NATURAL VENTILATION THROUGH DOUBLE-SKIN FACADES IN TALL BUILDINGS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

SILA DANIK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

FEBRUARY 2014

Approval of the thesis:

NATURAL VENTILATION THROUGH DOUBLE-SKIN FACADES IN TALL BUILDINGS

submitted by **SILA DANIK** in partial fulfillment of the requirements for the degree of **Master of Science in Architecture Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** _______________

Prof. Dr. Güven Arif Sargın
Head of Department, **Architecture** _______________

Prof. Dr. Soofia Tahira Elias-Ozkan
Supervisor, **Architecture Department, METU** _______________

Examining Committee Members:

Prof. Dr. Ömür Bakırer
Architecture Department, METU _______________

Prof. Dr. Soofia Tahira Elias-Ozkan
Architecture Department, METU _______________

Inst. Dr. Berrin Zeytun Çakmaklı
Architecture Department, METU _______________

Asst. Prof. Dr. Ayşegül Tereci
Architecture Department, Konya Karatay University _______________

Asst. Prof. Dr. A. Yağmur Topraklı
Architecture Department, Gazi University _______________

Date: 07.02.2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : SILA DANIK

Signature :

ABSTRACT

NATURAL VENTILATION THROUGH DOUBLE-SKIN FACADES
IN TALL BUILDINGS

Danık, Sıla
M. Sc., Department of Architecture
Supervisor: Prof. Dr. Soofia Tahira Elias-Ozkan

February 2014, 102 pages

Operation costs of buildings are getting higher as more complex systems are used and taller buildings are built. This issue has become more significant over the past few decades, having led to much research on less costly, more environment-friendly and energy-efficient techniques and technologies. Mechanical ventilation is one of the most critical and expensive parts of the operational systems especially in tall buildings, yet there are alternative ways to be provided to reduce our dependence on it. One of such technologies is the “double-skin facade” which promotes natural ventilation, reducing the energy consumption and eliminating the possible drawbacks of mechanical ventilation.

This study aimed to examine the natural ventilation performance of double-skin facades in high-rise buildings and their role in creating environments in accordance with the occupant comfort requirements. After providing relevant information on the subject, a case study which is a tall building with a double facade entirely ventilated by natural means was presented and the efficiency of the adopted ventilation strategy was analyzed by collecting data related to occupant comfort. According to the results derived from the measurements, it was concluded that natural ventilation provided by double-skin facades is capable of satisfying acceptable conditions on its own, even though the application of mechanical ventilation might be inevitable in some cases.

Keywords: Double-Skin Facade, Double Facade, Natural Ventilation, Occupant Comfort, Tall Buildings

ÖZ

YÜKSEK BİNALARDA ÇİFT KABUKLU CEPHELER ARACILIĞI İLE DOĞAL HAVALANDIRMA

Danık, Sıla
Yüksek Lisans, Mimarlık Bölümü
Tez Yöneticisi: Prof. Dr. Soofia Tahira Elias-Ozkan

Şubat 2014, 102 sayfa

Binaların kullanımına bağlı masraflar, daha karmaşık sistemlerin kullanılması ve daha yüksek binaların inşa edilmesi ile birlikte artmaktadır. Bu konu son dönemlerde daha önemli hale gelmiş, daha düşük maliyetli, daha çevre dostu ve enerji etkin teknik ve teknolojiler üzerine birçok araştırma yapılmasında etkili olmuştur. Mekanik havalandırma, özellikle yüksek binalarda, kullanım ile ilgili sistemlerin en kritik ve en pahalı parçalarından biri olsa bile, ona olan bağımlılığımızı azaltmak için sunulabilecek alternatif yollar vardır. Bu teknolojilerden biri, doğal havalandırmayı destekleyip enerji tüketimini azaltan ve mekanik havalandırmanın olası dezavantajlarını ortadan kaldıran “çift kabuklu cephe”dir.

Bu çalışma, yüksek binalardaki çift kabuklu cephelerin doğal havalandırma performansını ve kullanıcı konfor koşullarına uygun ortamlar oluşturulmasındaki rolünü irdelemeyi amaçlamıştır. Konuyla ilgili bilgi verildikten sonra, çift cephesi sadece doğal yollarla havalandırılan bir yüksek bina vaka analizi olarak sunulmuş ve uygulanan havalandırma stratejisinin yeterliliği kullanıcı konforuyla ilişkili veri toplanarak incelenmiştir. Ölçümlerden elde edilen sonuçlara göre, bazı örneklerde mekanik havalandırma kullanımı kaçınılmaz olsa da, çift kabuklu cephelerle sağlanan doğal havalandırmanın uygun koşulları tek başına yerine getirebilecek yeterlilikte olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Çift Kabuklu Cephe, Çift Cephe, Doğal Havalandırma, Kullanıcı Konforu, Yüksek Binalar

To My Beloved Father

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LIST OF ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide
DL	Data logger
HVAC	Heating, ventilating, and air conditioning
IAQ	Indoor air quality
MRT	Mean radiant temperature
RH	Relative humidity

CHAPTER 1

INTRODUCTION

This study discusses the natural ventilation efficiency of double-skin facades in tall buildings. The argument and objectives of the study are presented in this chapter together with the research procedure and disposition of the material present in the following chapters.

1.1 Argument

There was an increased interest in energy savings and environmental protection as a reaction to the oil crisis emerged in 1973. These environmental issues gave rise to many discussions in the field of solar architecture as well as many others. Parallel to this, in the U.S. and Europe, there was a growing awareness of the importance of the building facades with good physical properties, of the potential of the passive use of insulation, and of the role played by variability in ventilation and sunshading. Encouraged by those developments, improvements were accelerated in the building materials industry, particularly in the field of glass technology, paving the way for double-skin facades.

Having originated from the traditional box-type window, which has a thermal buffer with glazed skins, a double-skin facade is a system consisting of two skins placed in such a way that air flows in the intermediate cavity. In general, double-skin facades are appropriate when buildings are subject to great external noise and wind loads. This mostly applies to high-rise structures. High velocity of the wind at the upper floors does not allow natural ventilation if a building has only one skin; hence, if the building is to be naturally ventilated via the windows for as great part of the year as possible, the double-skin construction offers distinct advantages in practice. Moreover, free ventilation in combination with increased sound insulation is a clearly evident way of saving energy.

Today especially in Europe, occupants are increasingly coming to accept natural ventilation concepts. This phenomenon may be seen as a reaction to wrongly dimensioned and badly maintained HVAC systems, inadequate ventilation, and poor indoor air quality, which are frequently named as the main causes of the "sick building syndrome."

Along with the functional qualities accepted by the majority, experts greatly differ in their assessment of the economic viability of double facades. The crucial question is whether the savings obtained by the use of a double-skin facade can compensate for the high investment cost of the facade. Investigations of this aspect mostly fail to provide detailed conclusions, because there are an immense number of parameters changing from region to region and from building to building. Nevertheless, it is a valid statement that a double-skin facade reduces the operation costs of a building with the reduction of energy consumption it provides.

The argument of this study is that natural ventilation promoted by double-skin facades provides efficient air circulation in tall buildings. Double facades offer not only natural ventilation but also noise and wind protection, improving occupants' comfort levels. It is foreseen fundamental to examine the case of double-skin facades in detail to be able to comprehend whether or not they are effective in terms of natural ventilation.

1.2 Objectives

This study aims to examine whether natural ventilation provided by double-skin facades performs well or not. Following the argument, objectives are defined to achieve a better understanding about the contribution of double-skin facades to efficient ventilation of high-rise buildings. Five objectives are therefore determined and listed below:

• To study the types and components of double-skin facades.
• To understand the basic principles of aerophysics and factors affecting the natural ventilation performance of double-skin facades.
• To examine the occupant comfort requirements and role of air flow in adjusting thermally acceptable environments.
• To analyze the functional efficiency of free ventilation promoted by double facades in high-rise buildings.
• To observe a case study to comprehend the outcomes of ventilating a double-skin facade in a tall building by natural means and to inspect the compliance of the conditions to the comfort requirements.

1.3 Procedure

In the first phase, literature is reviewed in detail to gain comprehensive information about the subject matter and to introduce the topic for which there is a growing tendency. Sources related to double facades, aerophysics, ventilation and occupant comfort are examined and relevant parts are explicated within the study.

Information about the case study, Sapphire Tower in Istanbul, is gathered in the second phase. Architectural drawings and photos are acquired from Tabanlıoğlu Architects and, mechanical drawings and technical details from GN Engineering. All documents obtained are used to analyze the building and its double facade.

In the third phase, measurements are made in order to be able to evaluate the natural ventilation efficiency in the facade. Data related to various environmental conditions is collected in the facade cavity and used to prepare charts to illustrate the situation.

In the fourth and last phase, recorded data is compared with the available requirements. Compliance of the results is analyzed to come to a conclusion about the effectiveness of the current ventilation method.

1.4 Disposition

This report is composed of four chapters. The first chapter is the "Introduction" in which the subject matter of the study, double-skin facades, is presented together with the argument and the problem definition is given. Objectives and procedure are also provided in this chapter.

"Literature Review" is the second chapter of this study and extensive information about double-skin facades is given in this chapter. Firstly, general features of double-skin facades are clarified. Then, factors related to aerophysics and natural ventilation of double-skin facades are studied. Finally, requirements for occupant comfort are examined.

The third chapter is the "Case Study: Istanbul Sapphire." In this chapter, material of the study, which is a case study, is presented and the reasons for selecting that particular case are set forth. Following the material, method of analysis is explained and necessary instruments are introduced.

The fourth chapter is the "Results and Discussions" in which the results of the measurements are explained. All data logged is illustrated by means of charts and comparisons between the floors are discussed.

“Conclusions” is the fifth and last chapter in which a summary of the study is provided and outcomes of the research are explained. Moreover, the conclusion derived from the measurements and analyses is provided.

CHAPTER 2

LITERATURE REVIEW

Comprehensive information about the subject matter is provided in this chapter. Evolution, types and components of double-skin facades, basic principles of aerophysics and natural ventilation, contribution of double-skin facades to the HVAC strategy, comfort requirements, and tall buildings with double-skin facades are examined.

2.1 The evolution of facade construction

The evolution of facade construction, as Oesterle, Lieb, Lutz & Heusler (2001) state, started when the traditional single-glazed casement was supplemented by a glazed outer window, which is called “box-type window.” The same authors further explain that following this development, double-glazed window was introduced in the late 1950s, insulating double-glazing elements and thermally divided metal and plastic frames were developed in the 1970s and special types of neutral sunscreen glass with a high degree of selectivity came into the market in the 1990s.

The double-skin facades appeared as a result of adopting old tradition of creating a thermal buffer with glazed skins, as expressed by Oesterle, *et al.* (2001). The authors further mention that double-skin facades may be constructed as sophisticated building enclosures that can adapt to environmental conditions.

2.2 Double-skin facades

Double-skin facade is an additional glass skin on the outside surface of the building used as a tool to apply controlled natural ventilation for the building by stimulating the use of the solar and wind energy which may reduce the energy consumption of the building about 40-60% (Stec & van Paassen, 2003). In this chapter, detailed information about double-skin facades is provided.

2.21 Double-skin facade concept

There are different definitions of double-skin facades by a number of authors, and some of them will be given in this part to develop an overall concept of double-skin facades.

According to the source book written by the authors Loncour, Deneyer, Blasco, Flamant & Wouters (2004) for the Belgian Building Research Institute (BBRI), a double-skin facade is, “a facade covering one or several storeys constructed with multiple glazed skins. The skins can be air tighten or not. In this kind of facade, the air cavity situated between the skins is naturally or mechanically ventilated.”

Boake, Harrison, Collins, Balbaa, Chatham, Lee & Bohren (n.d.) explain double-skin facade as, “essentially a pair of glass ‘skins’ separated by an air corridor. The main layer of glass is usually insulating. The air space between the layers of glass acts as insulation against temperature extremes, winds, and sound.”

Arons (2000) defines double-skin facade as, “a façade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a twin skin.”

Uuttu (2001) describes double-skin facade as, “a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several metres. The glass skins may stretch over an entire structure or a portion of it.”

Another author defines double-skin facade as follows:

> *The term “double-skin façade” refers to an arrangement with a glass skin in front of the actual building façade. Solar control devices are placed in the cavity between these two skins, which protects them from the influences of the weather and air pollution a factor of particular importance in high rise buildings or ones situated in the vicinity of busy roads.* (Compagno, 1999)

2.22 Types of construction

The double-skin facade systems can be categorized by the type of construction, the origin, destination and type of the air flow in the cavity, *etc.* as mentioned by Poirazis (2004). Among these categories, type of construction is the most popular one when the literature is reviewed; hence this kind of classification is emphasized in this part.

The types indicated by Oesterle, *et al.* (2001), being very similar to the approach of Lee, Selkowitz, Bazjanac, Inkarojrit & Kohler (2002), are listed below:

• Box windows: In this case, horizontal and vertical partitioning divides the facade into smaller and independent boxes (Figure 2.1).

• Shaft-box facades: In this case, a set of box window elements are placed in the facade. These elements are connected via vertical shafts situated in the facade. These shafts ensure an increased stack effect (Figure 2.2).

• Corridor facades: Horizontal partitioning is realized for acoustical, fire security or ventilation reasons (Figure 2.3).

• Multistory facades: In this case, no horizontal or vertical partitioning exists between the two skins. The air cavity ventilation is realized via large openings near the floor and the roof of the building (Figure 2.4).

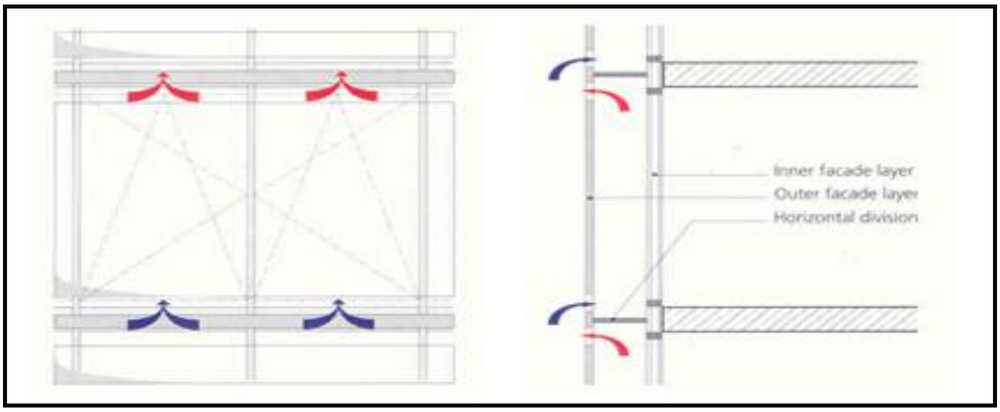


Figure 2.1 Elevation and section of a box window (Source: Oesterle, *et al.*, 2001)

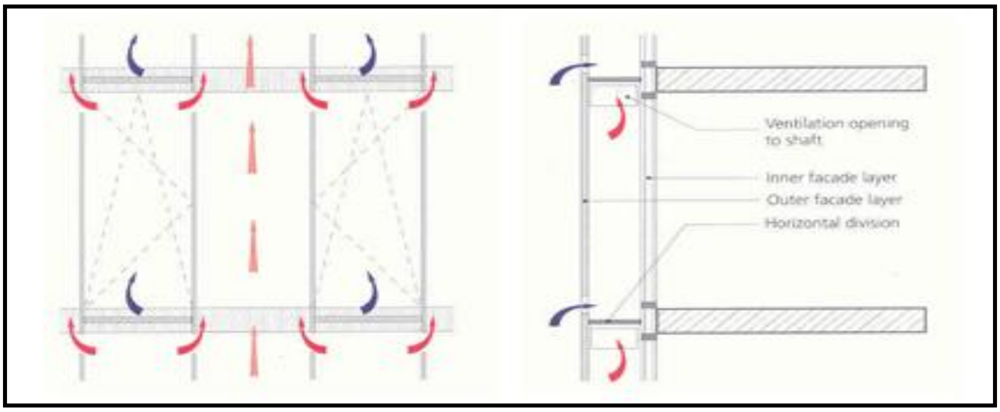


Figure 2.2 Elevation and section of a shaft-box facade (Source: Oesterle, *et al.*, 2001)

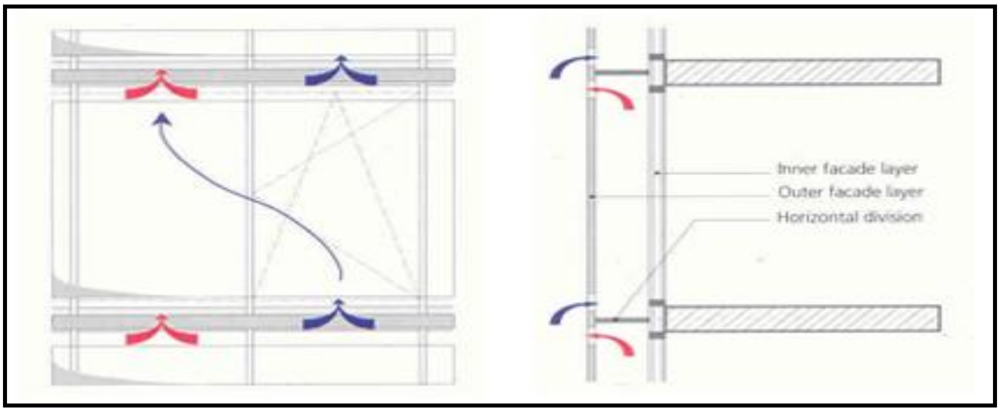


Figure 2.3 Elevation and section of a corridor facade (Source: Oesterle, *et al.*, 2001)

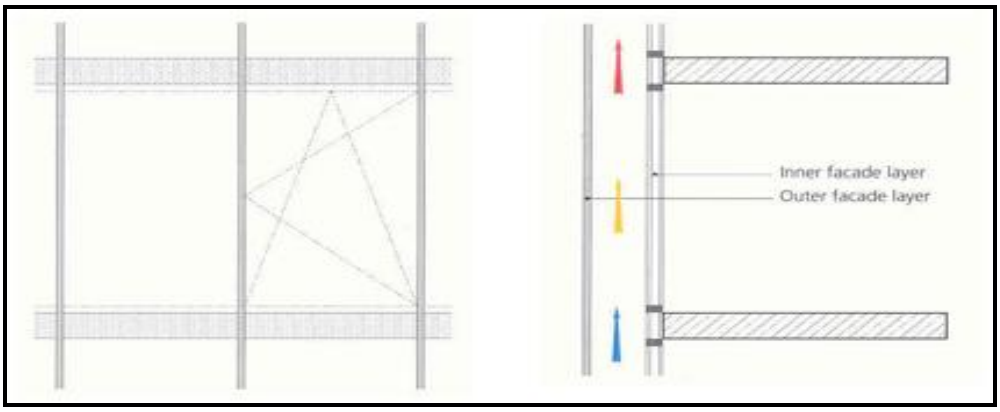


Figure 2.4 Elevation and section of a multistory facade (Source: Oesterle, *et al.*, 2001)

Uuttu (2001) classifies double-skin facade systems in a similar way described below:

• Building-high double-skin facades: In this case, the cavity is not separated at each storey; instead it extends over the whole height of the building.
• Storey-high double-skin facades: This type of facade consists of air channels separated horizontally at each intermediate floor.

• Box double-skin facades: This facade is a stockwise ventilated facade with horizontal partitions at each storey and vertical partitions on each window.
• Shaft facades: This type is a combination of a building-high double-skin facade and a storey-high double-skin facade.

2.23 Types of facades

Oesterle, *et al.* (2001) mention that determining the architectural form of the windows and facade has an effect on the construction down to the very details, thus different facade types are listed below:

• Solid facades with conventional openings
• Strip-window facades
• Curtain-wall facades

2.24 Components of double-skin facades

Essential components of a double-skin facade system are the air-intakes and extracts, inner and outer facade, and the facade cavity; these are explained in detail under the following headings.

i. Air-intakes and extracts

Oesterle, *et al.* (2001) describes air-intakes as openings in the outer facade where external air enters the facade cavity, and usually, the height of these openings are smaller than the depth of this cavity, causing an initial peak velocity together with a corresponding pressure loss. While designing air-intakes, the authors further explain, protection against the weather and birds/insects is necessary and should be kept in mind, and, for example, it may be provided with openings having an appropriate aerodynamic form and application of wires or nets over them.

Air-extracts, on the other hand, are described by Lee, *et al.* (2002) as the openings through where the air which circulated in the facade and excess heat are drawn off. Oesterle, *et al.* (2001) indicate that the principles applying to air-intakes also apply to air-extracts, but an additional factor, namely the deflections to which the airstream is subject, has to be considered.

Another author mentions the importance of good ventilation and its relevance with openings:

> *The air exchange between the environment and the cavity is depending on the wind pressure conditions on the building's skin, the stack effect and the discharge coefficient of the openings. These vents can either be left open all the time (passive systems), or opened by hand or by machine (active systems).* (Compagno, 1999)

ii. Inner and outer facade

Hensen, Barták & Drkal (2002) mention that the outer facade is used to block/slow the wind in, and allow interior openings and access to fresh air without the associated noise or turbulence. Windows on the inner facade, as Straube & van Straaten (n.d.) express, can be opened, while ventilation openings in the outer facade moderate excess temperatures within the facade. They further explain that the effectiveness of the inner facade in terms of its ventilating function depends on the opening movement of the windows (the actual free cross-section in an open position) and the distribution of the opening areas over the height (Figure 2.5).

