-driven OB model with Modelica Dymola
Pan et al. (2018)[163]	A study on influential factors of occupant window-opening behavior in an office building in China	China	Real-Time Monitoring, Case Study Building
Zhou et al. (2018)[164]	Case study of window operating behavior patterns in an open-plan office in the summer	China	Case Study Building, Questionnaires, And Field Survey
Wei et al (2019)[165]	Comparison of different window behavior modeling approaches during transition season in Beijing, China	China	Logistic regression model, Markov model and ANN, Case Study Building
Abdullah et al. (2020)[166]	Open-plan office design for improved natural ventilation and reduced mixed-mode supplementary loads	Turkey	Case Study Building, Taguchi method, Dynamic Simulation
Han et al. (2020)[167]	A novel reinforcement learning method for improving occupant comfort via window opening and closing	China	The model-free RL method, Markov decision processes, Q-learning and SARSA
Zhou et al. (2020)[168]	An action-based Markov chain modeling approach for predicting the window operating behavior in office spaces	China	Markov chain modeling approach, Experimental modeling, Markov decision processes

2.1.2 Thermal Comfort

Thermal Comfort, one of the major determinants of IEQ, can be defined as how occupants adapt and react to thermal conditions of the indoor environment [169]. The mental state of an individual's perception of the thermal environment is the definition of ASHRAE [170] standard 55 uses for thermal comfort. In contrast, at least 85% of the building occupants should be comfortable and satisfied with their thermal environment [171]. Even occupants' perception is not well defined, and thermal comfort needs are not easy to assess. Four main parameters that affect the thermal environment: are air temperature, relative humidity, mean radiant temperature (surrounding temperature), and air velocity [176].

Air temperature is a significant determinant of indoor air quality, which should be considered in building ventilation, and it can cause considerable discomfort for building occupants. The poor conditions of thermal comfort and higher indoor temperatures can cause health risks occurring as SBS symptoms. Besides, the perception of thermal conditions influences how occupants behave, and it is a good incentive on work productivity that exceeds the demand of original design on ventilation strategies.

By the results of several studies on task performance of office, occupants show that productivity is reduced when temperatures changes above or below the comfort temperature range. For instance, under average temperatures, task performance reduced approximately 91% [172].

The ventilation system effectively controls indoor temperatures, air velocity, and humidity parameters since HVAC or other ventilation systems are associated with regulating air circulation with the indoor space. Thermal control systems (heat, cold, and moisture) must be estimated and planned independently from ventilation systems intended to reduce health risks related to indoor air pollution [173].

The control over these systems by occupants to be manual or automated are main discussions in the literature because the occupant interaction and control over these systems, which is acted consciously or spontaneously, can cause discomfort by partial or full draughts within the indoor environment caused by high air velocity, or lack of air movement at higher temperatures [174]. The high temperatures may result in decreased work productivity, and delayed task completions or lower temperatures may cause physical mobility to reduce along with discomfort or occasionally pain [175].

The metabolic activities and other characteristics of occupants are also essential on thermal comfort since they differ between individuals and effect. It is harder to achieve a comfortable environment for all of the occupants but rather a comfortable sensation only [176]. However, even with various climatic conditions, socio-culture indexes, and living conditions, comfortable temperatures are demanded similarly under diverse clothing preferences, occupant activities, or air movement and humidity [177].

Other than the occupant behavior and ventilation strategies, there are other determinants of thermal sensation of occupants, which are exposure times, occupant demographical characteristics of gender, age, or their psychological state, metabolic rate, health conditions along with levels of clothing, and climatic conditions of the building location. According to the review of Sansaniwal et al. [178] on practices related to occupant thermal comfort, there is substantial diversity in occupant's comfort demands associated with distinct socio-cultural settings and regional adaptive behavior. As a result, regional thermal comfort methods must be established to determine real-time comfort demands, which can be useful in the development of comfort standards.

The research supporting the association between thermal comfort and IAQ is limited and needs to be improved since such interactions heavily rely on occupant's adaptive behavior. Furthermore, the studies the main pitfall is the

interdisciplinary approach on thermal comfort that assists in actual measurement and includes other key variables such as building construction and design and energy consumption.

2.1.3 Visual and Acoustic Comfort

The other factors related to occupant comfort are visual and acoustic comfort parameters, which significantly influence occupant's health and productivity. Proper lighting and illumination levels are critical since they directly impact the occupant's visual comfort, defined as “the state of mind that expresses satisfaction with the visual environment” [179].

According to available studies, office occupants tend to carry out tasks where natural light is present such as close to a window or atrium space [180]. Adequate lighting levels provide the occupants realize their tasks seamlessly and in a more productive way by not exposing their eyes to a greater level than they can tolerate [181].

Acoustic comfort can be defined as protecting occupants from noise sources and providing an adequate acoustic environment for the building's intended use. Its assessment is especially critical in building types such as offices, where the risk of hearing loss is frequently modest, but sound irritation has a noticeable impact on subjective health. Furthermore, high noise levels can induce office occupants to cognitive distress and lack of attention, which may harm occupant productivity [182][183].

2.1.4 Indoor Environmental Quality Improvement Methods

The reviewed studies show that there are many setbacks to evaluate, analyze, and standardize all IEQ parameters at once while influences of occupant behavior and building systems vary. The solutions to improve IEQ can generally be categorized as occupant behavior factors, building design and system decisions, and operation and maintenance strategies [184]. While at the decision-making process, interdisciplinary

disclosure and evaluations are needed to contribute an integrated design outcome of a building design from the very beginning. Since ensuring comfort levels for occupants depends on reducing pollutants substance in the air, advancing ventilation rates, indoor air temperatures, and illuminance according to the occupant demand, the type of materials and building appliances take a significant share of IEQ improvement methods.

After the design decision period, the contaminations should be avoided while integrating building systems and structural elements in the construction period. Also, both design and construction stages should consider the applications and operations of these processes that produce pollutants and consume energy along with later maintenance uses.

After the building is constructed and ready to use, the analysis on real-time conditions should be evaluated by both the building and occupant's feedback, guiding further design strategies and methodologies. The research methodologies, the models of behavioral, statistical, experimental, and real-time surveys should be conducted holistically to obtain competent data for each building region while also diminishing the diversified results occurred by occupant's perception. Also, the communication between disciplines and feedback provided with previous studies should be used for future decisions.

2.3 Indoor Environmental Quality and Energy Use in Office Buildings

2.3.1 Building Systems and Design Strategies

It is expected that the lack of planning of building and building systems considering IEQ parameters will suffer from increased indoor air pollution caused by inadequate ventilation and increased pollutants subsistent in the indoor environment. Some of the major problems due to poor building systems and design strategies related to IEQ are leaking roofs, improperly built building envelopes, window and door openings that do not prevent the circulation of undesirable pollutants between spaces, water, and

air infiltration through building cracks.

Outdoor air is transferred through openings of the building adjacent to the sources of air pollutants such as fuel-burning vehicles, combustion products, or emissions are drawn back to the building, increasing pollutants densities [174]. Defective building systems or strategies enhance this exposure of building to external contaminations.

Furthermore, deficient strategies on ventilation, heating, and cooling can increase the energy use of these systems while ensuring specific comfort parameters to be optimum levels and preventing these contaminations. Besides, the poor design decisions may manifest themselves as unsteady and weakened building systems functioning, augmenting more energy use on operation and maintenance performance.

Several strategies are available to reduce the energy use related to high-performance building conditions on IEQ, including active or passive, along with traditional or contemporary practices that can be applied to new or retrofitted buildings.

Specific methods to reduce energy use while enhancing IEQ differ by the occupant demands, behavior, and building function. In-office buildings, the periods and activities are significant determinants of energy use since the operation of HVAC systems is dependent on occupant presences and the use of the work environment.

The work scheduling of occupants influences the opening-closing behavior on windows, air-conditioners, fans, heating and cooling tools which changes the energy use during the day by their task arrangement and individual preferences. To deteriorate partial discomfort such as droughts occurred by poor building façade, or low temperatures due to inadequate material selection the individual occupant behaviors can expand total energy use by turning on AC at unnecessary levels. Also, the occupant behavior of closing windows can increase CO₂ or other pollutants' concentrations indoors.

If the exterior conditions are suitable, the climate provides passive strategies to

lower energy use. In proper temperature, fresh air, and humidity rates, some passive strategies such as cross-window ventilation and wind chimneys can be applied to reduce active energy use to circulate contaminated air to the outdoor and fresh air to the indoors.

In contemporary practices, the automated systems generally tend to be used in office buildings, especially in high-raised buildings. The impermeable and uncontrollable building facades, HVAC systems can create uncomfortable environments for their occupants because they do not operate and interact with occupant's needs simultaneously.

2.3.2 IEQ in Nearly Zero/Net Zero Energy Buildings

Nearly Zero Energy Building (NZEB) is originated from the European Union's legislative authority on regulations regarding the energy performance of buildings [185]. By the legislation, member nations must develop national policy and strategies to achieve targets, including establishing the concept of nZEBs at all new buildings and public buildings till 2019 and all new buildings till 2021 [186].

They are increasing energy use in the building sector while total area is rising, and this rapid growth severely influences living standards in the building sector. Governments should adopt related policies regarding IEQ measures at the national level to ease accelerated global energy consumption. In Turkey, the building sector shares second place in energy consumption with 30% and a continuous increase in total energy use [187].

There are initial considerations in nZEB design, which consist of passive strategies as building orientation, natural ventilation and lighting, insulation, and the use phase change materials; energy-efficient systems of HVAC, domestic hot water, and other technologies; and renewable systems of PV, wind and solar to generate energy [188]. Studies related to nZEB have been conducted in the past years and showed that nZEB can grant the objective by effectively decreasing heating and cooling building

systems accordingly energy use [189].

On their analysis and calculations of applying a novel-ventilated heating floor in nZEB, Guo et al. [190] found that it can enhance heating and cooling rates up to around 17% and 13%, respectively. And using phase change material affects the thermal comfort by expanding thermal storage about 77% showing nZEB design can substantially influence IEQ parameters and occupant comfort and energy-efficient measures. As García-Ballano et al. [191] reported in their study that saving energy potentials can vary up to approximately 58% at the building level. NZEB design concept should be done comprehensively to attain high energy performance and a high level of IEQ, which also shows that these considerations are feasible and economically enduring [192]. The nZEB design measures are just one part of the energy-efficient building design concept to be followed.

2.3.3 Standards and Guidelines on IEQ

By reviewing subsequent and more recent literature, it can be seen that various measures are affecting IEQ. Therefore formulating a standard procedure or systematic solutions that can be used for all cases is preposterous. Considering exterior, indoor conditions, and human-based parameters including behavioral, psychological, or physiological to find commonalities to improve indoor environmental quality in different cases is hard to pursue. It is also significant to acknowledge all parameters of IEQ affecting the building occupant's requirements.

Each parameter is generally divided into distinct standards. As in ASHRAE standards, thermal comfort and indoor air quality measure separately covering ventilation rate for acceptable rates, comfortable indoor air temperatures, or material preferences. The other standards, such as ISO and CEN, have been established to consider thermal comfort and indoor air quality, but they neglect other parameters of acoustics and lighting.

In the case of separated or exclusive standards of IEQ parameters, ISO 17772, EN 15251, EN16798, and ISHRAE 10001 can be counted as standards that encompass IEQ in general. On the other hand, ISO EN 7730, ASHRAE 55, GB/T 50785, and SS 553 examine the thermal comfort specifically while ASHRAE 62.1 and 62., AS 16682, SS 554 establish standards for indoor air quality as in Table 4 [193].

Table 4: IEQ standards and their scope in detail (Adapted from Khovalyg et al., 2020).

<i>Standards</i>	<i>Parameters</i>	<i>Scope Considerations</i>
ISO 17772	IEQ in general	An additional part of the user guide would provide measures for building energy performance calculations considering input parameters of thermal comfort, IAQ, acoustics, and humidity.
EN 15251	IEQ in general	Providing measures for calculations of building energy performance considering input parameters of thermal comfort, IAQ, acoustics, and lighting, which primarily considers non-industrial buildings.
ASHRAE 55 ISO 7730 GB/T 50785	Thermal Comfort	They are providing thermal sensation and comfort strategies to which occupants are exposed indoors by considering parameters of temperature, humidity, air velocity, etc., along with instruments, different conditions, time, and place.
SS 553 / SS 554	Indoor Air Quality	Providing demand for ventilation and air-conditioning in commercial, office, and institutional buildings.
ASHRAE 62.1	Indoor Air Quality	It provides methods to reach minimum IAQ by defining safe contaminant densities and occupant satisfaction levels that exclude residential buildings.
ASHRAE 62.2	Indoor Air Quality	It provides requirements to specific sources considering ambient air, construction phase, moisture, biological growth, and ventilation system rates.
ISHRAE 1001	IEQ in general	It provides technical guidelines under the activity levels in non-residential and residential buildings considering input parameters of thermal comfort, IAQ, acoustics, and lighting.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Methodology

This thesis aims to investigate IEQ's impact on occupant comfort and energy in an office building. By the objectives of the thesis, a case study building has been proposed to analyze the total energy use, fresh air ventilation rates, and indoor air temperatures considering climatic conditions of building location, decisions on the building systems and materials, and natural ventilation strategies.

For building energy modeling and simulations, DesignBuilder software is used. The data relating to selected parameters are collected from simulations assessed through generated building modeling variations and scenarios to compare the results under indoor air quality and thermal comfort measures.

The variations and scenarios are modeled by adjusting natural ventilation schedules and window layouts, and glazing areas in an office environment. It applies as changed fresh air intake levels and changes operation length of HVAC systems varying in energy use levels; by changing preferences of building material and HVAC systems as affecting energy use and indoor temperatures. Furthermore, all of the results from collected data are examined by making correlations and comparisons, looking at the advantages and disadvantages of each case.

This chapter consists of information about the created and adjusted office building environment, including (Figure 5) :

- Architectural design details as building zones, areas, measurements, characteristics, and material selection,

- The details of each generated building modeling variation with ASHRAE 90.1 Baseline Systems and Proposed Building Systems,

- The mechanical system details of variations, including the type of heating, cooling, and ventilation systems, their activity schedules, infiltration rates, availability of lighting control, and other determinations made on building design

- The details of each scenario are created by focusing on the considerations of ventilation system scheduling, material selection, and window layout & glazing area.

- Information about the data acquisition process, including how building simulations are conducted and data is obtained for each building alternative.

The variations and scenarios are made by the scope of literature review findings and standards considering particularly related parameters. Since the thesis covers indoor environment quality measures in general, thermal comfort and indoor air quality have been the main focus of the evaluations and minor lighting preferences, yet not considering acoustics. While the variations are decided primarily for the thesis's main objective of providing information about the IEQ impact on energy use, the scenarios are created to present the availability and usability of different preferences and measures that affect occupant comfort and energy use at the proposed project system design.

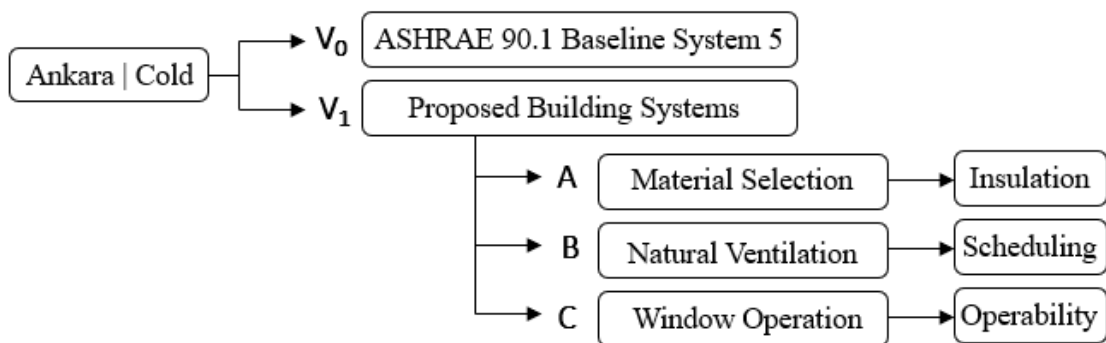


Figure 5: The variations and scenarios that are decided to be analyzed

Furthermore, the alteration of scenarios is made by both architectural and mechanical concerns to analyze IAQ and thermal environment parameters. For fresh air intake rates and energy use parameters, the ventilation strategies as adjusted scheduling and window layout & glazing area are decided to be analyzed, while for the temperature parameters, the PMV values are obtained.

3.2 Case Building

3.2.1 Architectural Design and Details

A reference building is created by design considerations that incorporate an evaluation of the compatibility of proposed solutions regulated by the mechanical systems and design principles of an office reference building (Figure 6). The decisions are established as providing recommended energy-efficient levels and applicability of architectural design decisions to make related comparisons. The building is a six-story building with a total area of 1500 m² which its area of 1250 m² is conditioned.

