OPTIMIZING THE FENESTRATION OF TYPICAL TURKISH SCHOOL BUILDING WITH RESPECT TO DAYLIGHT AND THERMAL PERFORMANCE

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ABSTRACT

OPTIMIZING THE FENESTRATION OF TYPICAL TURKISH SCHOOL BUILDING WITH RESPECT TO DAYLIGHT AND THERMAL PERFORMANCE

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The aim of this study is the maximization of the occupant comfort with the minimization of the energy consumption for artificial lighting, heating and cooling in typical Turkish school buildings through the better design of the fenestrations which were predetermined with a directive called "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" i.e. the "General Principles For Preparing Architectural Projects For Educational Buildings" as a monotype regardless of orientation and climate. The study was conducted through the daylight and thermal analysis of a typical classroom diversified with alternative fenestration configurations for north and south orientations with a simulation software, namely "Ecotect Analysis 2011". In addition, the simulated data were validated through the daylight analysis of the classrooms of a school building located in Çankaya District of Ankara with data loggers.

The study provides information about the effects of the area, shape, location and orientation of windows as well as the effects of a lightshelf and an overhang on the daylight and thermal performance of these buildings. According to the study, the directive fails for both north and south orientations and visual comfort can be reached only for south facing classrooms with the use of a lightshelf, therefore, classrooms facing north should be avoided unless the classroom sizes are changed. The study also reveals that a more detailed analysis is required to optimize the fenestration of these building with respect to thermal and daylight performances and it is not appropriate to set a monotype window design for all orientations and climates.

Keywords: Daylighting, Classroom Fenestration Design, Solar Control, Visual Comfort, Thermal Performance

ÖZ

TİPİK BİR TÜRK OKUL BİNASININ PENCERELERİNİN DOĞAL AYDINLATMA VE ISIL PERFORMANS AÇISINDAN OPTİMİZASYONU

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Bu çalışmanın amacı; tipik bir Türk okul binasının yön ve iklim dikkate alınmaksızın "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" isimli bir yönerge ile belirlenmiş, tek tip pencere tasarımına daha iyi bir çözüm bularak, konfor koşullarının artırılması ile yapay aydınlatma, ısıtma ve soğutma için harcanılan enerjinin azaltılmasını sağlamaktır. Bu çalışma, güney ve kuzey yönleri için farklı pencere tasarımlarıyla çeşitlendirilmiş tipik bir sınıfın doğal aydınlatma ve ısıl performans analizlerinin "Ecotect Analysis 2011" isimli benzetim programında yapılmasıyla gerçekleştirilmiştir. Bununla birlikte, benzetim programından elde edilen verilerin doğrulanması amacıyla, Ankara'da yer alan bir okul binasının sınıfları, veri kaydediciler kullanılarak doğal aydınlatma açısından analiz edilmiş olup, söz konusu analizin sonuçları benzetim programından elde edilen verilerin güvenilirliğini göstermiştir.

Bu çalışma; pencere alanı, şekli, konumu ve yönü ile konsol ve ışık raflarının tipik bir Türk okul binasının doğal aydınlatma ve ısıl performansına etkileri üzerine bilgi sağlamaktadır. Bu çalışmaya göre, yönerge ile belirlenmiş pencere tipi hem kuzey hem de güney yönü için görsel konfor şartlarını sağlayamamış olup, görsel konfor koşulları ancak ışık rafı kullanılarak sadece güneye bakan sınıflarda sağlanabilmiştir. Dolayısıyla, sınıf boyutları değiştirilmedikçe kuzeye bakan pencerelerden kaçınılması gerektiği sonucuna varılmıştır. Bununla birlikte; bu çalışma sınıf pencerelerinin doğal aydınlatma ve ısıl performans açısından optimize edilmesi için daha detaylı bir çalışma gerektiğini ve tek tip bir pencere tasarımının tüm yön ve iklimlerde kullanılmasının uygun olmayacağını ortaya çıkarmıştır.

Anahtar Kelimeler: Doğal Aydınlatma, Sınıf Pencerelerinin Tasarımı, Güneş Kontrolü, Görsel Konfor, Isıl Performans

To My Mum

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AAC	Autoclaved Aerated Concrete
ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
CIE	International Commission On Illumination
DDH	Discomfort Degree Hours
Deghrs	Degree Hours
EPS	Expanded Polystyrene
Hrs	Hours
IESNA	Illuminating Engineering Society of North America
Low-e	Low Emissive
RH	Relative Humidity
SHGC	Solar Heat Gain Coefficient
TS	Turkish Standards
UV	Ultra Violet
U-Value	Coefficient of Thermal Transmittance
VT	Visible Transmittance

CHAPTER 1

INTRODUCTION

This chapter consists of four main sections. These sections present information about the argument for the study, objectives of the study, procedure of the study and the disposition of subject matter, respectively.

1.1 Argument

The primary aim of a building is to satisfy comfort conditions for its occupants through the control of environmental parameters. Building environmental control systems are all operated by moving energy into or out of a building. Energy need for environmental control systems are mostly met by non-renewable sources polluting the environment. With the use of solar energy, which is renewable and nonpolluting, energy resource depletion could be reduced and energy conservation could be achieved. It is a decentralized source of energy available to everyone. Solar energy is not noisy, not costly and free from odors. On the other hand, solar energy has weaknesses stemming from its diffuseness, intermittent availability and uneven distribution. (Lechner, 2001)

Specifically, light energy from the sun, that is daylight, can replace the energy used in artificial lighting. For example, one watt of natural light replaces more than three watts of primary energy used by a fluorescent light and even more if replacing tungsten light bulbs. (Thomas, 1999) Daylighting can be used either actively or passively. In passive systems; daylight is collected without the use of complicated controls and mechanical devices. Due to the fact that passive systems are consisted of common building components such as window, wall, floor or ceiling, it has a little or no additional first costs. (Littler and Thomas, 1984) Daylighting is usually the most significant energy saving measure in non-domestic buildings while passive solar space heating is the most significant one in domestic buildings. (Baker and Steemers, 2000) 70 percent of the lighting energy could be saved through daylighting in most non domestic buildings such as schools. With the use of daylighting, cooling loads could also be reduced due to the generation of less heat by daylighting than artificial lighting for a given amount of light. (Lechner, 2001) On the other hand, energy consumption is not an indicator of the degree of comfort in buildings, thus while reducing the energy consumption with these systems, internal environmental quality could not be reduced. The comfort inside for the occupants should still be provided by the building. (Thomas, 1999)

In addition to the energy conservation through daylighting, due to its dynamic nature, it also satisfies biological need by responding to the natural rhythms of day. A research showed an improvement of about 20 percent in the performance of students in daylit schools over standard schools due to the stimulating effect stemming from the changes in the quality and intensity of natural light (Lechner, 2001) Daylight from windows and skylights give occupants contact with the outside world as well as it brings out the natural contrast and color of objects with its optimum. (Goulding and Lewis, 1994) On the other hand, literature lacks information about daylighting design in comparison with the other system designs. Buildings are designed regarding thermal performance rather than daylighting in consequence of which artificially lit buildings appear.

The climate and micro-climate of the site, the orientation of the building, the building design, especially the fenestration design, occupancy times and occupant behavior significantly affects the daylight performance of a building. The occupancy time of a school ideally matches the daylight availability time. Schools can save energy with a reasonable daylighting design while maintaining the internal comfort conditions. School designs should be optimized not only with regard to daylight performance but also thermal performance should be considered.

In Turkey, the directive named as "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" i.e. the "General Principles For Preparing Architectural Projects For Educational Buildings" (2010) sets up rules for the architecture of the Turkish school buildings. This legislation forces unique design for schools at different orientations and in different site settings which results a school design reflecting a heedless uniformity. However, schools which are densely populated can be designed regarding both daylighting and thermal aspects with respect to site conditions and orientations. By doing so, with an optimized fenestration design, artificial lighting systems can be displaced with daylighting and visual comfort conditions inside the building can be enhanced without the reduction of thermal performance.

1.2 Objectives

The study was conducted to optimize the façade design of typical school regarding the daylight and thermal performance through the comparison of the different fenestration configurations for different orientations in a specific climatic condition. In this study, it was assumed that school was located in Ankara. By the study, energy consumption can be minimized with a maximized occupant comfort.

The fundamental objectives of the study are;

- to explore the effect of orientation; the effect of area, shape and position of the windows; the effect of solar control devices namely overhang and lightshelf; on daylight and thermal performance and comfort conditions.
- to determine the better fenestration configurations for different orientations in terms of their relative performance
- to understand the relation between daylight and thermal performance of alternative fenestration compositions.

- to analyze the reasons of visual and thermal discomfort conditions with respect to design criteria.

- to validate the directive named as "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" i.e. the "General Principles For Preparing Architectural Projects For Educational Buildings" (2010).

1.3 Procedure

The first phase of the study was the collection of the current official information regarding the design of schools. Then, the collected information was analyzed in order to identify the typical properties of a classroom on which the Ecotect model based. Next, fenestration alternatives were created for different orientations and after the completion of the Ecotect modeling and settings, series of daylight and thermal simulations were run with different fenestration configurations for different sky settings at specific dates. Data output of these analyses were collected. After that, to verify simulated data, the classrooms of a school building located in Çankaya district of Ankara were analyzed in terms of daylight performance with data loggers and also with Ecotect Analysis 2011. The results were evaluated according to daylight and thermal performances regarding the recommendations and guidelines cited in the Literature Review.

1.4 Disposition

There are five chapters in this report. This first chapter comprises of the argument, the objectives, the procedure of the study and the disposition summarizing the following chapters. The second chapter includes literature review on the various aspects of daylighting design and relevant aspects of thermal design, with the detail information about the fenestration design. The third chapter provides a detail description of the material and method of the study. The fourth chapter includes the results obtained from the computer analyses and discussions of these analyses. The fifth chapter states the conclusion of the study by summarizing its findings and offering recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Energy

The Sun emits electromagnetic radiation reaching the earth. The amount and composition of the solar radiation does almost not change until it reaches the outer edge of the earth's atmosphere. This quite unvarying amount is called the solar constant. (Lechner, 2001) However, when this radiation passes through the earth's atmosphere, series of losses occur resulting in a change in quantity and quality of solar radiation. A part of this beamed radiation is scattered due to atmospheric constituents such as air molecules, water droplets, dust particles; another part is absorbed by water vapor, ozone, carbon dioxide and other gases. (Olgyay, 1963) In the process of being scattered and absorbed, a certain part is lost back to space, another part is diffused throughout the atmosphere and reaches the surfaces as diffuse radiation. However, the remaining part of the original beamed radiation still passes through the atmosphere without any change and reaches the surfaces as direct-beam radiation. (Heerwagen, 2004) Due to these losses, the actual surface at the ground level receives considerably less solar energy which, in turn, is partly reflected and mostly absorbed by the surface of the earth. As a result, the incident solar radiation arriving at a building surface consists of direct shortwave radiation from the sun, diffuse shortwave radiation from the sky vault and reflected short-wave radiation from the surrounding terrain. (Olgyay, 1963)

The solar spectrum includes the ultraviolet, visible and infrared radiation. These three forms of radiation differs from each other by the wavelength range over which each exits. The visible part of the spectrum is the daylight including direct sunlight and diffuse light from the sky. Daylight is also reflected from the ground and surrounding surfaces. Thus, daylight entering a window consists of direct sunlight, sky light and reflections from the nearby surfaces. (Lechner, 2001)

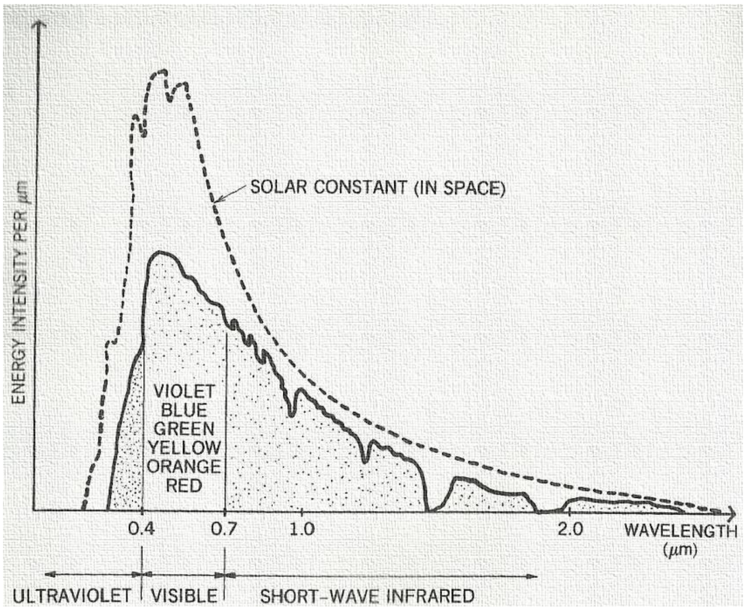


Figure 2.1 The Solar Spectrum (Lechner, 2001)

2.1.1 Factors Affecting Availability of Solar Energy

The amount and composition of solar radiation reaching the Earth's surface vary widely with solar geometry, elevation and the composition of the atmosphere. In addition to these factors; the availability of solar radiation at the building site can be affected by such microclimatic factors as vegetation, natural and built-up surroundings and form of land (Lechner, 2001)

a) Solar Geometry

The sun's position in the sky can be described in terms of two angles: solar altitude and solar azimuth. These angles refer only to direct radiation. "Solar altitude is defined as the vertical angle between the horizon and the line of sight to the sun. Solar azimuth is the horizontal angle between the projection on the ground of the line of sight to the sun and the North South axis." (Watson and Labs, 1983) Altitude angle is a function of the geographic latitude, time of year, and time of day. At low altitude angles, the sun rays pass through more of the atmosphere consequently the radiation reaching the surface will be lesser in amount and more modified in composition than the high altitude angles. In addition, at low altitude angles, a beam of sunlight will illuminate a larger area which is related to cosine law. (Lechner, 2001)