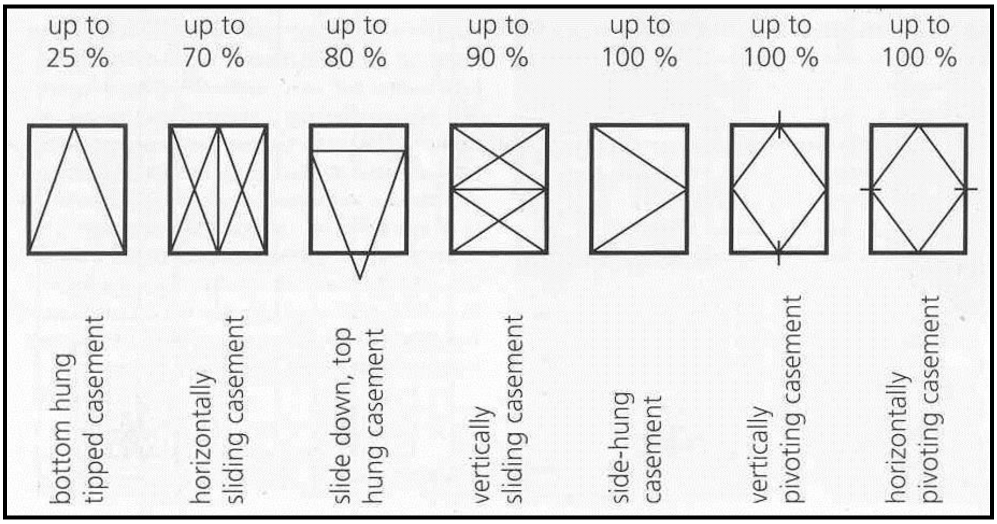


Figure 2.5 Comparison between various casement opening types in the inner facade and their relative ventilating effectiveness (Source: Oesterle, *et al.*, 2001)

iii. Facade cavity

Uuttu (2001) defines a facade cavity, also called “buffer zone” or “intermediate space,” as the area formed by the two separate glass skins in double-skin facades whose width varies from 20 cm up to several meters. The author further explains that the cavities can be equipped with a service platform, which enables walking in the cavity for cleaning and maintenance purposes, and sunblinds can be placed inside the cavity, protected from rain and snow.

The most crucial part of a double-skin facade is designing the facade cavity, as Boake, *et al.* (n.d.) bring out, and there is a variety of types such that the cavity can be continuous vertically (undivided) across the entire facade, divided by storey (best for fire protection, heat and sound transmission), or divided vertically into bays to optimize the stack effect. The types of the facade cavity are closely interconnected to the construction types of double-skin facades, thus it is possible to state that the approaches of Lee, *et al.* (2002), Oesterle, *et al.* (2001) and Uuttu (2001) explained in the part 2.22 can be said to imply the cavity types, as well.

2.3 Ventilation of double-skin facades

Natural ventilation performance of double-skin facades is the main attraction of this literature survey; hence, the basics of this subject, particularly aerophysics, and items contributing to it are provided in this chapter.

2.31 Aerophysics

According to Oesterle, *et al.* (2001), aerophysics, “involves all questions relating to the flow of air toward, around and within buildings. It is an omnibus term like constructional physics, since it covers various aspects such as aerodynamics and thermodynamics.” The same authors further discuss that aerophysics, although many are generally unfamiliar with the term in buildings, has played a role in construction for a number of years. To create a better understanding about this term/discipline, its basic principles and requirements are explained in this part.

i. Basic principles

Airstreams and ventilation of the facade cavity are the interest points of this section. Definition given by Oesterle, *et al.* (2001) is that an airstream is simply the movement of air currents caused by the pressure differences, that is, air flows from a space with high pressure to one with low pressure if the two are linked. Three main causes for the airstreams in the building context emphasized in the same source are listed below:

• Pressure differences caused by mechanical operations
• Pressure differences caused by thermal buoyancy
• Pressure differences caused by the action of wind

Among these, thermal buoyancy is examined in more detail since it provides a base for the working principle of double-skin facades, as the authors imply. They explain that cooler and heavier exterior air causes excess pressure at the bottom, forcing its way into the facade cavity where the air is warmer and lighter as a result of the insolation, and this warmer air rises and causes excess pressure at the top where it is then ejected – this pressure difference between bottom and top of the facade creates the thermal buoyancy phenomenon.

Since the difference between room and external temperatures is a motive force for the ventilation, although excessive heat gains have to be avoided, the maximum excess temperature of the exhaust air is often defined as a criterion, as Oesterle, *et al.* (2001) imply. They further explain that in determining the maximum excess temperature, the temperatures measured at head level within an accessible facade cavity and at about half the height of the windows (or above the height of the air-intakes in the inner facade) are more important than the temperature of the exhaust air.

ii. Basic requirements

Aerophysical requirements, in the case of double-skin facades, are mainly related with the “strength” of the air flow, which is described by Oesterle, *et al.* (2001), in terms of the volume of air needed for ventilation and speed of the airstream. They explain that there are certain parameters and boundary values for the provision of adequate natural ventilation of a room, and exemplify some of these requirements as follows:

• In offices where the ventilation is from one side, the minimum opening area (for both air-intakes and extracts) in the facade should be 2% of the floor area, and the maximum room depth can also be set at two and a half times the clear room height.
• Where natural ventilation is required to function as intermittent ventilation for a large part of the year, a high air-change rate (the relationship between the volume of air supplied per hour and the volume of the relevant space) should be possible when the inner facade is open.

iii. Wind characteristics

Wind can have a major influence on air currents in and around buildings, and this is explained by Oesterle, *et al.* (2001) as the fact that the building forms an obstacle to the airstream. The authors further mention that particularly high-rise buildings stand in wind's way and the portion of the airstream that encounters a building is dammed up in front of it, thereby creating a state of excess pressure. Moreover, as a result of the flow of air around the building, significant pressure differences are expected especially at the corners.

a. Wind loads

Oesterle, *et al.* (2001) imply that the wind loads on a high-rise building play an important role and they are mainly of two types: stationary loads that act on the entire building, and instationary loads resulting from gusts. A gust is:

> *… an increase of wind speed that is limited in place and time. It will usually occur in conjunction with a slight change of wind direction as well. Since a gust is caused by turbulence, there will always be a brief reduction of the wind speed immediately before or after the gust. Overall, therefore, an even flow of wind will be accompanied by a constant fluctuation of wind speeds and directions measured at any one location.* (Oesterle, *et al.*, 2001)

The same authors also mention that instationary loads are significant in dimensioning the facade and they exhibit many special characteristics in the context of double-skin facades. Furthermore, the influences of the surroundings manifest themselves through instationary loads, affecting especially other high-rise buildings within a radius of up to several kilometers.

Oesterle, *et al.* (2001) express that the air flow around high-rise buildings is affected by the plan forms of them and it consists of the following elements:

• Horseshoe vortex: Wind on the windward face applies a downward pressure and curls round the foot of the building on both sides. The wind energy from the upper air strata is drawn down to ground level, resulting in a noticeable increase in the wind speed.

• Air flow around the plan form: When the relation of the height to the cross section is considered, the airstream around high-rise buildings is virtually two-dimensional over the middle section. Where the plan form is angular, a breakaway of the airstream occurs behind the corners that are set at right angles to the wind, and where the plan form is circular, the points of separation depend on the air flow speed and the radius of the curve.

• Topflow: A three-dimensional airstream is developed at the top of a high-rise building where a large part of the wind flows upward over the roof, similar to a horseshoe vortex. Over flat roofs, the topflow results in large-scale turbulence with one positive aspect that the wind forces have almost no effect on the flat roof itself. The form of topflow has a major influence on the layout of the necessary chimney stacks and air-extract heads, which require steady air flow conditions.

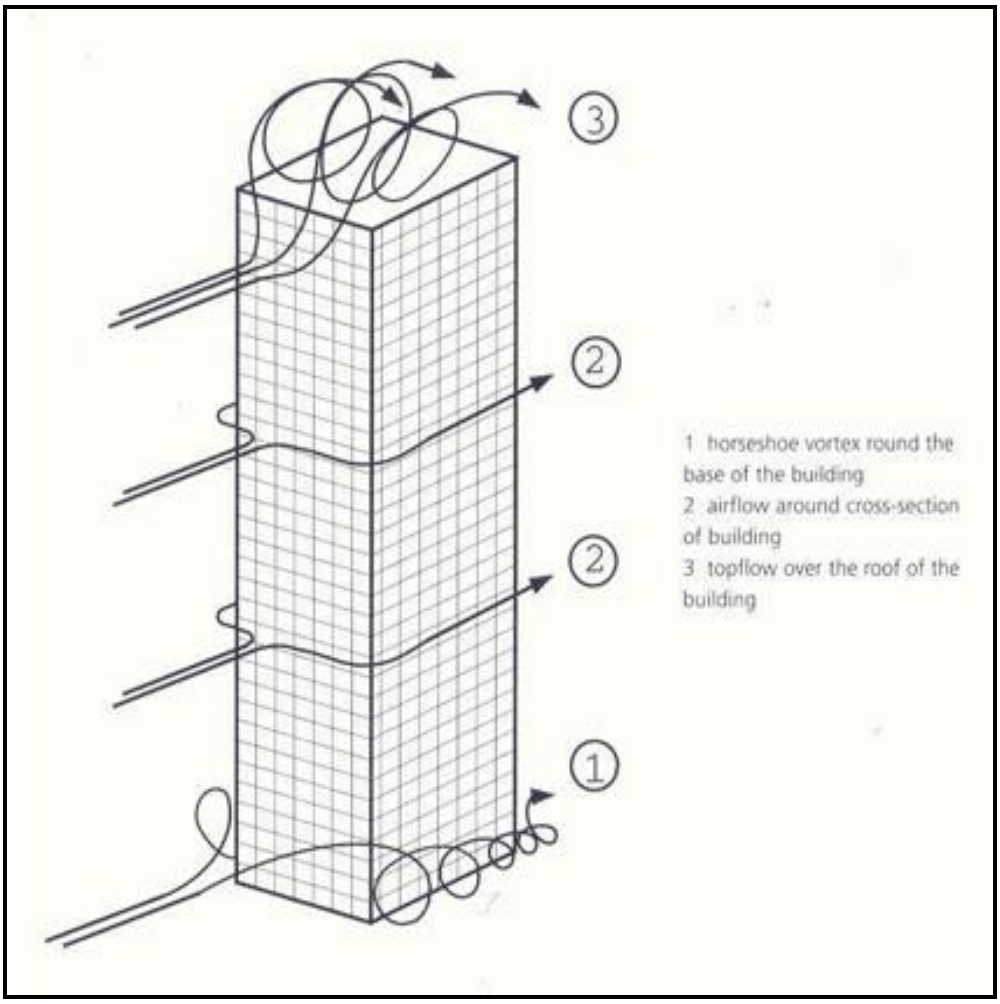


Figure 2.6 Diagram of air flow around high-rise buildings (Source: Oesterle, *et al.*, 2001)

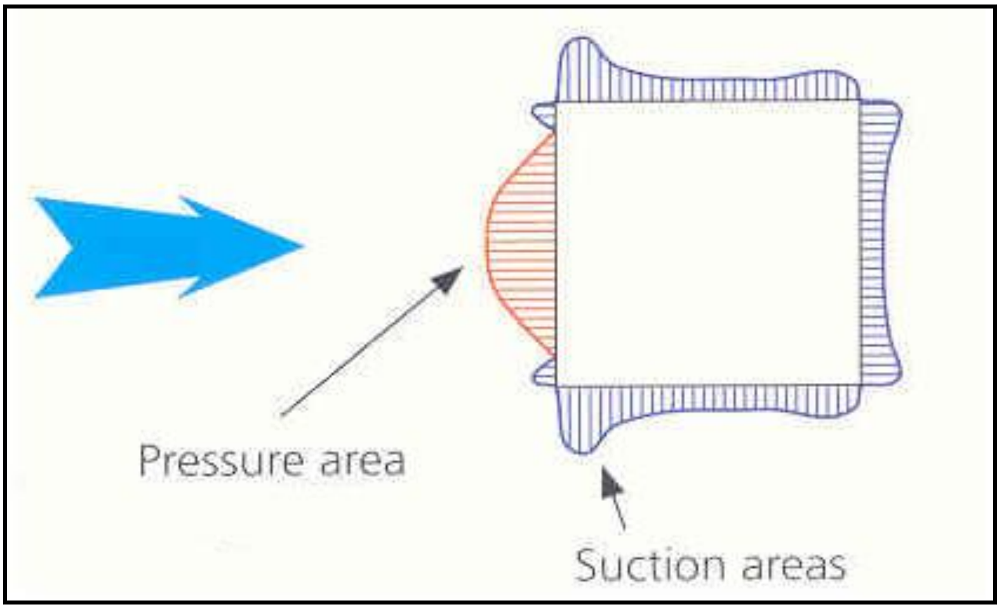


Figure 2.7 Qualitative pressure distribution around a high-rise building with a square plan, where the wind direction is at right angles to one side (Source: Oesterle, *et al.*, 2001)

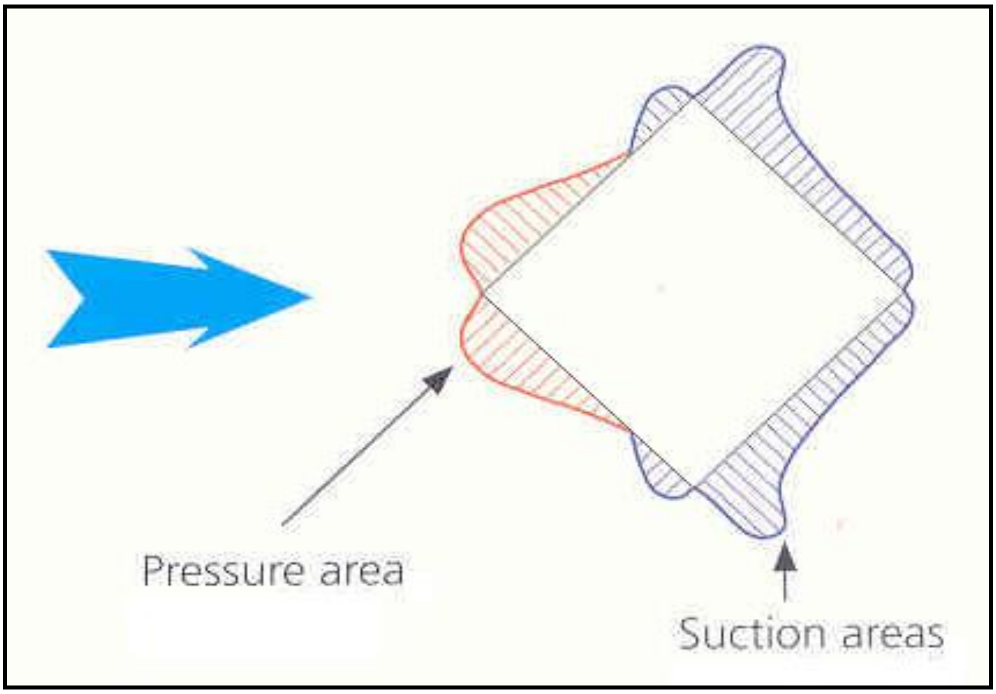


Figure 2.8 Qualitative pressure distribution around a high-rise building with a square plan, where the wind direction is on the diagonal (Source: Oesterle, *et al.*, 2001)

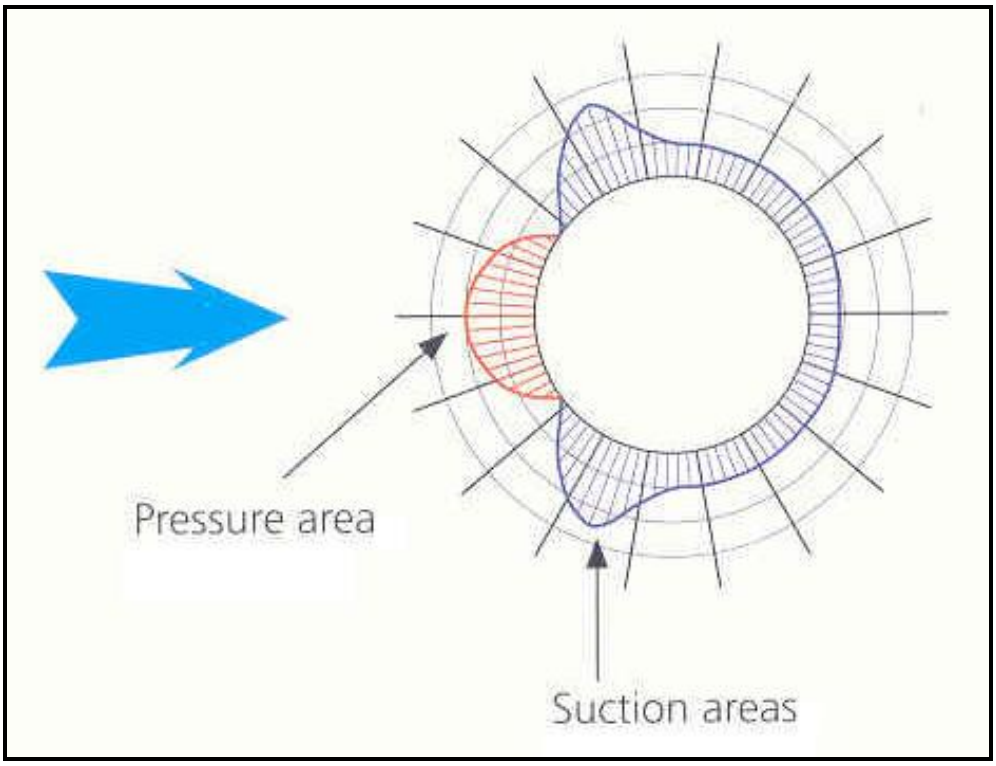


Figure 2.9 Qualitative pressure distribution around a cylindrical high-rise building (Source: Oesterle, *et al.*, 2001)

b. Drafts

Two strategies exist to prevent the wind pressures around high-rise buildings resulting in unwanted drafts internally when the windows are open:

> *• The layout can be divided in such a way that the sequences of rooms are clearly oriented to either the windward or the leeward side of the building. In this case, the two sides should be separated from each other by self-closing, tightly sealing doors or, even better, by air locks with two sets of doors. The system will have to function for wind from all directions.*
> *• A facade with an intermediate buffer space can be erected around the entire building. By creating a by-pass airstream through the intermediate space, a state of pressure equilibrium can be achieved on the different sides of the building, thereby*

eliminating pressure differences (to a large extent), so that they will have no effect in the internal spaces. (Oesterle, *et al.*, 2001)

In some cases, these strategies are the only ways to limit undesirable effects of wind within the rooms, as Oesterle, *et al.* (2001) bring out. Furthermore, a good windward/leeward separation can considerably reduce wind-induced drafts where natural window ventilation is foreseen (Figure 2.10).

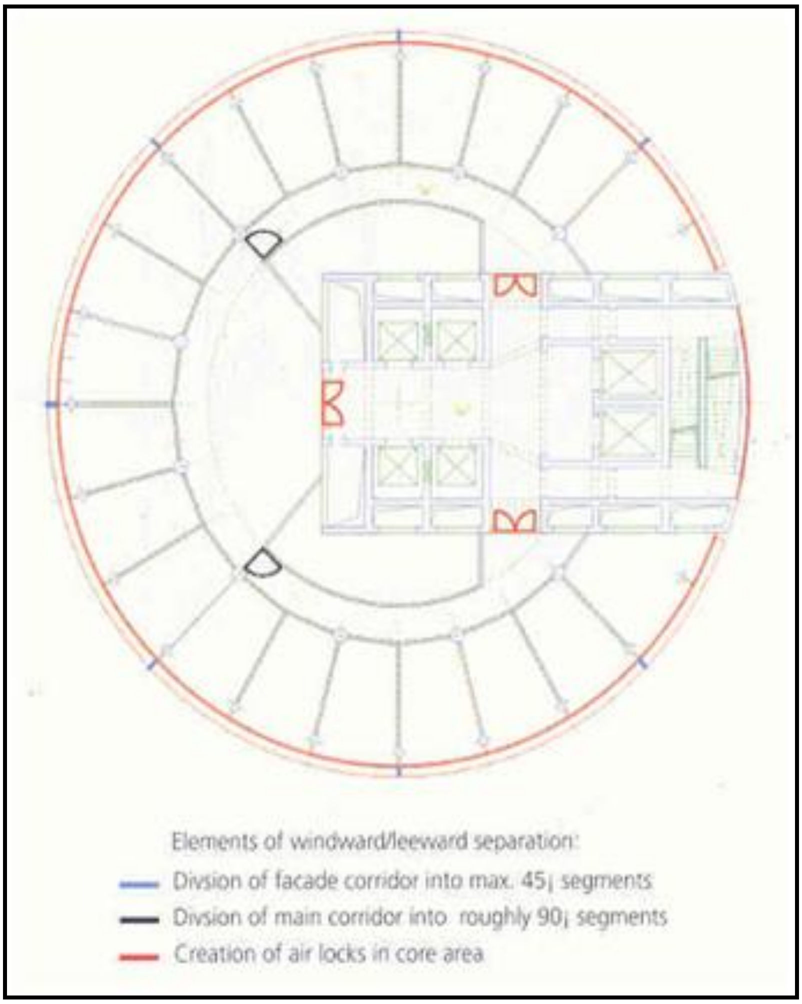


Figure 2.10 Example of measures to achieve a windward/leeward separation by closing off compartments in the layout and in the facade: Business Tower, Nuremberg (Source: Oesterle, *et al.*, 2001)

2.32 Natural ventilation

One of the main advantages of the double-skin facade systems is that they can allow natural ventilation, and, if designed well, the natural ventilation can lead to reduction of energy consumption during the occupation stage and improve the comfort of the occupants (Boake, *et al.*, n.d.).