The following details are determined the same in both variation groups of V_0 and V_1 except it is stated otherwise by following scenarios of V_1 . The circulation space, including restrooms, stairs, elevators, is positioned at the center of each floor, surrounded by open-plan office space. The building zones are decided as two separate zones, including the core circulation space (Zone 2), which is not conditioned, and open-plan office space (Zone 1) (Figure 7) as a whole since specific office spaces are not divided with entire height walls (Figure 8). The activity schedule hours for both occupancy and HVAC systems are decided as 7 am to 6 pm at all seasons. At Zone 2, the occupancy rate is determined as low with a density of 0,07 people per m² since the circulation space is not used primarily by occupants during work hours. For all cases, at Zone 2, there is not an operation of HVAC system during the day, along with no lighting control or office equipment load.

The decisions on selected materials are made correspondingly to the local climatic conditions since it is linked with the heat demand of a building for a year. For the variations of ASHRAE 90.1 Baseline and proposed design, the preferences of materials are the same to be able to compare and analyze other determinants of IEQ on occupant comfort and energy efficiency. On the other hand, in the analyzed scenarios (A cases), the insulation material of EPS is changed to provide its impact on related concepts.

For material selections in all cases, the heat transmission coefficient values are planned appropriately to the Turkish Standard Institution for insulation in buildings [194] as $0.47 \text{ W/m}^2\text{K}$ for exterior walls by the layers of 0.03 m gypsum plastering, 15 mm air gap, 0.05 m EPS expanded polystyrene, 0.19 m concrete hollow and light blocks and 0.02 m gypsum plastering, respectively.

For all other coefficients, materials are planned as $0.35 \text{ W/m}^2\text{K}$ for basement walls, $0.35 \text{ W/m}^2\text{K}$ for medium-weight roofs by examinations of international standards of EN 12667, ISO 6946, and related studies about thermal insulation in buildings [195]. For the floors, it is determined as $0.314 \text{ W/m}^2\text{K}$ for foundation floors with layers of timber flooring, screed, concrete.

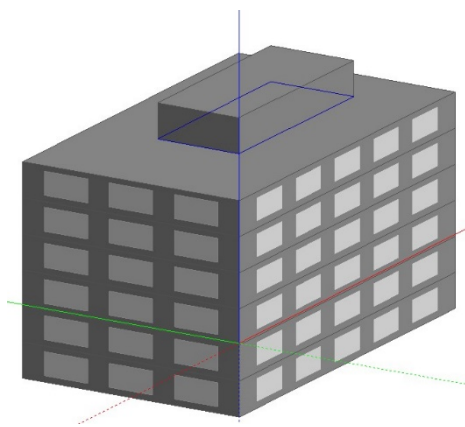


Figure 6: Building modeling

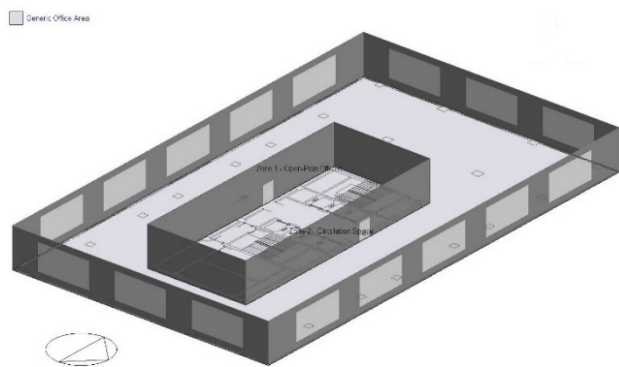


Figure 7: Building modeling zones

The windows are decided in a fixed size of 3.00 x 6.00 m as repetitive along the exterior walls, 0.80 m above each floor with a 30% window glazing with a 30% operable glazing area. For glazing, the U-value by the ISO 10292 standard is set to 1.9 W/m²K with an air gap of 13 mm between layers. The airtightness value for the building is 0,5 ac/h for each area. The infiltration max flow rate is 0,008 m³/s-m.

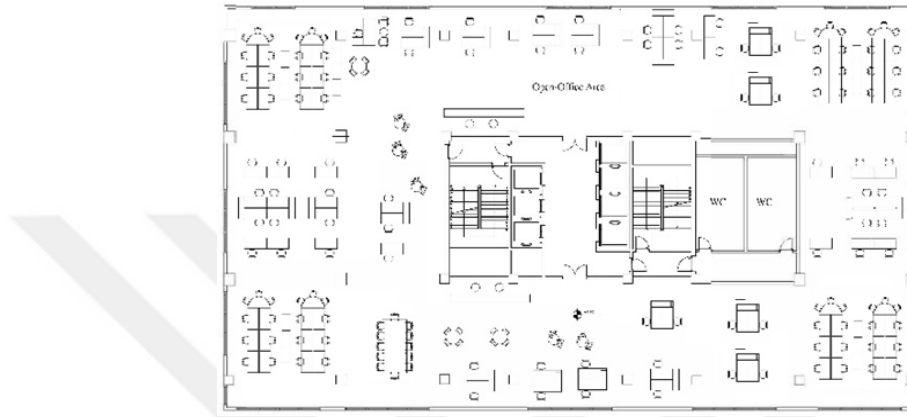


Figure 8: Building modeling floor plan

3.2.2 Climatic Conditions of Selected Cities

The climatic conditions of Ankara city are very cold during the winter period, warm during the summer period, and dry all year long. For average ambient air temperatures, the highest value is 30°C in August, and the lowest value is -5 °C in January. The prevailing wind direction has been decided in as north which is at the long edge of the backside of the building.

Indoor air temperatures are highly associated with building location ambient air temperatures; accordingly, temperature changes during the year affect the annual heating and cooling loads of buildings, IAQ levels, and thermal comfort of occupants. The generated variations based on different climatic conditions indicate the impact of exterior conditions as ambient air temperatures, wind pressure, and humidity on IEQ implicitly energy use, and the measures to be considered while selecting appropriate building systems.

3.2.3 Building Modeling Variations and Scenarios

The base model created by the selected architectural design and details is modified according to different considerations to analyze the deviation between their simulation results. Eight building modeling cases have been generated in total,

- by different Mechanical systems as two different variations groups: ASHRAE 90.1 baseline HVAC Systems (V_0 :Variation Group 0) / Proposed HVAC Systems (V_1 :Variation Group 1)
- by different insulation materials of EPS as changing the thickness: EPS 5 cm (A_1) / EPS 10 cm (A_2)
- by different ventilation strategies as changing the natural ventilation scheduling: No natural ventilation (B_0) / in 30 min period (B_1) / in an hour (B_2)
- by different window layout and glazing area: with proposed design layout and 30% operable glazing area (C_1) / with larger windows and more operable glazing area (C_2)

3.2.3.1 Variation Groups and Mechanical Systems

Variation Group 0 (V_0): ASHRAE 90.1 HVAC Systems

According to ASHRAE [196] 90.1 baseline HVAC requirements, the systems should be chosen according to the building type, usage, floor number, climatization condition in zones, and heating sources. The HVAC systems are chosen based on the ASHRAE 90.1 requirements on mechanical systems.

By the proposed building types of the appendix G, the created base building is categorized as system 5 since it is a nonresidential building with more than five floors and a floor area of 15000 m². Furthermore, it is placed in the subcategory of system 5.0 since the fossil fuel and purchased heat as heating energy use is preferred for the base building modeling. Systems 5 is called Packaged VAV with Reheat which its system type

is packaged rooftop variable air volume (VAV) with reheat. The system requirements include VAV as fan control, direct expansion as cooling type, hot water fossil fuel boiler as ventilation, and DWH (domestic hot water) system type. All of the HVAC units are scheduled the same as occupant activity schedules which are from 7 am to 6 pm (Figure 9). There is no lighting control in this variation group, and for lighting type, it is decided by the ASHRAE 90.1 Table 9.6.1 requirements. There is no natural ventilation availability in all zones of the building.

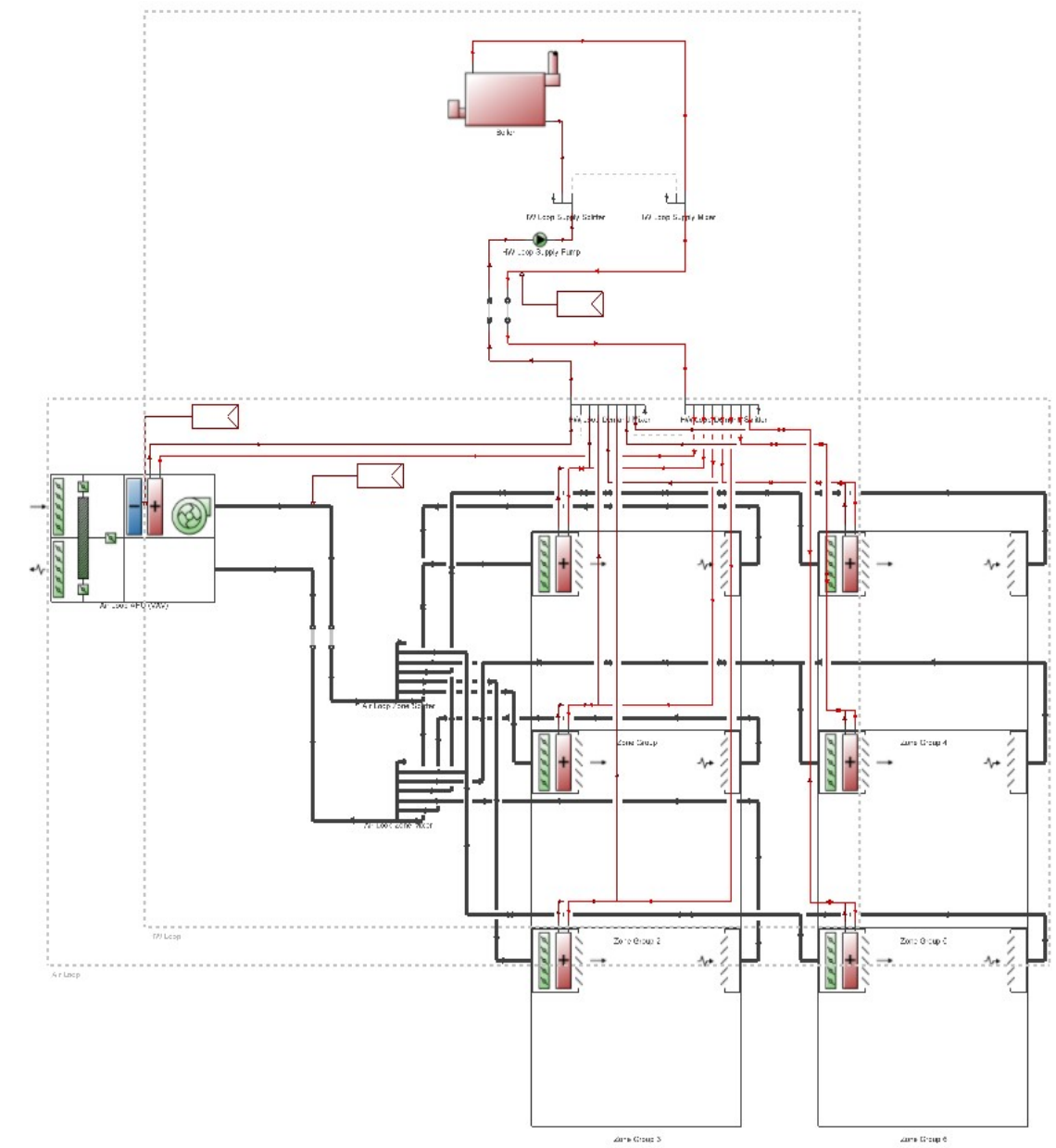


Figure 9: ASHRAE 90.1 HVAC systems set for variation group 0 (V₀)

Variation Group 1 (V₁) (A1, B1, C1): Proposed HVAC Systems

The adequate amount of fresh air and its distribution should be appropriately decided to provide the required indoor air quality. Also, the humidity throughout the building environment should be controlled primarily in hot and humid weather, which affects the sensation perceived by occupants and indoor air temperatures [197]. Accordingly, the preferred method for the air-conditioning system is selected as a 4-pipe fan coil unit (FCU) with HRV (heat recovery ventilation) units to ensure ASHRAE 62.1 standard of ventilation for acceptable IAQ levels (Figure 10). Determinations have been made for the ventilation system in the office building to provide a temperature of 22°C in the winter period and 24°C in summer.

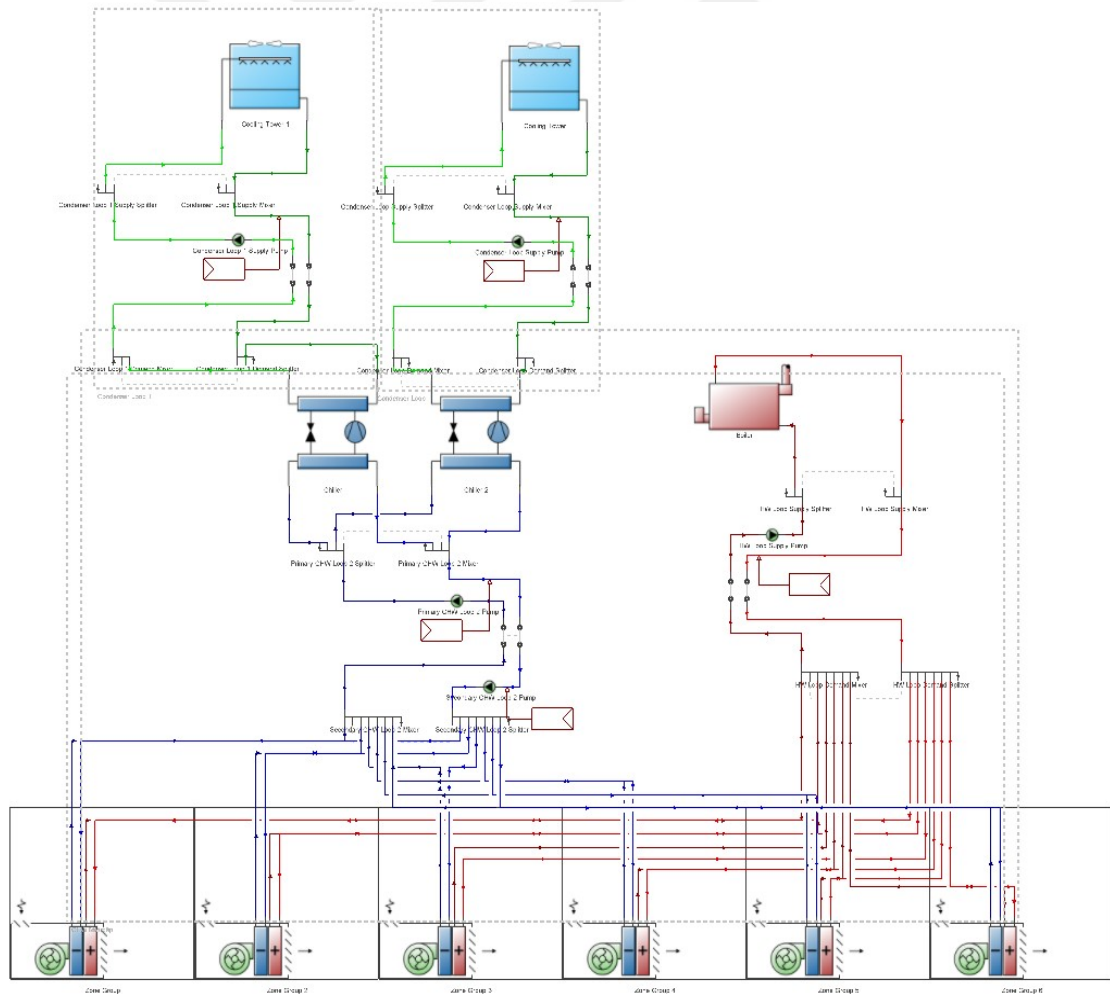


Figure 10: Proposed HVAC systems set for variation group 1 (V₁)

For heating systems, two condensing boilers with 90% efficiency including a capacity of 206 kW, pumps with 7600W electric power, and 0.0253 m³/s mand temperatures of 80°C/60°C are selected. For the cooling systems, chiller groups are preferred as water-cooled conforming to international standards and a COP value of 6.5. For each chiller, there is a separate cooling tower with a capacity of 640 kW and 29/35 °C inlet and out water temperatures. The cooling tower's electric power of pumps is 21600W and 2400 W with flow rates of 0.07 m³/s and 0.077 m³/s, respectively.