Position of the sun in the sky is often represented on sun path diagrams where the solar altitude and azimuth angles for the whole year, hour by hour are plotted. Sun path diagrams, varying with latitude, composed of series of curves. For specific latitude, each curve represented the sun path of one day and whole curves constitute a year. (Lechner, 2001) Lines at right angles to these curves are the hour lines referring to solar time which is defined, for a given location, so that 12 noon occurs precisely when the sun is at its highest elevation. (Baker and Steemers, 2000) In yearly basis, the highest sun path is in summer solstice, the lower sun path is in winter solstice and the middle sun path is in equinox. In daily basis, the highest point of a path is at solar noon, the lowest is at sunrise and sunset. In addition, the highest the path, the shortest the distance, the greatest the amount of energy received at the ground level. (Lechner, 2001)

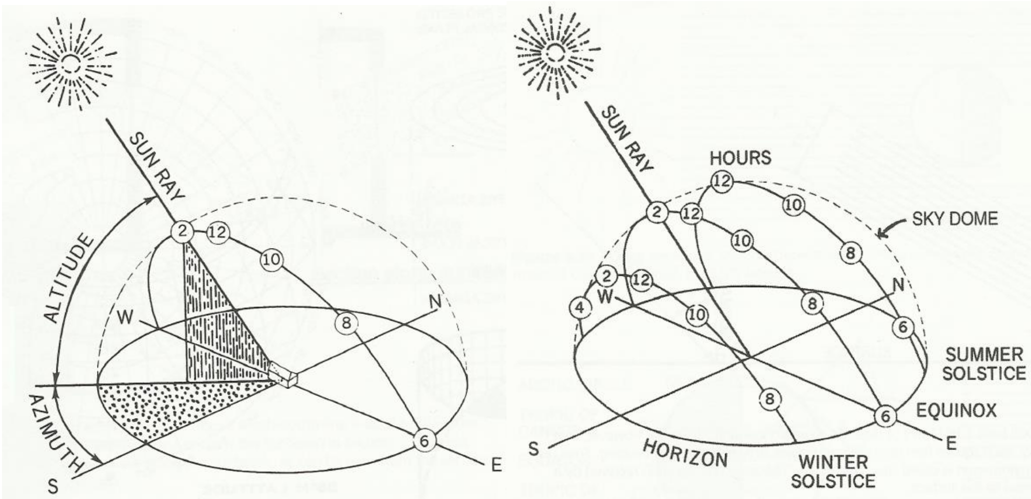


Figure 2.2 Altitude-Azimuth Angles and Three Sun Paths of June 21, September/March 21 and December 21 (Solstices and Equinoxes) (Lechner, 2001)

b) Atmospheric Conditions

The atmospheric conditions of the site affect the ratio of diffuse to direct radiation. At cloudy, humid and dusty days, the amount of diffuse radiation, which is independent of solar geometry, is increased and becomes the dominating component of solar radiation. (Lechner, 2001) For instance; the ratio of diffuse to direct radiation may be 1 during cloudy days while it may be only 0.15 during clear days. (Olgyay, 1963) Cloudiness is described as indices between 0 and 1, 0 and 8 or 0 and 10 representing the fraction of the sky that is covered by the cloud or it can also be indicated as sunshine hours. (Baker and Steemers, 2000)

c) Elevation and Other Microclimatic Factors

The intensity of the radiation received on the earth's surface increases with the height above sea level. The vegetation, natural and built-up surroundings also affects the received radiation on the surfaces. They can interfere with the line of sight to the sun or obstruct the parts of the sky-vault from a given point of observation resulting in a desired or undesired shade changing with seasons and also block of daylight. (Olgyay, 1963) On the other hand, vegetation can reduce glare effects. Meanwhile, the reflected component of the solar radiation received on a particular surface is affected by the reflective or absorptive characteristics of the surrounding surfaces. (Thomas, 1999)

Table 2.1 Solar Reflectance (Albedo) (Lechner, 2001)

Surface	Solar Reflectance	
	Normal Finish	"Cool"*
White—high reflectance	85	—
White—typical	75	80
Cream-color coating	60	67
Galvanized steel	50	—
Aluminum	50	—
Weathered concrete	35	—
Light gray coating	30	50
Middle green coating	30	40
Brick red coating	25	30
Dark green coating	25	30
White asphalt shingles	20	—
Dark bronze coating	10	25
Dark asphalt shingles	10	—
Black membrane	5	—

*Available only as a special coating.

2.1.2 The Interaction of Solar Radiation with Surfaces

When solar radiation strikes a surface, three different interactions happened: it is reflected, absorbed or transmitted with the relative proportions depending on the characteristics and condition of the material surface and the wavelenght of the incoming radiation. (Thomas, 1999) For example, in terms of wavelength, glass changes from 0 to about 80 percent transmission in the ultra-violet part of the spectrum. Longer wavelenghts of UV pass the glass, but shorter UV does not. On the other hand, a textured, bumpy surface will absorb more radiation than a smooth surface of same material and color. Since the solar energy is concentrated near the visible part of the spectrum, color values of surfaces significantly affect the type of interaction. In addition, these three values also depend on the incidence angle of the radiation with respect to the surface. For example, transmittance of solar radiation through glazing is almost constant for an angle of incidence from 0˚ to about 45˚ whereas, the transmittance of solar radiation through glazing is considerably reduced above 70˚. (Lechner, 2001) These parameters can be qualified by total, which means all visible and invisible radiation or only by visible radiation. For example, the division of the reflected light flux to the incident light flux gives the light reflectance of that surface. (Baker and Steemers, 2002)

Table 2.2 Light Reflectance (Thomas, 1999)

Material	*Reflectance*
1. *Internal*	
White paint[a]	0.85
White paper	0.8
Light grey paint	0.68
Strong yellow paint	0.64
Wood – light veneer	0.4
Strong green paint	0.22
Quarry tiles	0.1
Carpet – deep colours	0.1
2. *External*	
Snow (new)	0.8
Portland stone	0.6
Sand	0.3
Brickwork (red)	0.2
Green vegetation	0.1

[a] BS 4800 colour codes are given in the original reference.

On the other hand, materials can be optically classified according to transmission of light as transparent, translucent and opaque. (Heerwagen, 2004) For opaque materials, the absorption of radiation takes place at the surface, whereas for transparent materials the absorption takes place in the body of the material and is dependent upon the thickness of the material. (Baker and Steemers, 2002)

Light can be transmitted or reflected in a specular, diffused or mixed manner. The diffusion of light means that the reflected or transmitted light flux is distributed in all directions although the incident beam may be direct whereas the specularity means the opposite. Rough surfaces have mostly diffuse character when compared to the specular character of smooth surfaces. Color also has an effect on diffusivity that is the darker the surface the lower the diffuse reflectance. However, because the specular reflection takes place in the outermost layer of the surface, the specularity may remain constant for light and dark surfaces. (Baker and Steemers, 2002)

2.2 Daylighting

The aim of a good daylight design is first to provide fully sufficient light for efficient visual performance and second to ensure a comfortable and pleasing environment appropriate to its purpose. Thus not only quantity but also quality of light is important. (Baker and Steemers, 2002) Providing sufficient daylight to buildings can be quite a challenge due to the great variability in available daylight. It can sometimes be less or sometimes be more. (Thomas, 1999) The period of time when daylight is likely to satisfy the lighting needs of a building can be calculated for specific latitude using a set of curves published by the CIE. Out of these curves, the percentage of the occupancy times, when a required exterior horizontal level of illumination will be reached, can be read. (Goulding, 1994)

2.2.1 Different Means to Describe Light

Light is measured by the rate of energy transfer evaluated in terms of its effect on the average human eye. This flow rate named as light or luminous flux and described by the unit lumen. The spread of light over a surface is expressed in terms of lumens per unit area and named as illumination and measured in lux. The property of a source to emit light in a given direction is called the luminous intensity and is measured in candelas. Luminance is the amount of light that is reflected of a surface or light coming from a source in a specific direction and expressed in terms of candelas per unit area. The luminance of a reflecting surface depends upon the illumination and the reflecting characteristics of the surface. (Hopkinson, 1966)

The physical brightness is a term used for the luminance of an object as measured by photometer whereas the subjective brightness or apparent brightness is another term used for the luminous sensation which is seen by the adapted eye in the given surroundings. Apparent brightness depends upon the light received from the surface and the light received from the whole field of vision. (Hopkinson, 1966) Thus the brightness (apparent brightness) of an object is related also to the geometry of viewer in relation to the light source. On the hand, the effect of light sources on color appearance is called color rendering. (Lechner, 2001)

2.2.2 Vision

Things are seen by virtue of their brightness and color, especially by the differences in brightness and color. Brightness is a function of light received at the eye, while color is related to a rather complicated manner with its spectral composition. Human being judges the brightness of an object relative to the luminance of the surroundings which can be specified as adaptation level meaning the average luminance of all objects in the whole visual field. (Hopkinson, 1966) For example, the moon appears much brighter during nighttime than during daytime due to the difference in adaptation level although its luminance remains the same. (Baker and Steemers, 2002)

The adaptation level in a room can be sky dominated if the area of sky occupies a considerable portion in the field of view and the sky is bright. As a result, although objects in the darker parts of the room may be receiving high levels of illumination, they will seem to be dark. In the same way, adaptation level in a room can be objects dominated, if the objects occupy a large part of the field of view. If the objects have low reflectance, the result will be the increase in the apparent brightness of the sky as seen through the window. (Hopkinson, 1966)

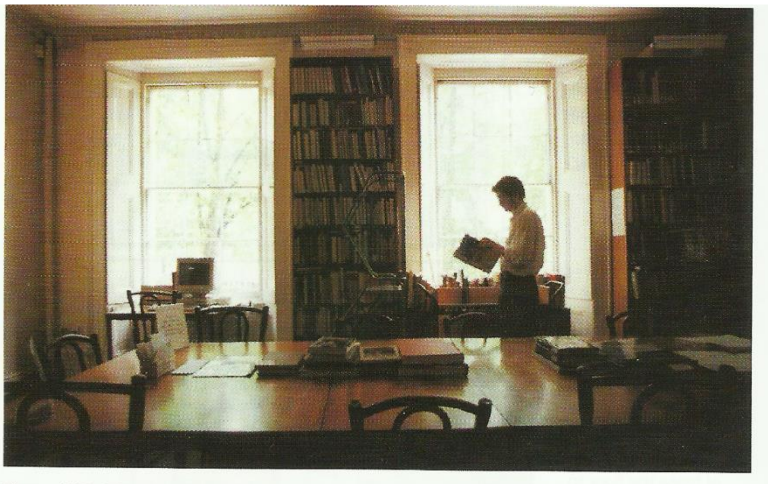


Figure 2.3 The Increase in the Apparent Brightness of the Sky Seen Through Window (Baker and Steemers, 2002)

Goodness of the vision can be measured by visual performance. Ensuring good visual performances means that visual tasks need to be performed with accuracy, safety and at reasonable speed. (Baker and Steemers, 2002) Without introducing any question of color, Good vision -performance- results from a combination of good lighting and good sight. Good sight is related to inherent visual capacity of people while good lighting is related to the factors that are inherent in the task such as the critical detail, and the critical contrast of the task. (Hopkinson, 1966)

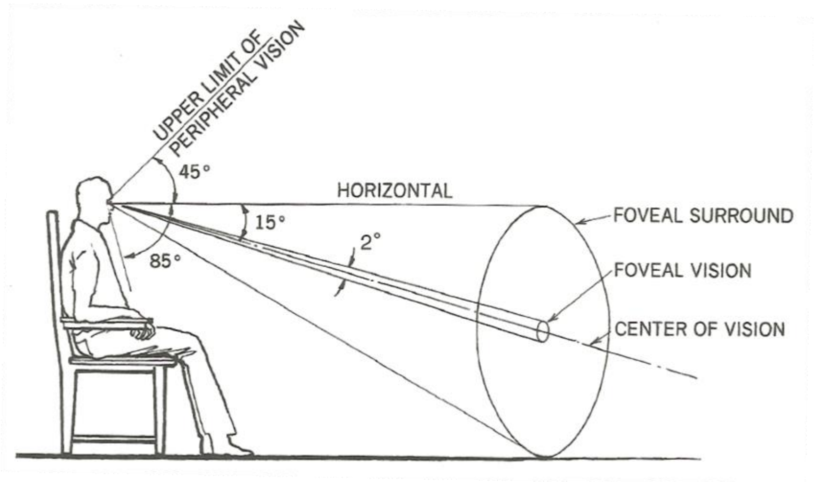


Figure 2.4 Field of Vision - 130˚ Vertical, 180˚ Horizontal (Lechner, 2001)

2.2.3 Skylight and Sunlight

Skylight and sunlight differs not only in quantity, but also in such qualities as diffuseness, color and efficacy. (Lechner, 2001) The sky vault -whether overcast, partly cloudy or clear- is a large diffuse source of illumination with a variable luminance distribution and has relatively low brightness whereas the sun -when not obscured by clouds- is a localized, directional and intense source of illumination and has relatively high brightness. (Hopkinson, 1966)

The sky conditions affect both the quantity and quality of daylight. Under overcast sky conditions, due to the obstruction of sunlight by clouds, the main challenge is the quantity, while under clear sky conditions the main challenge is mostly the quality. Although the illumination from an overcast sky is relatively low, it is still 10 to 50 times greater than what is needed indoors. (Lechner, 2001) Moreover, on a standard overcast day, the approximate level of illumination of a horizontal skylight is three times greater than the vertical window. (Thomas, 1999)

The brightness of a standard overcast sky at the zenith is typically three times greater than at the horizon. The brightness of a standard clear sky at zone around the sun is about 10 times greater than the darkest part of the sky which is opposite the sun in the same vertical plane in a direction 90˚ away from the position of sun. (Lechner, 2001) Although the luminance of the sky changes with orientation, in common daylighting practice, it is accepted that the luminance of the sky is independent of orientation. (Goulding, 1994)