Different types of facades can be applied in different climates, orientations, locations and building types in order to provide fresh air before and during the working hours and these types can be crucial for temperatures, the air velocity and the quality of the introduced air inside the building (Tenhunen, Lintula, Lehtinen, Lehtovaara, Viljanen, Kesti & Mäkeläinen, n.d.).

i. Natural ventilation performance of double-skin facades

In this part, items affecting the natural ventilation performance of double-skin facades, such as wind, depth of facade cavity, *etc.* are discussed.

a. Wind

Awbi (2003) describes wind as the most significant component of the driving force in natural ventilation, particularly in hot seasons. As Oesterle, *et al.* (2001) define, wind is generated by thermal buoyancy in the areas of high and low pressure, and it simply balances these different pressures.

b. Opening sizes of air-intakes and extracts

Oesterle, *et al.* (2001) express that the removal of heat from a room or from the facade cavity can be a major criterion, especially on hot days, in dimensioning the air-intakes and extracts. The same authors suggest that, if possible, room temperatures should remain below the peak external temperatures, and the temperatures in the facade cavity should not be much above this level.

To be able to calculate the sizes of the openings necessary for sufficient volume of air to circulate, the pressure equilibrium between thermal uplift and pressure losses is established and after using the relevant formulae it can be said that the area of the air-intakes and extracts should be more than 1 m^2, respectively (Oesterle, *et al.*, 2001).

c. Depth of facade cavity

Poirazis (2004) mentions that the depth of facade cavity has a great amount of influence on the air velocity and type of flow inside the cavity (for both mechanical and natural ventilation).

Another source introduces briefly the concept of different cavity depths and describes its influence on the air temperatures inside the cavity:

> *Dimensions of the façade together with the openings determine the flow through the façade. The thinner cavity the higher flow resistance and the smaller flow through the cavity. On the other hand the thinner cavity the more intensive convection heat transfer and higher growth of air temperature in the cavity. These lead to the following conclusions:*
>
> *1. In the cold period it is more suitable to use thin cavities to limit the flow and increase the cavity temperature.*

> *2. In the hot period the double skin façade should work as a screen for the heat gains from radiation and conduction. It is difficult to claim in general if the thin or deep cavities will perform better because in one case the cavity temperature and in other case temperature of the blinds will be higher.* (Stec & van Paassen, 2003)

Similarly, Oesterle, *et al.* (2001) present an extensive description of the function and the air flow of the cavity in relation with constructional parameters. The authors mention that only when the depth of facade cavity is relatively shallow (less than 40 cm) significant pressure losses are likely to occur; otherwise, the cavity offers no major resistance to the air flow.

ii. Contribution of double-skin facades to the HVAC strategy

As Stec & van Paassen (2003) describe, an HVAC system can be used in the following ways in a double-skin facade:

• Full HVAC system: Double-skin facade is not a part of the HVAC system which can result in high energy use. On the other hand, the user can select controlled mechanically conditions inside or natural ventilation with the use of double-skin facade.
• Limited HVAC system: Double-skin facade contributes partly to the HVAC system or plays the major role in creating the right indoor climate.
• No HVAC: Double-skin facade fulfills all the requirements of an HVAC system. This is the ideal case which can lead to low energy use.

a. Attainable air change with natural ventilation

According to Oesterle, *et al.* (2001), the main forces activating natural ventilation are defined as wind and thermal uplift; so, weather conditions play an important role in the effectiveness of a double-skin facade. The authors give an example that especially on hot days with windless conditions, the air flow volume necessary for the removal of hot air from a facade cavity exposed to insolation is considerably greater than that required for room ventilation.

b. Non-omittable amount of mechanical ventilation

The question if the HVAC system can be totally or partially omitted in a building with a double-skin facade or not is examined by Oesterle, *et al.* (2001) and they concluded that there is no general rule to be confirmed in this sense since any such removal or reduction depends on many constraints that apply in each individual case. The authors indicate that there are, although rare, successful examples of buildings with double-skin facades are ventilated entirely by natural means while unsuccessful examples of the same application are many more where the lack of mechanical ventilation and cooling have led to serious complaints from users about overheating and subjective feeling to be exposed to an inadequate supply of fresh air in the occupied rooms. They also explain the conditions have to be met in order to eliminate mechanical plants in buildings with double-skin facades, based on experience gained from a few exceptional cases:

- Adequate sound insolation against external noise should be provided even where windows are opened for ventilation purposes.
- Statutory guidelines, which cover the provision of adequate opening areas in the facade and impose limitations on the depth of rooms, for workplaces have to be met.
- The overall maximum cooling load should not exceed about 35-40 W/m^2 in office spaces. This means that the proportion of facade glazing in relation to the overall area of the facade may have to be limited.
- The double-skin facade should be constructed in such a way that contact with the outdoor realm is immediately perceptible.

• Outside the heating period, the inner facade layer should be opened at night to allow heat to escape from the rooms.

2.4 Occupant comfort

Comfort, as Bradshaw (2006) defines, is the absence of discomfort. The author explains that occupant comfort is ensured in an environment where conditions do not cause inconvenience by insufficient or excess heat, humidity, air flow, *etc.* There are many factors that affect occupant comfort in a positive or negative way. ASHRAE (“Standard 55,” 2004) addresses them as environmental and personal factors: temperature, humidity, thermal radiation, air flow, odors, dust, acoustics, lighting, *etc.* are the environmental factors and, activity level and clothing are the personal factors.

2.41 Basic requirements

Since this study concentrates on the natural ventilation performance of double-skin facades, factors such as air flow, temperature and humidity, which affect each other and are interrelated in the case of ventilation, are analyzed in detail while some others are briefly mentioned and requirements to be met in order to satisfy occupant comfort are explained in this part.

i. Activity level

ASHRAE (“Standard 55,” 2004) describes metabolic rate as, “the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface.” This rate is revealed in “met” units and a met, as defined by the same standard, is the amount of heat produced per unit surface area of an average sedentary person, and any metabolic rate can be derived from this basic unit.

Metabolic rate varies with age, gender, body weight and surface area, surrounding environmental conditions and most simply, with activity level (Bradshaw, 2006). The author suggests that activity levels during certain physical activities should be determined in order to designate comfort conditions as human body produces heat in proportion to the level of exercise (Table 2.1).

Table 2.1 Metabolic rate at different typical activities (Source: Bradshaw, 2006)

Activity	Metabolic Rate in Met Units	Activity	Metabolic Rate in Met Units
Resting		Miscellaneous Work	
Sleeping	0.7	Watch-repairing, seated	1.1
Reclining	0.8	Lifting/packing	1.2 to 2.4
Seated, reading	0.9	Garage work (e.g., replacing tires, raising cars by jack)	2.2 to 3.0
Office Work			
Seated, writing	1.0	Vehicle Driving	
Seated, typing or talking	1.2 to 1.4	Car	1.5
Seated, filing	1.2	Motorcycle	2.0
Standing, talking	1.2	Heavy vehicle	3.2
Drafting	1.1 to 1.3	Aircraft flying, routine	1.4
Miscellaneous office work	1.1 to 1.3	Instrument landing	1.8
Standing, filing	1.4	Combat flying	2.4
Walking (on Level Ground)		Leisure Activities	
2 mph (0.89 m/s)	2.0	Stream fishing	1.2 to 2.0
3 mph (1.34 m/s)	2.6	Golf, swinging and walking	1.4 to 2.6
4 mph (1.79 m/s)	3.8	Golf, swinging and with golf cart	1.4 to 1.8
Domestic Work		Dancing	2.4 to 4.4
Shopping	1.4 to 1.8	Calisthenics exercise	3.0 to 4.0
Cooking	1.6 to 2.0	Tennis, singles	3.6 to 4.6
House cleaning	2.0 to 3.4	Squash, singles	5.0 to 7.2
Washing by hand and ironing	2.0 to 3.6	Basketball, half court	5.0 to 7.6
Carpentry		Wrestling, competitive or intensive	7.0 to 8.7
Machine sawing, table	1.8 to 2.2		
Sawing by hand	4.0 to 4.8		
Planing by hand	5.6 to 6.4		

ii. Clothing

Bradshaw (2006) puts forth that the amount of clothing, which provides thermal insulation in accordance with its function, has a remarkable impact on occupant comfort. The clothing insulation is described as a "clo" value and a clo is a numerical expression of an ensemble's thermal resistance (ASHRAE, "Standard 55," 2004).

During the summer months, occupants tend to wear lightweight clothes with insulation values ranging from 0.35 to 0.6 clo and, during the winter months, thicker and heavier clothes with insulation values ranging from 0.8 to 1.2 clo (Bradshaw, 2006). The author further argues that indoor temperature range is higher in the summertime than it is in the wintertime when ambient temperature necessary for occupant comfort is lower by means of additional clothing, such that reducing the indoor temperature by approximately 7°C is acceptable if 1.0 clo of insulation is added and, moreover, thermal sensation does not change. Clo values for typical ensembles are listed in Table 2.2.

Table 2.2 Clo values for individual items of clothing (Source: Bradshaw, 2006)

Men		Women	
Clothing	**clo**	**Clothing**	**clo**
Underwear		Underwear	
Sleeveless	0.06	Girdle	0.04
T-shirt	0.09	Bra and panties	0.05
Briefs	0.05	Half slip	0.13
Long underwear, upper	0.10	Full slip	0.19
Long underwear, lower	0.10	Long underwear, upper	0.10
		Long underwear, lower	0.10
Shirt		Blouse	
Light, short sleeve	0.14	Light, long sleeve	0.20
long sleeve	0.22	Heavy, long sleeve	0.29
Heavy, short sleeve	0.25	Dress, light	0.22
long sleeve	0.29	Dress, heavy	0.70
(Plus 5% for tie or turtleneck)			
Vest, light	0.15	Skirt, light	0.10
Vest, heavy	0.29	Skirt, heavy	0.22
Trousers, light	0.26	Slacks, light	0.10
Trousers, heavy	0.32	Slacks, heavy	0.44
		Sweater	
Sweater, light	0.20	Light, sleeveless	0.17
Sweater, heavy	0.37	Heavy, long sleeve	0.37
Jacket, light	0.22	Jacket, light	0.17
Jacket, heavy	0.49	Jacket, heavy	0.37
Socks		Stockings	
Ankle length, thin	0.03	Any length	0.01
thick	0.04	Panty hose	0.01
Knee high	0.10		
Shoes		Shoes	
Sandals	0.02	Sandals	0.02
Oxfords	0.04	Pumps	0.04
Boots	0.08	Boots	0.08
Hat and overcoat	2.00	Hat and overcoat	2.00

iii. Temperature

Temperature, as Bradshaw (2006) states, is the most important factor affecting occupant comfort due to the fact that a narrow range of comfortable temperatures may be provided with no effect of the other factors and this range becomes quite wide by the appropriate combinations of them. Table 2.3 suggests various temperature ranges for summer and winter months and for different types of spaces. Those values may serve as guidelines; nevertheless, other environmental and personal factors should also be taken into consideration owing to the fact that they have a major effect on adjusting appropriate thermal conditions.

Table 2.3 Guideline room air temperatures (Source: Bradshaw, 2006)

Type of Space	°C Summer	°C Winter
Residences, apartments, hotel and motel guest rooms, convalescent homes, offices, conference rooms, classrooms, courtrooms, and hospital patient rooms	23–26	20–22
Theaters, auditoriums, churches, chapels, synagogues, assembly halls, lobbies, and lounges	24–27	21–22
Restaurants, cafeterias, and bars	22–26	20–21
School dining and lunch rooms	24–26	18–21
Ballrooms and dance halls	21–22	18–21
Retail shops and supermarkets	23–27	18–20
Medical operating rooms[a]	20–24	20–24
Medical delivery rooms[a]	21–24	21–24
Medical recovery rooms and nursery units	24	24
Medical intensive care rooms[a]	22–26	22–26
Special medical care nursery units[a]	24–27	24–27
Kitchens and laundries	24–27	18–20
Toilet rooms, service rooms, and corridors	27	20
Bathrooms and shower areas	24–27	21–24
Steam baths	43	43
Warm air baths	49	49
Gymnasiums and exercise rooms	20–22	13–18
Swimming pools	24	24
Locker rooms	24–27	18–20
Children's play rooms	24–26	16–18
Factories and industrial shops	27–29	18–20
Machinery spaces, foundries, boiler shops, and garages	—	10–16
Industrial paint shops	—	24–27

Temperature in question is the air (dry-bulb) temperature of the environment, but there are some other determinants of the thermal comfort of the occupants to be mentioned.

a. Mean radiant temperature

ASHRAE ("Standard 55," 2004) defines mean radiant temperature (MRT) as, "the temperature of a uniform, black enclosure that exchanges the same amount of thermal radiation with the occupant as the actual enclosure." The standard expresses that it may be considered as a spatial average of the temperature of surrounding surfaces weighted by their view factors with respect to the occupant. Bradshaw (2006) gives a similar definition of MRT and adds that occupant comfort is affected by the direction and rate of radiant heat exchange between the occupant and the surrounding enclosure. The author also suggests that the MRT should be between 18 and 27°C for the occupants in the offices.

b. Operative temperature

Description given by ASHRAE ("Standard 55," 2004) is that operative temperature is the uniform temperature of an enclosure that exchanges the same amount of heat by radiation and convection with the occupant as the surrounding surfaces. Another description by the same standard is that operative temperature is the average of the air temperature and MRT weighted by the convection heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant, respectively. The standard further clarifies that operative temperature can be assumed to be approximately equal to the arithmetic mean of the air temperature and MRT in an environment where sedentary activities (1.0-1.3 met) are carried out, air velocity does not go above 0.20 m/s and no direct sunlight is allowed.

c. Effective temperature

Effective temperature is an indicator of comfort and cannot be measured by a thermometer; it is defined by Bradshaw (2006) as, “an experimentally determined index of the various combinations of dry-bulb temperature, humidity, radiant conditions, and air movement that induce the same thermal sensation.” Those combinations form thermo-equivalent conditions which are explained by the same author to be based on clothing insulation of 0.6 clo, sedentary activity level of 1.0 met, relative humidity of 50%, air flow rate of 0.20 m/s or less and 1 hour of exposure time.

iv. Humidity

Humidity is the moisture content of the air in a given space and relative humidity (RH), which is a value used to evaluate the humidity level, is the ratio of the partial pressure of the water vapor in the air to the saturation pressure of the water vapor at the same dry-bulb temperature and the same total pressure, times 100 (Bradshaw, 2006). The author indicates that occupants can tolerate a wider range of humidity than temperature and so, thermal comfort of sedentary occupants is only slightly affected by humidity. The same author further proposes that RH should be in the range of 20 to 60% in the summertime and in the range of 20 to 50% in the wintertime and, even though occupant tolerance to humidity is high, humidity level should be kept under control since high humidity delays body heat loss by evaporation and can cause condensation on cold surfaces, and low humidity dries throat and nasal passages.

v. Air flow

Air flow, as Bradshaw (2006) brings out, is a fundamental factor affecting body heat loss by convection and evaporation, and removal of air contaminants. The author suggests that there is no minimum air flow rate for thermal comfort in an environment where temperature is within acceptable limits and yet, when the temperature exceeds the limits, removal of excess body heat by natural air flow becomes insufficient and can be supported by means of artificial mechanisms. According to the same author, although there is not a lower limit for air flow rate, velocities below 0.05 m/s may cause stagnation and air stratification, and, although velocities up to 0.25 m/s are favorable, every 0.075 m/s increase in the air speed above 0.15 m/s causes the thermal sensation to drop by 1°C (Table 2.4). Additionally, it should be kept in mind that air velocity satisfying occupant comfort also depends on the other environmental factors such as temperature, humidity and MRT.

Table 2.4 Subjective response to air motion (Source: Bradshaw, 2006)

Air Velocity		
fpm	m/s	Occupant Reaction
0 to 10	0 to 0.05	Complaints about stagnation
10 to 50	0.05 to 0.25	Generally favorable (air outlet devices normally designed for 50 fpm in the occupied zone)
50 to 100	0.25 to 0.51	Awareness of air motion, but may be comfortable, depending on moving air temperature and room conditions
100 to 200	0.51 to 1.02	Constant awareness of air motion, but can be acceptable (e.g., in some factories) if air supply is intermittent and if moving air temperature and room conditions are acceptable
200 (about 2 mph) and above	1.02 and above	Complaints about blowing of papers and hair, and other annoyances

2.42 ASHRAE standards

Even though the requirements mentioned in the part 2.41 are primarily based on the interpretations of guidelines which are presented by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and are often referenced in building codes, it is considered to be essential to cover ASHRAE's Standard 55 (Thermal Environmental Conditions for Human Occupancy) and Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) under a separate heading in order to provide comprehensive assistance. It should be noted that the comfort conditions suggested by the standards are acceptable to at least 80% of the occupants within an experimental space.

i. Temperature

A comfort zone is determined as the combinations of air temperatures and MRTs providing thermally acceptable environmental conditions together with the factors like activity level, clothing insulation, humidity and air flow (ASHRAE, "Standard 55," 2004). The standard demonstrates two methods to be used to designate a range of temperatures for the comfort zone: the first one is a simplified graphical method used for a number of applications and the second one is a computer program based on a heat balance model used for a wider range of applications. Since the spaces of our concern where activity levels and clothing insulation values meet the criteria of the graphical method, it is examined in more detail.

Graphical method is appropriate to determine temperature limits for the spaces where activity level is between 1.0 and 1.3 met, clothing insulation is between 0.5 and 1.0 clo and air speed is below 0.20 m/s (ASHRAE, "Standard 55," 2004). The comfort zone satisfying above criteria is illustrated in Figure 2.11 where the operative temperatures specified are accepted by 80% of the occupants. Two zones shown are established for clothing insulation of 0.5 and 1.0 clo for warm and cool environments, respectively, and range of temperatures for other clothing insulation values can be calculated by linear interpolation. Accordingly, using the clo value ranges that Bradshaw (2006) put forth in the part 2.41, it can be concluded that operative temperatures range between 22.5 and 26°C for the summertime and between 20 and 23.5°C for the wintertime. These values are based on an activity level of 1.2 met and RH of 60%, and the temperature range is lowered by 0.6°C for each 0.1 clo increment of clothing insulation.

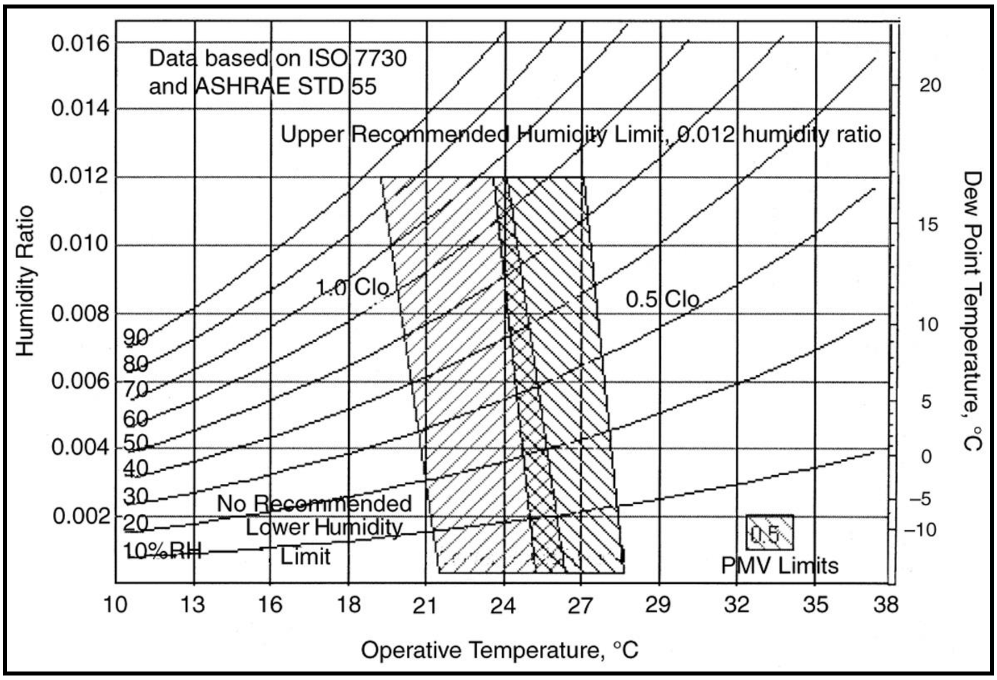


Figure 2.11 Acceptable range of operative temperature and humidity for spaces satisfying above criteria (Source: ASHRAE, "Standard 55," 2004)

ii. Humidity

ASHRAE ("Standard 55," 2004) suggests that RH of an environment should not exceed 70% for thermal comfort conditions. On the other hand, the standard does not denote any minimum RH limit due to the fact that there is no specified lower humidity limit for thermal comfort. Be that as it may, factors not related to thermal comfort such as dryness of the eyes, throat and nasal passages may put an unwritten limit for low humidity environments.

iii. Air flow

Upper air flow rate limit for the comfort zone is stated to be 0.20 m/s by ASHRAE ("Standard 55," 2004) while no lower limit is mentioned. However, as the standard explains, air velocity can be elevated to ensure thermal comfort where temperature is above the upper limit and air flow can be controlled by the occupants. This process is called as "elevated air speed" and it can be used to offset the air temperature and MRT limits by up to 3°C considering an environment where activity level is between 1.0 and 1.3 met and clothing insulation is between 0.5 and 0.7 clo. It should also be noted that elevated air speed cannot go above 0.80 m/s and adjustments cannot be made in steps greater than 0.15 m/s.