3.2.3.2 Variation Group 1 Scenarios

Each scenario group's preferences are respectively determined by the previous scenario group's results as continuing with one that has the most reduced energy use and comfort levels to find the best-proposed design. A case group is the same with V₁ preferences, only differencing in A₂ case with EPS thickness. B₀ case is the same with A₂ case differencing in B₁ and B₂ cases with natural ventilation availability and scheduling. C case group is the same with B₂ case preferences differencing in the availability of window layout and glazing area.

Scenario A: Insulation Materials by EPS thicknesses

The two of the various groups, which are detailed as it is mentioned, are established primarily to compare building systems' impact on energy use and occupant comfort. By creating different scenarios on insulation material of V₁, it is aimed to detect the differences between heat gains, cooling, and heating energy uses, and on occupant comfort levels in the proposed design of V₁.

In the energy-efficient building design, the insulation materials' thicknesses are characterized as one of the significant determinants of heat recovery and gains of the building [198]. For this reason, in the A₁ case, the insulation material thickness is selected as 0,05 m as same in both baseline variation groups of 1 and 2. To form a variation in the

second case named A₂, the EPS thickness is changed to 0,1 m.

Scenario B: Natural Ventilation Scheduling

According to the literature findings, the natural ventilation availability has a substantial influence on energy use and occupant comfort by being a passive cooling method, circulating air between outside and inside with less energy, and reducing the load of active building systems.

Therefore, in the same proposed variation group V₁, three different scenarios are created by changing the natural ventilation availability and operating schedules. The data settings in modeling software are determined as scheduled natural ventilation. According to previous results of two A cases, the A₂ insulation thickness as 0,1 m is selected for all of the three B scenarios for the minor energy use data.

In the first case (B₀), it is determined as there is no natural ventilation available for all times and seasons. In the second (B₁) case, the schedule of natural ventilation is set 30 minutes till 12.00 pm by zone daily. For the last (B₂) case, the schedule of natural ventilation is set 1 hour till 12.00 pm by zone daily with 5 ac/h outside air rate from 7 am to 6 pm period as in Table 5.

Table 5: The natural ventilation schedules of B₁ and B₂ cases

	Hour /Season	7.00 am	10.00 am	12.00 pm	3.00 pm	6.00 pm	12.00 am
B₀	<i>No Natural Ventilation</i>						
B₁	<i>Summer</i>	0.	0.25	0.5	0.25	0	0
	<i>Winter</i>	0	0.25	0.5	0.25	0	0
B₂	<i>Summer</i>	0.	0.5	1	0.5	0	0
	<i>Winter</i>	0	0.5	1	0.5	0	0

Scenario C: Window Layout and Glazing Area

After evaluating natural ventilation availability and scheduling influence on energy use and occupant comfort levels, by the results of B cases, the window layout and glazing area are inspected by their effect on energy use and ventilation rates. The two-

sided relationship between ventilation strategies and building design preferences is inspected through these cases.

In the C_1 case, all of the previously proposed preferences are kept the same as the B_1 case which has the longest natural ventilation scheduling. In the C_2 case, only the window layout changed as larger windows which have 100% fitted glazing layout, 80% window to wall ratio with 70% operable glazing area (Figure 11).

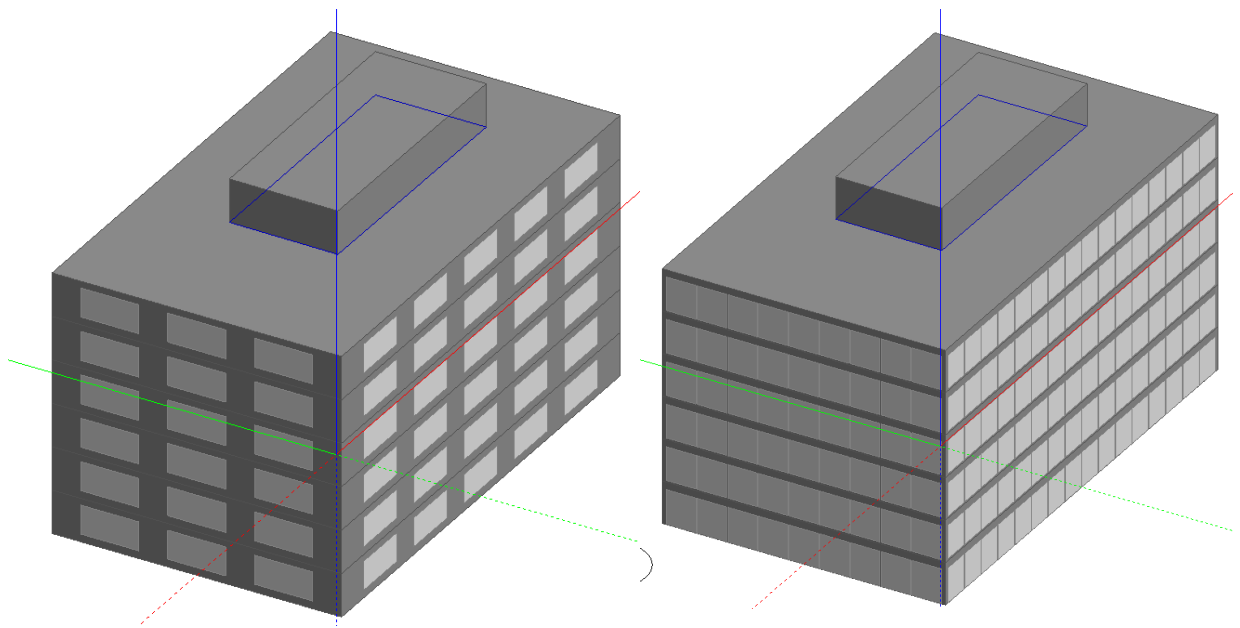


Figure 11: The window layouts of C_1 (left) and C_2 (right) cases

CHAPTER IV

RESULTS AND DISCUSSION

This chapter includes all of the data obtained from the separate simulation results of created variations and their scenarios. All of the simulation data have been examined and compared according to thermal comfort, IAQ, and energy use considerations.

Firstly, the various groups and scenarios are compared by net source and site energy use levels to see how they perform with proposed design measures. Then, all case results are simultaneously inspected by their energy use level, indoor temperatures, ambient temperatures, humidity, PMV measures, and ventilation rates.

- The main baseline variation groups V_0 and V_1 are primarily analyzed by their energy use levels to reveal the building system's influence on energy use. Correspondingly, the comfort levels, ventilation rates, and PMV results are examined to see if any correlation and impact on IEQ measures.
- A scenario is compared to see the influence of insulation material thickness.
- B scenarios are analyzed to see the influence of natural ventilation strategies and scheduling on fresh air intakes, including mechanical, natural, and infiltration.
- C scenarios are examined to see how the architectural window layout impacts occupant comfort and energy use.
- Lastly, the results are linked with the current situation and research gaps, including the recent Coronavirus outbreak and the Republic of Turkey's Ministry of Environment and Urbanization Guideline Book on nZEB design.

4.1 Results

4.1.1 Energy Use

To assess the compare energy uses of building systems, the two variation groups formed by the different mechanical system preferences as ASHRAE 90.1 baseline HVAC Systems (V0) and proposed HVAC systems (V1) are examined their total end uses, net site, and source energy.

In the changes between the end uses of variation groups, the cooling energy has the most prevailing variance with an almost 70% decrease in natural gas use of V1. In comparison, there is a 20,4% decrease in electricity in heating energy use. Also, in the V0 case, there is almost 63% more fan usage than in V1 (Figure 12).

By the available compounds in the ASHRAE baseline, there is almost zero pump energy use in V0 while there is 3544,93 kWh energy used in V1, which is about 0,9% of the total end-use. Since there is no lighting control in V0, the indoor lighting covers a substantial value with 80% more electricity use in V1. And there is 39% more energy use in indoor equipment end-use of V1.

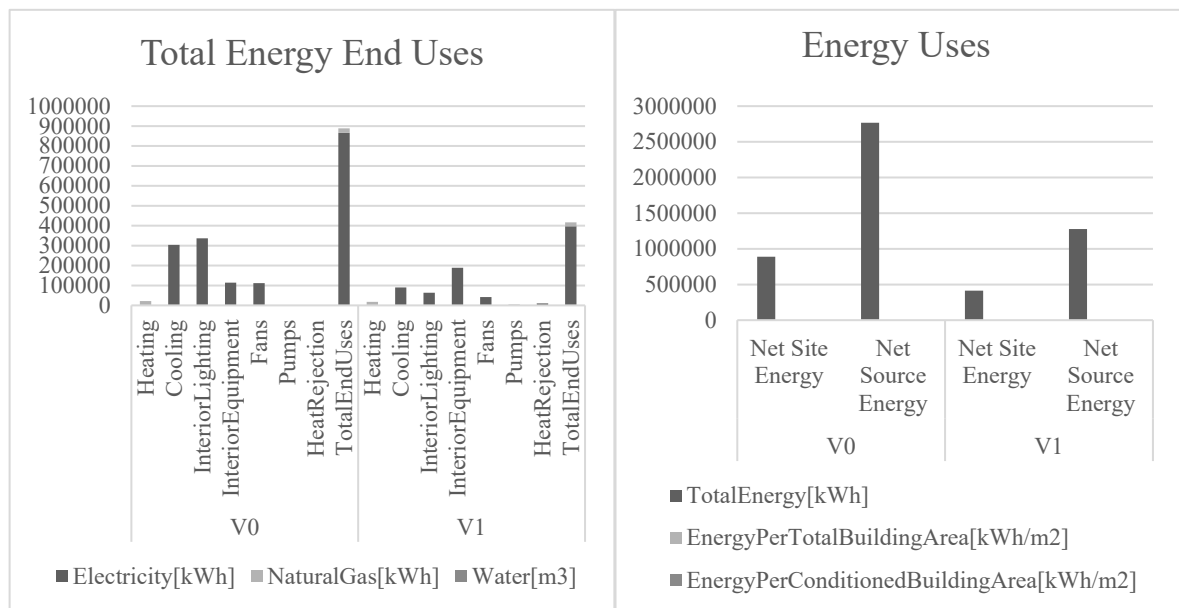


Figure 12: The energy uses and the total end uses of V0 and V1

In the V_0 case, there is no heat rejection energy use since HVAC systems do not have any cooling tower compound and maintain without it. On the other hand, in V_1 , with two cooling towers operating between 7 am to 6 pm, the total heat rejection use is 9764,7 kWh in electricity and 1296,25 m³ in water use. This only covers 2% of the total electricity end-use of V_1 and all water use while there is 54% less total end-use rather than in the V_0 case. In the net energy uses, there is a 53,3% difference in net site energy and a 53,8% difference in net source energy between V_0 and V_1 .

The results show that V_1 has higher energy performance than the V_0 case even though the system compound uses more fan and pump end uses. A scenario is established by changing the insulation material thickness to link its effect on energy uses compared to building systems. In the A_2 case, there is a 39% decrease in heating energy use while there is only a slight difference in the cooling energy with an almost 4% increase in A_2 (Figure 14).

Interior lighting and interior equipment end uses are almost identical between A_1 and A_2 scenarios since both groups have lighting control with LED preferences. There is no significant difference between fans, pumps, and heat rejection end uses between two A cases. These results show that there is only a 0,6% increase in the electricity end-use of A_2 in the total use of 2527 kWh.

However, by changing the insulation material thickness from 0,05 m to 0,1 m, the heating end-use as natural gas is increased up to 39% covering all the natural gas fuel consumption in the A_2 . And there is 2% less consumption in total end uses in A_1 case. Overall, while the electricity use is almost the same between the two cases, the natural gas use is higher in A_1 due to heating load and an unsubstantial water end-use difference between the A scenarios.

Additionally, there is approximately a 1% increase in the net site energy and only

0,03% with a 456 kWh decrease in net source energy (Figure 13). The variance trends in energy per conditioned and unconditioned building area are almost the same with percentages between these two cases. These differences are correlated with temperature and humidity variance by heat gains and losses in the enclosed spaces of an office building under the variation in insulation materials' thicknesses influencing PMV measures and ventilation rates in these scenarios (pg.58).

In the B scenario, the impact of different natural ventilation strategies can be predominantly seen in heating and cooling end uses with an 85% increase in heating and a 26% decrease in cooling when natural ventilation is available. There isn't any difference between B₁ and B₂ in the case of total end uses, while there is a 10% increase at total from B₀ to B₁ (Figure 15).

The differences that occur at the other end uses are an 11% increase in fans, a 16% decrease in pumps, and heat rejection, respectively, from B₀ to B₁. When natural ventilation is available in B₁ and B₂, the total end-use decreases up to 4% in electricity, 15% in water and increases five times more in natural gas from the heating load. And for the net site and source energy use levels in the availability of natural ventilation (B₁-B₂), there is a reduction of 11% in the site and about 1% in source energy use.

The energy levels per conditioned and unconditioned building area reach their minimum values in the B₀ case among all other variation and scenario groups with 46,44 kWh/m² in total building area and 60,34 kWh/m² in a conditioned area. In the same variance manner, there is no substantial difference between A1 and A2 (B₀), which shows that the availability of natural ventilation only affects about a 5% decrease in energy use per total building area of net site energy and a 6% decrease in net source energy. When the architectural layout is changed from smaller window sizes to wider fit 100% glazing window layout, the heating energy increases by approximately 31% in natural gas.

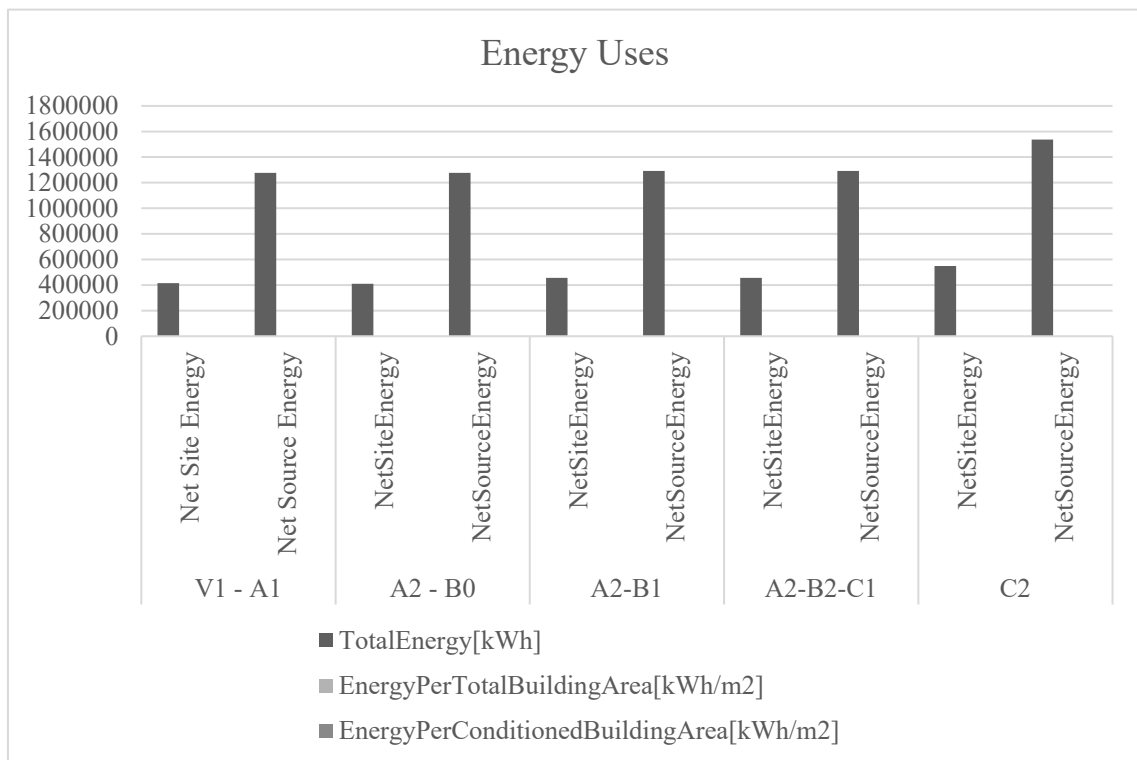


Figure 13: The total energy uses in all scenarios (A-B-C) as natural gas, electricity, and water use