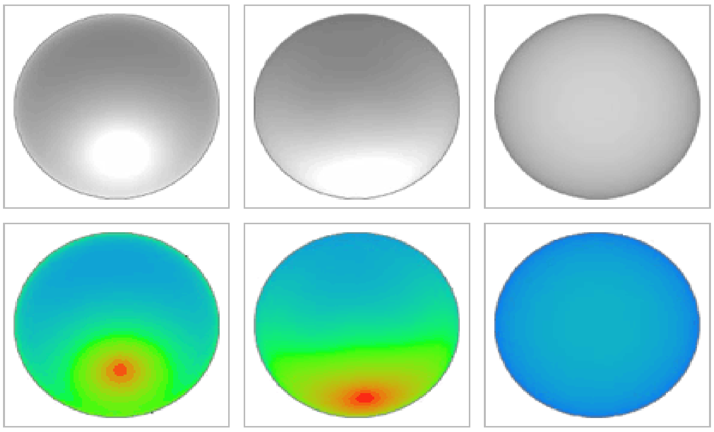


Figure 2.5 Comparison of the 3 Main CIE Sky Models (http://wiki.naturalfrequency.com/wiki/Sky_Illuminance)

On the other hand, knowledge of spectral energy distribution of daylight is unnecessary for most daylight calculation and design purposes. (Hopkinson, 1966)

2.2.4 Daylight Level Metrics

The daylight illumination in an interior can be described either in absolute terms as illumination value or as a percentage in the way of daylight factor. "The daylight factor is the ratio of the internal illumination to the illumination simultaneously available outdoors which is measured for an unobstructed view of sky." In daylight factor concept, the effects of direct and reflected sunlight are excluded. Thus, daylight factor concept is inapplicable in the calculation of the daylight illumination in sunny climates -clear or partly cloudy sky with sunlight. (Hopkinson, 1966)

In the calculation of daylight factor, the daylight reaching any point on a work surface is comprised of sky component; externally reflected component which is the reflection of light into the daylit space from external objects and internally reflected component which is the reflections of light from the interior surfaces. There should be a line of sight to a point in room with the sky to get that point light from the sky. Actually, due to the fact that the cloud cover of the sky seen from window changes instant to instant, daylight factor also change from instant to instant but for simplification the cloud cover of sky accepted as invariant in most daylight factor calculations. (Hopkinson, 1966)

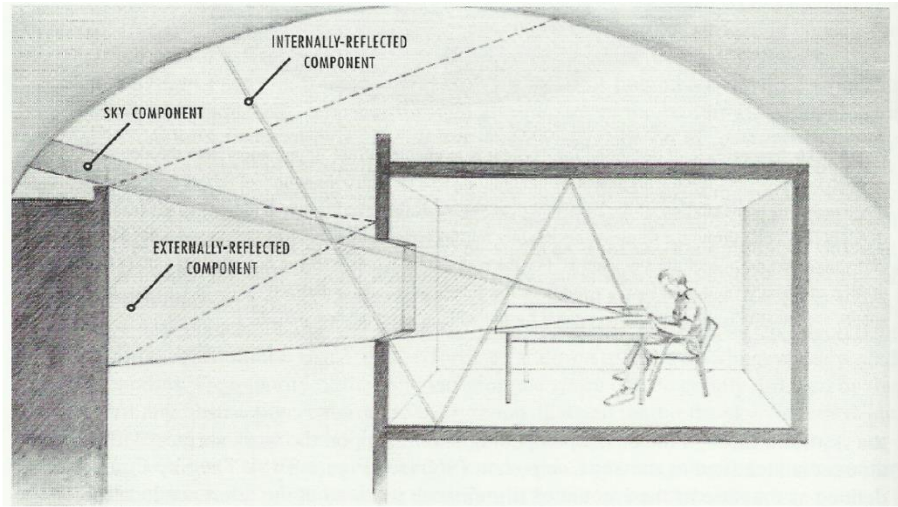


Figure 2.6 Three Components Comprising Daylight Factor (Heerwagen, 2004)

The daylight factor is a kind of static daylight performance metric which concentrates on specific sky conditions. If it is combined with shading studies including the direct solar component, buildings will exhibit a considerably better energy balance than those designed only according to a daylight factor concept. But, only static shading devices such as lightshelves or overhangs can be considered in this combined approach whereas the performance of dynamic shading devices remains elusive. Also, even though this combined approach considers building orientation and latitude, the climatic conditions of the site is not considered "whereas dynamic daylight performance metrics such as the daylight autonomy or useful daylight illuminance capture the site-specific, dynamic interaction between a building, its occupants, and the surrounding climate on an annual basis." On the other hand, absolute benchmark levels for dynamic performance metrics still lack. **(**Reinhart, Mardaljevic and Rogers, 2006) "Daylight Autonomy is expressed as the percentage of occupied time during the year when a minimum work plane illuminance threshold of 500 lux can be maintained by daylight alone. " On the other hand, useful daylight illuminance also provides information about the excessive daylight levels associated with glare, occupant discomfort and unwanted solar gains. (Haberl and Kota, 2009) It uses 100 lux as lower and 2000 lux as upper thresholds dividing the year into three parts accordingly. In this concept, the values between 100 and 2000 lux are accepted as useful. Also, in daylight autonomy, the illuminance level which is above ten times the target illuminance is accepted as an upper limit and named as daylight autonomy maximum. (Reinhart and Wienold, 2010)

2.2.5 Elements of Daylighting Design

The penetration, distribution and amount of daylight depends on orientation; space organization, geometry and dimension of spaces; the location, form and dimension of openings; the locations and surface properties of internal partitions; the location, dimension and form of solar control devices; the light and thermal characteristics of glazing materials. (Goulding, 1994)

Windows in vertical walls and skylights are conventional openings used in daylighting. In addition to these conventional openings; lightwells or shafts, tubular skylights, heliostats, fiber optics or light pipes can be used in bringing daylight into the interior of buildings. (Lechner, 2001)

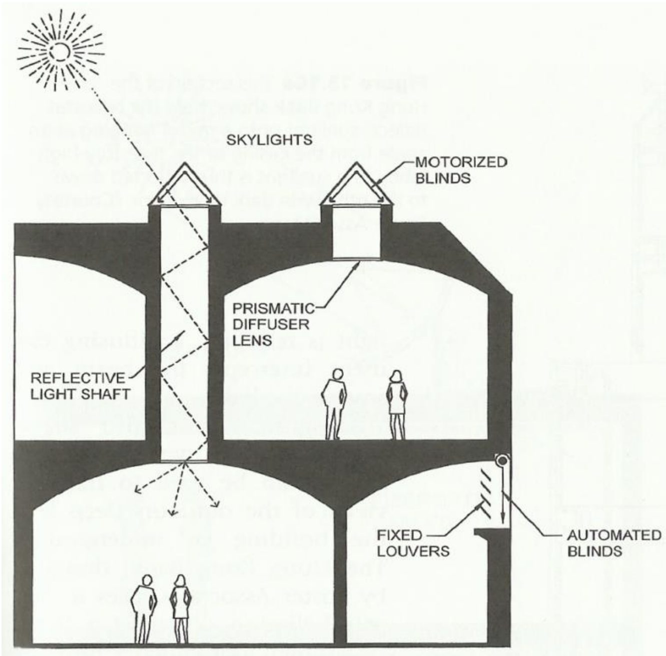


Figure 2.7 Skylights and Light Shaft (Lechner, 2001)

Moreover, there are advanced daylighting techniques to control direct beam sunlight based on the reflection, redirection and diffusion of it with the use of reflectors, lightshelves or integrated window elements usually made of a repetitive optical devices. (Baker, 2002)

The reflectance of surfaces in a room has a considerable impact on the penetration of light deep into the room. (Baker and Steemers, 2002) The ceiling, which is the critical reflector in a room, should have the highest reflectance factor while the floor and small pieces of furniture might have relatively low reflectance. (Lechner, 2001) When the ceiling has a role as a reflective surface, profiles such as downstand beams or coffers running parallel to the window wall should be avoided because these will become self-shadowing, redirecting light back towards the window or absorbing it by multiple reflection. (Baker and Steemers, 2002) The reflectance of walls has a more importance when the room is predominantly lit by daylight from a side window. The manner of reflectance is also important in terms of visual comfort. Diffuse reflectors should be used instead of the specular ones. (CIBSE, 1994) After being coated with a light-colored paint or some other paint-like finishing material, most common building materials such as gypsum wallboard, plywood, plaster or concrete can fulfill the function of diffuse reflection. (Baker and Steemers, 2002) In addition, internal room surfaces around windows should have a higher reflectivity in order to degrade luminance ratio between the window and the surrounding surfaces. (Heerwagen, 2004) Moreover, this contrast grading should be taken into account in the choice of the reflectivity of window frames and window sills, which are recommended to have reflectance of % 60-90. (Hopkinson, 1966)

Table 2.3 Ranges of Reflectances (CIBSE, 1994)

Room Surface	Reflectance Range	Relative Illuminance
Ceiling	0.6-0.9	0.3-0.9
Walls	0.3-0.8	0.5-0.6
Working Planes	0.2-0.6	1
Floor	0.1-0.5	_

The dimensions of the building, in both plan and section, have fundamental effect on the depth of daylight penetration inside. For a side lit space, the critical parameter is the plan depth. “As a rule of thumb, without advanced daylighting techniques, a room can be adequately daylit for a depth equal to the twice the floor to ceiling height and strictly twice the floor to top of window height. For daylighting design, this limitation of plan depth requires a shallow plan building. (Baker and Steemers, 2002) On the other hand, it is also claimed that a side lit space can be sufficiently daylit for a depth equal to approximately two-and-a-half times the height of the window. (Heerwagen, 2004) Moreover, CIBSE (1994) states that a side lit space can be sufficiently daylit for a depth equal to two times the distance between workplane and window head.

2.2.6 Visual Comfort

Visual comfort is defined as the “absence of a sensation of physiological pain, irritation, or distraction that could be felt as a result of some visual condition.” (Hopkinson, 1966) Achievement of comfortable lighting conditions in a space depends on the amount, distribution and quality and contrast of the light there. (Goulding, 1994) Occupant’s subjective preferences are of at least equal importance. (Baker and Steemers, 2002)

a) The Amount and Distribution of Light

Figure 2.8 Lighting Quality in a Classroom of the College La Vanoise (Baker and Steemers, 2002)

There should be enough light to perform a visual task in an environment. The partially or fully insufficient support for visual performance for a long time can cause fatigue. (Baker and Steemers, 2002) CIBSE (1994) published the recommended light levels varied with different tasks and varied in accordance with the orientation of task. CIBSE (1994) recommended 300 lux of illuminance for horizontal tasks and 500 lux of illuminance for vertical tasks in a school classroom. In addition, CIBSE (1994) recommended that if electric lighting is out of use during daytime hours, the average daylight factor should not be less than %5.

The variations of natural light levels inside a room can create extreme sharp contrasts while little variations can, though not harmful, cause tiredness and lack of attention. (Hopkinson, 1966) The variations of light levels inside a room can be expressed as diversity which is described as the ratio of maximum illuminance to the minimum illuminance found over the workplane and is recommended not to exceed 5:1. It is also recommended that the uniformity of illuminance over any task and immediate surround which is described as the ratio of minimum illuminance to average illuminance should not be less than 0.8 (CIBSE, 1994) For a side lit space, another ratio is defined by Lynes as the ratio of average daylight factor at the front half of a room to the average daylight factor at the back half of a room and recommended not to exceed 3, otherwise the back half of the room will appear unacceptably gloomy. (Baker and Steemers, 2002)

Moreover, one criterion for acceptable variety of light levels in spaces with windows on one wall is that "(d/w+d/h) shall not exceed 2/(1-Rb) where d is the depth of the room, w is the width of the room, h is the height of the window head above floor level and Rb is the area weighted average reflectance of the half of the interior remote from the window. " (Thomas, 1999)

b) Glare and Veiling Reflections

The issue of visual comfort is not just the illuminance, the luminance of surfaces, particularly vertical surfaces, is also a key factor in functional daylight design. (Baker and Steemers, 2002) In addition, since human vision is more sensitive to contrasts than amounts, the distribution of the luminances in the visual field which can be measured in luminance ratios is an important parameter in providing the visual comfort. (Heerwagen, 2004) The visual field comprises three distinct parts that have quite different characteristics. The eye is most sensitive to luminance ratios near the center of vision and least sensitive at the edge of peripheral vision. Consequently, the acceptable luminance ratios actually depend on the part of the field of view which is affected. (Lechner, 2001) The luminance of the surroundings should be graded in such a way that "the immediate surroundings to the work are slightly less bright than the work itself and the general surroundings are correspondingly slightly less bright than the immediate surroundings." The ratio between general background, immediate surrounding and task should be 10:3:1 respectively. The degree of brightness grading is not critical at low illumination levels while it is critical at higher illumination level levels. In addition, accepted maximum luminance ratio values change according to function. (Hopkinson, 1966)

Table 2.4 Maximum Recommended Luminance Ratios for Indoor Lighting (Lechner, 2001)

Ratio	Areas	Example
3:1	Task to immediate surroundings	Book to desk top
5:1	Task to general surroundings	Book to nearby partitions
10:1	Task to remote surroundings	Book to remote wall
20:1	Light source to large adjacent area	Window to adjacent wall

On the other hand, it also claimed that luminance ratios higher than 10/1 create more powerful contrasts and luminance ratios greater than 40/1 can cause glare in an office or school environment. (Keeler and Burke, 2013)

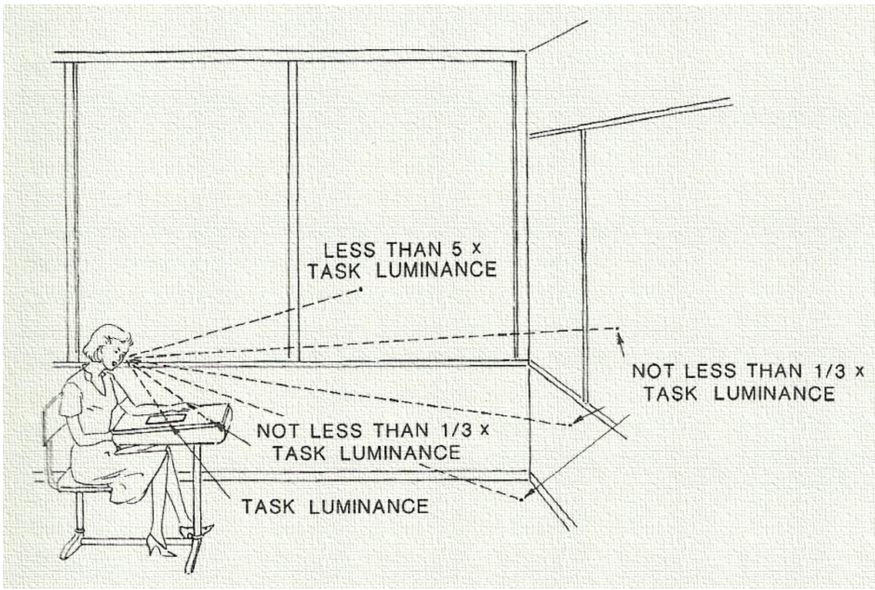


Figure 2.9 IESNA (1989) Luminance Recommendations for a Classroom.