Another issue related to air flow is the indoor air quality (IAQ). Air flow in an environment should be sufficient to provide acceptable IAQ and this can be achieved, as ASHRAE ("Standard 62.1," 2007) describes, when, "there are no known contaminants at concentrations determined to be harmful to building occupants, and when a substantial majority (80% or more) of those persons exposed to the indoor air do not express dissatisfaction with its quality."
One of the contaminants to be kept under control is the carbon dioxide (CO_2) concentration in the indoor air. ASHRAE ("Standard 62.1," 2007) states that CO_2 concentration in the outdoor air ranges between 300 and 500 ppm, and in a space where sedentary activities are carried out, indoor CO_2 concentration may go up to 600-700 ppm above the outdoor air level. Table 2.5 presents steady-state CO_2 concentrations for various occupancy types based on an outdoor CO_2 concentration of 400 ppm.

Table 2.5 Steady-state CO_2 concentrations for different occupancy types (Source: Bradshaw, 2006)

Occupancy Category	Activity level (met)	Steady State CO_2 Concentration (ppm)
Classrooms (age 9 plus)	1	1025
Restaurant dining rooms	1.4	1570
Conference/meeting	1	1755
Lobbies/prefunction	1.5	1725
Office space	1.2	990
Sales	1.5	1210

CHAPTER 3

CASE STUDY: ISTANBUL SAPPHIRE

In this chapter, the subject material, research method, and results are explained. The material, a case study in Turkey, is introduced, the method by which the case study is analyzed is clarified and the results of the analysis are presented.

3.1 Materials

Since the study focuses on natural ventilation performance of double-skin facades in tall buildings, it is considered to be appropriate to work on a case study. The case study and the instruments used in order to analyze it are provided in this section.

3.11 Istanbul Sapphire

Istanbul Sapphire is selected as the case study owing to the fact that it is one of the few buildings in Turkey with a double-skin facade, the facade is entirely ventilated by natural means, and it has not been examined before by the others with respect to the subject of this study. Moreover, it is currently the tallest building in Turkey, which renders it more important as a case study.

Figure 3.1 Istanbul Sapphire (Source: Tabanlıoğlu Architects)

i. Location of the building

Istanbul Sapphire is a mixed-use building with residence, leisure and middle-size shopping center facilities, and is located on the Levent-Maslak axis, which is the main “central business district” of Istanbul. Büyükdere Boulevard has been developing as a business administration zone during the last two decades in consequence of the fact that industrial zone has been moving to the periphery and administration zone has been moving to the city center. Along with the surrounding high-rise buildings, Istanbul Sapphire has become an important icon of the district. It is the tallest building in Turkey with the height of 261 meters and it stands out in the Istanbul skyline with its elegant form and contemporary design.

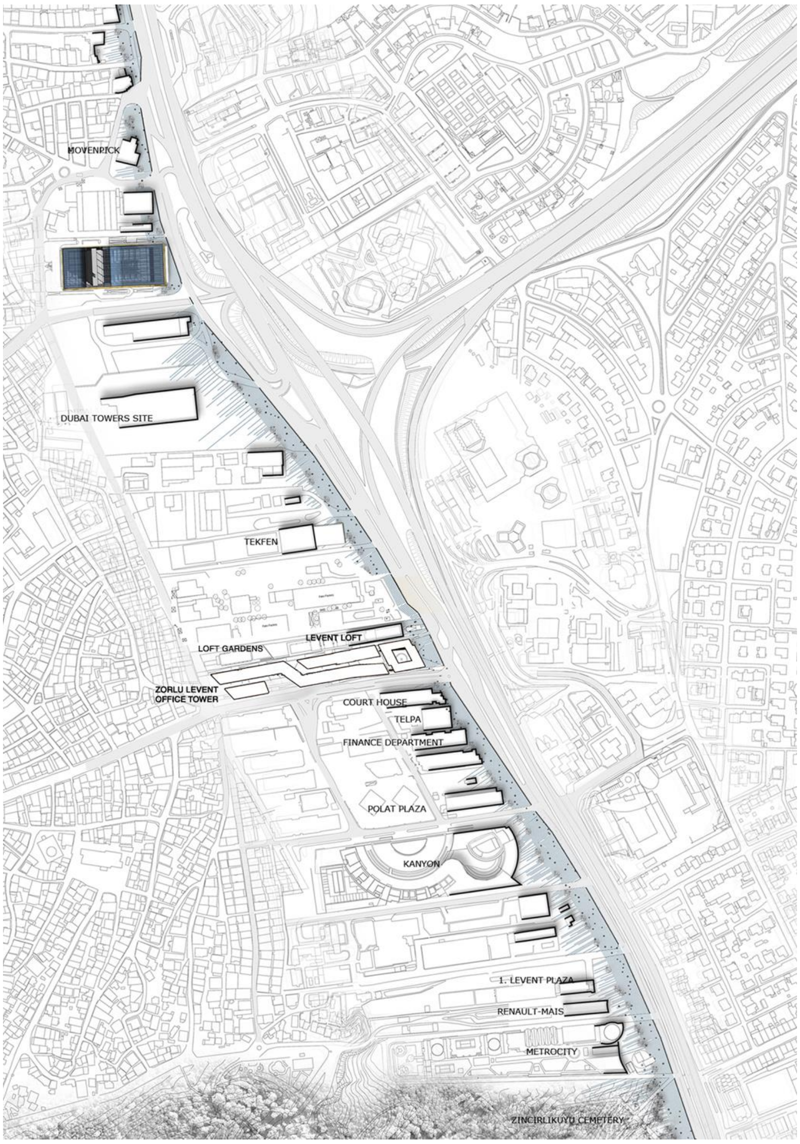


Figure 3.2 Levent-Maslak axis (Source: Tabanlıoğlu Architects)

ii. Design of the building

The 61-storey-high residence block is composed of four separate housing zones and four common areas between them. Housing zones host several apartments of different sizes and layouts with private terraces or gardens. In the buffer zones between the housing zones, there are recreation areas used for common social activities and indoor gardens, and also mechanical systems and maintenance facilities. There is a 6-storey underground car parking reserved for the residents, separated from the car parking reserved for the people coming to the shopping center which is right below the residence block.

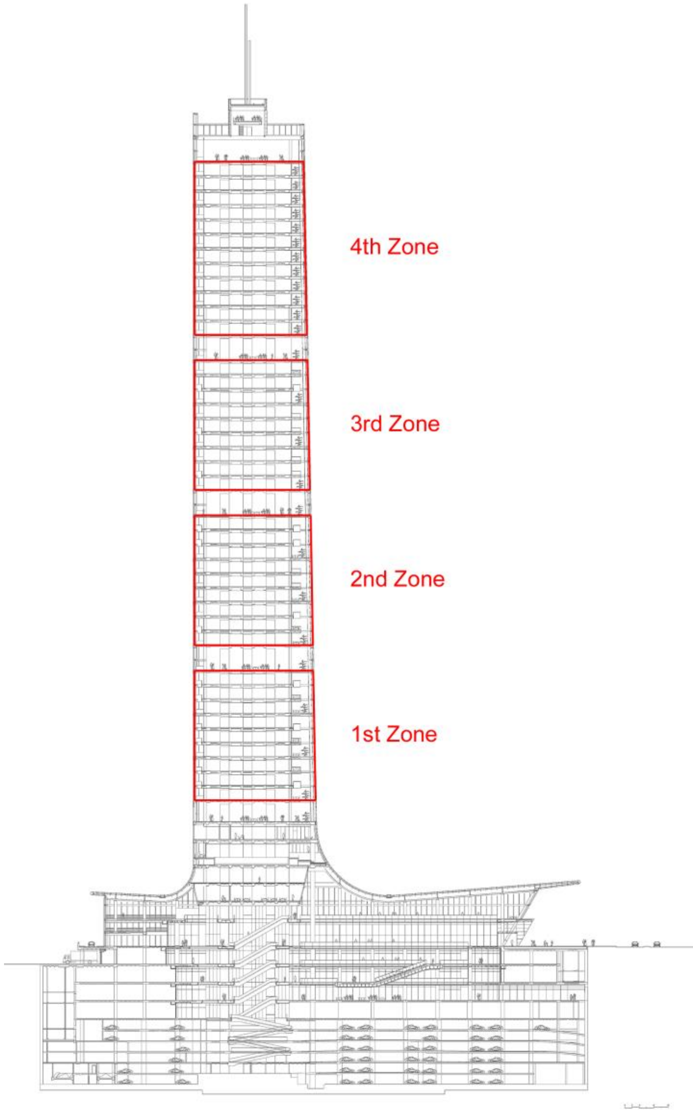


Figure 3.3 Section of the building showing housing zones (Source: Tabanlıoğlu Architects)

The vertical circulation is provided by 14 elevators (8 of them are high-speed elevators), 13 escalators and 8 conveyor belts. Two elevators have direct access to the restaurant and observation desk on the top floor, ensuring the privacy of the residents.

Mechanical, electronic, lighting and security systems of the building are controlled by an automation unit. Real-time data collected by input devices can be monitored with a controller and commands can be sent to output devices from the controller, if necessary. This automation system ensures that environmental factors are kept within the specified range and informs the staff about the status on each floor. Besides, all the apartments have home control panels by which occupants can manage electricity, HVAC and security settings of their own environments. Floor convectors and fan coil units are employed as heating and cooling systems in the apartments, respectively.

iii. Facade of the building

The building has a double-skin facade applied in a different manner. Conventional double facades are generally not deeper than 1 meter but in the case of Istanbul Sapphire, the depth is several meters and the space created is used as indoor gardens. The facade cavity is divided horizontally at every 3 floors in the first, second and third zones creating 12-meter-high spaces and is divided at each floor in the fourth zone. Each 3-storey-high component has a garden floor and two floors overlooking the garden with internal balconies (Figure 3.4). There are 9 or fewer apartments sharing a garden zone depending on their sizes. Double facade employed by the building falls under both corridor and multistory facade types.

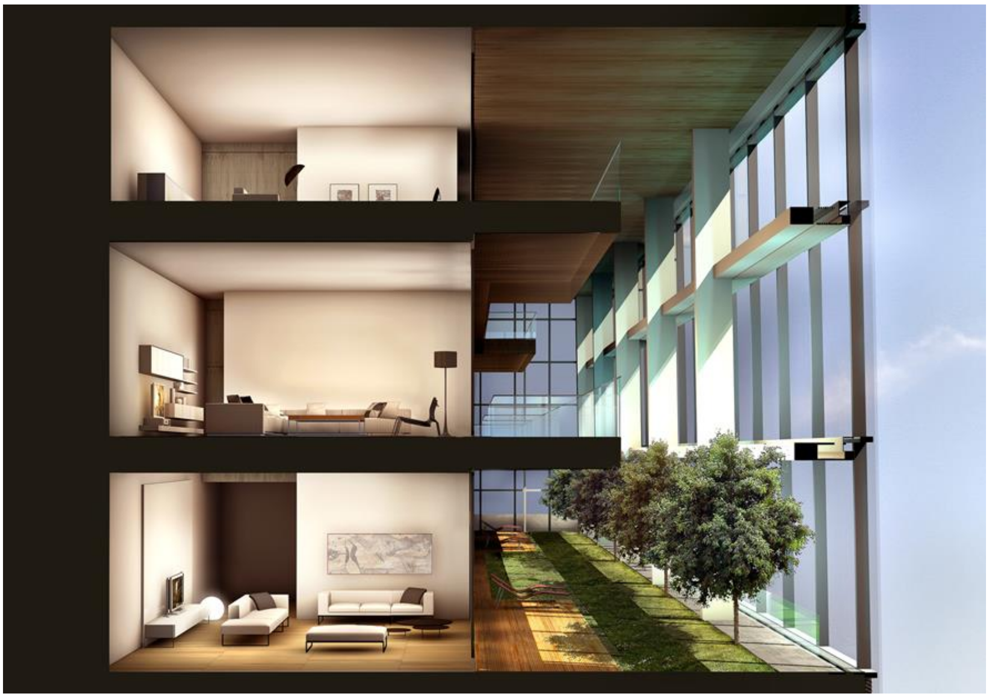


Figure 3.4 Section of a 3-storey-high garden zone (Source: Tabanlıoğlu Architects)

The facade cavity is ventilated only by natural means: air enters the cavity from the inlets at the bottom of the garden zone, circulates through the cavity and exits from the outlets at the top of the zone (Figure 3.5). The outer shell also provides protection from the adverse weather conditions and noise, and gives the opportunity of having an outdoor-like environment even if the occupants are at the high levels.

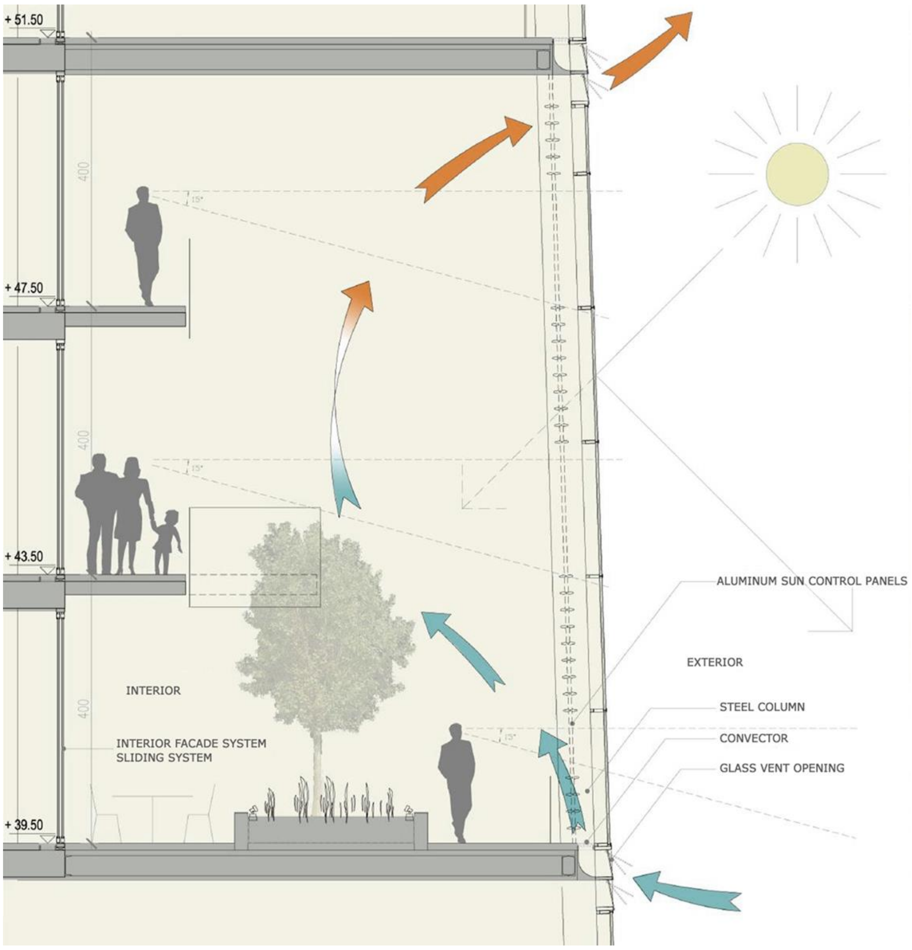


Figure 3.5 Ventilation of the facade cavity (Source: Tabanlıoğlu Architects)

When the temperature inside the cavity reaches to the upper limit designated by the automation unit of the building, flaps open to evacuate the hot air. Sensors placed inside the cavity collect temperature data and send signals to the flaps. These signals are received by the electrical unit of the flaps and louvers open by rotating around their centers. Air passes through the louvers while entering the cavity from the inlets and exiting from the outlets. Besides, there are grilles fixed at an angle of 45° just outside the flaps to reduce the effects of the wind and prevent rain penetration. However, flaps stay closed if the wind speed is above 45 km/h to prevent drafts in the facade cavity and they only open in case of a fire. Details of the inlets and outlets are provided in Figure 3.6 and 3.7, respectively.

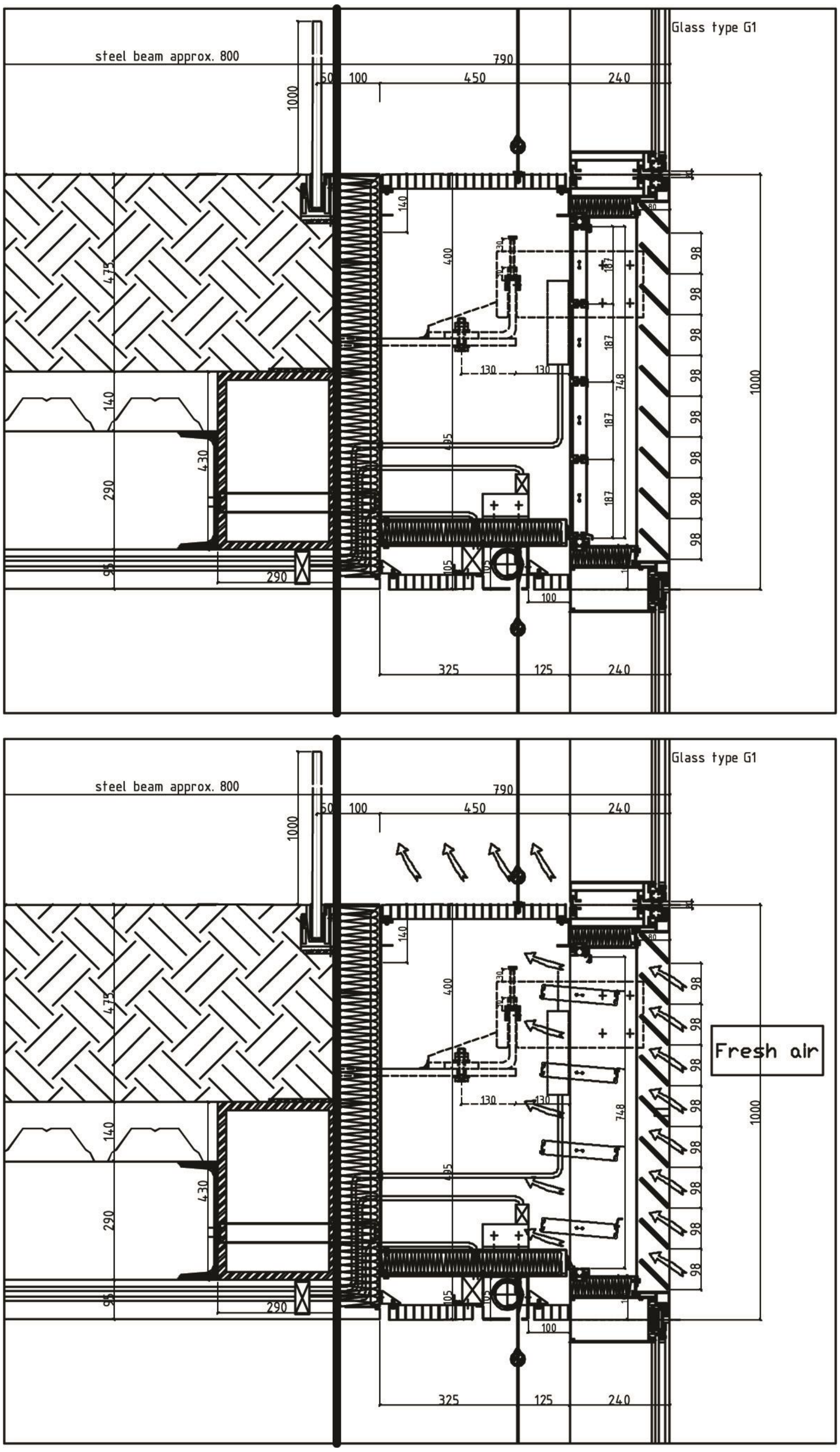


Figure 3.6 Section of the closed (above) and open (below) inlet (Source: Metall- und Fassadenplanung)

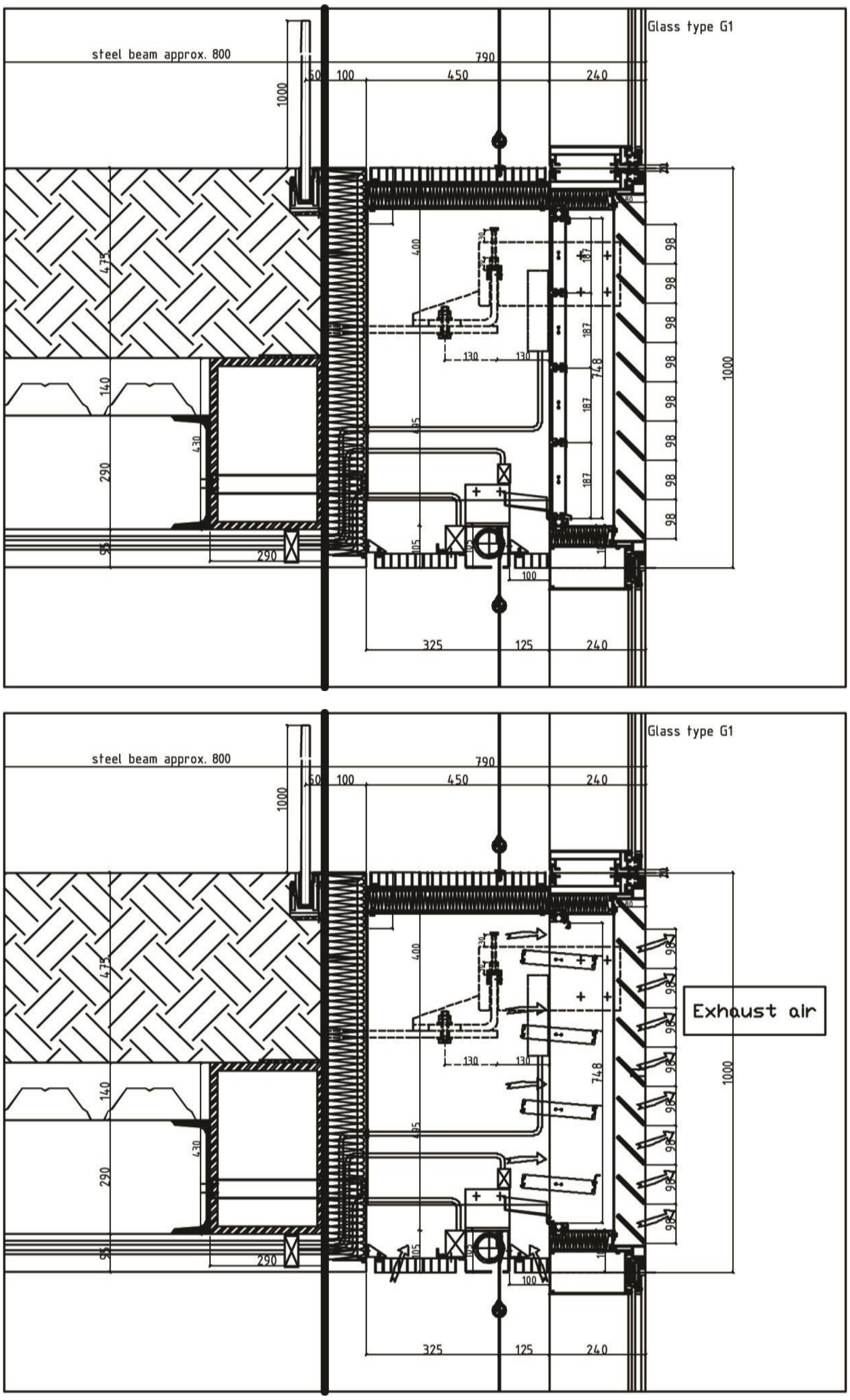


Figure 3.7 Section of the closed (above) and open (below) outlet (Source: Metall- und Fassadenplanung)

3.12 Data loggers

In order to gather data about the environmental conditions of the case study, devices called "data loggers" are used. A data logger is defined by Graf (1999) as, "a system to measure a number of variables and make a written tabulation and/or record in a form suitable for computer input." Type of data to be collected can be programmed beforehand and, data loggers can be deployed and left alone since they automatically measure and record information as long as they are activated. Some data may be collected with a built-in sensor and some with an external sensor or instrument.