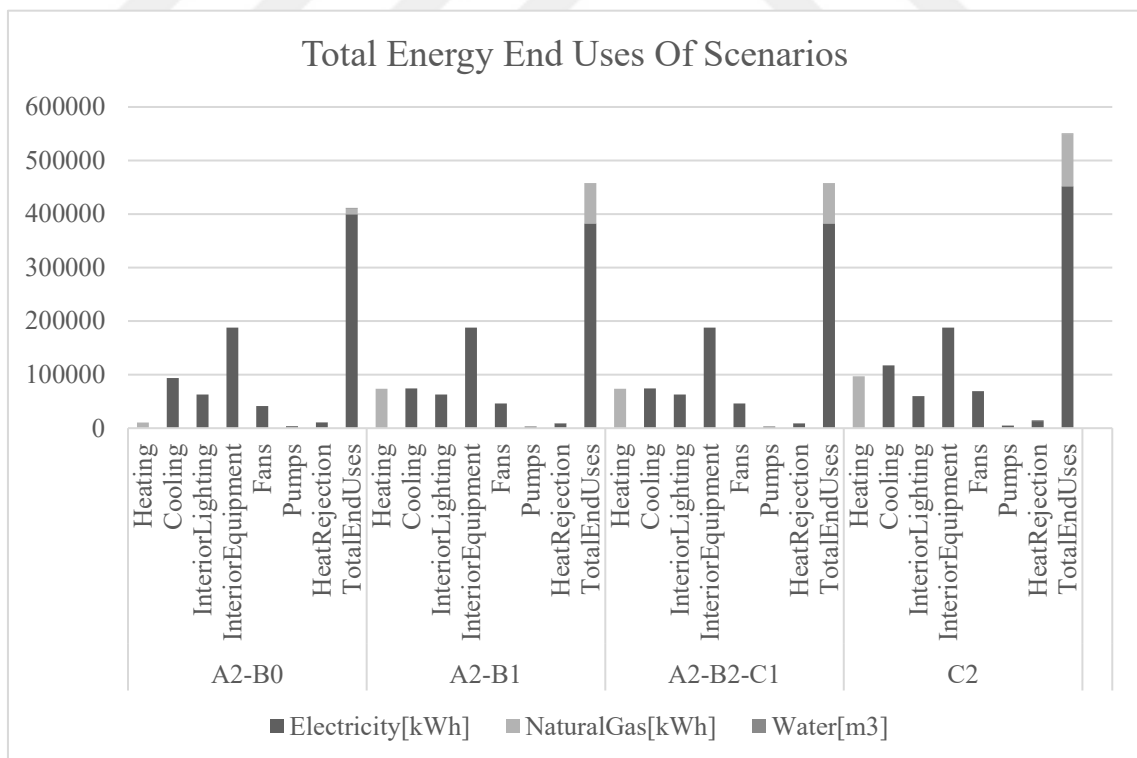


Figure 14: The total energy uses in all scenarios (A-B-C) as natural gas, electricity, and water use

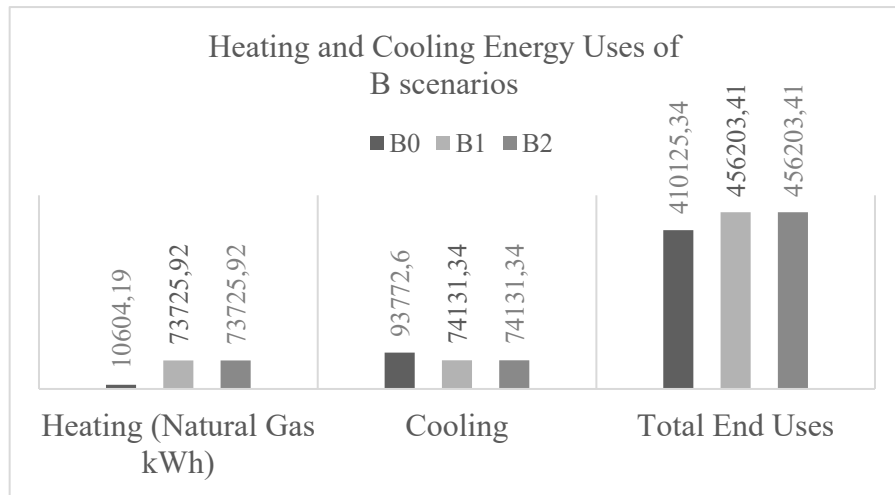


Figure 15: The heating and cooling end uses in the B scenarios

Also, the cooling energy consumption increases by more than a half, with 58% from C₁ to C₂. The interior lighting end-use levels reduce only 4%, correlating with the decrease in lighting demand indoors by natural sunlight. The pumps energy consumption increases up to 55%, and fans increase about 49% in electricity. Additionally, the heat rejection in electricity use is 18%, in water use, 55% more in the C₁ case.

At the energy per total building area levels, C₂ has the second-highest values as 62,16 kWh/m² in total and 80,76 kWh/m² in conditioned space. Comparison of net source and site energy use levels between C scenarios shows that the C₁ case has approximately 20% higher efficiency in all energy uses.

In all variation and scenario groups, as is mentioned earlier, B₀ has higher efficiency in the total energy per area uses while V₀ has the lowest energy efficiency. Also, B₀ has the lowest heating end-use in natural gas. On the other hand, the B₁ and B₂ cases have the lowest values as 382477 kWh electricity in the total end uses.

With a 100% glazing window layout in a cold climate like Ankara, the cooling end-use is in its second-lowest value in C₂ as 117,305 kWh in electricity. In contrast, B₀ without natural ventilation case has the lowest cooling end-use as 93772,6 kWh in electricity.

4.1.2 Occupant Comfort

The correlation between these differences in energy uses (Figure 13), and variations between the two variation groups' comfort levels are inspected. The results of Fanger Predicted Mean Vote (PMV), calculated according to ISO 7730, show that V_0 has the least variance peaking in winter month December only with -1,3 PMV and in fall month with 0,1 PMV (Figure 16). It indicates that in the V_0 case, summers are not too hot, nor winters are too cold, not resulting in discomfort levels between the values -2 to +2 PMV.

Among all variation and scenario groups, there are several discomfort peaking points generally in the summer month of July, as reaching too hot levels including 2,2 PMV in the V_2 case, 2,4 PMV in the A_2 , and at its highest value with 2,9 PMV in the C_2 case. Meanwhile, in the temperature levels, the variance trend is different in A_1 and A_2 cases rather than others. Since there is no natural ventilation availability or scheduling the values are changing lesser depending on the outdoor conditions.

Even if, there is no significant difference in energy use between B_1 and B_2 where two different ventilation scheduling is proposed, PMVs, temperatures, and relative humidity indoors differ substantially in summer and winter periods. In the B_2 case which has longer and continuous natural ventilation availability, the fresh air intake levels increase mostly during the summer while external filtration is less in the B_2 case.

In the main variation groups where different HVAC systems are used, in V_0 the indoor temperatures stay lower in the winter period which the heating demand is not covered to bridge ambient temperatures of cold temperatures in Ankara to indoors (Figure 17). In the summer period, V_0 case stays at the room temperatures rather than hotter degrees in V_1 peaking in July as 31,4 °C. When the insulation material thickness is changed in A scenarios, the indoor temperatures during the year increase approximately

0,5 °C degrees in A₂.

The relative humidity rates also have an influence on these changes since in the A scenarios, A₁ shows steady rates along with ventilation rates both mechanical and natural. During the year B₁ is the best-case scenario in the manner of PMV rates. It does not show any extreme rises or falls in discomfort, also the relative humidity rates show a steady trend in B₁ and B₂ cases with natural ventilation availability.

Since the openings are wider with 100% glazing, and 50% more operability, they open to exposure of exterior conditions much more in the C₂ case. The temperatures have the most varied results in the case of occupant comfort peaking at the hottest degree as 33,10 °C in July and decreasing down to 17,40 °C in December while the relative humidity is similar to C₁. In the PMV values, the C₂ case has the most discomfort rates ranging between 2,80 PMV and -1,50 PMV. The ventilation rates are also different in this case with the external ventilation values is higher with a 232 kWh in C₁ due to the operable area (Figure 18)(Figure 19).

The overall results in temperatures, humidity, ventilation, and PMV values show the main difference is made by building system choice with fan usage, and window layout is the second predominating factor affecting the indoor comfort levels. The ventilation scheduling has its impact substantially on fresh air intake levels where the availability is a choice, but scheduling can be also considered to reduce the mechanical loads on building systems. The insulation material thickness has its influence primarily in indoor temperatures by maintaining the variance between ambient air to indoor air.

To be able to provide healthy and comfortable indoor spaces, the occupant comfort depends on different measures consequently the optimum proposal of all variation and scenario groups should be decided based on their energy uses and other factors such as cost, occupant type, and building typology.

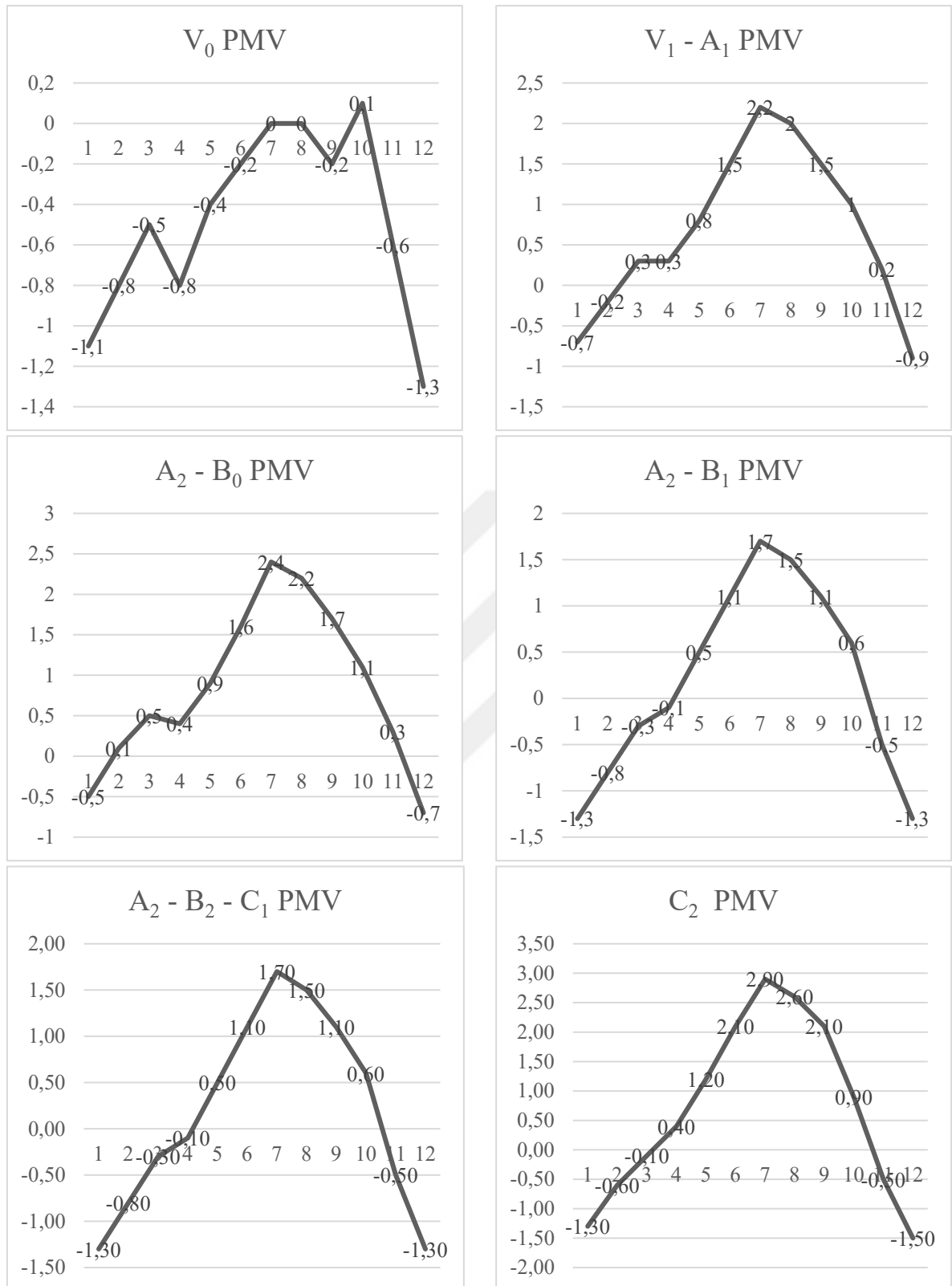


Figure 16: PMV Results of all variations and scenarios

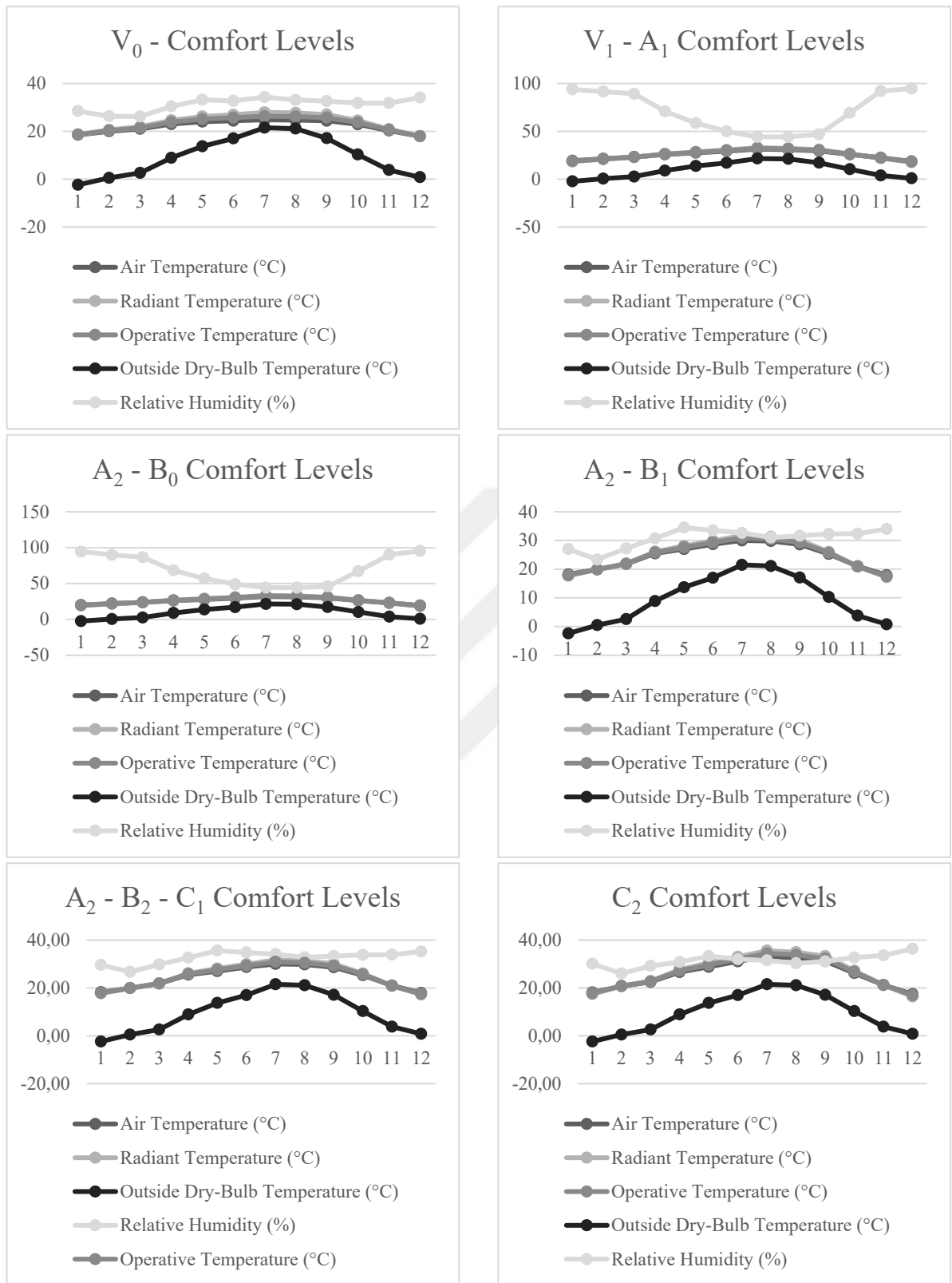


Figure 17: The comfort levels including temperature values, and humidity of all variations and scenarios