While brightness is one of the factors which improves seeing, unwanted high brightness can cause glare. The glare means unfavorable adaptation to good seeing. When eyes encounter a significantly greater brightness level than the adaptation level due to the existence of a light source or brilliant area in the field of view, they are challenged to re-adapt, if the re-adaptive process does indeed require a significant change, a person may experience feelings of physiological irritation or even pain. This is called discomfort glare. On the other hand, if the unfavorable adaptation situation results in a reduction in the ability to see, it called is disability glare. It is a direct function of the luminous intensity of the glaring light source. “Since the disabling effects of glare in lighted buildings are rarely of much consequence, there is no advantage in devising calculating techniques to handle problems which may arise.” It is observed that discomfort glare has with little or no decrease in visual performance. In daylighting, glare is a direct function of the luminance of the sky and of the size of the visible sky seen through window. Glare is however, an inverse function of the luminance of the surroundings. A window can cause more glare when it is in the line of sight than when it is displaced from the direction of viewing. Thus glare changes from point to point in a room. In daylight design, the main problem regarding glare prevention is to limit the view of sky while maintaining the required illumination level inside and also maintaining the internal surface luminances which determine the adaptation level. (Hopkinson, 1966)

Figure 2.10 Glare from Windows (Baker and Steemers, 2002)

Glare indices are used to compare the probability of glare between different systems of daylighting. For example, daylight glare index considers the discomfort glare produced by the direct view of the unobstructed sky with the exclusion of sunlight. Therefore, it lacks in assessing discomfort glare caused by daylight in total. (Baker and Steemers, 2002) A new index called daylight glare probability solves the problem of glare from windows with consideration of the discomfort glare caused by the direct sunlight. DGP responds better to most daylight situations including those with many or large solid angle direct or specular luminance sources. (Wienold and Christoffersen, 2006)

On the other hand, veiling reflections occur when light enters an observer's field of view by reflection off of a task surface and when the luminance of this light is substantially brighter than the general illumination level over the task surface. For instance, for a daylit interior, it can be minimized if the direction of viewing is parallel to the window surface. (Heerwagen, 2004) The offending zone for veiling reflections is on the ceiling for horizontal tasks while it is behind the viewer for vertical tasks. Veiling reflections often best avoided by using non-specular surfaces. If specular surfaces cannot be avoided, then it can be avoided by working with geometry. (Lechner, 2001)

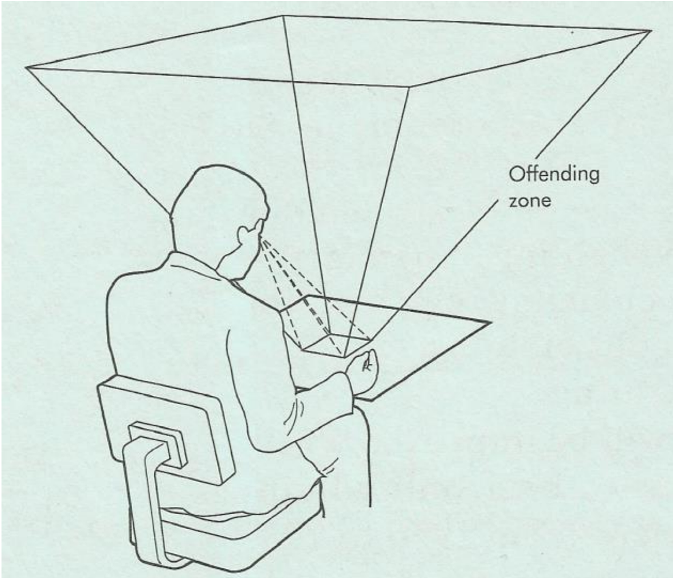


Figure 2.11 Schematic Diagram of Offending Zone (CIBSE, 1994)

2.3 Heat gain and Loss of a Building

Heat gain and loss mechanisms which results in heating or cooling loads, is needed to be examined and quantified in order to be able to identify how best to provide the energy required and how to reduce the demand as much as possible without reduction in the thermal comfort inside. (Thomas, 1999)

2.3.1 Heat Gain and Loss Mechanisms

The heat flow into a building from the outside is approximately cyclical on a daily and yearly basis due to the sun's position in the sky. The thermal forces exerting the exterior building surfaces are combinations of radiative and convective impacts. The radiative impacts are incident solar radiation and radiant heat exchange between the building and its environment. (Olgyay, 1963) In addition heat can also be lost through ground by conduction. (Thomas, 1999)

The radiant heat exchange is consisted of exchange of long-wave thermal radiation between the building and the heated ground or nearby surroundings and outgoing long-wave thermal radiation exchange from building to sky. (Olgyay, 1963) Thermal radiative transfer will occur only if there is a "line of sight" between two surfaces and radiant heat waves pass from one object to another without warming the air in between resulting in a heat loss or gain according to the net positive radiant exchange between surfaces. (Watson and Labs, 1983) The amount of radiant heat emitted from a surface is mostly determined by the temperature and emittance of that surface, as the temperature increases the heat emitted increases. Thermal radiation interacts with surfaces like solar radiation. When it strikes a surface; it is reflected, transmitted or absorbed according to the material characteristics. However, a material may interact differently with thermal radiation than solar radiation. For example, glass mostly transmits solar radiation whereas it mostly absorbs thermal radiation. (Thomas, 1999)

Table 2.5 Emittances and Absorbtances of Selected Materials (Thomas, 1999)

Item	*Emittance (at 10–40 °C)*	*Absorptance (for solar radiation)*
1. Black non-metallic surfaces such as asphalt, carbon, slate, paint	0.90–0.98	0.85–0.98
2. Red brick and tile, concrete and stone, rusty steel and iron, dark paints (red, brown, green, etc.)	0.85–0.95	0.65–0.80
3. Yellow and buff brick and stone, firebrick, fireclay	0.85–0.95	0.50–0.70
4. White or light cream brick, tile, paint or paper, plaster, whitewash	0.85–0.95	0.30–0.50
5. Bright aluminium paint; gilt or bronze paint	0.40–0.60	0.30–0.50
6. Polished brass, copper, monel metal	0.02–0.05	0.30–0.50

”

When incident solar radiation either visible or invisible absorbed by a surface, it is converted into heat and causes always a heat gain inside the building which is called solar gain and is independent of temperature difference. (Lechner, 2001) The total solar radiation passing through glazing, which is the transmission of the solar radiation and conduction of the absorbed heat inside, is quantified by a factor called solar heat gain coefficient. Actually, the value of solar heat gain coefficient is not constant for latitude; it changes with the position of the sun in the sky and with the window orientation. On the other hand, the effect of sun on the opaque building materials is taken into account in the sol-air temperature concept. The sol-air temperature is a fictious outside air temperature including the combined effect of actual air temperature and solar radiation and also other radiant impacts such as night sky. (Watson and Labs, 1983)

There is a convective heat transfer from the building surfaces to the ambient external or internal air resulting in heat loss or gain. The rate of the transfer is affected by the surface area, temperature difference and the nature of contact in between which is determined by the characteristic of a surface such as roughness or the existence of wind. This contact nature is generally described as a surface convection coefficient or film conductance. (Heerwagen, 2004) On the other hand, heat is transferred through the building envelope by conduction the rate of which is a function of the surface area, the temperature difference between the inside and outside surfaces and the thermal resistance of the envelope. The opposition of materials and air spaces to the heat flow is called thermal resistance. It is largely a function of the number and size of air spaces that a material contains. (Lechner, 2001) For a building component**,** the reciprocal of the sum of all resistances, including that of the surface film coefficients, is called the overall coefficient of the heat transfer or the overall conductance coefficient and symbolized as the U. (Watson and Labs, 1983) On the other hand, two walls of equal thermal resistances may have a different response time to change their temperature when given the same amount of heat. This situation is related with the property called thermal capacity which is the heat storage ability of a body and given by the product of its mass with specific heat. (Littler and Thomas, 1984) In addition, building respond to heat inputs is related to the admittance of the building elements and higher admittance elements absorb more energy for a given change in temperature. Buildings also lose or gain heat with air infiltration through construction joints and through cracks around windows and doors and with ventilation. (Watson and Labs, 1983)

Internally, activities of the occupants and processes such as lighting and running of equipment cause heat gain to a building. Buildings can be classified as internally dominated building or envelope dominated building depending on the majority and minority of internal heat gains. If the internal sources cause major loads when compared to the rate of loss or gain through building envelope, it is called internally dominated building which is mostly densely occupied, artificially lit and tends to have small surface area to volume ratio. If the internal sources cause minor loads when compared to the rate of heat loss or gain through the building envelope, it is called envelope dominated building which tends to have a large surface area to volume ratio, has a thermal performance primarily determined by its envelope and is very much affected by the climate. (Lechner, 2001) A more precious way to define buildings than by the above two types is by the balance point temperature. The balance point temperature is the lowest outdoor air temperature at which the interior remains within comfort limits without a heating requirement. (Watson and Labs, 1983) When the heating load is equal to the internal heat gains, the thermal balance point is said to be reached. The balance point temperature for a typical internally dominated building is about 10˚C and for typical externally dominated building is about 15˚C. The underheated period of a year starts below the balance point temperature of any building whereas the overheated period of the year starts at approximately 5˚C above the balance point temperature because the comfort zone mostly has a range of about 5˚C wide. Consequently, the lower the balance point temperature of a particular building, the shorter will be the underheated period and the longer will be its overheated period (Lechner, 2001)

2.3.2 Thermal Comfort

Heerwagen (2004) defines the thermal comfort as "the state of being able to pursue some activity without experiencing thermal stress" while Givoni described it as "the absence of irritation and discomfort due to heat or cold or in a positive sense, as a state involving pleasantness. "(Heerwagen, 2004) On the other hand, ASHRAE defines the thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment". (Lechner, 2001)

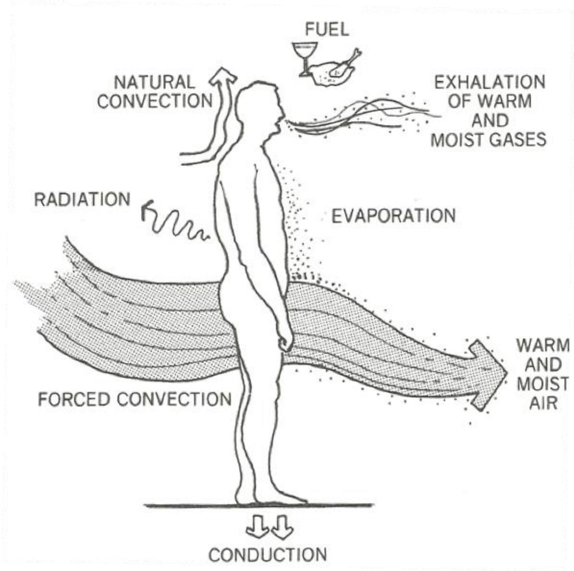


Figure 2.12 Heat Exchange Method of a Body (Lechner, 2001)

Human beings need a control of heat exchange to maintain a constant temperature of body regardless of the relatively wide variations in the external environment. Thus, human beings have several mechanisms to regulate heat flow to guarantee the thermal balance of the body which is reached when the sum of the metabolic heat production of the body with heat gain from environmental heat sources and sinks is equal to the sum of the heat loss during the useful work performed with heat loss to environment. (Lechner, 2001) The body exchanges heat with its environment through conduction, conduction-convection, evaporation-convection and radiation. (Watson and Labs, 1983)

There are environmental and personal thermal comfort parameters certain combinations of which creates thermally comfortable conditions inside a building. (Heerwagen, 2004)

a) Environmental Parameters Affecting Thermal Comfort

The four environmental parameters affecting thermal comfort conditions are the air temperature, mean radiant temperature of the surroundings, the air speed and the relative humidity. (Littler and Thomas, 1984) The air temperature determines the rate at which heat is lost to the air by mostly convection and also by conduction whereas it almost does not affect the rate of evaporation of skin moisture which primarily depends on the humidity of the air. (Thomas, 1999) The air movement affects heat transfer rate between skin and air by convection as well as by evaporation from the body. The increase in the air velocity is become less desirable if the moisture content of the air is decreased. On the other hand, the mean radiant temperature of the surroundings seen by the body affects the rate of radiant heat exchange between the body and the surroundings. Surface temperatures may differ considerably from point to point in a room. Accordingly, the resulting mean radiant temperature and thus net radiant heat exchange will vary with positions in a room. For any given observation point, radiation effects are proportionate to their distance from the radiating surface. (Olgyay, 1963) In addition, the radiant cooling and heating ability of any surface must be evaluated according to its area in proportion to the area and temperature of other surfaces in the room. (Watson and Labs, 1983)