3.2 Method

In this part of the study, measurement process and data collection to evaluate the natural ventilation performance of the double facade of Istanbul Sapphire are presented. Selecting appropriate locations, placing data loggers and transferring recorded data to the HOBO software are explained in detail.

Measuring the air flow rate, temperature, humidity and CO_2 concentration in the facade cavity is considered to be crucial since they are the key indicators of occupant comfort and important parameters of the analysis of natural ventilation efficiency. All collected data is evaluated and compared with the requirements, and results are discussed in the Chapter 4.

Preparations for the measurement and the process itself took place in late April, 2012. Data loggers and some other necessary instruments were obtained from the Building Science Laboratory of METU Faculty of Architecture. HOBO software was installed to be able to set the data loggers to measure air flow, temperature, humidity and CO_2 data, and to activate them to start working on the day measurements would be made.

After getting the permission from Biskon Yapı A.Ş. to enter the indoor gardens, empty and available apartments were identified. One apartment from each housing zone having the same facade direction would be the best case to be able to compare the possible differences related to height and to increase the reliability of the results. Regrettably, there were only two apartments satisfying above criteria, one on the 31st floor in the third zone and the other on the 45th floor in the fourth zone, and measurements were made on these two floors. Moreover, data collection was permitted only for one day which is not sufficient to come to a final conclusion, but collected data is expected to give an idea about the situation in the facade cavity.

The first apartment on the 31st floor had an internal balcony on the second floor of a 3-storey-high garden zone and the second one on the 45th floor had a single storey independent garden. The first apartment had north and east facades while the second one had north, east and west facades. As the first apartment did not have a west facade and the indoor gardens in question were along the east facade of the building, no measurement was made at the west facade of the second apartment.

3.21 Deployment of data loggers

Having two apartments, two data loggers were set to record temperature and also humidity data, other two were set to record CO_2 data and one was set to record air flow data due to the fact that only one anemometer was available, which is the instrument for measuring air speed, and it was carried between the floors and used in turn.

The anemometer was connected to the data logger no.09 (DL 09) and used on both floors. One of the CO_2 sensors was connected to DL 10 and used on the 45th floor while the other one was connected to DL12 and used on the 31st floor.

Temperature sensors were connected to DL 11 and DL 13 and used on the 31^{st} floor and 45^{th} floor, respectively (Table 3.1).

Table 3.1 Deployment and setting of data loggers

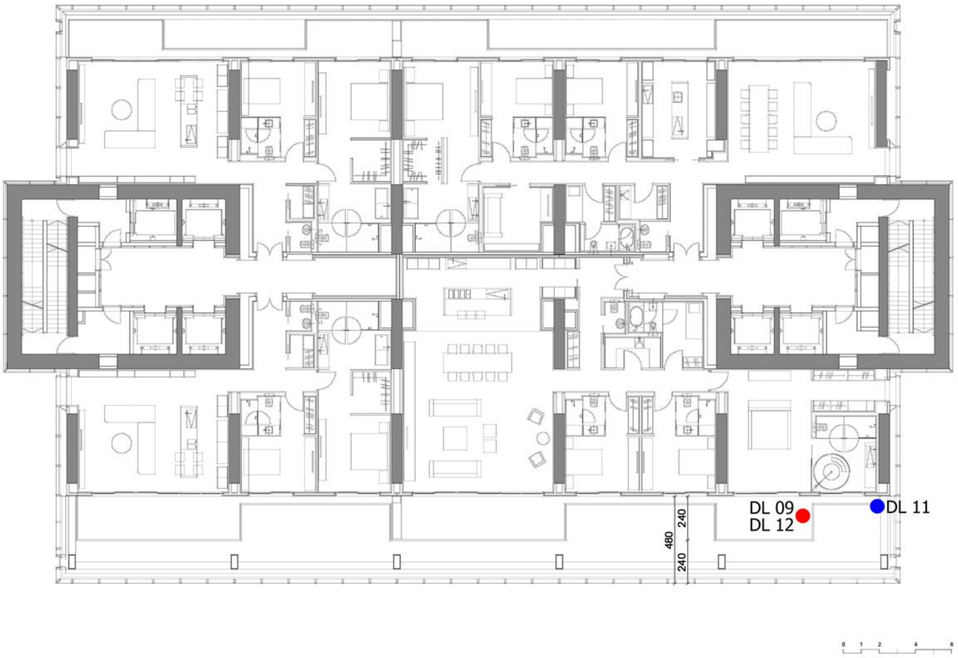
Logger	Location	Data	Start time	End time
DL 09	31^{st} floor	Air flow rate	12:20	13:15
			14:40	15:35
	45^{th} floor		11:00	11:55
			13:30	14:25
DL 10	45^{th} floor	CO_2	11:00	16:30
DL 11	31^{st} floor	Surface temp.	12:30	12:30 (+1)
DL 12	31^{st} floor	CO_2	11:00	16:30
DL 13	45^{th} floor	Surface temp.	12:30	12:30 (+1)

Considering the space available for placing the loggers on both floors, a location which had the same distances from the outer shell and was pertinent to the guidelines for the measurement process of air flow and CO_2 was determined. Although enough distance from the shell (450 cm from the north and 400 cm from the east facade) was ensured, data loggers and, external CO_2 sensors and the anemometer connected to the loggers could not be located at an appropriate height due to the lack of a tall object on which the loggers could be placed and so, they were positioned on 50-cm-high boxes (Figure 3.8). Nevertheless, measurements were expected to give accurate results.

Figure 3.8 Deployment of DL 09 (both), DL 10 (left) and DL 12 (right)

Temperature sensors, which are also external instruments, were to be mounted on the outer facade window and north facade was chosen as the first apartment was on the second floor, preventing any contact with the east facade. Another obstacle was that first apartment's terrace railing prevented from attaching the sensor on the north facade window itself and it had to be mounted on the railing glass which is 75 cm away from the north facade. Both sensors on two floors were attached to a 1-meter-high point (Figure 3.9). Locations of the data loggers are shown in Figure 3.10 and Figure 3.11.

Figure 3.9 Deployment of DL 11 (left) and DL 13 (right)



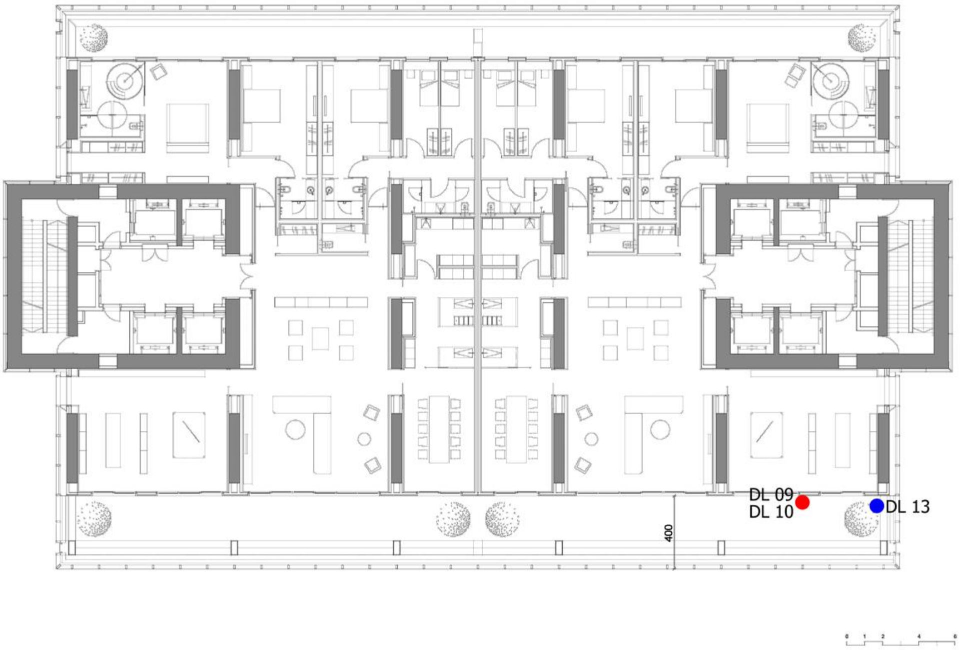


Figure 3.10 Locations of data loggers (Above: 31st floor / Below: 45th floor)

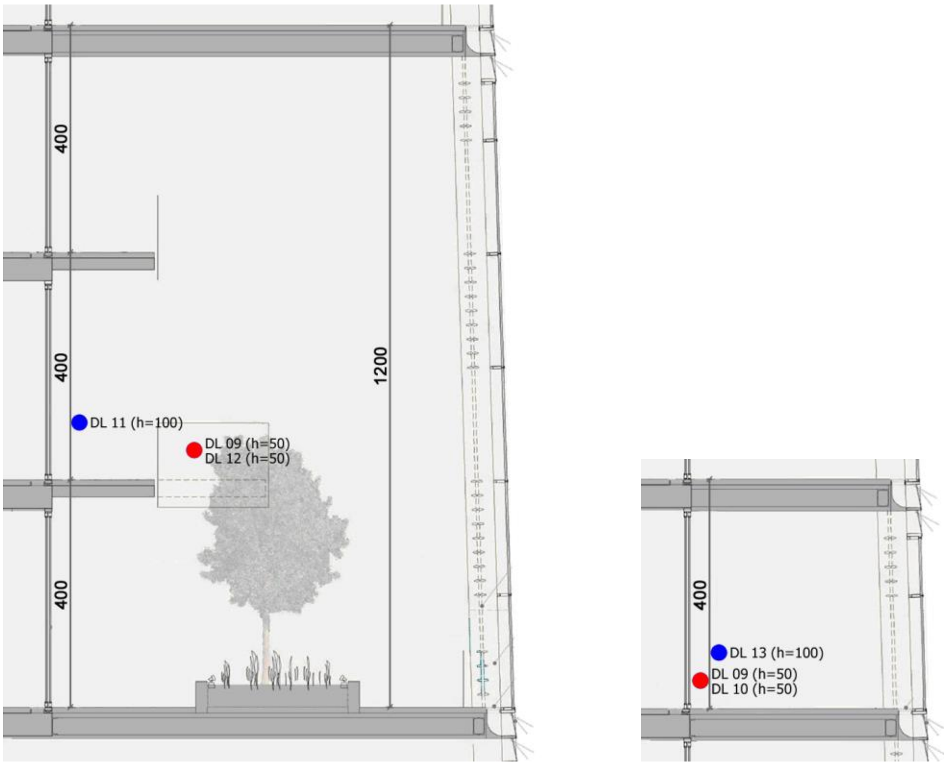


Figure 3.11 Locations of data loggers (Left: 31st floor / Right: 45th floor)

3.22 Measurement process

Temperature and CO_2 loggers were set to a logging interval of 10 minutes and air flow logger was set to a logging interval of 5 minutes since the anemometer was to be used in turn leading to less time allocated for a measurement on a single floor. Initial plan was to make the measurements from the morning to the evening, but when Biskon Yapı A.Ş. gave permission to leave the data loggers which did not need electricity to work, loggers recording the temperature and humidity data were left for the nighttime and so, a 24-hour of data log was achieved. Logging process of the loggers of the same type except the air flow logger started and ended with small time differences. Data that was recorded while deploying the loggers to the specified locations was ignored.

3.23 Transfer of data

As well as activating the loggers, HOBO software was also used to load the recorded data into the computer. Each logger was separately connected to the computer and data stored in the devices were transferred and saved in the folders. Once loaded, all data was available in the list form with date and time labels, and used to prepare charts for the analysis and comparison.

CHAPTER 4

RESULTS AND DISCUSSIONS

The results of the measurements including air flow rate, temperature, humidity and CO_2 concentration, compliance of these results with the ASHRAE standards and comparisons made between the floors are provided in this chapter.

4.1 Air flow rate

When the air speed limits proposed by Bradshaw (2006) and ASHRAE ("Standard 55," 2004) in the part 2.4 are collated, it is accepted that air flow rates up to 0.25 m/s are appropriate and they satisfy the comfort zone criteria, but speeds below 0.05 m/s (stagnation limit) and above 0.20 m/s (draft limit) should not be totally ignored. These limits are taken into account while interpreting the results.

The first measurement took place on the 45th floor and a total of four measurements were made in turn between two floors. Each measurement was made for 60 minutes and 12 values were obtained with the logging interval of 5 minutes. All the values can be seen in Table C.3 and C.4 in Appendix C.

To begin with, two measurements made on the 45th floor are discussed. The chart prepared using the values obtained from the measurements is presented in Figure 4.1. According to the results of the first measurement, 91.6% of the values fall within the comfort zone limits; 9.1% of these values are below the stagnation limit and 9.1% are above the draft limit, but they are negligible. Remaining 8.4% of the values are above 0.25 m/s, most probably due to the open flaps. The highest air flow rate is observed to be 0.29 m/s and the lowest air flow rate to be 0.02 m/s which can be neglected. It can also be said that the rising temperature led to a variable air flow course and to a higher air flow rate average than those of the following measurement made on the same floor.

The second measurement on the 45th floor reveals slightly different results. Considering the chart illustrated in Figure 4.1, all of the values are in the comfort zone limits and 25% of them are below the stagnation limit. Although this result looks similar to that of the first measurement, the highest and the lowest values that air velocity reaches are 0.10 m/s and 0.01 m/s, respectively, and all the other values in between are around the stagnation limit which may cause a slight discomfort. When the relationship between the air velocity and temperature is examined, it is observed that temperature was acceptable and so, flaps were possibly closed.

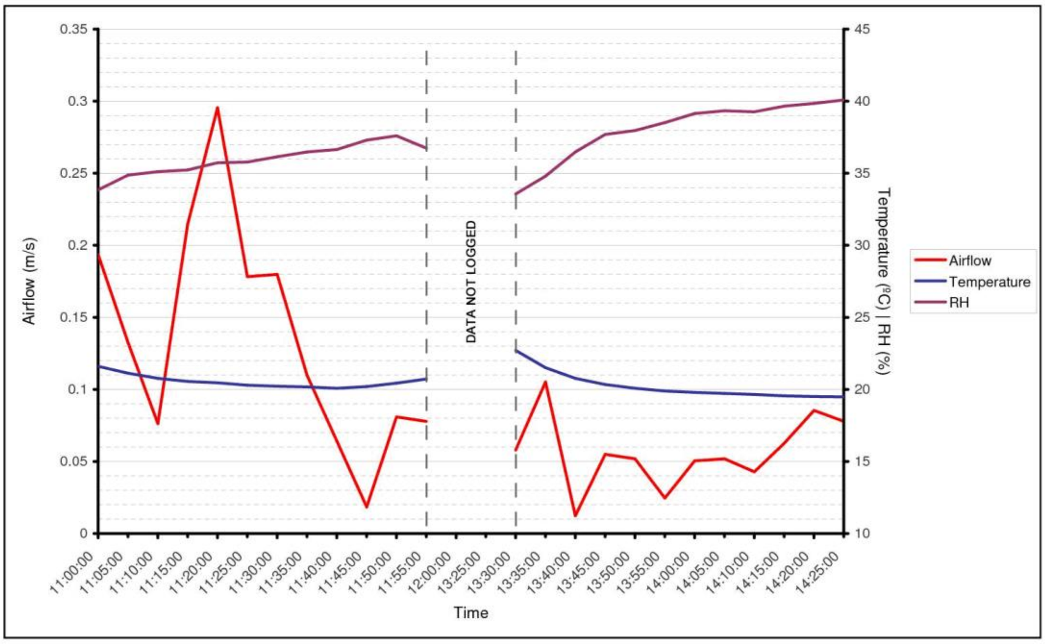


Figure 4.1 Air flow and temperature relationship on the 45th floor

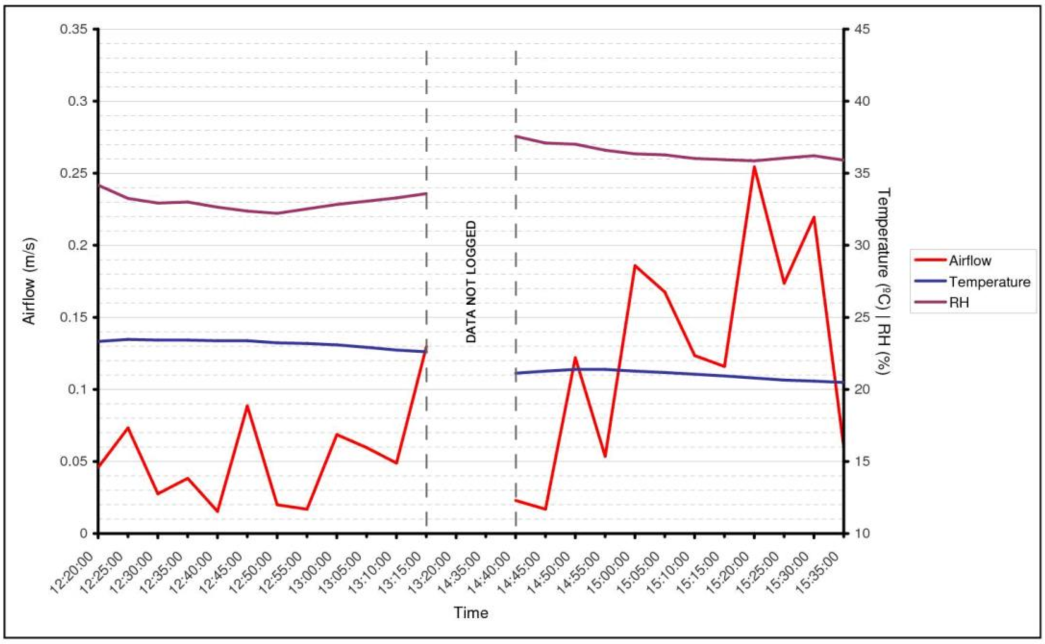


Figure 4.2 Air flow and temperature relationship on the 31st floor

Other two measurements were made on the 31st floor. The chart shows that all of the values of the first measurement are within the limits of the comfort zone and 58.3% of them are below the stagnation limit, a value to which attention should be paid (Figure 4.2). Moreover, the highest air velocity is observed to be 0.13 m/s and the lowest air velocity to be 0.02 m/s. That high percentage probably results from the fact that temperature is within the comfort zone limits, leading to a weak air flow.