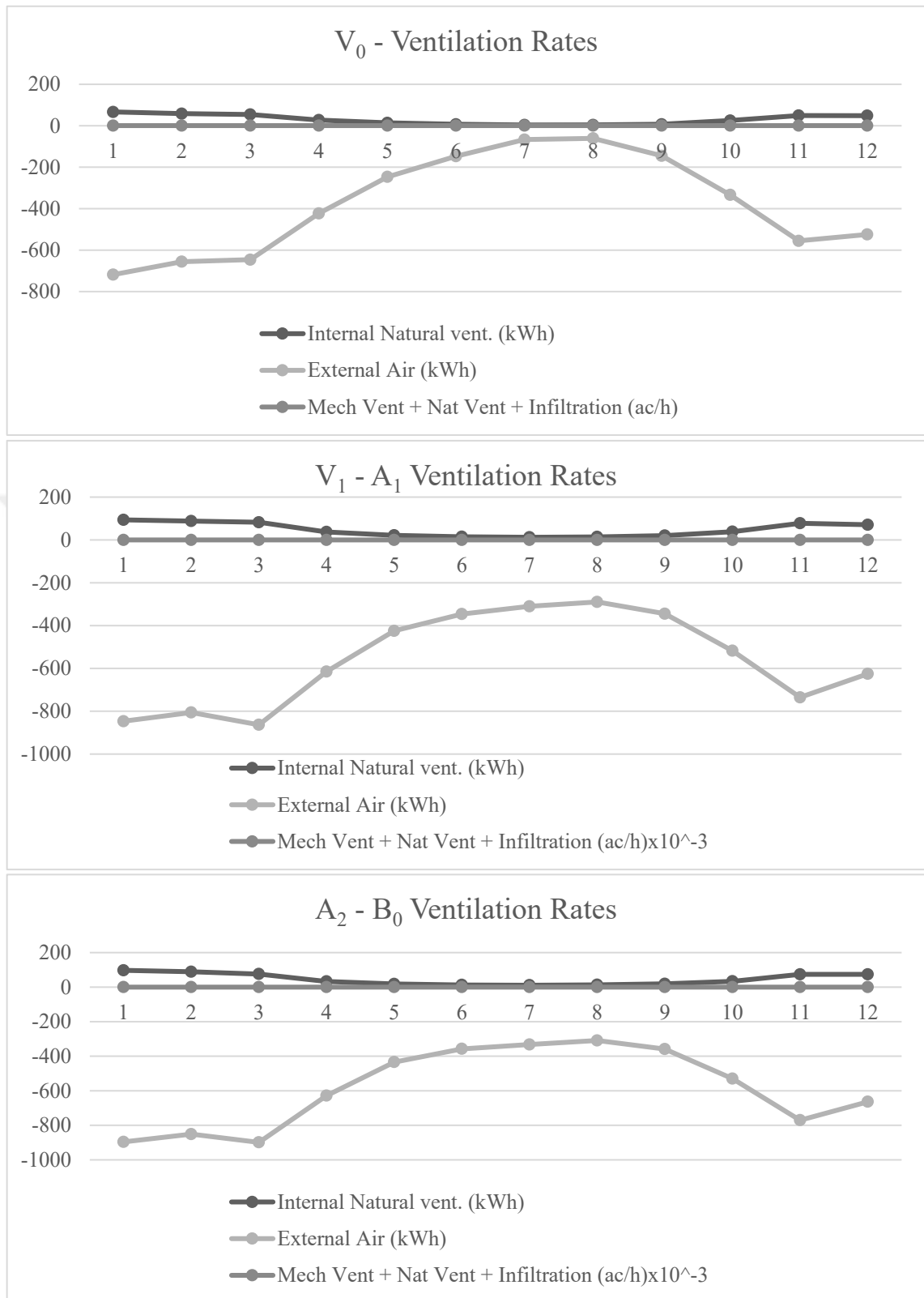


Figure 18: The ventilation rates in all variations and scenarios I

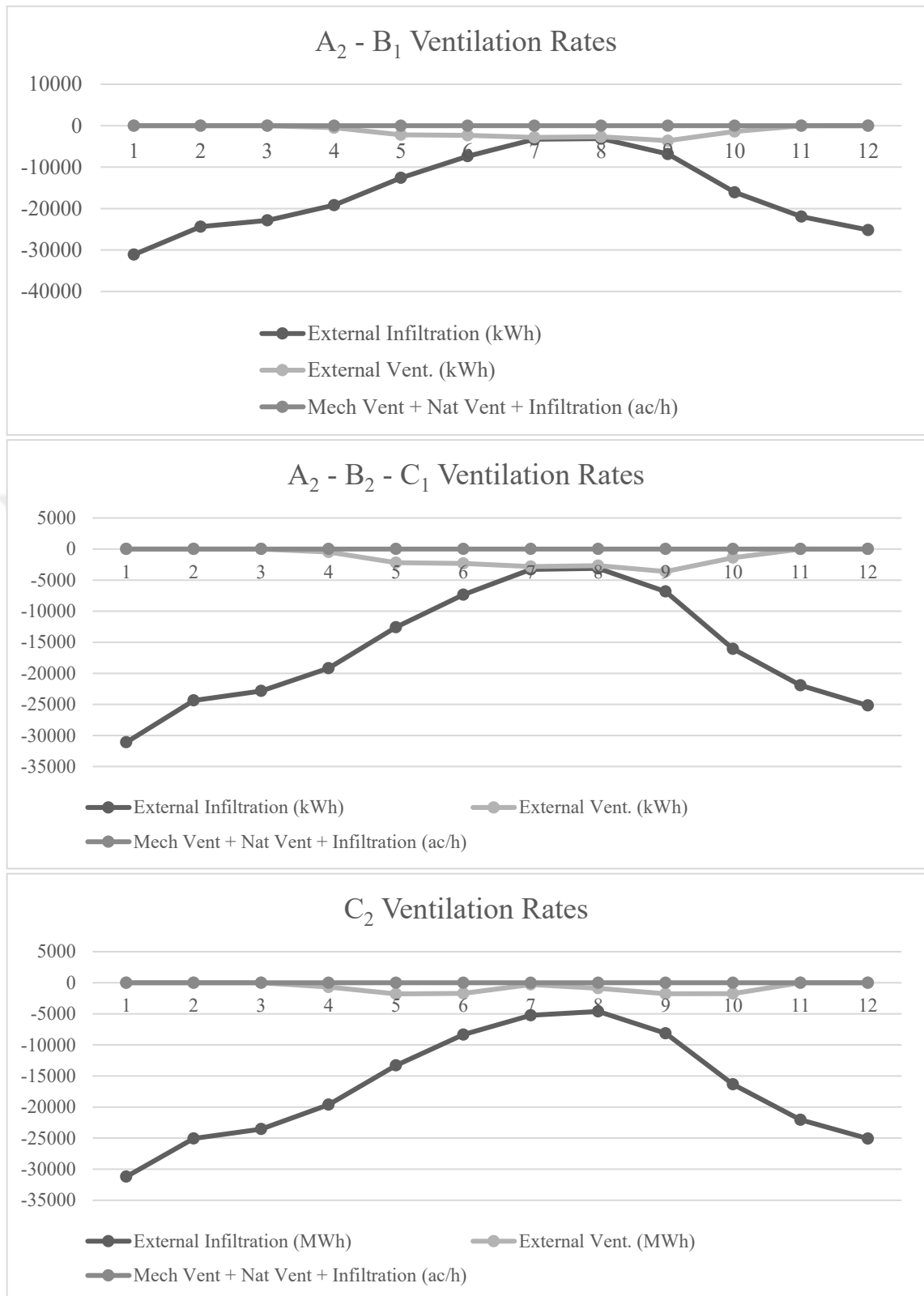


Figure 19: The ventilation rates in all variations and scenarios II

4.2 Current Situation and Research Gaps

4.2.1 Covid-19 Pandemic and IAQ

Latest technologies, industrial, and agricultural developments, as well as exceptional mobility of humans and materials, have vastly enhanced financial as well as wellness measures, and yet have simultaneously resulted in one of many global concerns, as evidenced by pollutants in water, soil, and air (Paleologos et al., 2021). Under these rapid changes, the world problems need to be dealt with new strategies, standards, and methods to establish reactive and adequate solutions that effect quickly. The issues, including the increment in time spent indoors, energy use, air pollution, consumption of world resources, bring about the necessities of different perceptions on human health and energy efficiency. The US Clean Air Act, the first extensive regulatory initiative designed to control air pollution, has encouraged governments to accept that environmental standards need to form an implicit aspect of a nation's legislative system.

This situation is highlighted more than ever with the recent global outbreak of coronavirus disease (COVID-19). COVID-19 was recognized as an epidemic by the World Health Organization (WHO) in its initial emergence in March 2020. Viral infections have lately been found to be able to persist in civilization indefinitely. Many outbreaks have occurred throughout human existence, yet this outbreak is unique (Megahed et al., 2020). Throughout the struggle, humankind is facing some unforeseeable event, and everyone is engaged in preventing the outbreak.

The occupant health and, correspondingly, IEQ has taken attention primarily by its parameter of IAQ to take urgent action. Since air circulation, particle filtration, and occupancy are vital for virus spread diseases, the perception of IAQ parameters and their relationship with the medical field shifted from familiar solutions and strategies. It has been seen that the IAQ parameters should be inspected not only by needed comfort levels

but also by considering contamination and exposure risks. Additionally, the recent studies examine that the considerations on building design should be taken in a long time comprehension for the future risks since different pandemic occurrence is highly possible in incoming years. Besides, the regulations and standards are opened to discussing these potential risks and how to overcome them with a less fatal rate. Other than individual precautions and perception of pandemics, there is a strong need for interdisciplinary caution to ensure sufficient health levels to cope with crisis obstacles.

Occupant behavior is influenced by an absence of evidence, contradictory statements, incompatibility with COVID-19, and human occupant perception. Despite the level of risk implicated or even the existing factors that may affect the chance of getting COVID-19, the occupant's perspective significantly alters the risk perception and influences their behaviors. As a result, the statement to the occupants will be unclear in any way where there is missing data concerning COVID-19, such as whether it transmits via the air, how far it spreads, and in which direction it migrates.

Ambiguity generates uncertainty, and perception may dominate over as a result. While personal quarantine because of the virus disease may prevent occupants from infection, inadequate ventilation caused by the dread of developing COVID-19 may also cause additional health concerns. Therefore, the other social, economic, and psychological aspects of such an outbreak or informing about related knowledge are also significant determinants on reconstructing the regulations and strategies (Cortiços et al., 2021). In enclosed places, residents' wellbeing and health have to be the top focus. According to the evaluated publications, IAQ can be improved utilizing nonpharmacologic methods and engineering management, although both have advantages and disadvantages. Finding a midway position for all the solutions that can help lower infection is the best way to follow.

4.2.2 The Republic of Turkey's Ministry of Environment and Urbanization Guidelines on nZEB design

The purpose of the Environment and Urban Ministry's report (2020) is to provide information on the implementation of almost zero energy buildings (nZEB) within the scope of energy performance improvement policies in buildings in Turkey. The report is organized within the scope of the "Energy Efficiency in Public Buildings in Turkey" The German Climate Technology Initiative (DKTI) program, funded by the Federal German Ministry, carried out under the coordination of The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and in partnership with the Ministry of Environment and Urbanization (MoEU). It is to reduce the energy consumption of existing public buildings in Turkey and thus greenhouse gas emissions.

Reducing energy consumption and using energy from renewable sources in the construction sector constitute essential measures to reduce the European Union's (EU) energy dependence and greenhouse gas emissions. Although the objectives and roadmaps of the countries differ, the methods applied are similar. All roadmaps try to achieve the same overall goal by following EU directives. The relevant instruments introduced by the EU in this process are summarized below. These tools include the directives and financial instruments that track the strategy documents that set the targets.

In Turkey, the energy performance of buildings is determined using the BEP-TR software with the calculation method within the scope of the Communiqué on the Energy Performance National Calculation Method in Buildings.

The study method starts with the determination of the reference features for each building type using the Turkish Statistical Institute (TUIK) data. There are established scenarios for building envelope for different climatic zones that are determined as İzmir (Climatic Zone 1), İstanbul (Climatic Zone 2), Ankara (Climatic Zone 3) ve Erzurum (Climatic Zone 4). Since the thesis building's climatic zone is selected as Ankara, the net

energy change rates according to building material preferences in the report's scenarios show the exact trend with proposed A cases: increasing the thickness of insulation material from 0,06 m to 0,1 m as in the A case from 0,05 to 0,1 m, reduces the energy use down to 24,9%.

Similar to building envelope scenarios as in the A cases, the report of the ministry, includes different proposed building heating and cooling system design requirements as in the various groups. Different from the methodology, the report includes renewable energy resources use, condensing boiler, and heat pump of soil and air.

In Turkey, the definition of nZEB has been determined to have a realistic and optimal initial investment cost in terms of implementation, considering the current condition of the construction, heating, cooling, and supporting sectors. The location of the buildings will provide useful flexibility to reduce performance deficiencies due to the number and density of building users and design features and ensure that nZEB targets can be met.

In conclusion, it should be noted that nZEB definitions or energy-efficient measures are general regulations. The methods to be used to reach these definitions may vary based on building, region, city, and climate zones.

CHAPTER V

CONCLUSION

This thesis research aims to investigate the impact of IEQ on occupant comfort and energy use. The results obtained from simulation data show that proposed HVAC systems and design considerations, which are according to the energy-efficient design principles regarding providing occupant comfort needs, are competent rather than the other selected HVAC systems. Meanwhile, there are still setbacks in the proposed strategies related to energy efficiency corresponding to the reluctant responses to extreme conditions on available design decisions and unexpected exterior changes.

The comparison analysis on the variation and scenario groups, created with different considerations, including mechanical systems, material selection, ventilation strategies, and building design decisions on window layout, supported that IEQ parameters are highly influential on the comfort levels and energy use of the buildings.

Furthermore, materials, design decisions, and system appliance selection among different energy use types of heating, cooling, and ventilation are eminently correlated with each other under the related parameters of IEQ. The building system components have an impact on energy end-use types. Also, lightning control has a highly efficient choice to reduce indoor lighting end-use. To ensure higher energy efficiency, the comfort factors such as PMV, indoor temperatures, humidity levels should be inspected correspondingly to make a comparison in deciding the best possible option.

This study intended to provide an evaluation of the inter-relation of the examined subjects to give knowledge about the relationship of occupant's demands with their comfort level perception to their environment under the varied indoor and outdoor

conditions. It highlights the holistic approach needed in terms of architectural and mechanical improvements in the research field. The studies should be conducted related to the impact of IEQ on different issues such as occupant productivity and health further on since the total comfort perception is immensely associated with them as well.



APPENDIX A

DESIGNBUILDER MODELING DETAILS

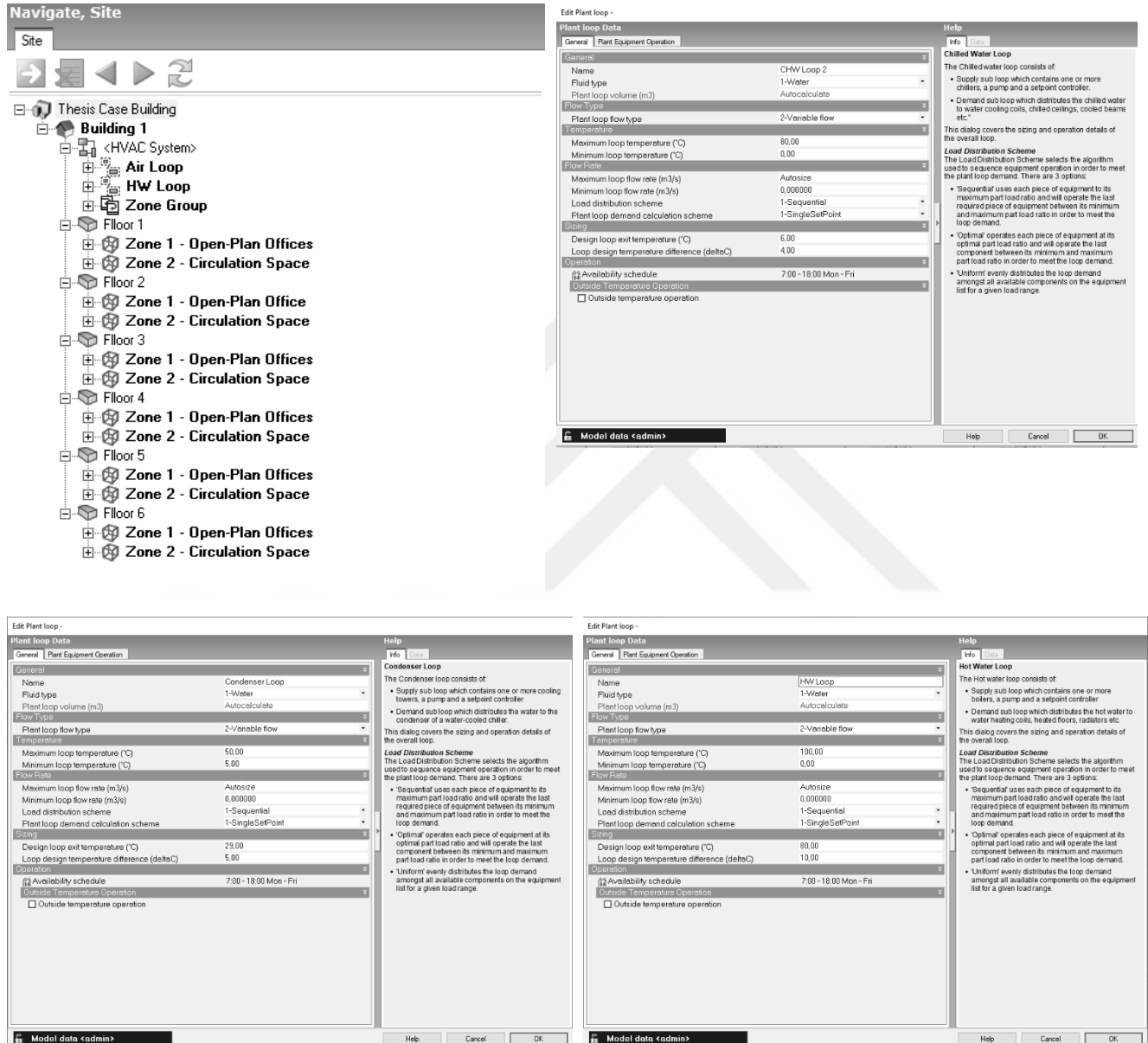


Figure A-1: DesignBuilder HVAC template details of Variation Group 0 (V₀) with the ASHRAE 90.1 Appendix G preferences