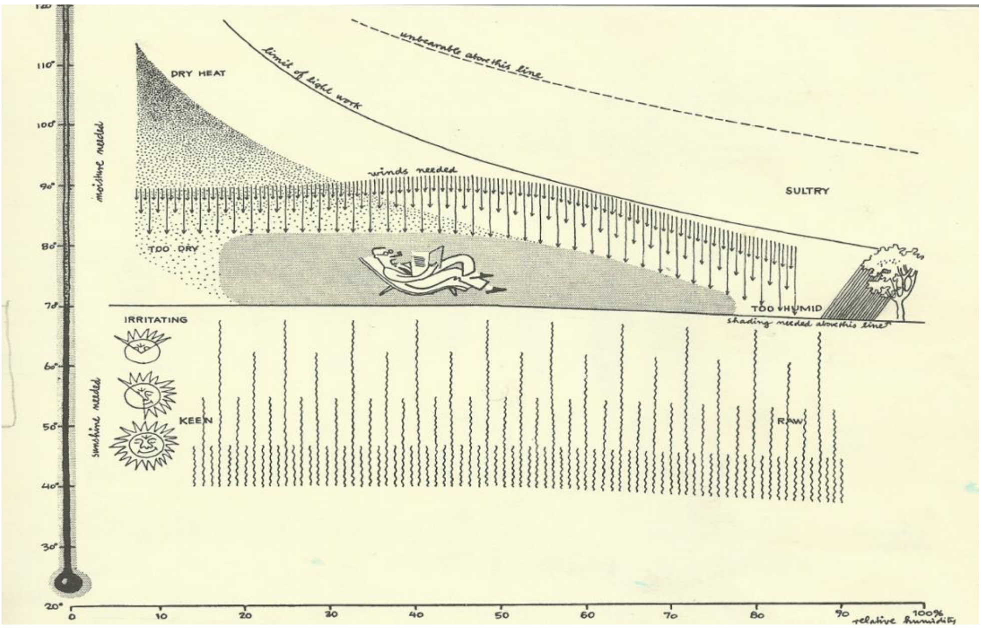


Figure 2.13 Schematic Bioclimatic Chart (Olgyay, 1963)

There are indices to measure the thermal comfort such as dry bulb temperature, wet bulb temperature, adjusted dry bulb temperature employing an averaging of the air temperature and the mean radiant temperature (Heerwagen, 2004), the dry resultant temperature considering the inside air temperature, mean radiant temperature and indoor air speed (Littler and Thomas, 1984) or by effective temperature which is a weighted composition of dry bulb temperature, wet bulb temperature and relative air velocity. (Watson and Labs, 1983) Besides these single number indices, charts and graphs are also used to describe the thermally comfortable environment such as the bioclimatic charts and psychometric charts portraying the interrelationship of comfort parameters and the needed actions to reestablish the thermal comfort. (Heerwagen, 2004)

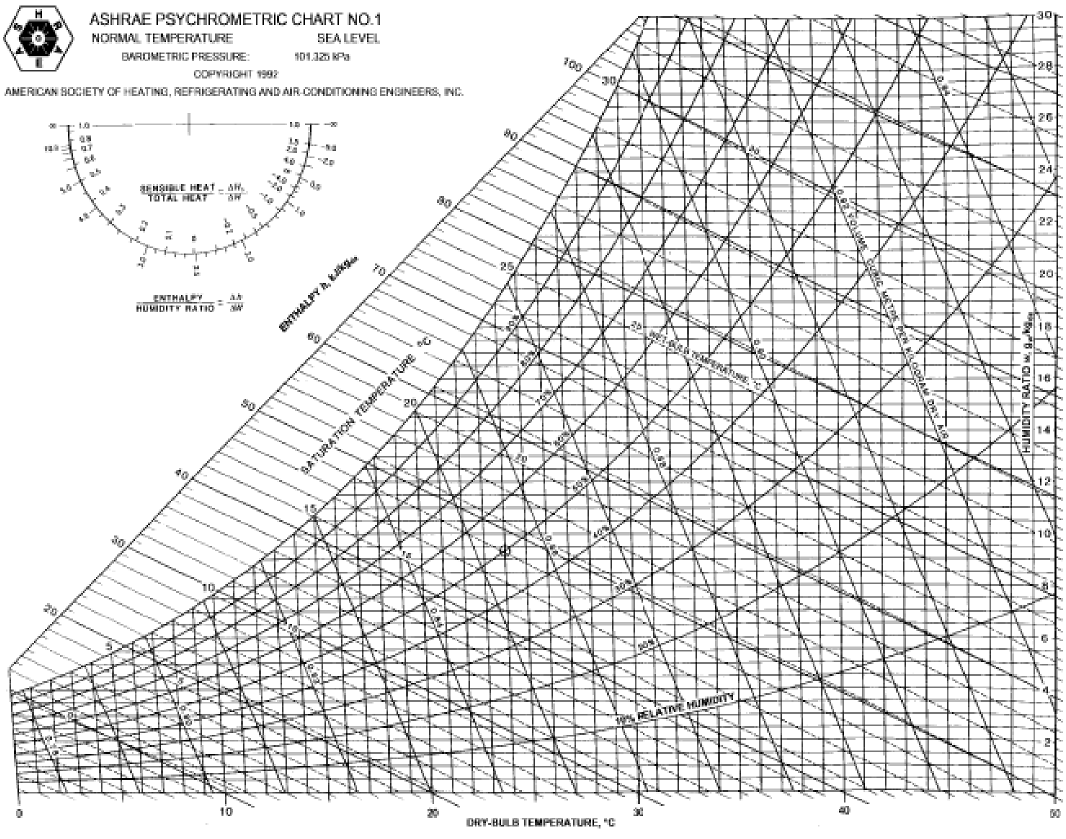


Figure 2.14 ASHRAE Psychometric Chart (ASHRAE, 2009)

In this chart above, horizontal axis describes the dry bulb temperature, vertical axis represents the actual amount of water vapor in the air called humidity ratio and curved line describes the relative humidity. This chart is also used to describe the sensible, latent, total heat content of the air. The certain combinations of air temperature and relative humidity are plotted on this chart and defined an area known as the comfort zone. In the definition of comfort zone, the mean radiant temperature is assumed to be near the air temperature and the air velocity is assumed to be modest. However, the boundaries of the comfort zone are not absolute due to the variations in the perception of thermal comfort because of such factors as culture, health and age of person. In addition, the comfort zone can be shifted through the change in parameters such as mean radiant temperature, air velocity, physical activity or clothing. (Lechner, 2001) Moreover, occupants can be satisfied with the thermal conditions of the environment outside the comfort zone through the adaptive behavior which can be defined as a kind of action taken by the occupant to improve his or her comfort. (Baker and Steemers, 2000)

Table 2.6 Typical Recommended Humidity and Temperature Ranges for Classrooms (ASHRAE, 2011)

Category/Humidity Criteria	Temperature, °C	
	Winter	Summer
Classrooms, Laboratories, Libraries, Auditoriums, Offices [a, e]		
30% rh	20.3 to 24.2	23.3 to 26.7
40% rh	20.0 to 23.9	23.1 to 26.7
50% rh	20.3 to 23.6	22.8 to 26.1
60% rh	19.7 to 23.3	22.8 to 25.8

b) Personal Parameters Affecting Thermal Comfort

Personal parameters affecting thermal comfort conditions are activity level and clothing. Activity level affects the metabolic heat production and usually is expressed in unit Met. On the other hand, the insulation level of clothing is described by the unit clo. "Clothing rated at 1 clo will keep a person so clothed comfortable at an air temperature less than the air temperature required to keep the same person comfortable while nude." (Heerwagen, 2004)

Table 2.7 Metabolic Rates (Heerwagen, 2004)

Metabolic rates for various activities for an average-sized adult man (i.e., where average-sized is commonly defined as 175 cm of height [69 in] and having a weight of 70 kg [154 lbs]) include the following:

ACTIVITY	NUMBER OF METS*
Sleeping	0.7
Seated, quiet	1.0
Typing w/ electric typewriter (40 wpm)	1.0
Drafting	1.2
Walking @ 2 MPH (3.2 km/hr)	2.0
Walking @ 3 MPH (4.8 km/hr)	2.6
Dancing	2.4–4.4
Tennis, singles	4.6
Squash, singles	7.2
Wrestling	8.7

2.4 Fenestration Design with Static Solar Control Devices in Terms of Daylight and Thermal Performance

Fenestration design is fundamentally a problem of optimization. Window presence enables a passage of too much heat, cold or light into a building when compared to an opaque wall. (Heerwagen, 2004) The advantages of solar gain and admission of light need to be balanced against potential overheating and heat loss through windows. Heat loss through windows which is mostly related to the U-value of a window is independent of orientation while light admission or solar gain depends considerably on orientation (Thomas, 1999) Fenestration design with respect to sun requires a careful control to maintain the temperature of the room between the comfort limits, to prevent sunlight from directly falling onto occupants, to reduce the illuminance of particular surfaces to avoid glare, to prevent the view of the sun to avoid glare. In addition, avoidance of sky view to prevent glare may also be required. However, in daylighting design, these objectives have to be met without the impairment of the daylighting conditions up to a need for artificial light. (Baker and Steemers, 2002) There is a contradiction in the optimization of window sizes simultaneously for low energy consumption requiring small sizes with high visual comfort requiring large sizes. (Ochoa, Aries and Hensen, 2012)

The area, shape, location and thermal and optical properties of windows and dimension, type and location of a shading device has a greater influence on the heat loss, heat gain and light admission through windows. (Heerwagen, 2004)

2.4.1 Window Orientation

The south can be accepted as the best orientation for daylighting due to the relatively higher quantity of light consistent throughout a day as well as ease of solar control resulting from a high solar altitude angle. Horizontal shading devices are appropriate for this orientation. The second best orientation for daylighting, although the quantity of light is rather low, is north due to the consistency and color quality of light as well as a relatively less need for solar control. Small fins can be used in this orientation. The worst orientations for daylighting are east and west due to the inconsistency in the amount of light throughout a day and a difficulty of solar control resulting from a low solar altitude angle. Dynamic shading devices or closely arranged eggcrate systems can be used for this orientation which in turn decrease the internal light levels and fail to maintain view. (Lechner, 2001)

On the other hand, orientation of a building has a greater influence on solar gains than daylighting due to the fact that diffuse and reflected sunlight are useful for daylighting. In terms of solar gains, an optimum orientation for a site would give maximum radiation in the underheated period and minimum radiation in the overheated period. (Lechner, 2001) South is the most advantageous orientation, allowing variations of which up to a certain degree to the southeast and southwest can be tolerable, due to the admittance of the greatest amount of radiation at the winter and the least amount at the summer. Whereas facades facing east and west receive maximum sunlight during summer minimum in winter with admittance of sunlight for only half of each day. Thus these orientations are the least advantageous. On the other hand, the climate, micro-climate, occupancy times of the buildings and daily temperature variations have an influence on the favorableness of the orientation. For instance, solar heat can be more necessary in the early morning when a greater heating demand exists and undesirable in the late afternoon in temperate climates resulting in a preference of more easterly orientations. (Olgyay, 1963)

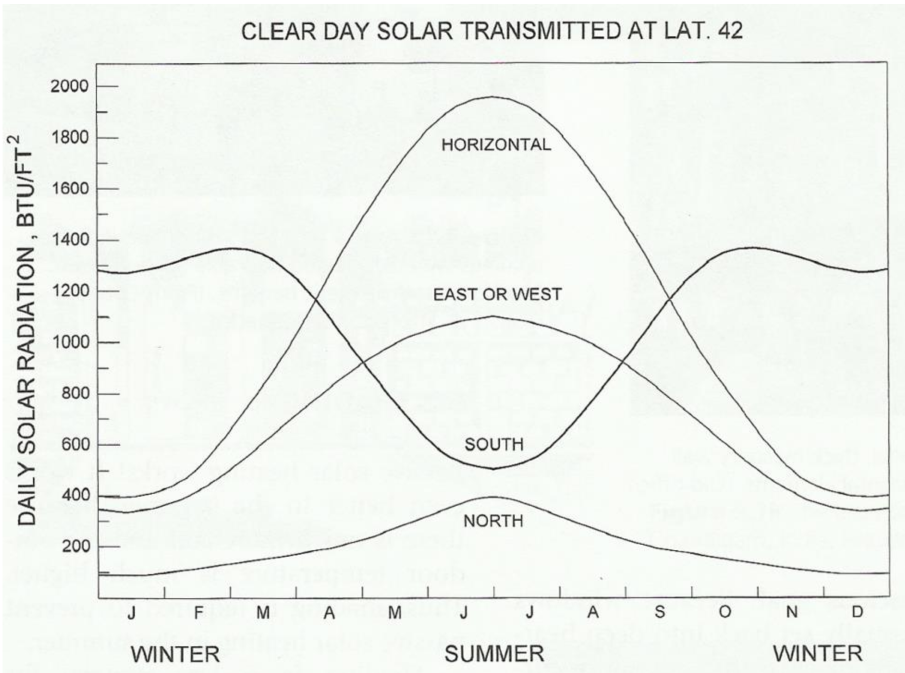


Figure 2.15 Solar Radiation According to Orientation (Lechner, 2001)