The second measurement on the 31st floor exhibits better results. According to the chart presented in Figure 4.2, 91.6% of the values fall within the comfort zone limits; 18.2% of these values are below the stagnation limit and 9.1% are above the draft limit. Remaining 8.4% of the values are above 0.25 m/s, presumably due to the open flaps. Results look very similar to those of the first measurement on the 45th floor, also with the highest air speed value of 0.26 m/s and the lowest air speed value of 0.02 m/s. With negligible bottom and top values, overall situation is considered to be very convenient. When the relationship between the air velocity and temperature is examined, it can be stated that temperature has a downward course as a consequence of increasing air flow rate in response to the elevated temperature in the garden zone.

4.2 Temperature and humidity

Considering the summertime temperature limits determined by ASHRAE ("Standard 55," 2004) for the comfort zone in the part 2.42, the range of 22.5 to 26°C is employed for the analysis of temperature data. For the analysis of humidity, on the other hand, summer RH range of 20 to 60% as mentioned by Bradshaw (2006) is used since this range complies with the suggestion of ASHRAE ("Standard 55," 2004) to keep RH below 70%. It should be noted that because the space in question is not a conventional indoor space but rather a buffer zone between the indoor and outdoor, results are not expected to fully meet the above criteria.

Measurements took place on the 45th and 31st floors simultaneously for a 24-hour period with a logging interval of 10 minutes. Temperature data was both collected with the external sensors connected to the data loggers and the built-in sensors inside those loggers while humidity data was collected with the built-in sensors. All data logged is available in Table C.1 and C.2 in Appendix C.

Outdoor temperature values recorded on the day measurements took place are gathered from the archive of Euro Weather website. Temperature, humidity and temperature versus humidity analyses are separately made for both floors. Temperature data logged simultaneously with the external sensors and the built-in sensors is used together in those analyses in order to be able to observe the difference between the surface temperature measured with the external sensors and the actual air temperature measured with the built-in sensors.

Initially, temperature alternation on the 45th floor is discussed. Values recorded for 24 hours reveal that temperature in the facade cavity has a similar course to that of the outdoor temperature throughout the measurement process, except for the early morning phase (Figure 4.3). This situation may have occurred due to the fact that the cavity is primarily on the east side of the building and direct sunlight may have given rise to a rapid warm-up, which took some time to be reduced by evacuating the hot air. Surface temperature reaches the highest value of 27.1°C at 12.00 and the lowest value of 15.2°C at 00.00, and zone temperature reaches the highest value of 24.6°C at 12.40 and the lowest value of 15.3°C at 01.00. Although the highest surface temperature exceeds the upper limit of the comfort zone by 1°C, this is due to the rapid warm-up and can be ignored. The highest air temperature, on the other hand, is a favorable value right between the comfort zone limits. Both values are above the highest outdoor temperature as expected but it can also be said that the air temperature would have been much higher without effective ventilation. Considering the fact that the facade cavity is a transition space between the outdoor and indoor, both of the lowest temperature values are well-balanced between the lowest outdoor temperature and the lower limit of the comfort zone. This means that heat is preserved well inside the cavity during the night.

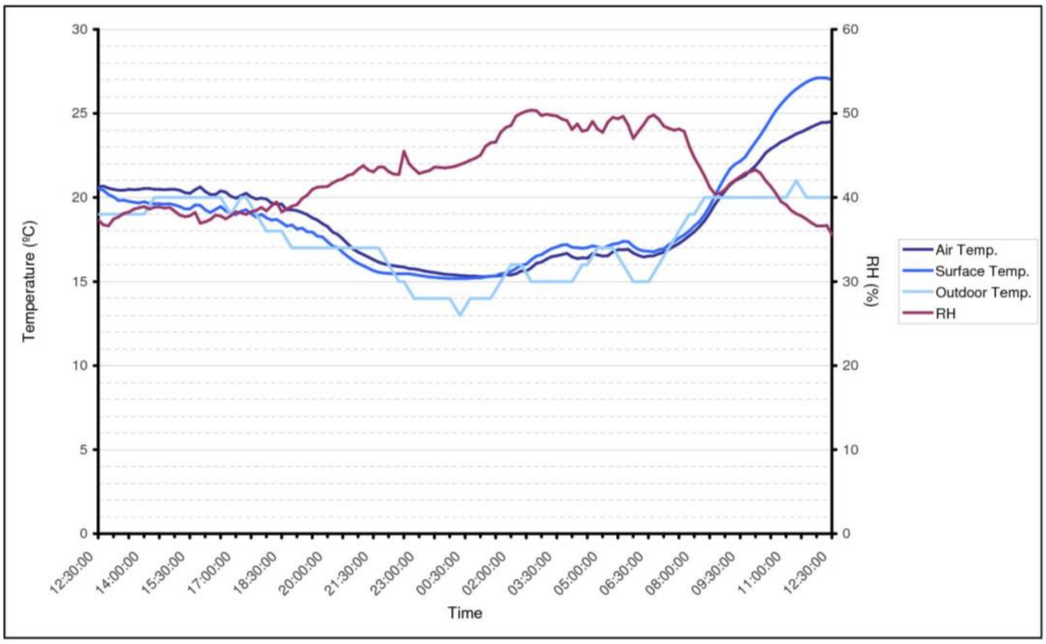


Figure 4.3 Temperature and RH relationship on the 45th floor

Figure 4.4 shows the behavior of temperature on the 31st floor. While being slightly more variable than the chart of the 45th floor, rapid warm-up in the early morning also exists on the chart of the 31st floor, most probably because of the same reason. The highest surface temperature of 26.7°C is observed at 10.10 and the lowest temperature of 18°C at 03.00, and the highest zone temperature of 29.4°C is observed at 10.50 and the lowest temperature of 18.8°C at 03.00. These values, especially the highest temperature values, are very similar to those of the 45th floor. Even though the highest surface temperature exceeds the upper limit of the comfort zone just a little, the highest air temperature exceeds that limit by 3°C, the reasons of which should be examined. While the surface temperature is affected more by the direct sunlight as the external sensor faces the sun in the case of 45th floor, air temperature is affected dramatically more than the surface temperature in the case of 31st floor, because the effect of the solar gain on the air temperature is more than the effect of the heat gain of the glass on the surface temperature. Besides, the warm-up is very rapid and lasts only for half an hour and may be ignored. Additionally, both of the lowest temperature values are higher than those of the 45th floor as much as 3°C which is due to the height.

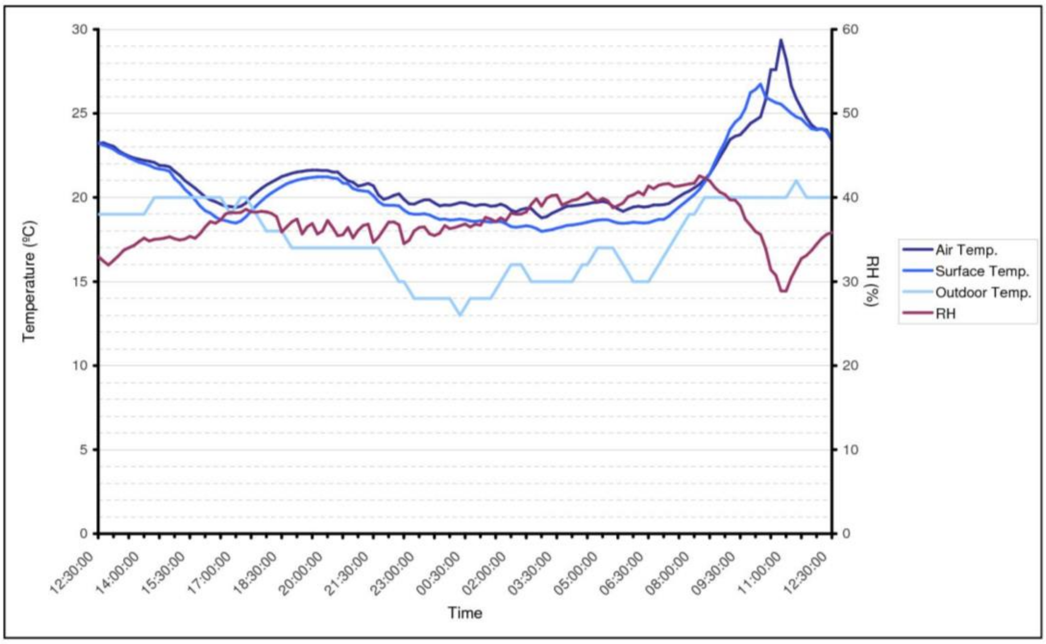


Figure 4.4 Temperature and RH relationship on the 31st floor

The other parameter to be examined in this part is humidity. Figure 4.3 presents the change of RH over time on the 45th floor. The highest RH value of 50.4% is observed at 02.40 and the lowest RH value of 35.6% at 12.30. Average daily RH is calculated to be 42.7%, daytime average to be 40.5% and nighttime average to be

46%. All the values are within the suggested limits and averages are favorable. Temperature and RH relationship on the 45th floor is illustrated in Figure 4.8 and it is seen that two parameters change over time in an inverse relation with each other, as expected.

RH chart of the 31st floor displays a similar course to that of the 45th floor with slightly more ups-and-downs (Figure 4.4). RH reaches the highest value of 42.6% at 08.10 and the lowest value of 28.9% at 11.00. Average daily RH is found to be 37.1% while daytime and nighttime averages are 36.8% and 37.6%, respectively. Although RH averages of the 31st floor are slightly lower than those of the 45th floor, they are within the limits and appropriate. Figure 4.10 shows the relationship between temperature and RH on the 31st floor over the 24-hour period. It is clearly observed that the parameters are greatly in accordance and inversely proportional.

4.3 CO_2 concentration

According to the CO_2 concentration limits established by ASHRAE ("Standard 62.1," 2007) in the part 2.42, indoor CO_2 concentration around 1000 ppm is accepted to be convenient where outdoor CO_2 concentration is around 400 ppm. Even though the facade cavity is an enclosed space, CO_2 concentration in the cavity is expected to be close to that of outdoor rather than that of indoor due to the fact that the space is naturally ventilated.

Measurements were simultaneously made on the 45th and 31st floors between the hours 11.00 and 16.30 with a logging interval of 10 minutes. CO_2 data was recorded with the external sensors connected to the data loggers. All data logged is provided in Table C.5 and C.6 in Appendix C.

Firstly, change of CO_2 concentration over time on the 45th floor is examined. The curve displays a consistency in the course of CO_2 concentration with no major fluctuation (Figure 4.5). Average CO_2 concentration is found to be 382 ppm which is eminently an outdoor value and very satisfactory since the space is used as an indoor garden. CO_2 and air flow relationship on the 45th floor is illustrated in Figure 4.6 and it can be said that CO_2 concentration drops slightly when the air speed rises, which is an indication of open flaps.

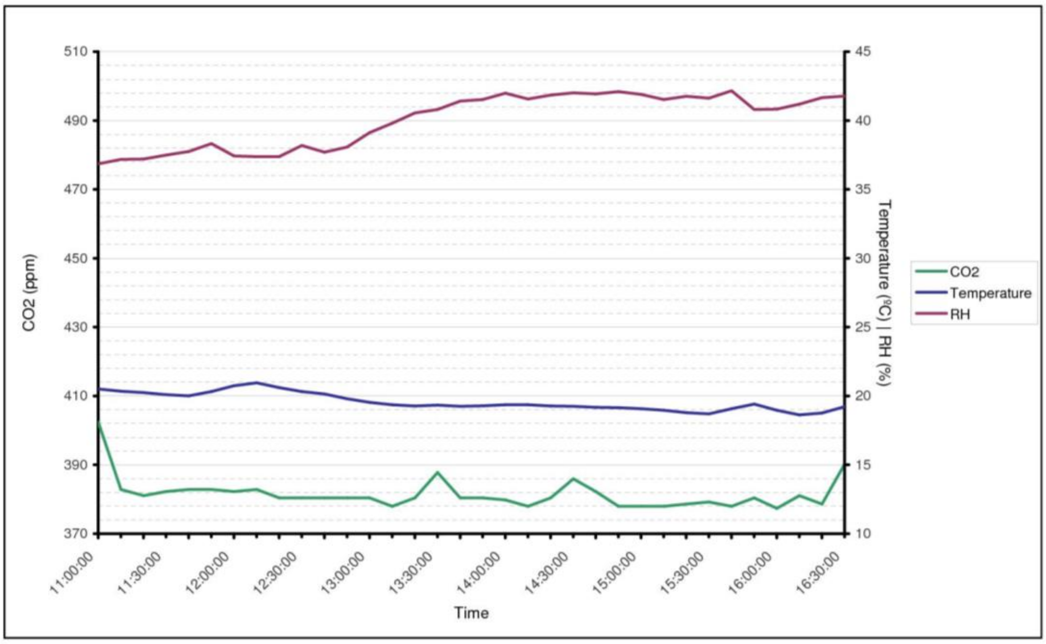


Figure 4.5 CO_2, temperature and RH relationship on the 45th floor

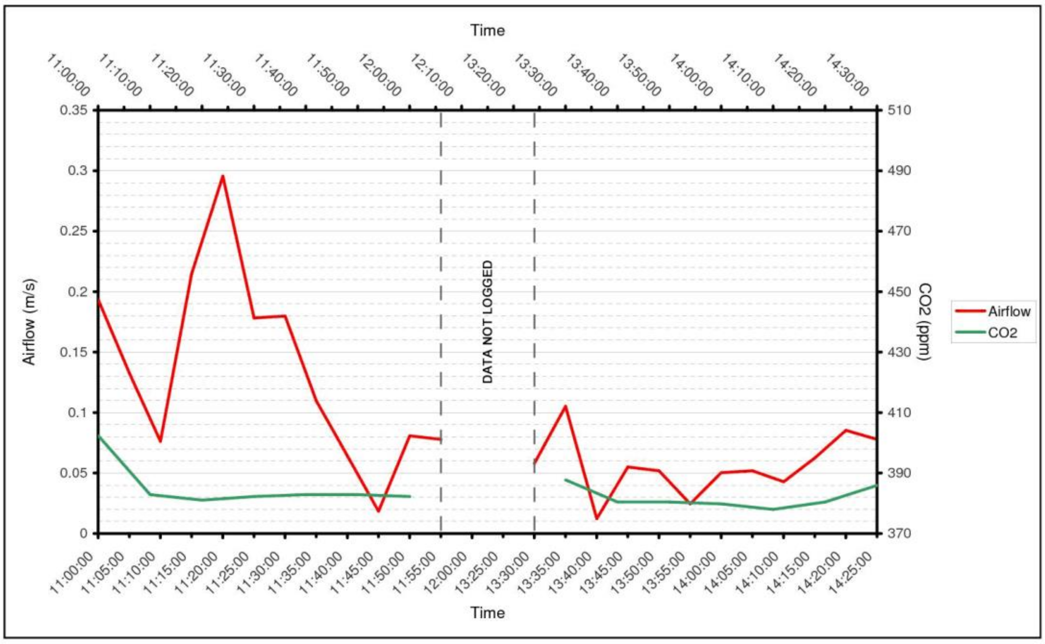


Figure 4.6 Air flow and CO_2 concentration relationship on the 45th floor

Behavior of CO_2 concentration on the 31st floor looks similar to that of the 45th floor (Figure 4.7). Average CO_2 concentration is calculated to be 482 ppm which is again a very appropriate value. Figure 4.8 shows the relationship between CO_2 and air flow on the 31st floor and it is observed that CO_2 concentration has a downward tendency as expected when the air flow rate rises.

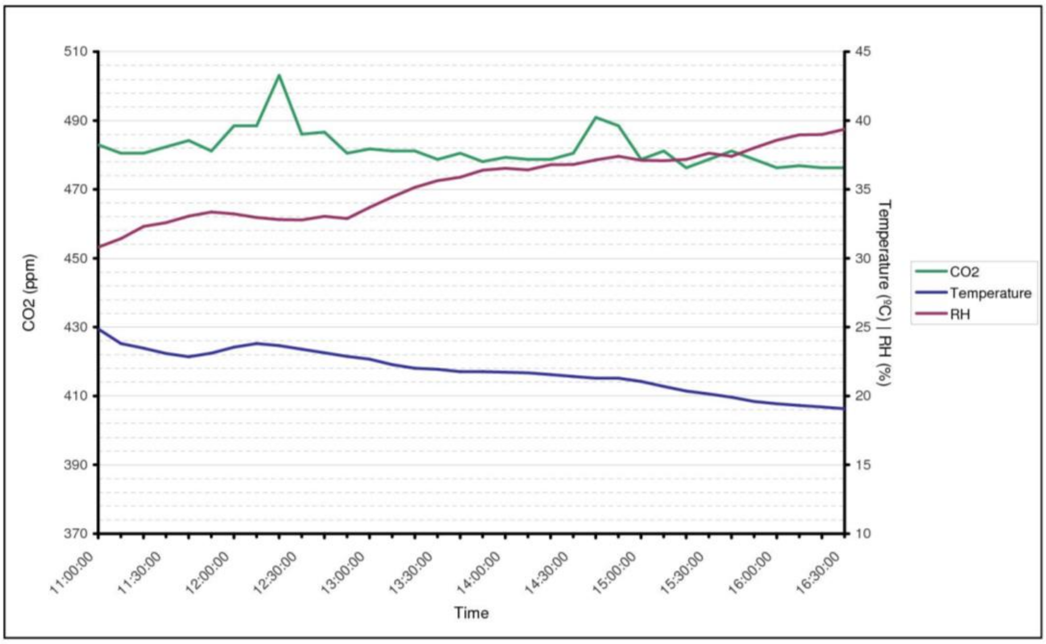


Figure 4.7 CO_2, temperature and RH relationship on the 31st floor

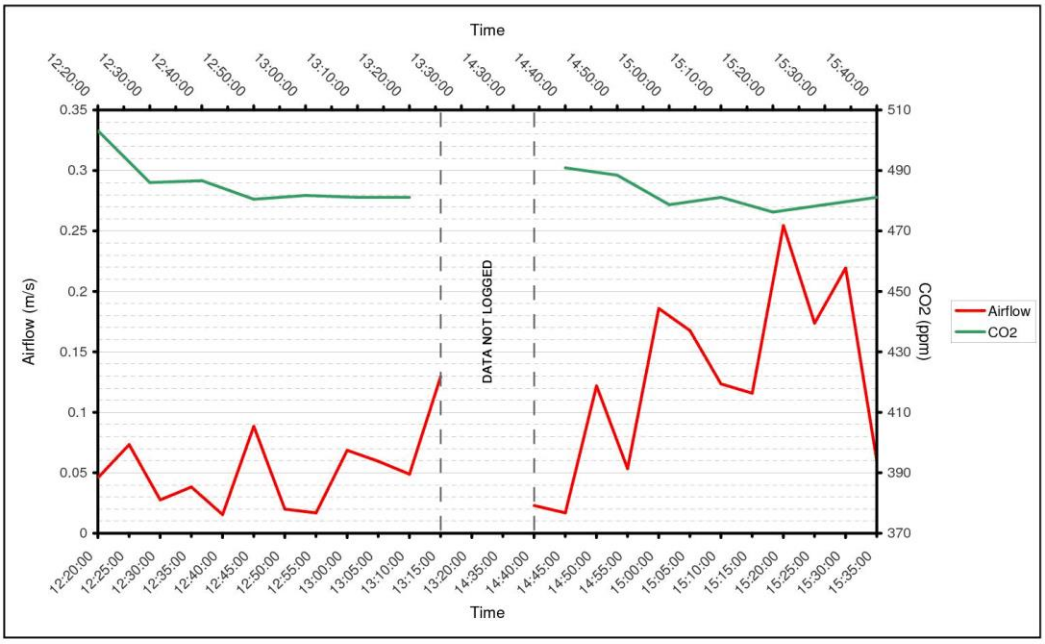


Figure 4.8 Air flow and CO_2 concentration relationship on the 31st floor

4.4 Comparison between two floors

Initially, air flow rates recorded on two floors are illustrated in Figure 4.1 and 4.2. It is observed that rise in the air speed led to a decline in temperature on both floors. It is also seen that air flow rate on the 45th floor is higher in the first measurement than it is in the second one whereas the opposite case applies to the 31st floor. This situation arose from the fact that the cavity on the 45th floor has a high temperature in the morning and air flow rate stays at a low level after evacuating the hot air.

Comparison made between the temperature curves of two floors displays a similar behavior. There is a difference between the concurrently recorded values on the curves varying up to 4°C which is due to the height; it is an expected result that temperature values of the 45th floor would be lower than those of the 31st floor since outdoor temperature, and temperature in the cavity as a consequence, decreases with height. It is also a valid statement that because the garden zones are more like atriums with large volumes surrounded by a large glass facade, the solar gain is more in the 3-storey-high zones than it is in the 1-storey-high gardens, leading to a higher level of temperature on the 31st floor. Similar to that of temperature comparison of two floors, the RH chart reveals that the curves have a close behavior throughout the process but are different by about 10-12% probably due to the fact that vegetation is denser on the 45th floor. Temperature and RH values of two floors are compared in Figure 4.9.