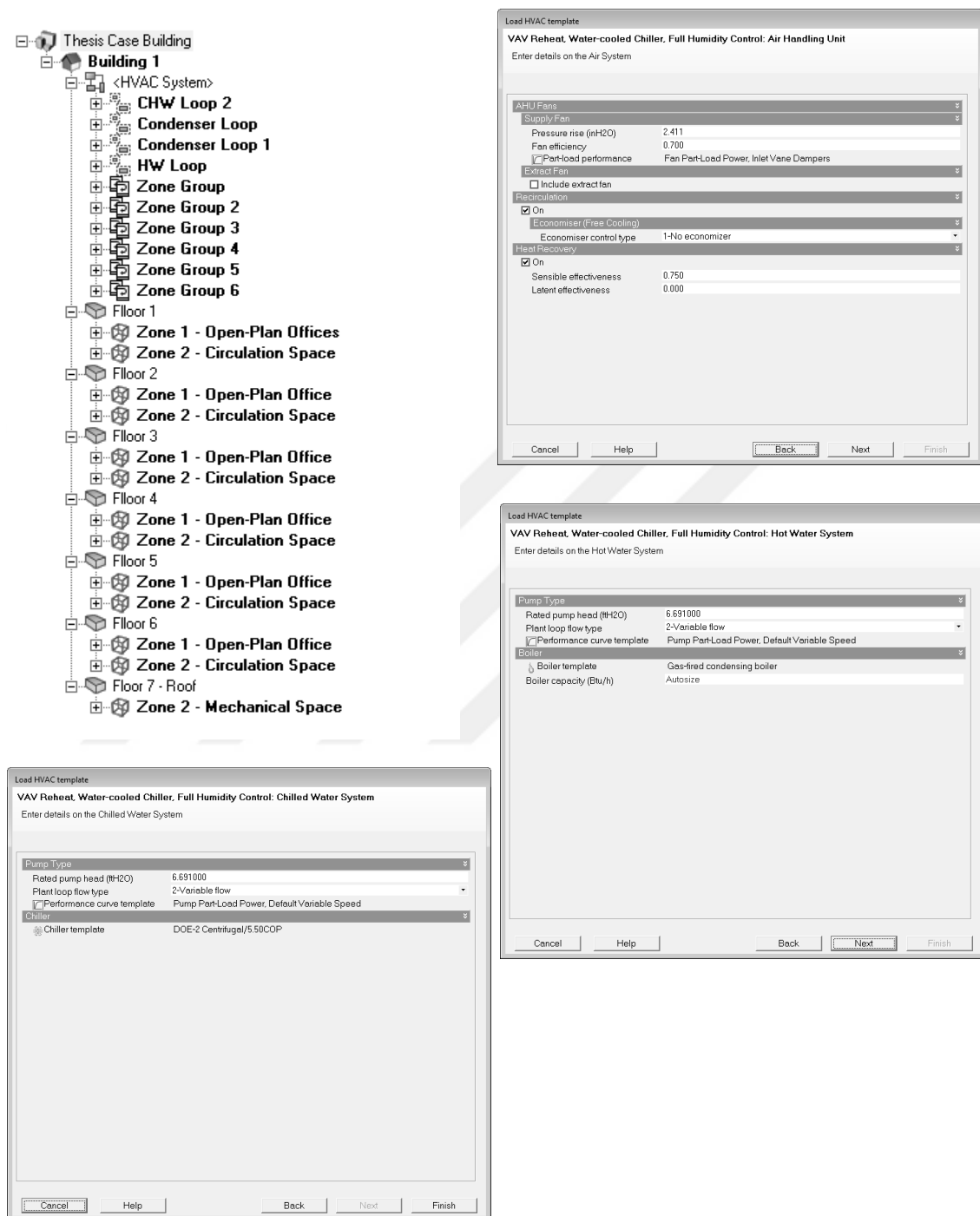


Figure A-2: DesignBuilder, HVAC template details of Variation Group 1 (V_1) with the proposed building system preferences

Constructions Data

LayersSurface propertiesImageCalculatedCostInternal sourceCondensation analysis

General

NameThesis Walls EPS A1

SourceDesignBuilder

CategoryWalls

RegionTURKEY

Definition

Definition method1-Layers

Calculation Settings

Layers

Number of layers5

Outermost layer

MaterialGypsum Plastering

Thickness (m)0.0300

Bridged?

Layer 2

MaterialAir gap 15mm

Thickness (not used in thermal calcs) (m)0.0300

Layer 3

MaterialEPS Expanded Polystyrene (Standard)

Thickness (m)0.0500

Bridged?

Layer 4

MaterialConcrete blocks/tiles - block, hollow, ligh

Thickness (m)0.1900

Bridged?

Innermost layer

MaterialGypsum Plastering

Thickness (m)0.0200

Bridged?

Help

InfoData

Construction Layers

Set the number of layers first, then select the material and thickness for each layer.

Insert layerDelete layer

Bridging

You can also add bridging to any layer to model the effect of a relatively more conductive material bridging a less conductive material. For example wooden joists bridging an insulation layer.

Note that bridging effects are NOT used in EnergyPlus, but are used in energy code compliance checks requiring U-values to be calculated according to BS EN ISO 6946.

Energy Code Compliance

You can calculate the thickness of insulation required to meet the mandatory energy code U-value as set on the Energy Code tab at site level.

This calculation identifies the 'insulation layer' as the layer having the highest r-value and requires that no bridging is used in the construction.

Set U-Value

Model dataInsert layerDelete layerHelpCancelOK

Constructions Data

LayersSurface propertiesImageCalculatedCostInternal sourceCondensation analysis

General

NameThesis Walls EPS A2

SourceDesignBuilder

CategoryWalls

RegionTURKEY

Definition

Definition method1-Layers

Calculation Settings

Layers

Number of layers5

Outermost layer

MaterialGypsum Plastering

Thickness (m)0.0300

Bridged?

Layer 2

MaterialAir gap 15mm

Thickness (not used in thermal calcs) (m)0.0300

Layer 3

MaterialEPS Expanded Polystyrene (Standard)

Thickness (m)0.1000

Bridged?

Layer 4

MaterialConcrete blocks/tiles - block, hollow, ligh

Thickness (m)0.1900

Bridged?

Innermost layer

MaterialGypsum Plastering

Thickness (m)0.0200

Bridged?

Help

InfoData

Construction Layers

Set the number of layers first, then select the material and thickness for each layer.

Insert layerDelete layer

Bridging

You can also add bridging to any layer to model the effect of a relatively more conductive material bridging a less conductive material. For example wooden joists bridging an insulation layer.

Note that bridging effects are NOT used in EnergyPlus, but are used in energy code compliance checks requiring U-values to be calculated according to BS EN ISO 6946.

Energy Code Compliance

You can calculate the thickness of insulation required to meet the mandatory energy code U-value as set on the Energy Code tab at site level.

This calculation identifies the 'insulation layer' as the layer having the highest r-value and requires that no bridging is used in the construction.

Set U-Value

Model dataInsert layerDelete layerHelpCancelOK

Figure A-3: DesignBuilder, The building materials details of walls in A₁ (above) and A₂ cases (below)

REFERENCES

- [1] IPCC. (2014). Climate Change 2014: Synthesis Report
- [2] European Union (EU). (2008). The E.U. Air Quality Directive 2008/50/E.C. of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. <http://data.europa.eu/eli/dir/2008/50/oj>
- [3] World Health Organization. Occupational and Environmental Health Team. (2006). WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide: global update 2005: summary of risk assessment. *World Health Organization*. <https://apps.who.int/iris/handle/10665/69477>
- [4] Seinfeld JH, Pandis S. (2006). Atmospheric chemistry and physics. *2nd ed. Hoboken (N.J.): John Wiley*.
- [5] United States Environmental Protection Agency (EPA). (1997). Exposure factors handbook volume 3: Activity factors. EPA/600/P-95/002Fa. Washington, DC.
- [6] United States Environmental Protection Agency (EPA). 1989. Report to Congress on indoor air quality: Volume 2. EPA/400/1-89/001C. Washington, DC.
- [7] US Consumer Product Safety Commission. (1995). Indoor Air Pollution: An Introduction for Health Professionals. *American Lung Association*.
- [8] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2004) Standard 55–2004. Thermal Environmental Conditions for Human Occupancy. Atlanta, GA.
- [9] Mishra, A. K., & Ramgopal, M. (2013). Field studies on human thermal comfort—an overview. *Building and Environment*, 64, 94-106.
- [10] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2013). Standard 62.1-2013 Ventilation for acceptable indoor air quality. *American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.* Atlanta, GA, 40.
- [11] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2009). IAQ guide: best practices for design, construction, and commissioning.
- [12] Maroni, M., Seifert, B., & Lindvall, T. (Eds.). (1995). Indoor air quality: a comprehensive reference book. *Elsevier*.
- [13] Kumar, P., Morawska, L., Birmili, W., Paasonen, P., Hu, M., Kulmala, M., ... & Britter, R. (2014). Ultrafine particles in cities. *Environment international*, 66, 1-10.

- [14] Johansson TB, Goldemberg J, editors. (2005). New York, NY, USA. United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy Council.
- [15] IEA. (2020). *World Energy Balances: Overview*, IEA, Paris. (<https://www.iea.org/reports/world-energy-balances-overview>)
- [16] Fritz-Morgenthal, S., Greenwood, C., Menzel, C., Mironjuk, M., & Sonntag-O'Brien, V. (2009). The global financial crisis and its impact on renewable energy finance. *Frankfort School of Financial Management*. Frankfurt, Germany.
- [17] Ahuja, D., & Tatsutani, M. (2009). Sustainable energy for developing countries. *SAPI EN. S. Surveys and Perspectives Integrating Environment and Society*, (2.1).
- [18] Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394-398.
- [19] Eurostat. (2014). Final energy consumption by sector. Available at: (<http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search/database>).
- [20] DoE, U. S. (2011). Building's energy data book. *Energy Efficiency & Renewable Energy Department*, 286.
- [21] EERE. (2012). Building energy data book: Table 2.2.1. Total number of households and buildings, floor space, and household size, by year. *Building's energy data book*. Retrieved May 10, 2021, from (<http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.2.1>)
- [22] Nicol, J. F., & Humphreys, M. (1998). Understanding the adaptive approach to thermal comfort. *ASHRAE transactions*, 104, 991-1004.
- [23] World Health Organization. (1990). Indoor air quality: biological contaminants: report on a WHO meeting, Rautavaara, 29 August-2 September 1988. *World Health Organization*. Regional Office for Europe.
- [24] Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-story residential net-zero energy building in Denmark. *Energy*, 36(9), 5600-5609.
- [25] European Commission (EC). (n.d.). Energy Performance of Buildings Directive (EPBD). (https://ec.europa.eu/energy/content/nzeb-24_en) (accessed May 11, 2021).
- [26] Zhang, S., Huang, P., & Sun, Y. (2016). A multi-criterion renewable energy system design optimization for net-zero energy buildings under uncertainties. *Energy*, 94, 654-665.
- [27] Liu, Z., Zhou, Q., Tian, Z., He, B. J., & Jin, G. (2019). A comprehensive analysis on definitions, development, and policies of nearly zero energy buildings in China. *Renewable and Sustainable Energy Reviews*, 114, 109314.
- [28] Sakhare, V. and R. Ralegaonkar (2014). Indoor environmental quality: review of parameters and assessment models. *Archit. Sci. Rev.* 57(2), 147–154.

- [29] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). (2010). Guideline 10P, Interactions Affecting the Achievement of Acceptable Indoor Environments, Second Public Review. *ASHRAE*, Atlanta, USA.
- [30] Arghand, T., T. Karimipناه, H. B. Awbi, M. Cehlin, U. Larsson, and E. Linden (2015). An experimental investigation of the flow and comfort parameters for under-floor, confluent jets, and mixing ventilation systems in an open-plan office. *Build. Environ.* 92, 48–60.
- [31] United States Environmental Protection Agency (EPA), Indoor Environments Division. (2001). IAQ Tools for Schools: Indoor Air Quality and Student Performance. (<http://www.epa.gov/iaq/schools/perform.html>) (accessed May 12, 2021).
- [32] De Giuli, V., Da Pos, O., & De Carli, M. (2012). Indoor environmental quality and pupil perception in Italian primary schools. *Building and Environment*, 56, 335-345.
- [33] Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, 5(1), 1-11.
- [34] Antoniadou, P., & Papadopoulos, A. M. (2017). Occupants' thermal comfort: State of the art and the prospects of personalized assessment in office buildings. *Energy and Buildings*, 153, 136-149.
- [35] Yang, W., & Moon, H. J. (2019). Combined effects of acoustic, thermal, and illumination conditions on the comfort of discrete senses and overall indoor environment. *Building and Environment*, 148, 623-633.
- [36] Tomatis, L. (Ed.). (2012). Indoor and outdoor air pollution and human cancer. *Springer Science & Business Media*.
- [37] Van Kempen, E. E., Kruize, H., Boshuizen, H. C., Ameling, C. B., Staatsen, B. A., & de Hollander, A. E. (2002). The association between noise exposure and blood pressure and ischemic heart disease: a meta-analysis. *Environmental health perspectives*, 110(3), 307-317.
- [38] Cuijpers, C. E. J., Swaen, G. M. H., Wesseling, G., Sturmans, F., & Wouters, E. F. M. (1995). Adverse-effects of the indoor environment on respiratory health in primary-school children. *Environmental Research*, 68 (1), 11-23.
- [39] Bluysen, P. M., Aries, M., & van Dommelen, P. (2011). Comfort of workers in office buildings: The European HOPE project. *Building and Environment*, 46(1), 280-288.
- [40] Babaoglu, U. T., Milletli Sezgin, F., & Yag, F. (2020). Sick building symptoms among hospital workers associated with indoor air quality and personal factors. *Indoor and Built Environment*, 29(5), 645-655.