2.4.2 Area, Shape and Location of Windows

The appropriate window area is related to the required internal illuminance and the typical sky conditions in daylighting design. The greater the window area the greater will be the amount of light received indoors. (Baker and Steemers, 2002) In a side lit space, the area of a window is recommended to be about %30 to %35 of the total area of the window-wall and is also recommended to be equal to or greater than 1/16 of the floor area. (Heerwagen, 2004) However, reduction in window area reduce glare and some kind of a control should be provided for large windows to reduce the transmission or visible area of bright sky. (Hopkinson, 1966) In terms of window shape, wide horizontal windows provide a relatively uniform illumination distribution across a space when compared to the vertical strip windows. Hopkinson studied the influence of window shape on visual comfort by testing the aspect ratios varying between 1/10-40/1. As a result, at same conditions of environmental brightness, a wide horizontal window caused no more glare than the square one; a tall narrow window provided the most glare and the window had a length to height ratio of 10:1 caused the least glare. As a guideline, the width of the window should be greater than the height and the window width should be at least %60 to %75 of the total width of the window-wall. (Heerwagen, 2004) For a given area of opening, although the mean daylight factor is only weakly affected by the window locations, the distribution of light will generally improves with the increase in the mounting height of the window in the wall. Therefore, high windows, clerestories or skylights are excellent for daylighting whereas low windows at eye level are for view. (Baker and Steemers, 2002) Moreover, daylight will be more uniformly distributed in a space with spread out windows rather than concentrated ones as well as in a space with windows on more than one wall. (Lechner, 2001)

In terms of solar gains, heat losses through the glazing and the risk of overheating increase with the increase in the glazing area to collect more solar energy. Therefore, large glazing areas are not recommended. (Baker and Steemers, 2000) Unless large amount of daylight is required, window area as a percentage of floor area is recommended generally not to exceed %20 because of summer overheating and winter heat losses. The increase in the U value of the window, use of night shutters and shading devices increase the optimum window area. (Lechner, 2001)

2.4.3 Thermal and Optical Properties of Windows

Due to the fact that window is the most thermally transmissive element in most buildings; the U value of a window has a considerable impact on the thermal performance of a building. Since "the resistance to heat flow of a window is more or less independent of the thickness of the glazing material because resistance of glass is small compared with the film resistances", windows require special insulation treatments. (Littler and Thomas, 1984) For example, two or three panes of glass sandwiched together with a layer of air or inert gas between each pane are used to increase the thermal resistance of single pane windows. (Jaber and Ajib, 2011)

As the glazed area increases, the benefit of the thermal insulation of the window becomes more significant. However, improvement in the U value of a window causes a diminishment in the light transmission while solar gain through windows is mainly influenced by the transmittance of the glazing. (Baker and Steemers, 2000) On the other hand, night insulation over windows such as shutters and curtains are highly recommended to eliminate the black-hole effect of bare glazing at night. (Lechner, 2001)

Table 2.8 Characteristics of Glazing Systems (Thomas, 1999)

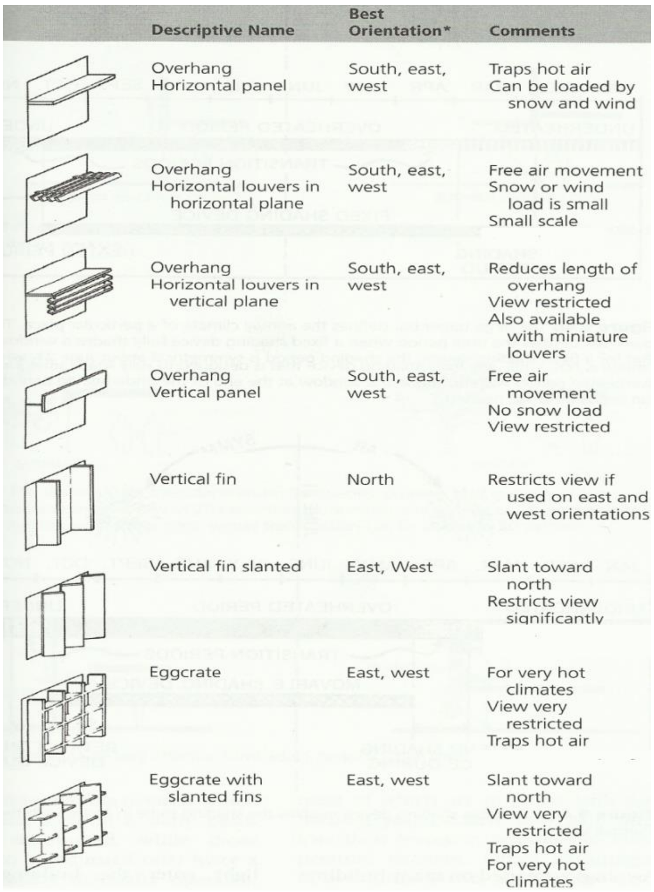
Type	*U-value ($W/m^2 K$)*	*Light transmittance*	*Solar radiant heat transmittance* [a]	
			Direct	*Total*
Single (4 mm clear float glass)	5.4	0.89	0.82	0.86
Double glazing (6 mm clear float inner, 12 mm airspace,[c] 6 mm clear float outer)	2.8	0.76	0.61	0.72
Double with low emissivity coating (6 mm Pilkington K inner, 12 mm airspace, 6 mm clear float outer)	1.9	0.73	0.54	0.69
Double with low emissivity coating and cavity (6 mm Pilkington K inner, 12 mm airspace with argon, 6 mm clear float outer) [13]	1.6	0.73	0.54	0.69

In addition to the U-value, solar heat gain coefficient (SHGC) is used as a performance indicator of a window in terms of energy efficiency. SHGC is used to calculate the solar gain through a window. (Jaber and Ajib, 2011) For cool daylight, the higher the light to solar gain ratio, the cooler the inside will be due to the fact that the heating effect is a function of the ratio of visible transmittance to total transmittance. (Lechner, 2001) The amount of the radiation transferred through windows in or out of a room can be controlled to a certain extent by changing the components of the glass or by applying special coatings. (Thomas, 1999) For instance to lower the heat gain through solar radiation, instead of a clear glass; tinted, heat absorbing, reflective or spectrally selective glasses can be used as a window glazing material. Due to the blockage of both light and infrared radiation and distortion in the color of the daylight, tinted glazing is not a good choice. Heat absorbing glass blocks more of the unwanted infrared radiation but released the absorbed heat to the interior. Reflective glazing is quiet better but it reflects both light and infrared radiation. For cool daylight, selective glass can be used due to the fact that it reflects the infrared radiation but do not reflect the visible portion of daylight. On the other hand, high performance windows do not eliminate the need for shading or the black hole effect at night. There are also responsive glazing systems which change in response to light, heat or electricity such as photochromic or thermo-chromic glazing. (Lechner, 2001)

2.4.4 Static Solar Control Devices

Glare and unwanted solar gains are usually dealt with solar control devices which also frequently interfere with the admission of light. (Lechner, 2001) In terms of glare, the main issue in window design is to reduce the luminance differences between windows, surrounding surfaces and the ambient conditions of the interior space. Therefore, solar control systems are usually used to control the glare source luminance. (Baker, 2002) In terms of thermal performance, due to the fact that the internal shading devices control the sun inside the building, they are not so much useful in rejecting the heat to interior while exterior shading devices release most of the absorbed energy to the outside. (Littler and Thomas, 1984) However, external devices have also disadvantages such that they have to be weather proof as well as to resist strong winds. (Baker and Steemers, 2000) In terms of solar control, the direct solar component is effectively controlled with exterior devices while the diffuse component usually controlled with additional indoor device or controlled within the glazing. The required shading period of any building depend on both the climate and occupancy of the building. (Lechner, 2001)

Static solar control devices reduce daylight as they reduce solar gains due to the fact that they are not geometrically selective. They are not selective between diffuse light and direct sunlight. Thus a room with a static solar control device may be under illuminated on overcast days. (Baker and Steemers, 2002) The retractable static shading devices are useful to adapt to different periods. For instance, the device can be retracted for full solar exposure at the end of the overheated period to increase the thermal performance. (Lechner, 2001)



Descriptive Name	Best Orientation*	Comments
Overhang Horizontal panel	South, east, west	Traps hot air Can be loaded by snow and wind
Overhang Horizontal louvers in horizontal plane	South, east, west	Free air movement Snow or wind load is small Small scale
Overhang Horizontal louvers in vertical plane	South, east, west	Reduces length of overhang View restricted Also available with miniature louvers
Overhang Vertical panel	South, east, west	Free air movement No snow load View restricted
Vertical fin	North	Restricts view if used on east and west orientations
Vertical fin slanted	East, West	Slant toward north Restricts view significantly
Eggcrate	East, west	For very hot climates View very restricted Traps hot air
Eggcrate with slanted fins	East, west	Slant toward north View very restricted Traps hot air For very hot climates

Figure 2.16 Examples of Static Shading Devices (Lechner, 2001)

An overhang is the simplest form of the solar control devices, relying upon the solar geometry i.e. it obstructs the part of the sky through which the sun passes. It is used to avoid the high altitude sun while allowing view thus they are not useful in low altitude sun which is mostly avoided by vertical fins or eggcrate systems blocking the view. In terms of daylighting, there must be a strong ground-reflected light to illuminate the underside of the overhang which should have a high reflectance. Horizontal louvers serving the same purpose have advantages over overhangs such as they reduce structural loads by allowing wind and snow to pass through and by avoiding the gathering of warm air under in summer. Louvers in a vertical or horizontal plane painted a light color are also beneficial because they only block direct sunlight but they reflect diffused sunlight. (Lechner, 2001)

On the other hand, light redirecting solar control devices such as a lightshelf will not only improve the quality of daylighting, but also enhance the illuminance in the darkest part of the room while the use of a sole shading devices such as an overhang in deep spaces or spaces potentially poor for ground-reflected light will worsen the illumination at the back of the room. "A lightshelf offers a solution by splitting the function of the window vertically-a lower area, protected with an overhang that illuminates the front part of the room, and an upper part providing illumination for the back part of the room. The latter is augmented by reflections from the top of the shelf (in effect replacing the ground reflected light)." A light shelf which may be placed inside or outside is usually located approximately 2 meters above floor level. (Baker and Steemers, 2002) On the other hand, in multistory buildings, wide windowsills acting as a pavement can be used to send light deep into the interior. (Lechner, 2001)

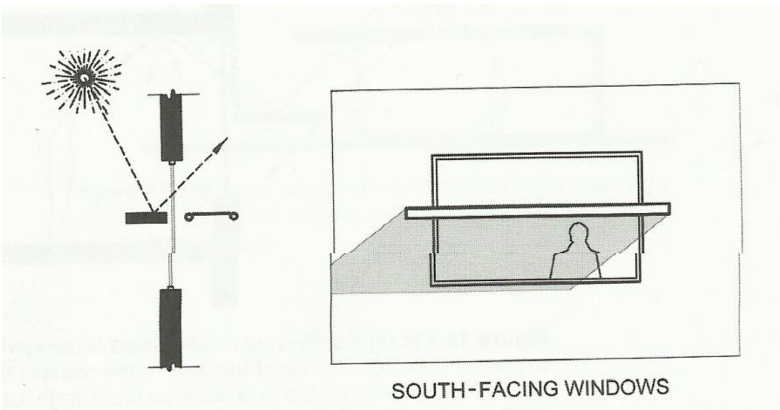


Figure 2.17 Lightshelf on a South Facing Façade (Lechner, 2001)

CHAPTER 3

MATERIAL AND METHOD

This chapter includes information about the material and method used in this study. The material section consists of information about the typical classroom of Turkish school buildings and the classrooms of a school building located in Ankara, the simulation software and data loggers, the collected data and weather data. The method section presents the data collection and data evaluation procedures.

3.1 Material

The study was carried out with a typical classroom of Turkish school buildings assumed to be located in Ankara. To validate the simulated data obtained from the study, the classrooms of a school building located in Çankaya district of Ankara were used. Therefore, the materials used in this study are the architectural drawings and relevant data of a typical classroom of Turkish school buildings and the classrooms of a school building located in Çankaya, the simulation software and data loggers, the data collected from the simulation software and by means of data loggers and weather data of Ankara.

3.1.1 Classrooms

The typical classroom of a Turkish school building and the two classrooms of the school building located in the Çankaya district of Ankara were used in this study.

a) The Typical Classroom of Turkish School Buildings

The basic architectural properties of the typical classroom of Turkish school buildings were laid down by a directive named as "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" i.e. the "General Principles for Preparing Architectural Projects for Educational Buildings" (2010). This directive states that educational buildings should not be higher than 1 basement + 1 ground floor + 3 normal floors and ground and normal floors should be 3.30 meters high. It also set rules for the windows such that they should be at least 1.8 meters high and should be located at least 0.1 meters away from the column, beam and wall edges. It further states that classrooms should be designed in such a way that light is taken inside from the left. This directive also sets the thickness of the interior walls at least to 0.2 meters. It presents options for the color of the interior and exterior wall paintings. It finally defines a typical classroom plan according to which classrooms must be designed. Thus, this plan of the typical classroom obtained from the directive was used in this study.