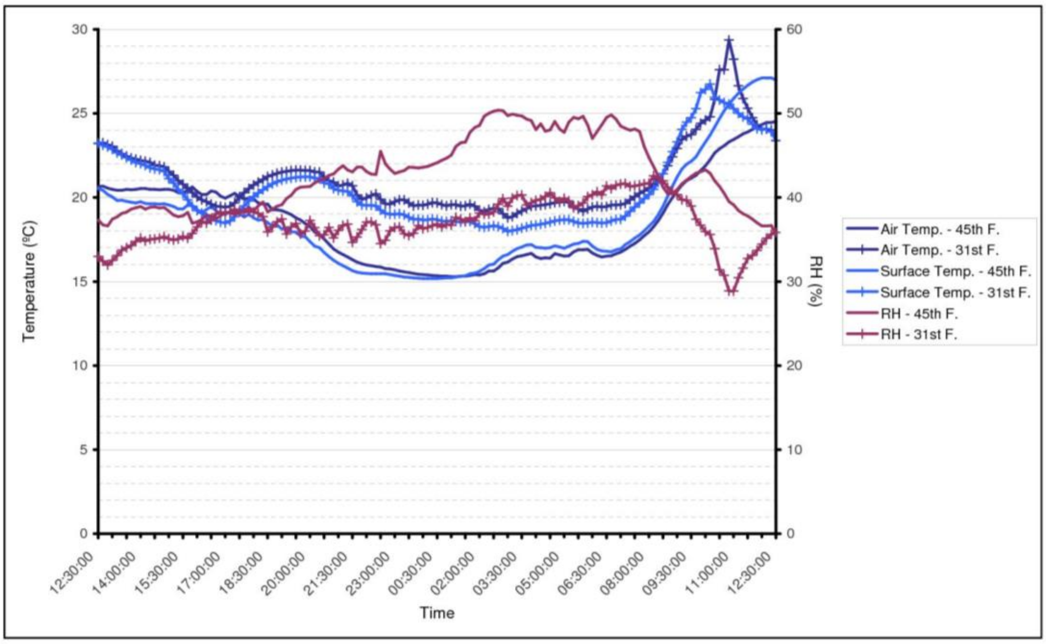


Figure 4.9 Temperature and RH relationship of two floors

When the CO_2 concentrations of two floors are examined, it is observed that there is a difference about 100 ppm between the curves while they are still at a favorable level (Figure 4.10). This difference is most probably due to the fact that CO_2 rises with hot air, and since the logger on the 31^{st} floor is located on the second floor of a garden zone, CO_2 concentration around that logger is higher than the one on the 45^{th} floor which is located at the floor level.

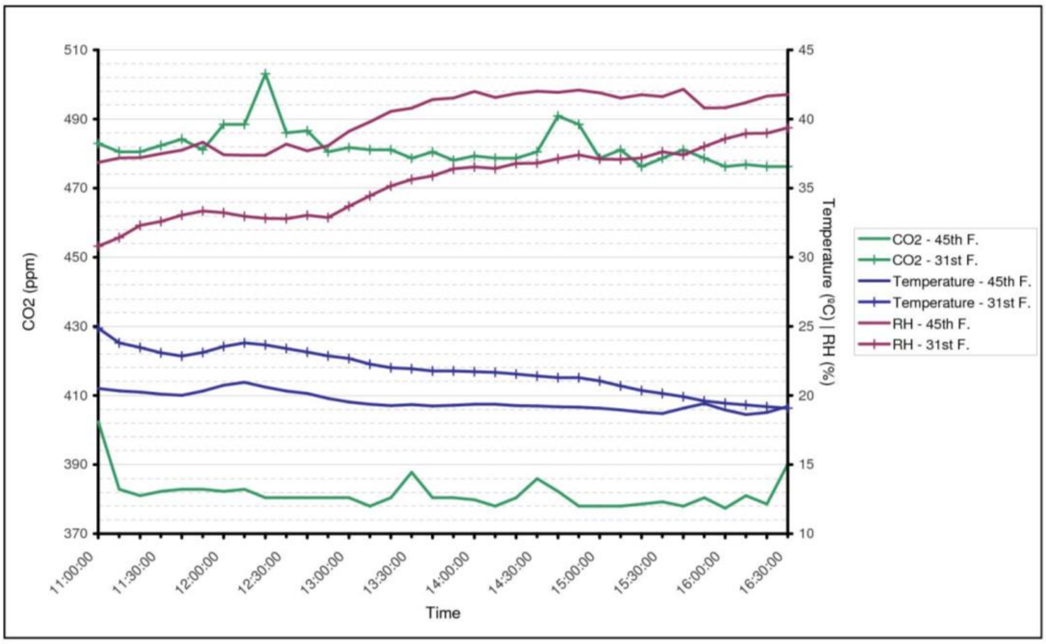


Figure 4.10 CO_2 comparison between two floors

CHAPTER 5

CONCLUSION

As the efficient use of energy became a crucial subject in the past few decades, improvements gained momentum in the building industry to reduce the energy consumption. Around the same time, the upward trend of building high-rise structures led to health problems related to poor air quality caused by inadequate natural ventilation. Double-skin facades which are especially appropriate to be applied to tall buildings enhance the occupant comfort and reduce operation costs by promoting natural ventilation. This advantageous system has been analyzed with the help of a case study and the conclusions obtained from the study are provided in this chapter.

Istanbul Sapphire has incorporated certain strategies to eliminate the potential disadvantages of living in a high-rise building as much as possible and to offer outdoor-like spaces to the occupants with the help of indoor gardens and ventilation by natural means. It claims to have achieved this aim by installing a double-skin facade. However, the glazed facade that is expected to protect the building from unfavorable weather conditions and noise, reduce energy consumption and improve the quality of supplied air cannot be called a double facade in the true sense because the space between the two glazed surfaces does not merit to be called a cavity, which is the description of an unoccupied space between the double-skin facade.

Even though each garden zone is referred to as a facade cavity throughout the study owing to the fact that it is the intermediate space between the inner and outer glass skins, it is exceptionally deep and used by the occupants, which renders it an atrium rather than a cavity of a double-skin facade. Although the building is featured to have employed a double facade in several sources and this may be true in theory, application and utilization of the facade in practice is very different than a conventional double-skin facade. It is prudent to suggest that the terminology used for the facade of Istanbul Sapphire is not appropriate.

Environmental conditions inside the facade cavity were examined to be able to evaluate the performance of natural ventilation. Although limited, data related to occupant comfort and which is affected by ventilation regime directly or indirectly were collected to assess the appropriateness of the conditions to the requirements. Recorded temperature, humidity, air flow rate and CO_2 concentration data was presented with the help of charts and results were compared with the available requirements.

Results of the measurements reveal that the ventilation method applied to the building performs efficiently and provides acceptable conditions within the garden zones. However, this outcome is based on a 24-hour data set which shows the case on that particular day and not adequate to assess the overall efficiency of the natural ventilation inside the facade cavity. More data should be collected during the other seasons as well, for a year-round period if possible, to be able to draw a better conclusion.

The difference between the surface temperature and the zone temperature is very low, meaning that air circulates at a sufficient rate that prevents hot air from stagnating inside the cavity which otherwise would lead to a much higher difference. Furthermore, RH and CO_2 values are all within the acceptable limits, supporting the statement that adopted ventilation strategy functions well. However, it is observed that temperature exceeded the upper limit of the occupant comfort requirements in the early morning phase, but it was due to the direct sunlight which caused a rapid warm-up in the facade cavity and was eliminated in a short period of time when the flaps opened to evacuate the hot air. Even though it was a short term situation, attention should be paid especially in summer since temperature in the cavity is expected to be higher. Hence, two scenarios are planned and recommended considering the fact that thermal comfort in the garden zones can be improved during that short period. Both scenarios are accepted to be valid only for April month.

First scenario suggests that the upper temperature limit for the flaps to open can be changed throughout the year. Since the real upper limit is unknown, 26°C, which is the upper limit of the comfort zone, is suggested as the new limit to ensure that temperature does not exceed comfort zone limit. This value can be determined more accurately for each month if a year-round data is collected, staying within the comfort zone limits.

Second scenario offers a different approach to the situation. Hours from 09.30 to 11.00 for the 31st floor and from 11.00 to 12.30 for the 45th floor are considered to be critical since rapid warm-up is observed to take place between those hours. Setting flaps to open at 09.30 and 11.00 for the 31st and 45th floor, respectively, can prevent the accumulation of hot air which could not be eliminated before the air temperature rapidly exceeds the upper limit. Hours at which flaps would be set to open for the other months can, again, be decided by collecting data for each month. Yet, opening the flaps in advance seems to be a less effective solution over the long term than re-adjusting the upper temperature limit.

As a conclusion, it can generally be said that natural ventilation provided by double-skin facades is effective with regard to creating environments consistent with the comfort requirements. Promoting natural ventilation in high-rise buildings, either with a double facade, with atriums or covered balconies, is highly important to be able to eliminate the drawbacks of mechanical ventilation. Although every application is unique, a building with a double facade can be ventilated only by natural means when designed properly. Mechanical ventilation still cannot be abandoned in many cases, but the dependence on it is getting less as the new techniques are introduced and, eventually, there might be no need in the future.

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APPENDIX A

ARCHITECTURAL DRAWINGS OF ISTANBUL SAPPHIRE

Figure A.1 Site plan (Source: Tabanlıoğlu Architects)

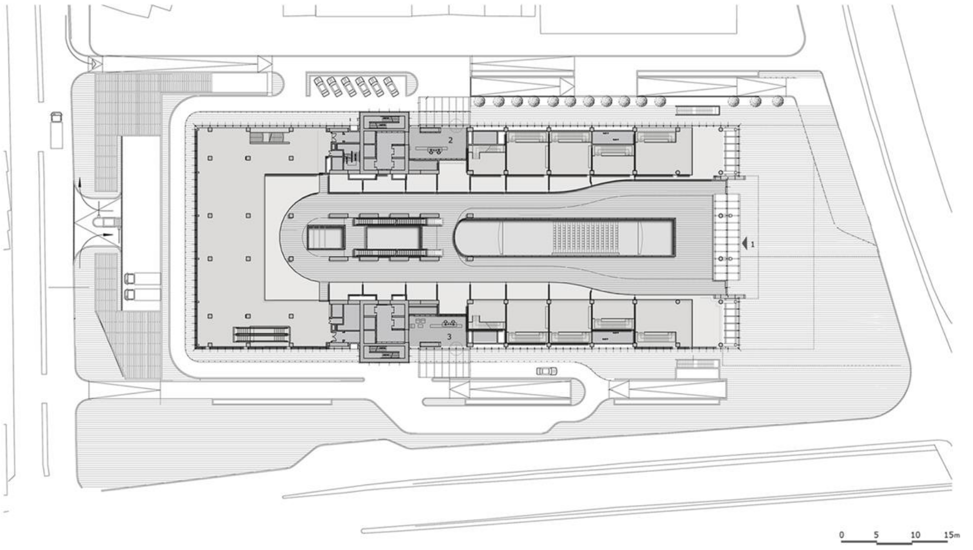

Figure A.2 Plan of the retail floor (Source: Tabanlıoğlu Architects)

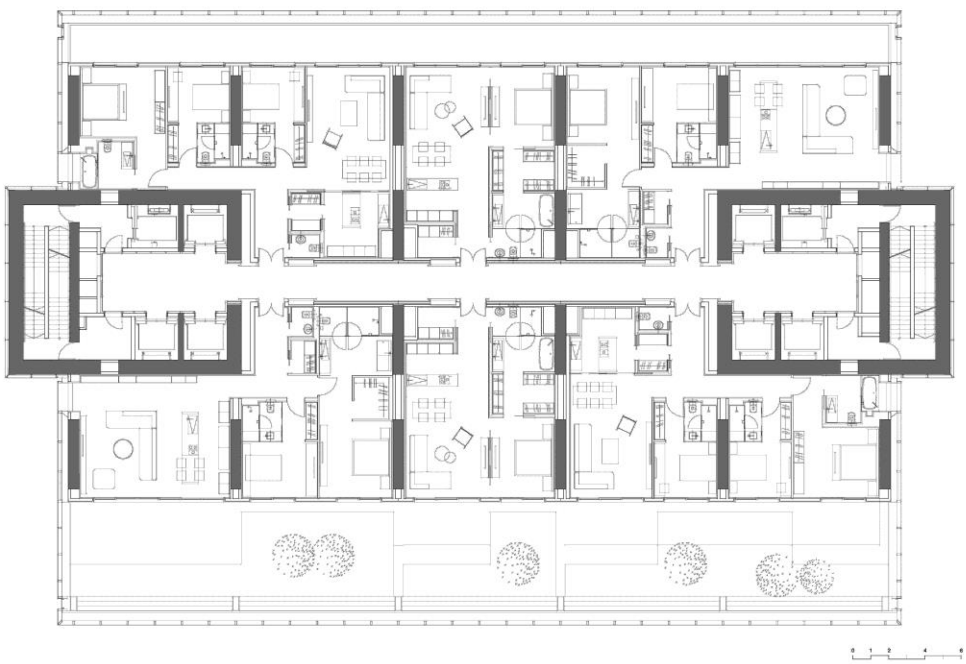

Figure A.3 Plan of the 6th floor, 1st zone (Source: Tabanlıoğlu Architects)

Figure A.4 Plan of the 21st floor, 2nd zone (Source: Tabanlıoğlu Architects)

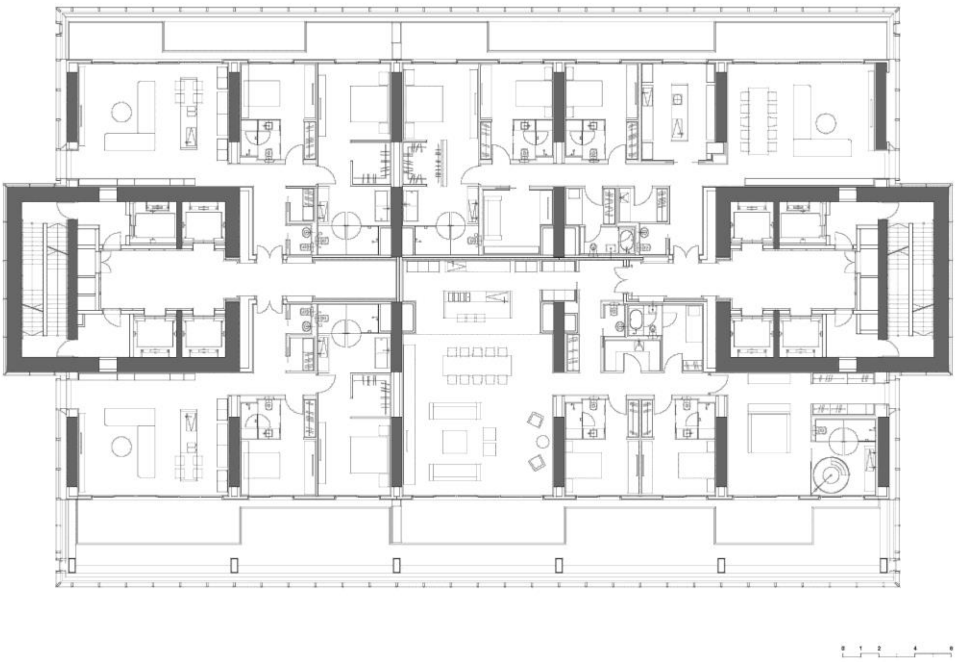

Figure A.5 Plan of the 34th floor, 3rd zone (Source: Tabanlıoğlu Architects)

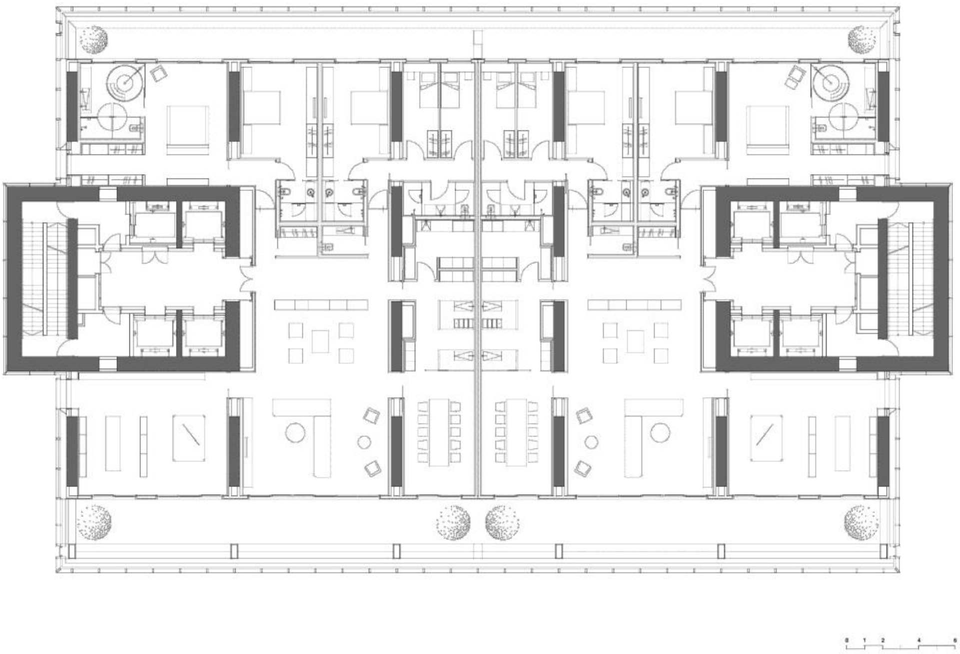

Figure A.6 Plan of the 44th floor, 4th zone (Source: Tabanlıoğlu Architects)

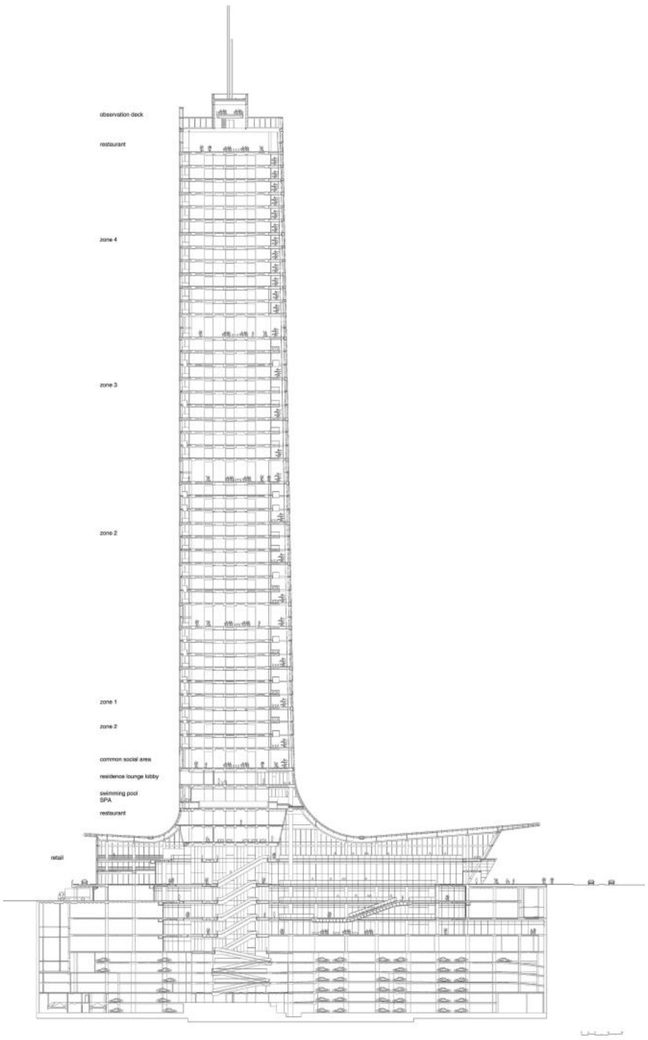

Figure A.7 Section of the building (Source: Tabanlıoğlu Architects)

APPENDIX B

IMAGES OF ISTANBUL SAPPHIRE

Figure B.1 Levent-Maslak axis (Source: Tabanlıoğlu Architects)

Figure B.2 A view from the shopping mall (Source: Tabanlıoğlu Architects)

Figure B.3 A view from the east facade (Source: Tabanlıoğlu Architects)

Figure B.4 A view from the east facade (Source: Tabanlıoğlu Architects)

Figure B.5 A view from the west facade (Source: Tabanlıoğlu Architects)

Figure B.6 A view from the east facade (Source: Tabanlıoğlu Architects)

Figure B.7 A view from the east facade (Source: Tabanlıoğlu Architects)

Figure B.8 A view of the inlets

APPENDIX C

RAW DATA COLLECTED BY DATA LOGGERS

Table C.1 Temperature and RH values on the 45^{th} floor (DL 13)

Date	**Time**	**Surface Temp. (°C)**	**Air Temp. (°C)**	**RH (%)**
26.04.12	12:30:00	20.531	20.65	37.313
26.04.12	12:40:00	20.436	20.674	36.738
26.04.12	12:50:00	20.174	20.555	36.624
26.04.12	13:00:00	20.031	20.484	37.432
26.04.12	13:10:00	19.817	20.436	37.698
26.04.12	13:20:00	19.841	20.436	38.103
26.04.12	13:30:00	19.77	20.484	38.276
26.04.12	13:40:00	19.722	20.46	38.611
26.04.12	13:50:00	19.674	20.484	38.782
26.04.12	14:00:00	19.746	20.531	38.921
26.04.12	14:10:00	19.651	20.531	38.618
26.04.12	14:20:00	19.627	20.484	38.849
26.04.12	14:30:00	19.627	20.484	38.883
26.04.12	14:40:00	19.603	20.46	38.746
26.04.12	14:50:00	19.627	20.484	38.815
26.04.12	15:00:00	19.555	20.484	38.378
26.04.12	15:10:00	19.46	20.436	37.9
26.04.12	15:20:00	19.318	20.293	37.717
26.04.12	15:30:00	19.318	20.246	37.814
26.04.12	15:40:00	19.555	20.46	38.24
26.04.12	15:50:00	19.532	20.627	36.937
26.04.12	16:00:00	19.27	20.365	37.115
26.04.12	16:10:00	19.103	20.174	37.367
26.04.12	16:20:00	19.294	20.174	37.908
26.04.12	16:30:00	19.46	20.388	37.794
26.04.12	16:40:00	19.222	20.317	37.449
26.04.12	16:50:00	19.056	20.079	37.831