- [41] Caillaud, D., Leynaert, B., Keirsbulck, M., & Nadif, R. (2018). Indoor mold exposure, asthma, and rhinitis: findings from systematic reviews and recent longitudinal studies. *European Respiratory Review*, 27 (148).
- [42] Sedlbauer, K. (2001) Prediction of Mould Fungus Formation on the Surface of and inside Building Components. *Ph.D. Dissertation*, Stuttgart University, Stuttgart.
- [43] Morawska, L. (2006). Droplet fate in indoor environments, or can we prevent the spread of infection?. *Indoor air*, 16(5), 335-347.
- [44] Levin, I., & Stokes, J. P. (1989). Dispositional approach to job satisfaction: Role of negative affectivity. *Journal of applied psychology*, 74(5), 752.
- [45] Nag, P. K. (2019). Sick building syndrome and other building-related illnesses. *In Office Buildings (pp. 53-103)*. Springer, Singapore.
- [46] Apte, M. G. (2000). Associations between indoor CO₂ concentrations and sick building syndrome symptoms in US office buildings: an analysis of the 1994-1996 BASE study data. *Indoor air*, 10(4).
- [47] Gomzi, M., Bobic, J., Radosevic-Vidacek, B., Macan, J., Varnai, V. M., Milkovic-Kraus, S., & Kanceljak-Macan, B. (2007). Sick building syndrome: psychological, somatic, and environmental determinants. *Archives of environmental & occupational health*, 62(3), 147-155.
- [48] Gül, H., İşsever, H., Ayraz, Ö., & Güngör, G. (2007). Occupational and environmental risk factors for the sick building syndrome in modern offices in Istanbul: a cross sectional study. *Indoor and Built Environment*, 16(1), 47-54.
- [49] Hansen, A. M., Meyer, H. W., & Gyntelberg, F. (2008). Building-related symptoms and stress indicators. *Indoor Air*, 18(6), 440-446.
- [50] Jaakkola, M. S., Yang, L., Ieromnimon, A., & Jaakkola, J. J. (2007). Office work exposures and respiratory and sick building syndrome symptoms. *Occupational and environmental medicine*, 64(3), 178-184.
- [51] Hedge, A., Burge, P. S., Robertson, A. S., Wilson, S., & Harris-Bass, J. (1989). Work-related illness in offices: a proposed model of the “sick building syndrome”. *Environment International*, 15 (1-6), 143-158.
- [52] Jaakkola, M. S., Nordman, H., Piipari, R., Uitti, J., Laitinen, J., Karjalainen, A., ... & Jaakkola, J. J. (2002). Indoor dampness and molds and development of adult-onset asthma: a population-based incident case-control study. *Environmental health perspectives*, 110 (5), 543-547.
- [53] Mendell, M. J., & Smith, A. H. (1990). Consistent pattern of elevated symptoms in air-conditioned office buildings: a reanalysis of epidemiologic studies. *American journal of public health*, 80 (10), 1193-1199.
- [54] Burge, P. S., Jones, P., & Robertson, A. (1996). Sick building syndrome. *Proceedings-Royal College Of Physicians Of Edinburgh*, 26, 603-611.

- [55] Niemelä, R., Seppänen, O., Korhonen, P., & Reijula, K. (2006). Prevalence of building-related symptoms as an indicator of health and productivity. *American journal of industrial medicine*, 49 (10), 819-825.
- [56] Shan, X., Zhou, J., Chang, V. W. C., & Yang, E. H. (2016). Comparing mixing and displacement ventilation in tutorial rooms: Students' thermal comfort, sick building syndromes, and short-term performance. *Building and Environment*, 102, 128-137.
- [57] Agarwal, R., & Gopinath, G. (2021). A proposal to end the COVID-19 pandemic. *Staff Discussion Notes*, 2021(004).
- [58] Duan, X., Sun, H., He, Y., Yang, J., Li, X., Taparia, K., & Zheng, B. (2021). Personal Protective Equipment in COVID-19: Impacts on Health Performance, Work-Related Injuries, and Measures for Prevention. *Journal of Occupational and Environmental Medicine*, 63 (3), 221.
- [59] Guzzo, R. A., & Bondy, J. S. (1983). A guide to worker productivity experiments in the United States, 1976-81. *New York: Pergamon Press*.
- [60] Marcus, B. and Schuler, H. (2001), *Schuler, H. (Ed.), Lehrbuch der Personalpsychologie*, Hogrefe, Göttingen
- [61] Vernon, H. M., & Bedford, T. (1926). A Physiological Study of the Ventilation and Heating in Certain Factories. *A Physiological Study of the Ventilation and Heating in Certain Factories.*, (35).
- [62] Vernon, H. M., & Bedford, T. (1930). A Study of Heating and Ventilation in Schools. *A Study of Heating and Ventilation in Schools.*, (58).
- [63] Herzberg, F. (1959). Motivation to work. *Routledge*.
- [64] Herzberg, F.I. (1966). Work and the nature of man. *World*.
- [65] Wang, C., Zhang, F., Wang, J., Doyle, J. K., Hancock, P. A., Mak, C. M., & Liu, S. (2021). How indoor environmental quality affects occupants' cognitive functions: A systematic review. *Building and Environment*, 107647.
- [66] World Green Building Council (WorldGBC). (2014). Health, Wellbeing & Productivity in Offices. *World Green Building Council*.
- [67] Chartered Inst. of Building Services Engineers. (1999). Environmental factors affecting office worker performance: A review of evidence. London (United Kingdom); Department of the Environment, Transport and the Regions, London (United Kingdom).
- [68] Wargocki, P., Seppänen, O., Andersson, J., Clements-Croome, D., Fitzner, K., & Hanssen, S. O. (2006). Indoor climate and productivity in offices. *REHVA guidebook*, 6.
- [69] Wilkins, A. J., Nimmo-Smith, I., Slater, A. I., & Bedocs, L. (1989). Fluorescent lighting, headaches, and eyestrain. *Lighting Research & Technology*, 21(1), 11-18.

- [70] Kang, S., Ou, D., & Mak, C. M. (2017). The impact of indoor environmental quality on work productivity in university open-plan research offices. *Building and Environment*, 124, 78-89.
- [71] Huang, L., Zhu, Y., Ouyang, Q., & Cao, B. (2012). A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices. *Building and Environment*, 49, 304-309.
- [72] Wargocki, P., Wyon, D. P., Baik, Y. K., Clausen, G., & Fanger, P. O. (1999). Perceived air quality, sick building syndrome (SBS) symptoms, and productivity in an office with two different pollution loads. *Indoor air*, 9(3), 165-179.
- [73] Lagercrantz, L., Wistrand, M., Willen, U., Wargocki, P., Witterseh, T., & Sundell, J. (2000). Negative impact of air pollution on productivity: Previous Danish findings repeated in new Swedish test room. In *Proceedings of Healthy Buildings 2000, Vol. 1* (pp. 653-658).
- [74] Wargocki, P., Wyon, D. P., & Fanger, P. O. (2000). Productivity is affected by the air quality in offices. In *Proceedings of Healthy Buildings (Vol. 1, No. 1, pp. 635-40)*.
- [75] Qiu, Y., Wang, Y., & Tang, Y. (2020). Investigation of indoor air quality in six office buildings in Chengdu, China-based on field measurements. In *Building Simulation (Vol. 13, No. 5, pp. 1009-1020)*. Tsinghua University Press.
- [76] Almeida, L. M., Tam, V. W., & Le, K. N. (2020). Quantification of the energy use due to occupant behavior collected in surveys: a case study of a green and non-green building. *Journal of Building Performance Simulation*, 13 (6), 777-803.
- [77] Crandall, R. W. (1983). Controlling industrial pollution: The economics and politics of clean air.
- [78] United States Environmental Protection Agency (EPA). (n.d.). Overview of the Clean Air Act and Air Pollution. (<https://www.epa.gov/clean-air-act-overview>)
- [79] Hepner, C. M., & Boser, R. A. (2006). Architects' perceptions of LEED indoor environmental quality checklist items on employee productivity. *International Journal of Construction Education and Research*, 2(3), 193-208.
- [80] Halios, C. H., Assimakopoulos, V. D., Helmis, C. G., & Flocas, H. A. (2005). Investigating cigarette-smoke indoor pollution in a controlled environment. *Science of the total environment*, 337(1-3), 183-190.
- [81] Chen, T. M., Kuschner, W. G., Gokhale, J., & Shofer, S. (2007). Outdoor air pollution: nitrogen dioxide, sulfur dioxide, and carbon monoxide health effects. *The American journal of the medical sciences*, 333(4), 249-256.
- [82] Anderson, J. O., Thundiyil, J. G., & Stolbach, A. (2012). Clearing the air: a review of the effects of particulate matter air pollution on human health. *Journal of medical toxicology*, 8(2), 166-175.

- [83] UNSCEAR, S. (2000). United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation, 2.
- [84] Cooke, T. F. (1991). Indoor air pollutants: a literature review. *Reviews on Environmental Health*, 9(3), 137-160.
- [85] Fierro, M. A., O'Rourke, M. K., & Burgess, J. L. (2001). Adverse health effects of exposure to ambient carbon monoxide. *University of Arizona Report*.
- [86] You, M. Q. (2013). Comments on China's new ambient air quality standards. In *Applied Mechanics and Materials* (Vol. 361, pp. 850-853). Trans Tech Publications Ltd.
- [87] Colbeck, I., & Nasir, Z. A. (2012). Indoor Air Quality in Asian Countries. *Asian Environmental Technology (AET)*, 28-29.
- [88] World Health Organization (WHO). (2000). Air Quality Guidelines for Europe 2000, Second Edition. *WHO Regional Publications; European Series, N.91*, Regional Office for Europe, Copenhagen, 288 pages.
- [89] Seppänen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO₂ concentrations with health and other responses in commercial and institutional buildings. *Indoor air*, 9 (4), 226-252.
- [90] Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO₂ an indoor pollutant? Direct effects of low-to-moderate CO₂ concentrations on human decision-making performance. *Environmental health perspectives*, 120 (12), 1671-1677.
- [91] Rao, M., George, L. A., Rosenstiel, T. N., Shandas, V., & Dinno, A. (2014). Assessing the relationship among urban trees, nitrogen dioxide, and respiratory health. *Environmental Pollution*, 194, 96-104.
- [92] American Society of Heating, Refrigerating, Air-Conditioning Engineers, & American National Standards Institute. (2001). Ventilation for acceptable indoor air quality (Vol. 62, No. 2001). *American Society of Heating, Refrigerating and Air-Conditioning Engineers*.
- [93] Hasselblad, V., Eddy, D. M., & Kotchmar, D. J. (1992). Synthesis of environmental evidence: nitrogen dioxide epidemiology studies. *Journal of the Air & Waste Management Association*, 42 (5), 662-671.
- [94] Salthammer, T. (2011). Critical evaluation of approaches in setting indoor air quality guidelines and reference values. *Chemosphere*, 82 (11), 1507-1517.
- [95] Porter, M., Karp, M., Killedar, S., Bauer, S. M., Guo, J., Williams, D. A., ... & Williams, M. A. (2007). Diesel-enriched particulate matter functionally activates human dendritic cells. *American journal of respiratory cell and molecular biology*, 37(6), 706-719.
- [96] Nurmatov, U. B., Tagiyeva, N., Semple, S., Devereux, G., & Sheikh, A. (2015). Volatile organic compounds and risk of asthma and allergy: a systematic review.

European Respiratory Review, 24 (135), 92-101.

- [97] Wigle, D. T., Arbuckle, T. E., Turner, M. C., Bérubé, A., Yang, Q., Liu, S., & Krewski, D. (2008). Epidemiologic evidence of relationships between reproductive and child health outcomes and environmental chemical contaminants. *Journal of Toxicology and Environmental Health, Part B*, 11 (5-6), 373-517.
- [98] Bell, M. L., McDermott, A., Zeger, S. L., Samet, J. M., & Dominici, F. (2004). Ozone and short-term mortality in 95 US urban communities, 1987-2000. *Jama*, 292 (19), 2372-2378.
- [99] Brown, T. P., Rushton, L., Muggleston, M. A., & Meechan, D. F. (2003). Health effects of a sulfur dioxide air pollution episode. *Journal of Public Health*, 25 (4), 369-371.
- [100] Harrison, P.T.C. (2002). Indoor air quality guidelines. *Occup. Environ Med.* 59; 73-74.
- [101] Abdul-Wahab, S. A., En, S. C. F., Elkamel, A., Ahmadi, L., & Yetilmezsoy, K. (2015). A review of standards and guidelines set by international bodies for the parameters of indoor air quality. *Atmospheric Pollution Research*, 6(5), 751-767.
- [102] World Health Organization. (1999). Strategic approaches to indoor air policy-making (No. EUR/ICP/EHBI 04 02 02). *Copenhagen: WHO Regional Office for Europe*.
- [103] World Health Assembly, 71. (2018). Health, environment, and climate change: a road map for an enhanced global response to the adverse health effects of air pollution: report by the Director-General. *World Health Organization*. (<https://apps.who.int/iris/handle/10665/276321>)
- [104] World Health Organization (WHO). (2009). Heseltine, E., & Rosen, J. (Eds.). *WHO guidelines for indoor air quality: dampness and mold*.
- [105] World Health Organization (WHO). (2010). *WHO guidelines for indoor air quality: selected pollutants*.
- [106] World Health Organization (WHO). (2014). *WHO guidelines for indoor air quality: household fuel combustion*. *World Health Organization*.
- [107] Salthammer, T. (2011). Critical evaluation of approaches in setting indoor air quality guidelines and reference values. *Chemosphere*, 82 (11), 1507-1517.
- [108] Health Canada. Exposure Guidelines for Residential Indoor Air Quality. (1989). A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health (EHD-TR-156). Ottawa, Canada: *Health Canada Publications – Communications*.
- [109] Finnish Society of Indoor Air Quality and Climate (FiSIAQ). (2000). Classification of Indoor Climate 2000: Target Values, Design Guidance and Product Regulations.
- [110] Health and Environment Alliance (HEAL). (2015). Air Pollution and Health in

Turkey: Facts, Figures and Recommendations.

- [111] European Environment Agency (EEA) (n.d). (<https://www.eea.europa.eu/themes/air/country-fact-sheets/2020-country-fact-sheets/turkey>) (Accessed May 15, 2021).
- [112] Corgnati, S., Gameiro da Silva, M., Ansaldi, R., Asadi, E., Costa, J. J., Filippi, M., ... & Wargocki, P. (2011). Indoor Climate Quality Assessment. *REHVA Guidebook No. 14*. Federation of European Heating, Ventilation, and Air Conditioning Associations.
- [113] Leaman, A. (1999) Window seat or aisle? Studies of buildings in use are showing the importance of personal control of one's environment, which includes windows. *Architects' Journal*, 3 March 1999.
- [114] Haymore, C. & Odom, R. (1993). Economic effects of poor indoor air quality. *Environmental Protection Agency Journal*, 19(4), 28–30
- [115] Karjalainen, S. (2016). Should we design buildings that are less sensitive to occupant behavior? A simulation study of effects of behavior and design on office energy consumption. *Energy Efficiency*, 9(6), 1257-1270.
- [116] Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviors on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews*, 80, 1061-1071.
- [117] CEN, C. (1998). CR 1752: Ventilation for buildings—design criteria for the indoor environment. *European Committee for Standardization*, Brussels.
- [118] Kim, J., Tartarini, F., Parkinson, T., Cooper, P., & De Dear, R. (2019). Thermal comfort in a mixed-mode building: Are occupants more adaptive?. *Energy and Buildings*, 203, 109436.
- [119] Kim, S. H., & Moon, H. J. (2018). Case study of an advanced integrated comfort control algorithm with cooling, ventilation, and humidification systems based on occupancy status. *Building and Environment*, 133, 246-264.
- [120] Meciarova, L. (2016). Examining The Impact of Indoor Air on Office Rooms Occupants-Case Study. *International Multidisciplinary Scientific GeoConference: SGEM*, 2, 367-372.
- [121] Hailemariam, E., Goldstein, R., Attar, R., & Khan, A. (2011). Real-time occupancy detection using decision trees with multiple sensor types. In *Proceedings of the 2011 Symposium on Simulation for Architecture and Urban Design* (pp. 141-148).
- [122] Lam, K. P., Höynck, M., Dong, B., Andrews, B., Chiou, Y. S., Zhang, R., ... & Choi, J. (2009). Occupancy detection through an extensive environmental sensor network in an open-plan office building. *IBPSA Building Simulation*, 145, 1452-1459.
- [123] Rijal, H. B., Tuohy, P., Nicol, F., Humphreys, M. A., Samuel, A., & Clarke, J. (2008). Development of an adaptive window-opening algorithm to predict the

thermal comfort, energy use, and overheating in buildings. *Journal of Building Performance Simulation*, 1(1), 17-30.