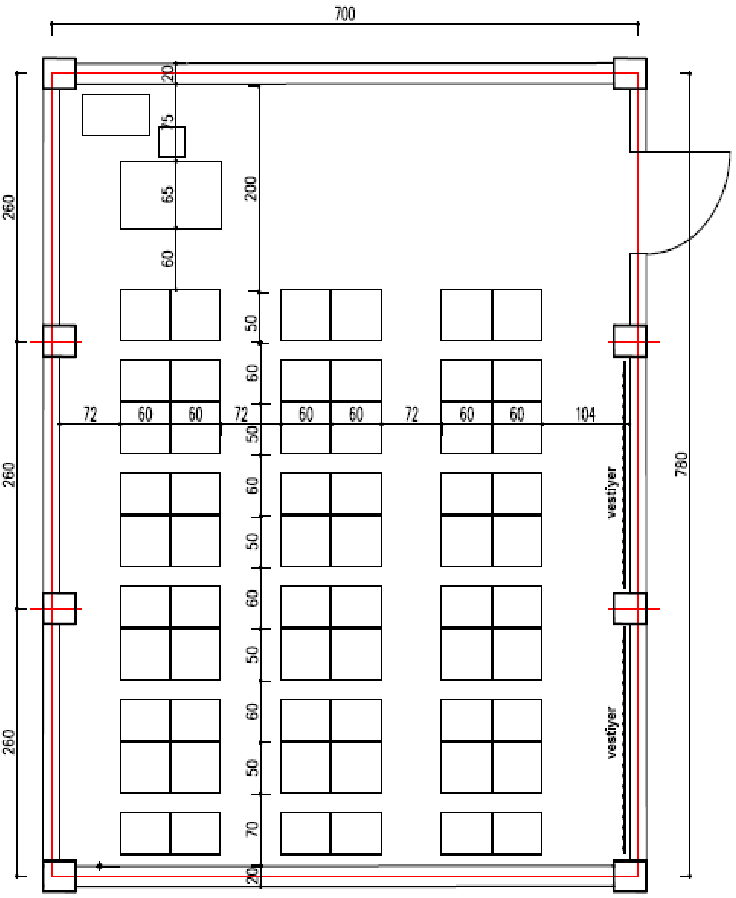


Figure 3.1 Architectural Drawing of a Typical Classroom
("Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri")

The classroom used as a basis for simulations has 3.3 m height, 50.25 m² floor area and was assumed to be located on the first floor of a four-story building with a single exterior-facing wall. The U-value of exterior wall and windows were determined according to TS 825 (2008) for Region 3 where Ankara is located.

Table 3.1 Maximum U-Values for Ankara (TS 825, 2008)

	Ud (W/m ²K)	UT (W/m ²K)	Ut (W/m ²K)	Up (W/m ²K)
Region 3	0.5	0.3	0.45	2.4

The timber frame double glazed low-e windows, properties of which were taken from Ecotect Analysis 2011 material library, were used. On the other hand, the density and conductivity values of other building components were taken from TS 825 (2008). Further properties were either calculated in Ecotect Analysis 2011 through the use of these values or taken from this software material library directly.

Table 3.2 Thermal Properties of Building Components
(Ecotect Analysis 2011 and TS 825, 2008)

Building Component	U-Value (W/m ²K)	Admittance (W/m ²K)	Thermal Decrement (0-1)	Thermal Lag (Hrs)	Emissivity
Exterior Wall (0.02 m Exterior Plaster + 0.5 m EPS + 0.2 m AAC Blocks + 0.02 m Interior Plaster)	0.36	3.32	0.22	7.8	0.9
	U-Value (W/m ²K)	Admittance (W/m ²K)	SHGC VT (0-1) (0-1)	Refractive Index of Glass	Emissivity
Window (Double Glazed Low-e Timber Frame)	2.26	2.2	0.7 0.75	1.74	0.78

The reflectance of surfaces was specified in Ecotect Analysis 2011 according to common surface colors used in schools. In addition, CIBSE recommendations 2002 were used as a guideline in determining the reflectance of overhangs and lightshelves. Surfaces were accepted as non-specular diffuse reflectors.

Table 3.3 Reflectance of Surfaces (Ecotect Analysis 2011 and CIBSE, 2002)

Building Components	Reflectance
Ceiling (White)	0.8
Floor (Gray)	0.3
Walls (Off-White)	0.7
Door	0.66
Tables (Snuff-Colored)	0.4
White Board	0.8
Overhangs and Lightshelves	0.7

The enrolment data for schools during the 2013-2014 Academic Year were provided from the official authority. The primary and secondary school entrance and exit times were taken as a basis and were optimized as 08:00 for entrance and 18:00 for exit for the study. The summer holiday was accepted as between 15 June-15 September and semester holiday and weekends were neglected.

b) The Classrooms Of A School Building Located In Çankaya District Of Ankara

The school building located in Çankaya district of Ankara was selected for the validation study. It is a four story school building and the classrooms either face north-west or south-east directions at which the school building has playground. The playground is surrounded by residential buildings at north-west direction and by a cluster of trees at south-east direction. The site plan of the school building taken from "Google Map" and the photo of the south-east (front) façade is given below.

Figure 3.2 Site Plan of the School Building Located in Çankaya District of Ankara (Google Map)

Figure 3.3 South-East (Front) Façade of the School Building Located in Çankaya District of Ankara (Photo by the Author)

A classroom facing north–west and a classroom facing south-east were selected for the analysis. The selected two classrooms have 3.2 m height, 46 m² floor area and located on the second floor of a four-story building with a single exterior-facing wall. The windows of these classrooms were located 0.84 m above the floor level and have 1.86 m height. Plans of classrooms and a photo of the interior of the classroom facing south-east are given below.

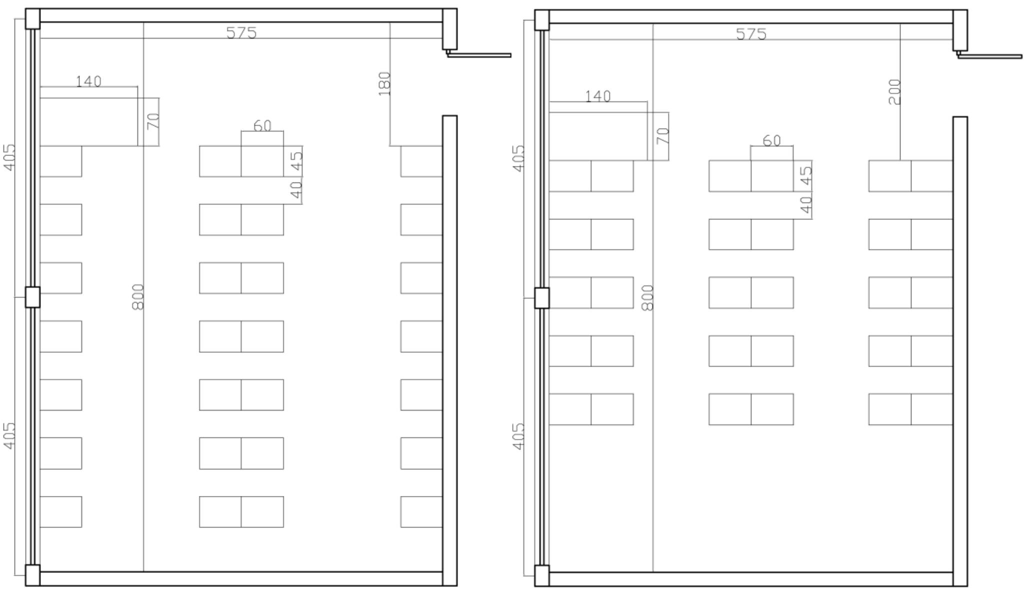


Figure 3.4 Floor Plans of the Classrooms Facing North-West (Left) and South-East (Right) of the School Building Located in Çankaya District of Ankara (Produced by the Author)

Figure 3.5 Interior of the Classroom Facing South-East (Photo by the Author)

The reflectance of the surfaces was specified in Ecotect Analysis 2011 according to their surface color. Surfaces were accepted as non-specular diffuse reflectors.

Table 3.4 Reflectance of Surfaces (Ecotect Analysis 2011)

Building Components	Reflectance
Ceiling (White)	0.8
Floor (Gray)	0.3
Walls (Off-White)	0.7
Door (Blue)	0.2
Tables (Snuff-Colored)	0.4
White Board	0.8

3.1.2 Simulation Software and Data Loggers

In this study, the data were obtained from the simulation software namely Autodesk Ecotect Analysis 2011 and Desktop Radiance. Further, data loggers were used to validate the simulated data.

a) Simulation Software

Autodesk Ecotect Analysis 2011 and Desktop Radiance were used to simulate the typical classroom and to collect data about thermal and daylight performance of the classroom.

“Ecotect is a conceptual design analysis tool that features overshadowing, shading design, lighting, acoustic and wind analysis functions as well as thermal. It uses CIBSE Admittance Method to calculate heating and cooling loads for any number of zones within a model. These load factors are direct and indirect solar gains, fabric gains, internal gains, inter-zonal gains, inter-zonal heat flow and pull-down loads due to intermittent usage.” (http://wiki.naturalfrequency.com/wiki/Thermal_Analysis_Methods, 2013). On the other hand, “Radiance is a public domain radiosity-based lighting simulation program originally written by Greg Ward at Lawrence Berkeley Laboratories. It is not included as part of the Ecotect distribution, but it can be used with Ecotect. Desktop radiance with Ecotect can be used for daylighting analysis for physically accurate and comprehensive lighting analysis.” (Haberl and Kota, 2009)

b) Data Loggers

The Hobo data logger which is shown in Figure 3.6 can record temperature, humidity and illuminance data at predetermined intervals. The beginning of the recording time can be arranged and loggers operate until they are stopped. Since the loggers are sensitive instruments, they should be placed in a way that they do not get moved or lost.

Figure 3.6 Hobo Data Logger (Photo by Author)

In this study, four data loggers were used to record data; two loggers were placed in the classroom facing north-west and two were placed in the classroom facing south-east. The recorded data were extracted by means of the software called "HOBOware Pro v.2.7.2" which presents data in both tabular and graphical format.

3.1.3 Collected Data

Illuminance and luminance values were collected from simulation software to analyze the daylight performance while monthly discomfort times in a degree-hour scale, in which the amount of time the internal temperature of the zone remains outside the specified comfort conditions is calculated for each month, were collected from simulation software to analyze the thermal performance. Degree hour discomfort values simply weight each hour of discomfort by the number of degrees outside the comfort band.

On the other hand, only illuminance values were collected by means of data loggers to validate the simulated data.

3.1.4 Weather Data

Weather data of Ankara was taken from the web site of the US Department of Energy Plus. This data was converted to appropriate format by Weather Manager Tool of Ecotect Analysis 2011. The design sky value was calculated as 7801 lux in Ecotect Analysis 2011 with Trangenza formula.

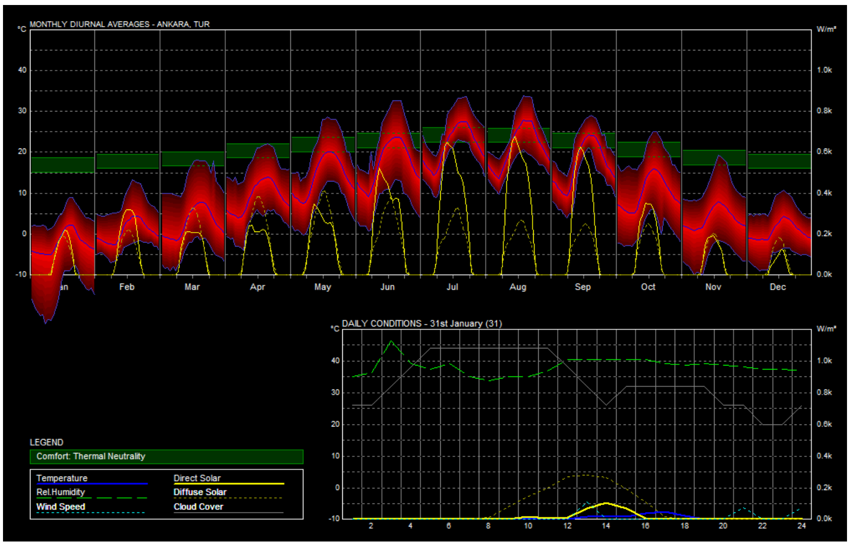


Figure 3.7 Ankara Weather Data (Weather Manager Tool Ecotect Analysis 2001)

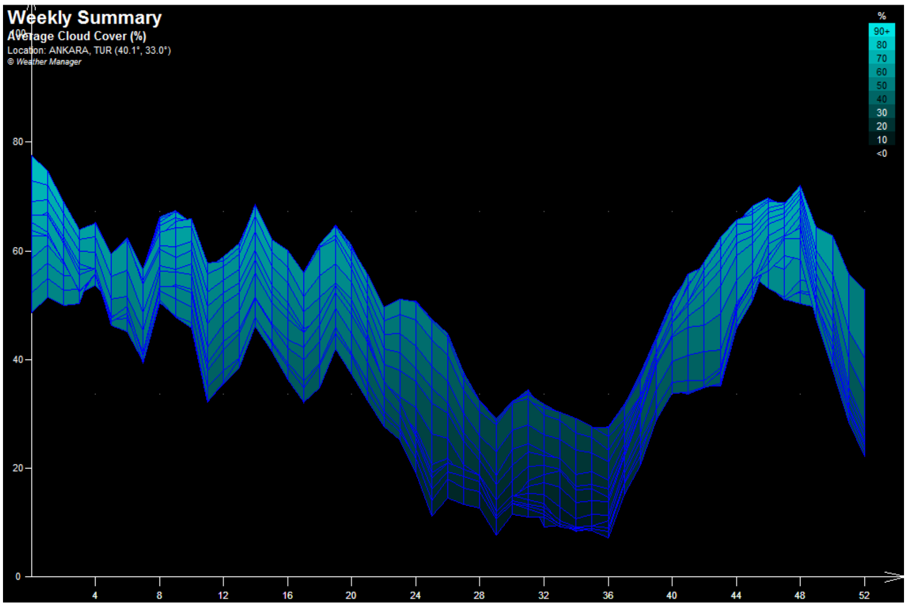


Figure 3.8 Ankara Weekly Summary of Average Cloud Cover
(Weather Manager Tool Ecotect Analysis 2001)

3.2 Method

The method in this study is mainly comprised of four main steps. Firstly, classroom model was produced in Ecotect; secondly, several steps of computer analysis were conducted and data were collected; thirdly, data were evaluated; fourthly, simulated data were validated.

3.2.1 Ecotect Modeling

The classroom was modeled with school desks and the white board according to the information given in material section. The height of school desks was accepted as 75 cm above the floor plane. The white board was modeled as 280 cm length and 120 cm width and placed in the middle of a side wall at 110 cm above floor plane. The material of columns and beams were ignored and columns and beams are accepted as a wall. For thermal simulations, it was assumed that the space is bordered on five sides by similar spaces. Therefore, interior walls, floor and ceilings were modeled adiabatically.