Date	Time	Surface Temp. (°C)	Air Temp. (°C)	RH (%)
26.04.12	17:00:00	18.985	19.96	38.291
26.04.12	17:10:00	19.175	20.103	38.17
26.04.12	17:20:00	19.27	20.246	37.982
26.04.12	17:30:00	19.032	20.031	38.298
26.04.12	17:40:00	18.842	19.912	38.454
26.04.12	17:50:00	19.008	19.96	38.829
26.04.12	18:00:00	18.794	19.912	38.42
26.04.12	18:10:00	18.652	19.674	39
26.04.12	18:20:00	18.699	19.603	39.462
26.04.12	18:30:00	18.509	19.603	38.288
26.04.12	18:40:00	18.295	19.27	38.623
26.04.12	18:50:00	18.366	19.27	38.958
26.04.12	19:00:00	18.129	19.222	39.154
26.04.12	19:10:00	18.176	19.103	39.876
26.04.12	19:20:00	17.962	18.985	40.263
26.04.12	19:30:00	17.938	18.794	40.972
26.04.12	19:40:00	17.701	18.652	41.221
26.04.12	19:50:00	17.653	18.438	41.264
26.04.12	20:00:00	17.368	18.271	41.312
26.04.12	20:10:00	17.106	17.938	41.737
26.04.12	20:20:00	17.011	17.796	42.049
26.04.12	20:30:00	16.725	17.534	42.217
26.04.12	20:40:00	16.487	17.225	42.64
26.04.12	20:50:00	16.272	16.939	42.804
26.04.12	21:00:00	16.082	16.749	43.368
26.04.12	21:10:00	15.939	16.606	43.773
26.04.12	21:20:00	15.796	16.463	43.27
26.04.12	21:30:00	15.652	16.296	43.056
26.04.12	21:40:00	15.557	16.153	43.623
26.04.12	21:50:00	15.509	16.058	43.612
26.04.12	22:00:00	15.485	15.986	43.085
26.04.12	22:10:00	15.461	15.939	42.787
26.04.12	22:20:00	15.461	15.891	42.75
26.04.12	22:30:00	15.461	15.867	45.49
26.04.12	22:40:00	15.461	15.772	43.999
26.04.12	22:50:00	15.414	15.748	43.382
26.04.12	23:00:00	15.366	15.7	42.858
26.04.12	23:10:00	15.318	15.629	43.044
26.04.12	23:20:00	15.27	15.581	43.201
26.04.12	23:30:00	15.247	15.533	43.616
26.04.12	23:40:00	15.223	15.485	43.578

Date	Time	Surface Temp. (°C)	Air Temp. (°C)	RH (%)
26.04.12	23:50:00	15.199	15.438	43.508
27.04.12	00:00:00	15.175	15.414	43.602
27.04.12	00:10:00	15.175	15.39	43.697
27.04.12	00:20:00	15.175	15.366	43.92
27.04.12	00:30:00	15.175	15.342	44.143
27.04.12	00:40:00	15.199	15.318	44.43
27.04.12	00:50:00	15.223	15.318	44.687
27.04.12	01:00:00	15.223	15.294	45.037
27.04.12	01:10:00	15.27	15.294	46.092
27.04.12	01:20:00	15.318	15.318	46.508
27.04.12	01:30:00	15.342	15.318	46.604
27.04.12	01:40:00	15.461	15.366	47.751
27.04.12	01:50:00	15.509	15.414	48.324
27.04.12	02:00:00	15.605	15.39	48.573
27.04.12	02:10:00	15.772	15.461	49.679
27.04.12	02:20:00	15.986	15.629	50.014
27.04.12	02:30:00	16.034	15.629	50.263
27.04.12	02:40:00	16.296	15.819	50.382
27.04.12	02:50:00	16.511	16.082	50.323
27.04.12	03:00:00	16.606	16.153	49.739
27.04.12	03:10:00	16.796	16.344	49.92
27.04.12	03:20:00	16.963	16.487	49.783
27.04.12	03:30:00	17.058	16.534	49.695
27.04.12	03:40:00	17.177	16.606	49.327
27.04.12	03:50:00	17.201	16.677	49.148
27.04.12	04:00:00	17.034	16.463	48.079
27.04.12	04:10:00	17.011	16.368	48.762
27.04.12	04:20:00	16.987	16.415	47.883
27.04.12	04:30:00	17.011	16.392	48.038
27.04.12	04:40:00	17.13	16.654	49.05
27.04.12	04:50:00	17.058	16.582	48.157
27.04.12	05:00:00	16.987	16.511	47.768
27.04.12	05:10:00	17.106	16.534	48.972
27.04.12	05:20:00	17.225	16.773	49.538
27.04.12	05:30:00	17.272	16.892	49.364
27.04.12	05:40:00	17.391	16.892	49.647
27.04.12	05:50:00	17.368	16.915	48.611
27.04.12	06:00:00	17.106	16.701	47.03
27.04.12	06:10:00	16.915	16.558	47.869
27.04.12	06:20:00	16.82	16.463	48.648
27.04.12	06:30:00	16.796	16.511	49.535

Date	**Time**	**Surface Temp. (°C)**	**Air Temp. (°C)**	**RH (%)**
27.04.12	06:40:00	16.773	16.534	49.82
27.04.12	06:50:00	16.892	16.654	49.302
27.04.12	07:00:00	16.939	16.749	48.495
27.04.12	07:10:00	17.201	16.915	48.231
27.04.12	07:20:00	17.368	17.106	48.002
27.04.12	07:30:00	17.582	17.272	48.15
27.04.12	07:40:00	17.772	17.486	47.86
27.04.12	07:50:00	18.01	17.724	46.068
27.04.12	08:00:00	18.295	17.962	44.742
27.04.12	08:10:00	18.58	18.271	43.673
27.04.12	08:20:00	18.985	18.628	42.536
27.04.12	08:30:00	19.484	19.08	41.202
27.04.12	08:40:00	20.079	19.579	40.46
27.04.12	08:50:00	20.674	20.007	40.472
27.04.12	09:00:00	21.223	20.388	40.946
27.04.12	09:10:00	21.7	20.746	41.649
27.04.12	09:20:00	21.987	21.008	42.076
27.04.12	09:30:00	22.154	21.151	42.489
27.04.12	09:40:00	22.417	21.318	42.905
27.04.12	09:50:00	22.872	21.604	43.069
27.04.12	10:00:00	23.304	21.891	43.3
27.04.12	10:10:00	23.713	22.25	42.877
27.04.12	10:20:00	24.195	22.657	41.992
27.04.12	10:30:00	24.702	22.896	41.317
27.04.12	10:40:00	25.162	23.088	40.5
27.04.12	10:50:00	25.55	23.304	39.512
27.04.12	11:00:00	25.89	23.448	39.121
27.04.12	11:10:00	26.207	23.617	38.459
27.04.12	11:20:00	26.451	23.785	38.068
27.04.12	11:30:00	26.671	23.905	37.807
27.04.12	11:40:00	26.867	24.05	37.411
27.04.12	11:50:00	27.014	24.195	36.98
27.04.12	12:00:00	27.112	24.339	36.617
27.04.12	12:10:00	27.112	24.46	36.628
27.04.12	12:20:00	27.112	24.46	36.663
27.04.12	12:30:00	26.989	24.532	35.601

Table C.2 Temperature and RH values on the 31st floor (DL 11)

Date	Time	Surface Temp. (°C)	Air Temp. (°C)	RH (%)
26.04.12	12:30:00	23.232	23.208	32.982
26.04.12	12:40:00	23.112	23.256	32.428
26.04.12	12:50:00	23.016	23.136	31.963
26.04.12	13:00:00	22.872	23.04	32.514
26.04.12	13:10:00	22.657	22.776	33.083
26.04.12	13:20:00	22.537	22.609	33.728
26.04.12	13:30:00	22.369	22.465	34.026
26.04.12	13:40:00	22.226	22.345	34.292
26.04.12	13:50:00	22.082	22.274	34.768
26.04.12	14:00:00	22.011	22.202	35.175
26.04.12	14:10:00	21.915	22.154	34.826
26.04.12	14:20:00	21.772	22.082	35.026
26.04.12	14:30:00	21.7	21.915	35.079
26.04.12	14:40:00	21.652	21.891	35.18
26.04.12	14:50:00	21.557	21.819	35.345
26.04.12	15:00:00	21.127	21.557	35.08
26.04.12	15:10:00	20.865	21.318	34.955
26.04.12	15:20:00	20.484	21.008	35.063
26.04.12	15:30:00	20.222	20.793	35.385
26.04.12	15:40:00	19.865	20.555	35.157
26.04.12	15:50:00	19.484	20.293	35.713
26.04.12	16:00:00	19.222	20.031	36.505
26.04.12	16:10:00	19.08	19.865	37.133
26.04.12	16:20:00	18.842	19.746	36.952
26.04.12	16:30:00	18.675	19.603	37.344
26.04.12	16:40:00	18.628	19.484	38.04
26.04.12	16:50:00	18.533	19.46	38.24
26.04.12	17:00:00	18.485	19.413	38.168
26.04.12	17:10:00	18.604	19.484	38.242
26.04.12	17:20:00	18.866	19.674	38.598
26.04.12	17:30:00	19.199	20.031	38.298
26.04.12	17:40:00	19.508	20.293	38.257
26.04.12	17:50:00	19.793	20.531	38.349
26.04.12	18:00:00	20.055	20.746	38.303
26.04.12	18:10:00	20.269	20.913	38.117
26.04.12	18:20:00	20.46	21.079	37.728
26.04.12	18:30:00	20.65	21.246	35.907
26.04.12	18:40:00	20.817	21.342	36.497
26.04.12	18:50:00	20.936	21.437	37.119

Date	Time	Surface Temp. (°C)	Air Temp. (°C)	RH (%)
26.04.12	19:00:00	21.032	21.509	37.432
26.04.12	19:10:00	21.103	21.557	35.663
26.04.12	19:20:00	21.151	21.604	36.488
26.04.12	19:30:00	21.199	21.628	36.9
26.04.12	19:40:00	21.223	21.628	35.67
26.04.12	19:50:00	21.223	21.604	36.01
26.04.12	20:00:00	21.223	21.604	37.272
26.04.12	20:10:00	21.151	21.509	36.411
26.04.12	20:20:00	21.127	21.509	35.453
26.04.12	20:30:00	20.865	21.223	35.563
26.04.12	20:40:00	20.817	21.008	36.43
26.04.12	20:50:00	20.531	20.913	35.191
26.04.12	21:00:00	20.436	20.674	36.091
26.04.12	21:10:00	20.388	20.746	36.677
26.04.12	21:20:00	20.365	20.841	36.822
26.04.12	21:30:00	20.103	20.698	34.656
26.04.12	21:40:00	19.746	20.15	35.29
26.04.12	21:50:00	19.555	19.888	36.185
26.04.12	22:00:00	19.532	19.984	37.077
26.04.12	22:10:00	19.532	20.126	37.091
26.04.12	22:20:00	19.508	20.222	36.762
26.04.12	22:30:00	19.246	19.888	34.512
26.04.12	22:40:00	19.056	19.627	34.899
26.04.12	22:50:00	19.008	19.603	36.022
26.04.12	23:00:00	19.008	19.746	36.443
26.04.12	23:10:00	19.032	19.865	36.489
26.04.12	23:20:00	18.961	19.865	35.672
26.04.12	23:30:00	18.818	19.674	35.484
26.04.12	23:40:00	18.699	19.508	35.74
26.04.12	23:50:00	18.723	19.555	36.662
27.04.12	00:00:00	18.652	19.532	36.287
27.04.12	00:10:00	18.675	19.603	36.43
27.04.12	00:20:00	18.723	19.698	36.642
27.04.12	00:30:00	18.675	19.674	36.843
27.04.12	00:40:00	18.604	19.579	36.495
27.04.12	00:50:00	18.58	19.508	36.827
27.04.12	01:00:00	18.628	19.579	36.699
27.04.12	01:10:00	18.58	19.579	37.645
27.04.12	01:20:00	18.533	19.484	37.433
27.04.12	01:30:00	18.557	19.508	37.132
27.04.12	01:40:00	18.58	19.603	37.58

Date	Time	Surface Temp. (°C)	Air Temp. (°C)	RH (%)
27.04.12	01:50:00	18.438	19.484	37.231
27.04.12	02:00:00	18.271	19.246	38.151
27.04.12	02:10:00	18.224	19.151	38.006
27.04.12	02:20:00	18.271	19.294	38.021
27.04.12	02:30:00	18.319	19.365	38.297
27.04.12	02:40:00	18.271	19.341	39.2
27.04.12	02:50:00	18.152	19.032	39.869
27.04.12	03:00:00	17.986	18.794	38.976
27.04.12	03:10:00	18.033	18.866	39.918
27.04.12	03:20:00	18.081	19.056	40.237
27.04.12	03:30:00	18.176	19.199	40.286
27.04.12	03:40:00	18.247	19.341	39.1
27.04.12	03:50:00	18.343	19.484	39.382
27.04.12	04:00:00	18.366	19.508	39.652
27.04.12	04:10:00	18.414	19.532	39.788
27.04.12	04:20:00	18.461	19.579	40.127
27.04.12	04:30:00	18.533	19.627	40.565
27.04.12	04:40:00	18.604	19.698	39.939
27.04.12	04:50:00	18.652	19.722	39.541
27.04.12	05:00:00	18.675	19.77	39.913
27.04.12	05:10:00	18.675	19.698	39.605
27.04.12	05:20:00	18.58	19.484	38.779
27.04.12	05:30:00	18.485	19.318	39.03
27.04.12	05:40:00	18.461	19.175	39.35
27.04.12	05:50:00	18.485	19.318	40.099
27.04.12	06:00:00	18.533	19.436	40.311
27.04.12	06:10:00	18.509	19.484	40.682
27.04.12	06:20:00	18.485	19.436	40.311
27.04.12	06:30:00	18.509	19.46	41.376
27.04.12	06:40:00	18.604	19.555	41.055
27.04.12	06:50:00	18.699	19.555	41.453
27.04.12	07:00:00	18.699	19.579	41.588
27.04.12	07:10:00	18.889	19.651	41.662
27.04.12	07:20:00	19.175	19.865	41.321
27.04.12	07:30:00	19.436	20.055	41.375
27.04.12	07:40:00	19.674	20.246	41.495
27.04.12	07:50:00	19.936	20.388	41.61
27.04.12	08:00:00	20.174	20.579	41.697
27.04.12	08:10:00	20.484	20.793	42.582
27.04.12	08:20:00	20.913	21.079	42.283
27.04.12	08:30:00	21.413	21.413	41.988

Date	**Time**	**Surface Temp. (°C)**	**Air Temp. (°C)**	**RH (%)**
27.04.12	08:40:00	22.082	21.891	41.209
27.04.12	08:50:00	22.729	22.417	40.63
27.04.12	09:00:00	23.304	22.92	40.348
27.04.12	09:10:00	24.05	23.448	39.729
27.04.12	09:20:00	24.484	23.641	39.682
27.04.12	09:30:00	24.75	23.737	38.981
27.04.12	09:40:00	25.283	24.05	37.411
27.04.12	09:50:00	26.231	24.412	36.692
27.04.12	10:00:00	26.426	24.605	35.954
27.04.12	10:10:00	26.744	24.798	35.592
27.04.12	10:20:00	25.963	25.841	33.916
27.04.12	10:30:00	25.793	27.604	31.392
27.04.12	10:40:00	25.647	27.604	30.752
27.04.12	10:50:00	25.55	29.365	28.887
27.04.12	11:00:00	25.283	28.221	28.869
27.04.12	11:10:00	25.016	26.646	30.459
27.04.12	11:20:00	24.798	25.89	31.601
27.04.12	11:30:00	24.677	25.307	32.748
27.04.12	11:40:00	24.363	24.75	33.119
27.04.12	11:50:00	24.098	24.315	33.708
27.04.12	12:00:00	24.026	24.074	34.451
27.04.12	12:10:00	24.098	24.074	35.144
27.04.12	12:20:00	23.905	24.026	35.623
27.04.12	12:30:00	23.4	23.376	35.837

Table C.3 Air flow rates on the 45th floor (DL 09)

Date	**Time**	**Velocity (m/s)**
26.04.12	11:00:00	0.1935
26.04.12	11:05:00	0.1326
26.04.12	11:10:00	0.0763
26.04.12	11:15:00	0.2148
26.04.12	11:20:00	0.2945
26.04.12	11:25:00	0.1783
26.04.12	11:30:00	0.1798
26.04.12	11:35:00	0.1098
26.04.12	11:40:00	0.0641
26.04.12	11:45:00	0.0185
26.04.12	11:50:00	0.0809
26.04.12	11:55:00	0.0778
26.04.12	13:30:00	0.058
26.04.12	13:35:00	0.1042
26.04.12	13:40:00	0.0124
26.04.12	13:45:00	0.055
26.04.12	13:50:00	0.0519
26.04.12	13:55:00	0.0246
26.04.12	14:00:00	0.0504
26.04.12	14:05:00	0.0519
26.04.12	14:10:00	0.0428
26.04.12	14:15:00	0.0626
26.04.12	14:20:00	0.0854
26.04.12	14:25:00	0.0778

Table C.4 Air flow rates on the 31st floor (DL 09)

Date	**Time**	**Velocity (m/s)**
26.04.12	12:20:00	0.0459
26.04.12	12:25:00	0.0733
26.04.12	12:30:00	0.0276
26.04.12	12:35:00	0.0383
26.04.12	12:40:00	0.0154
26.04.12	12:45:00	0.0885
26.04.12	12:50:00	0.02
26.04.12	12:55:00	0.0169
26.04.12	13:00:00	0.0687
26.04.12	13:05:00	0.0596
26.04.12	13:10:00	0.0489
26.04.12	13:15:00	0.1296
26.04.12	14:40:00	0.023
26.04.12	14:45:00	0.0169
26.04.12	14:50:00	0.122
26.04.12	14:55:00	0.0535
26.04.12	15:00:00	0.1859
26.04.12	15:05:00	0.1676
26.04.12	15:10:00	0.1235
26.04.12	15:15:00	0.1159
26.04.12	15:20:00	0.2554
26.04.12	15:25:00	0.1737
26.04.12	15:30:00	0.2194
26.04.12	15:35:00	0.0596

Table C.5 CO_2 concentrations on the 45th floor (DL 10)

Date	**Time**	**CO_2 (ppm)**
26.04.12	11:00:00	402.4
26.04.12	11:10:00	382.87
26.04.12	11:20:00	381.04
26.04.12	11:30:00	382.26
26.04.12	11:40:00	382.87
26.04.12	11:50:00	382.87
26.04.12	12:00:00	382.26
26.04.12	12:10:00	382.87
26.04.12	12:20:00	380.43
26.04.12	12:30:00	380.43
26.04.12	12:40:00	380.43
26.04.12	12:50:00	380.43
26.04.12	13:00:00	380.43
26.04.12	13:10:00	377.99
26.04.12	13:20:00	380.43
26.04.12	13:30:00	387.76
26.04.12	13:40:00	380.43
26.04.12	13:50:00	380.43
26.04.12	14:00:00	379.82
26.04.12	14:10:00	377.99
26.04.12	14:20:00	380.43
26.04.12	14:30:00	385.93
26.04.12	14:40:00	382.26
26.04.12	14:50:00	377.99
26.04.12	15:00:00	377.99
26.04.12	15:10:00	377.99
26.04.12	15:20:00	378.6
26.04.12	15:30:00	379.21
26.04.12	15:40:00	377.99
26.04.12	15:50:00	380.43
26.04.12	16:00:00	377.38
26.04.12	16:10:00	381.04
26.04.12	16:20:00	378.6
26.04.12	16:30:00	390.2

Table C.6 CO_2 concentrations on the 31st floor (DL 12)

Date	**Time**	**CO_2 (ppm)**
26.04.12	11:00:00	482.97
26.04.12	11:10:00	480.53
26.04.12	11:20:00	480.53
26.04.12	11:30:00	482.36
26.04.12	11:40:00	484.19
26.04.12	11:50:00	481.14
26.04.12	12:00:00	488.46
26.04.12	12:10:00	488.46
26.04.12	12:20:00	503.11
26.04.12	12:30:00	486.02
26.04.12	12:40:00	486.63
26.04.12	12:50:00	480.53
26.04.12	13:00:00	481.75
26.04.12	13:10:00	481.14
26.04.12	13:20:00	481.14
26.04.12	13:30:00	478.7
26.04.12	13:40:00	480.53
26.04.12	13:50:00	478.09
26.04.12	14:00:00	479.31
26.04.12	14:10:00	478.7
26.04.12	14:20:00	478.7
26.04.12	14:30:00	480.53
26.04.12	14:40:00	490.91
26.04.12	14:50:00	488.46
26.04.12	15:00:00	478.7
26.04.12	15:10:00	481.14
26.04.12	15:20:00	476.26
26.04.12	15:30:00	478.7
26.04.12	15:40:00	481.14
26.04.12	15:50:00	478.7
26.04.12	16:00:00	476.26
26.04.12	16:10:00	476.87
26.04.12	16:20:00	476.26
26.04.12	16:30:00	476.26