- [124] Rubin, A. I., Collins, B. L., & Tibbott, R. L. (1978). Window blinds as a potential energy saver: A case study. *US Department of Commerce, National Bureau of Standards*.
- [125] Yun, G. Y., Kong, H. J., & Kim, J. T. (2011). A field survey of occupancy and air-conditioner use patterns in open-plan offices. *Indoor and Built environment*, 20(1), 137-147.
- [126] Ahadzie, D. K., Opoku, R., Ware, S. N. O., & Mensah, H. (2020). Analysis of occupant behavior in the use of air-conditioners in public buildings in developing countries: evidence from Ghana. *International Journal of Building Pathology and Adaptation*.
- [127] Meng, X., Gao, Y., Hou, C., & Yuan, F. (2019). Questionnaire survey on the summer air-conditioning use behavior of occupants in residences and office buildings of China. *Indoor and Built Environment*, 28(5), 711-724.
- [128] Sundell, J., Levin, H., Nazaroff, W. W., Cain, W. S., Fisk, W. J., Grimsrud, D. T., ... & Weschler, C. J. (2011). Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor air*, 21(3), 191-204.
- [129] Al-Hemoud, A., Al-Awadi, L., Al-Khayat, A., & Behbehani, W. (2018). Streamlining IAQ guidelines and investigating the effect of door opening/closing on concentrations of VOCs, formaldehyde, and NO₂ in office buildings. *Building and Environment*, 137, 127-137.
- [130] Boonyayothin, V., Hirunlabh, J., Khummongkol, P., Teekasap, S., Shin, U. C., & Khedari, J. (2011). Ventilation control approach for acceptable indoor air quality and enhancing energy saving in Thailand. *International Journal of Ventilation*, 9(4), 315-326.
- [131] Zhang, Y., Liu, Q., & Meng, Q. (2015). Airflow utilization in buildings in hot and humid areas of China. *Building and Environment*, 87, 207-214.
- [132] Chenari, B., Carrilho, J. D., & da Silva, M. G. (2016). Towards sustainable, energy-efficient, and healthy ventilation strategies in buildings: A review. *Renewable and Sustainable Energy Reviews*, 59, 1426-1447.
- [133] Kim, H., Hong, T., & Kim, J. (2019). Automatic ventilation control algorithm considering the indoor environmental quality factors and occupant ventilation behavior using a logistic regression model. *Building and Environment*, 153, 46-59.
- [134] Kim, J., Hong, T., Lee, M., & Jeong, K. (2019). Analyzing the real-time indoor environmental quality factors considering the influence of the building occupants' behaviors and the ventilation. *Building and Environment*, 156, 99-109.
- [135] Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., & Davies, M. (2020). Long-term, continuous air quality monitoring in a cross-sectional study of three UK non-domestic buildings. *Building and Environment*, 180, 107071.

- [136] Yang, B., & Sekhar, C. (2014). Interaction of dynamic indoor environment with moving person and performance of ceiling mounted personalized ventilation system. *Indoor and Built Environment*, 23(7), 920-932.
- [137] Habchi, C., Chakroun, W., Alotaibi, S., Ghali, K., & Ghaddar, N. (2016). Effect of shifts from occupant design position on performance of ceiling personalized ventilation assisted with desk fan or chair fans. *Energy and Buildings*, 117, 20-32.
- [138] Habchi, C., Ghali, K., Ghaddar, N., Chakroun, W., & Alotaibi, S. (2016). Ceiling personalized ventilation combined with desk fans for reduced direct and indirect cross-contamination and efficient use of office space. *Energy Conversion and Management*, 111, 158-173.
- [139] Al Assaad, D., Ghali, K., Ghaddar, N., & Habchi, C. (2017). Mixing ventilation coupled with personalized sinusoidal ventilation: optimal frequency and flow rate for acceptable air quality. *Energy and Buildings*, 154, 569-580.
- [140] He, M., Li, N., He, Y., He, D., & Song, C. (2017). The influence of personally controlled desk fan on comfort and energy consumption in hot and humid environments. *Building and Environment*, 123, 378-389.
- [141] Schiavon, S., Yang, B., Donner, Y., Chang, V. C., & Nazaroff, W. W. (2017). Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by tropically acclimatized persons. *Indoor air*, 27(3), 690-702.
- [142] Al Assaad, D., Ghali, K., & Ghaddar, N. (2018). Effectiveness of intermittent personalized ventilation assisting a chilled ceiling for enhanced thermal comfort and acceptable indoor air quality. *Building and Environment*, 144, 9-22.
- [143] Al Assaad, D., Habchi, C., Ghali, K., & Ghaddar, N. (2018). Simplified model for thermal comfort, IAQ, and energy savings in rooms conditioned by displacement ventilation aided with transient personalized ventilation. *Energy Conversion and Management*, 162, 203-217.
- [144] Sekhar, C., & Zheng, L. (2018). Study of an integrated personalized ventilation and local fan-induced active chilled beam air conditioning system in hot and humid climates. In *Building Simulation* (Vol. 11, No. 4, pp. 787-801). Tsinghua University Press.
- [145] Khalil, S., Ghali, K., Ghaddar, N., & Itani, M. (2020). Hybrid mixed ventilation system aided with personalized ventilation to attain comfort and save energy. *International Journal of Sustainable Energy*, 39(10), 964-981.
- [146] Gao, R., Li, H., Zhang, H., Wang, C., Li, A., Du, W., & Deng, B. (2021). Research on a personalized targeted air supply device based on body movement capture. *Indoor air*, 31(1), 206-219.
- [147] Liu, W., Deng, Q., Ma, W., Huangfu, H., & Zhao, J. (2013). Feedback from human adaptive behavior to neutral temperature in naturally ventilated buildings: physical and psychological paths. *Building and Environment*, 67, 240-249.

- [148] Wang, H., & Chen, Q. (2013). Human-Behavior Oriented Control Strategies for Natural Ventilation in Office Buildings.
- [149] Bourikas, L., Costanza, E., Gauthier, S., James, P. A. B., Kittley-Davies, J., Ornaghi, C., ... & Huang, Y. (2018). Camera-based window-opening estimation in a naturally ventilated office. *Building Research & Information*, 46(2), 148-163.
- [150] Ornaghi, C., Costanza, E., Kittley-Davies, J., Bourikas, L., Aragon, V., & James, P. A. (2018). The effect of behavioral interventions on energy conservation in naturally ventilated offices. *Energy Economics*, 74, 582-591.
- [151] Kim, J., Kong, M., Hong, T., Jeong, K., & Lee, M. (2019). The effects of filters for an intelligent air pollutant control system considering natural ventilation and the occupants. *Science of the Total Environment*, 657, 410-419.
- [152] Zhai, Y., Honnekeri, A., Pigman, M., Fountain, M., Zhang, H., Zhou, X., & Arens, E. (2019). Use of adaptive control and its effects on human comfort in a naturally ventilated office in Alameda, California. *Energy and Buildings*, 203, 109435.
- [153] Kim, S. H., & Moon, H. J. (2018). Case study of an advanced integrated comfort control algorithm with cooling, ventilation, and humidification systems based on occupancy status. *Building and Environment*, 133, 246-264.
- [154] Fabi, V., Andersen, R. V., Corgnati, S., & Olesen, B. W. (2012). Occupants' window opening behavior: A literature review of factors influencing occupant behavior and models. *Building and Environment*, 58, 188-198.
- [155] D'Oca, S., & Hong, T. (2014). A data-mining approach to discover patterns of window opening and closing behavior in offices. *Building and Environment*, 82, 726-739.
- [156] Li, N., Li, J., Fan, R., & Jia, H. (2015). Probability of occupant operation of windows during transition seasons in office buildings. *Renewable Energy*, 73, 84-91.
- [157] Wang, L., & Greenberg, S. (2015). Window operation and impacts on building energy consumption. *Energy and Buildings*, 92, 313-321.
- [158] Fabbri, K. (2016). How to use online surveys to understand human behavior concerning window opening in terms of building energy performance. *Advances in Building Energy Research*, 10(2), 213-239.
- [159] Tahmasebi, F., & Mahdavi, A. (2016). An inquiry into the reliability of window operation models in building performance simulation. *Building and Environment*, 105, 343-357.
- [160] Markovic, R., Wolf, S., Cao, J., Spinnraker, E., Wölki, D., Frisch, J., & van Treeck, C. (2017). Comparison of different classification algorithms for the detection of user's interaction with windows in office buildings. *Energy Procedia*, 122, 337-342.
- [161] Stazi, F., Naspi, F., Bernardini, G., & D'Orazio, M. (2017). Comparing real and predicted window use in offices. A POE-based assessment. *Energy Procedia*, 134, 141-150.

- [162] Markovic, R., Grintal, E., Wölki, D., Frisch, J., & van Treeck, C. (2018). Window opening model using deep learning methods. *Building and Environment*, 145, 319-329.
- [163] Pan, S., Xiong, Y., Han, Y., Zhang, X., Xia, L., Wei, S., ... & Han, M. (2018). A study on influential factors of occupant window-opening behavior in an office building in China. *Building and Environment*, 133, 41-50.
- [164] Zhou, X., Liu, T., Shi, X., & Jin, X. (2018). Case study of window operating behavior patterns in an open-plan office in the summer. *Energy and Buildings*, 165, 15-24.
- [165] Wei, Y., Yu, H., Pan, S., Xia, L., Xie, J., Wang, X., ... & Li, Q. (2019). Comparison of different window behavior modeling approaches during transition season in Beijing, China. *Building and Environment*, 157, 1-15.
- [166] Abdullah, H. K., & Alibaba, H. Z. (2020). Open-plan office design for improved natural ventilation and reduced mixed-mode supplementary loads. *Indoor and Built Environment*, 1420326X20953458.
- [167] Han, M., May, R., Zhang, X., Wang, X., Pan, S., Da, Y., & Jin, Y. (2020). A novel reinforcement learning method for improving occupant comfort via window opening and closing. *Sustainable Cities and Society*, 61, 102247.
- [168] Zhou, X., Liu, T., Yan, D., Shi, X., & Jin, X. (2021). An action-based Markov chain modeling approach for predicting the window operating behavior in office spaces. In *Building Simulation* (Vol. 14, No. 2, pp. 301-315). Tsinghua University Press.
- [169] Lu, S., Fang, K., Qi, Y., & Wei, S. (2015). Influence of natural ventilation on thermal comfort in semi-open buildings under early summer climate in the area of tropical Island. *Procedia Engineering*, 121, 944-951.
- [170] American Society of Heating Refrigerating, and Air Conditioning Engineers (ASHRAE). (2004). ASHRAE Standard 55-2004. *Thermal Environmental Conditions for Human Occupancy*. Atlanta, GA.
- [171] Andersen, I., & Gyntelberg, F. (2011). Modern indoor climate research in Denmark from 1962 to the early 1990s: an eyewitness report. *Indoor air*, 21(3), 182-190.
- [172] Roth, M. (2017). Updating the ASHRAE Climate Design Data for 2017. *ASHRAE Transactions*, 123.
- [173] European Commission (EC). (2020). European Collaborative Action - Urban Air, Indoor Environment and Human Exposure, Report No 30, Framework for health-based ventilation guidelines in Europe, EUR 27640 EN. *Publications Office of the European Union*, Luxembourg, 2020.
- [174] European Commission (EC). (2003). Ventilation, Good Indoor Air Quality, and Rational Use of Energy. European Collaborative Action on Urban Air, Indoor Environment and Human Exposure. *European Commission*.
- [175] Ramsey, J. D., & Beshir, M. Y. (1997). Thermal standards and measurement techniques. *The occupational environment—its evaluation and control*, 660-691.

- [176] Passe, U., & Battaglia, F. (2015). Designing spaces for natural ventilation: an architect's guide. *Routledge*.
- [177] De Dear, R. J., Leow, K. G., & Ameen, A. (1991). Thermal comfort in the humid tropics. Part II. Climate chamber experiments on thermal acceptability in Singapore. *ASHRAE transactions*, 97(1), 880-886.
- [178] Sansaniwal, S. K., Mathur, J., & Mathur, S. (2020). Review of practices for human thermal comfort in buildings: present and future perspectives. *International Journal of Ambient Energy*, 1-27.
- [179] Steemers, K. (1994). Daylighting Design: Enhancing energy efficiency and visual quality. *Renewable Energy*, 5(5-8), 950-958.
- [180] Song, Y., Mao, F., & Liu, Q. (2019). Human comfort in indoor environment: a review on assessment criteria, data collection, and data analysis methods. *IEEE Access*, 7, 119774-119786.
- [181] Stalder, L. (2015). Sensing human comfort: An inclusive implementation of indoor environmental data collection.
- [182] Della Crociata, S., Simone, A., & Martellotta, F. (2013). Acoustic comfort evaluation for hypermarket workers. *Building and Environment*, 59, 369-378.
- [183] Rocca, M. (2017). Health and well-being in indoor work environments: a review of literature. In 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). IEEE.
- [184] Prakash, P. (2005). Effect of indoor environmental quality on occupant's perception of performance: A comparative study (*Doctoral dissertation*, University of Florida).
- [185] The European Parliament and the Council of the European Union (EU) (2010). Directive 2010/31/EU of The European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), *Official Journal of the European Union*.
- [186] Kanellakis, M., Martinopoulos, G., & Zachariadis, T. (2013). European energy policy—A review. *Energy Policy*, 62, 1020-1030.
- [187] Sağlam, N. G. (2017). A New Approach to Identify Achievable Nearly-Zero Energy Building Targets for Existing Building Retrofits. *Doctoral dissertation*.
- [188] Costa, J. F. W., Amorim, C. N. D., & Silva, J. C. R. (2020). Retrofit guidelines towards the achievement of net-zero energy buildings for office buildings in Brasilia. *Journal of Building Engineering*, 32, 101680.
- [189] Liu, Z., Zhou, Q., Yin, H., Xu, W., Yang, X., & Gao, J. (2021). Indoor environmental quality and energy consumption real-time assessment: A field measurement of a nearly zero-energy building in cold region of China. *Energy and Buildings*, 111093.

- [190] Guo, J., Dong, J., Wang, H., Jiang, Y., & Tao, J. (2021). On-site measurement of the thermal performance of a novel ventilated thermal storage heating floor in a nearly zero energy building. *Building and Environment*, 107993.
- [191] García-Ballano, C. J., Ruiz-Varona, A., & Casas-Villarreal, L. (2020). Parametric-based and automatized GIS application to calculate energy savings of the building envelope in rehabilitated nearly zero energy buildings (nZEB). Case study of Zaragoza, Spain. *Energy and Buildings*, 215, 109922.
- [192] Danza, L., Belussi, L., Barozzi, B., Bellazzi, A., Devitofrancesco, A., Depalma, M., ... & Scrosati, C. (2019). I-ZEB: Design and Development of a ZEB Test-Laboratory for an Integrated Evaluation of Building Technologies. In *IOP Conference Series: Earth and Environmental Science (Vol. 290, No. 1, p. 012092)*. IOP Publishing.
- [193] Khovalyg D., Ongun B. Kazanci, Halvorsen H., Gundlach I., Bahnfleth W. P., Toftum J., Olesen B. J. (2020). Critical review of standards for indoor thermal environment and air quality. *Energy and Buildings. Volume 213*, 109819. ISSN 0378-7788.
- [194] The Republic of Turkey's Ministry of Environment and Urbanization. (2020). Nearly Zero Energy Building (nZEB) Design Guideline Book. Ankara, Turkey. (In Turkish)
- [195] Dilmac, S., & Kesen, N. (2003). A comparison of the new Turkish thermal insulation standard (TS 825), ISO 9164, EN 832, and German regulation. *Energy and Buildings*, 35(2), 161-174.
- [196] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., (ASHRAE). (2019). *ASHRAE Standard 90.1*. Atlanta, GA
- [197] de Dear, R., & Fountain, M. (1994). Field experiments on occupant comfort and office thermal environments in a hot-humid climate.
- [198] Danza, L., Barozzi, B., Bellazzi, A., Belussi, L., Devitofrancesco, A., Ghellere, M., ... & Scrosati, C. (2020). A weighting procedure to analyze the Indoor Environmental Quality of a Zero-Energy Building. *Building and Environment*, 183, 107155.
- [199] Paleologos, K. E., Selim, M. Y., & Mohamed, A. M. O. (2021). Indoor air quality: pollutants, health effects, and regulations. In *Pollution Assessment for Sustainable Practices in Applied Sciences and Engineering (pp. 405-489)*. Butterworth-Heinemann.
- [200] Megahed, N. A., & Ghoneim, E. M. (2020). Indoor Air Quality: Rethinking rules of building design strategies in post-pandemic architecture. *Environmental Research*, 110471.
- [201] Cortiços, N. D., & Duarte, C. C. (2021). COVID-19: the impact on US high-rise office buildings' energy efficiency. *Energy and Buildings*, 111180.

VITA

Emine Şen received her bachelor's degree in Architecture with a full scholarship from Ozyegin University as a high-honor student in June 2019. In September 2019, she started her master's degree in Architecture with a full scholarship at Ozyegin University. Meanwhile, she continued her undergraduate studies in Architecture at the University of Pécs for one semester, and she has graduated from the Business Administration program at Anadolu University in 2020.

In her professional experience, she has been a teaching assistant in various undergraduate and graduate courses of Environmental Control and Design, Building Systems, Energy Efficiency In Urban And Building Scale since September 2020. Alongside her master's studies, she participated as a research student in continuing international and national participatory research projects of the Building Materials and Physics Laboratory at Ozyegin University.

She has several internships and work experience in architectural and construction firms, including Ronesans Holding, ÇEÇEN Engineering, and projects related to Gold LEED certification approval, TUBITAK competition, integrated and mixed-functional design. Her research interests cover the subjects of indoor environmental quality, integrated design tools, energy efficiency in buildings and urban design, nearly/net-zero energy buildings, and occupant comfort.