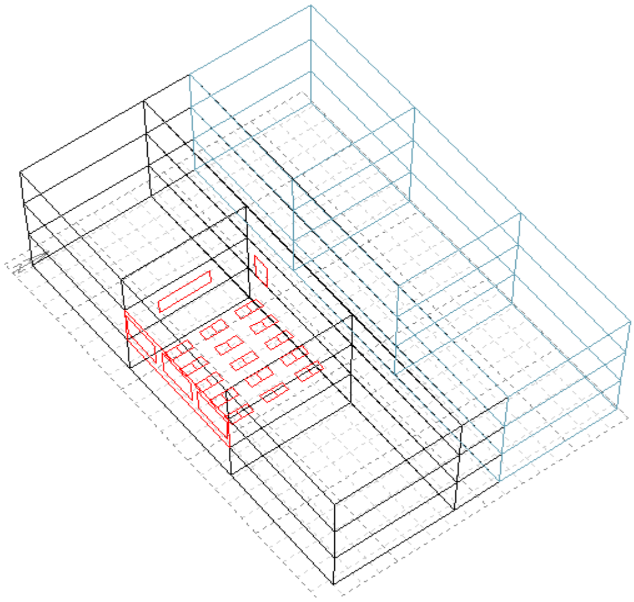
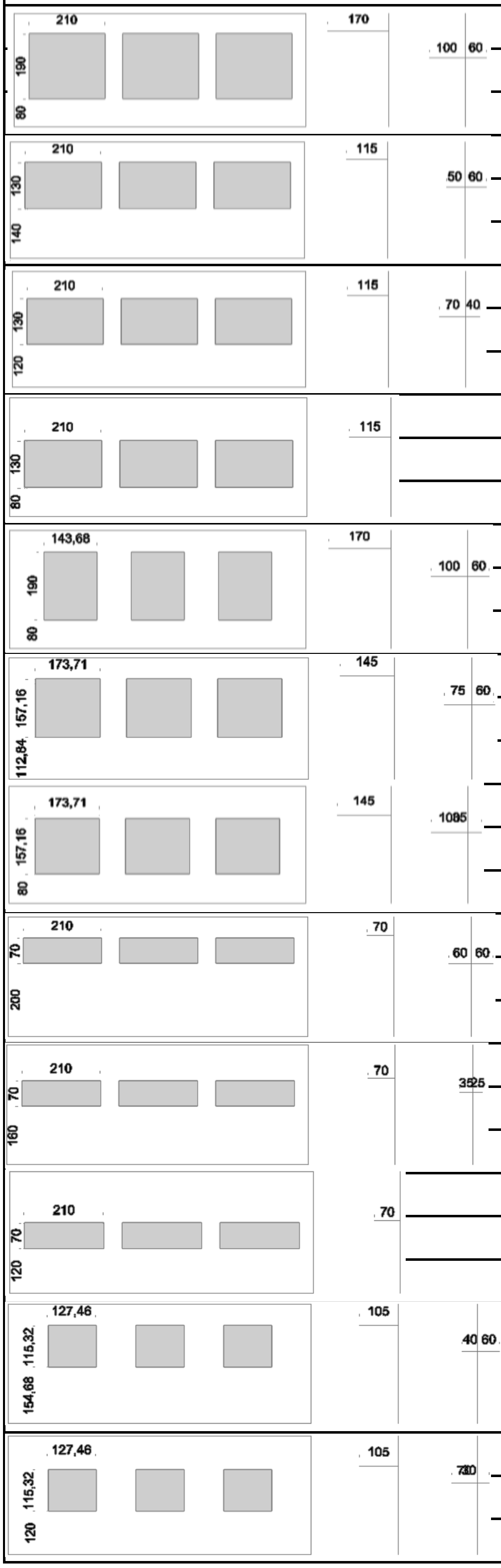


Figure 3.9 Ecotect Model of a Typical Classroom

The classroom model was diversified with alternative fenestration configurations. To reach the highest possible window dimensions, rules set by the directive -("Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri")- ,which is mentioned in material section, were used. The lowest parapet height was accepted as 80 cm regarding the work plane height. Thus, the highest possible window dimensions were defined as a 210 cm width and 190 cm height. Afterwards, different window configurations were generated by changing the window area and window aspect ratio. 6 different window configurations were chosen having same dimensions. After changing the parapet height, the number of window configurations was increased to 12.

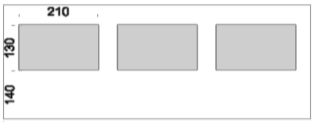
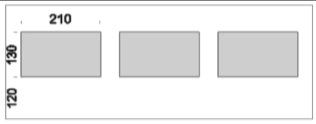
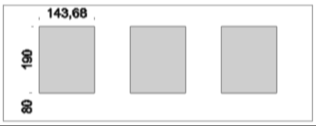
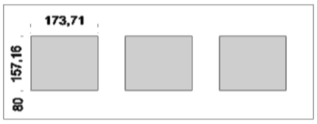
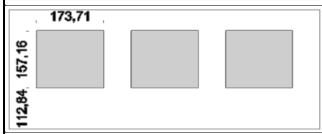
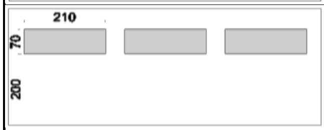
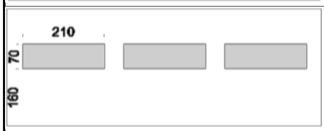
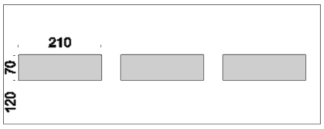
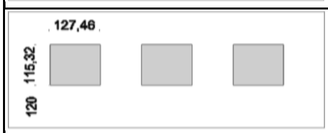
South windows were optimized with either an overhang or a lightshelf to ensure the exclusion of direct sun during the period between 21 March and 21 September when the sun is high in the sky in comparison with the other half of the year. Thus, the dimensions of overhangs and lightshelves were determined in a way that they provide a shade during a period between 21 March to 21 September. The overhangs were placed 10 cm above the window head and lightshelves, used for both interior and exterior, were placed 200 cm above the floor level. The overhang and exterior lightshelves were modeled in a way that they run along the building length continuously. At the end, 22 different fenestration configurations were achieved for south orientation. North windows were used without an overhang or a lightshelf. Thus 12 different window fenestration configurations were tested for that orientation. Fenestration configurations are given in Table 3.5 and Table 3.6 where WS is used instead of south facing window and WN is used instead of north facing window. In Table 3.5; WS1, WS3, WS5, WS7, WS8, WS10, WS12, WS14, WS16, WS18, WS19 and WS21 are the windows configured with an overhang while WS2, WS4, WS6, WS9, WS11, WS13, WS15, WS17, WS20 and WS22 are the windows configured with a lightshelf.

Table 3.5 Alternative Fenestration Configurations Created for Classrooms Facing South



......................................Sections of Elevations Overhangs / Sections of Lightshelves	Total Window Area (m²)	Window Area/ Wall Area	Window Area/Floor Area	Window Aspect Ratio
WS1	3.99	0.47	0.24	1.11
WS2	3.99	0.47	0.24	1.11
WS3	2.73	0.32	0.16	1.62
WS4	2.73	0.32	0.16	1.62
WS5	2.73	0.32	0.16	1.62
WS6	2.73	0.32	0.16	1.62
WS7	2.73	0.32	0.16	1.62
WS8	2.73	0.32	0.16	0.76
WS9	2.73	0.32	0.16	0.76
WS10	2.73	0.32	0.16	1.11
WS11	2.73	0.32	0.16	1.11
WS12	2.73	0.32	0.16	1.11
WS13	2.73	0.32	0.16	1.11
WS14	1.47	0.17	0.09	3.00
WS15	1.47	0.17	0.09	3.00
WS16	1.47	0.17	0.09	3.00
WS17	1.47	0.17	0.09	3.00
WS18	1.47	0.17	0.09	3.00
WS19	1.47	0.17	0.09	1.11
WS20	1.47	0.17	0.09	1.11
WS21	1.47	0.17	0.09	1.11
WS22	1.47	0.17	0.09	1.11

Table 3.6 Alternative Fenestration Configurations Created for Classrooms Facing North

Fenestration Configurations		Total Window Area (m^2)	Window Area/Window Wall Area	Window Area/Floor Area	Window Aspect Ratio
	WN1	3.99	0.47	0.24	1.11
	WN2	2.73	0.32	0.16	1.62
	WN3	2.73	0.32	0.16	1.62
	WN4	2.73	0.32	0.16	1.62
	WN5	2.73	0.32	0.16	0.76
	WN6	2.73	0.32	0.16	1.11
	WN7	2.73	0.32	0.16	1.11
	WN8	1.47	0.17	0.09	3.00
	WN9	1.47	0.17	0.09	3.00
	WN10	1.47	0.17	0.09	3.00
	WN11	1.47	0.17	0.09	1.11
	WN12	1.47	0.17	0.09	1.11

3.2.2 Data Collection

To perform the study, several steps of computer analysis were conducted for south and north orientations. East and West orientations were neglected due to the difficulty in shading and the low thermal and daylight performance of classrooms facing those orientations. The daylight and thermal analyses were run for each fenestration configuration given in Table 3.5 and Table 3.6 without any other parameter change.

The daylight analyses were carried out with Desktop Radiance. The classroom was simulated with overcast sky to obtain the minimum illuminance values. In addition, the classroom was also simulated with intermediate sky with sun on 21 March 12:00 to obtain the average values because the sun is in a midway between solstices in the sky at this date. Intermediate sky was chosen according to the cloudiness of Ankara which was demonstrated in Figure 3.8 The results were given on the analysis grids which were placed over the school desks and over the white board. The analysis grid over the school desks has regularly arranged 30 data points and over the white board has regularly arranged 18 data points. The luminance values were collected under intermediate sky with sun at 16:00 with a wide-angle Ecotect camera positioned at an eye level of the student sitting at the back most part of the classroom near the window looking through the middle of the white board.

In order to exclude external influences, the thermal analyses were performed under unheated and uncooled conditions with no internal gains. The comfort band was set according to the ASHRAE (2011) recommendations for classrooms cited in Literature Review. The occupancy of the classroom was set to 30 children as given in the directive.

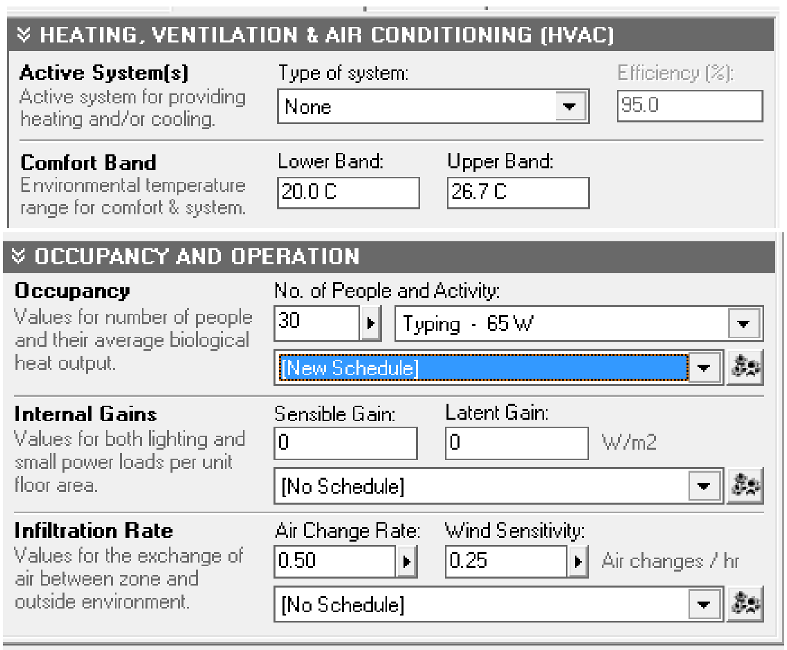


Figure 3.10 Ecotect Zone Settings

3.2.3 Data Evaluation

The collected data was analyzed and evaluated in order to show if there is a difference among these fenestration configurations. If there is a difference among collected data, comparisons were made regarding recommendations and guidelines mentioned in the Chapter 2 about the comfort conditions and also energy requirements, to conclude a performance ranking among window configurations to obtain the optimum solution regarding thermal and daylight performances.

3.2.4 Data Validation

To validate the simulated data; two classrooms, one is facing south-east and the other one is facing north-west, of a school building located in Çankaya district of Ankara were analyzed in terms of daylight performance with data loggers. The data loggers recorded data at the weekend -21-22 September- when the school is unoccupied, therefore, two days of illuminance data were collected. Two data loggers were placed in the classroom facing southeast and the other two were placed in the classroom facing northwest. The data loggers were placed over the school desk in window side and wall side of the classrooms. The location of data loggers are depicted with red dots in Figure 3.11 below.

Figure 3.11 Locations of the Data Loggers in the Classrooms Facing North-West (Left) and South-East (Right) (Produced by the Author)

On the other hand, these two classrooms were modeled in Ecotect Analysis 2011 with school desks and the whiteboard according to the information given in material section. The height of school desks are 69 cm above the floor plane. The white board has 200 cm length and 100 cm width and placed in the middle of a wall at 92 cm above floor plane. The analysis grids were located over the school desks in a way that the locations of data loggers match the grid points.

Due to the activity at the school on 22 September, to be on the safe side, only the illuminance data recorded on 21 September were used. Thus, daylight simulations were done on 21 September at 30 minutes intervals for both classrooms with intermediate sky with sun and with sunny sky with sun.

After data collection, to calibrate and validate the simulated data, the tabular illuminance data obtained from the analysis grid points corresponding to data logger positions were superimposed with the tabular illuminance data obtained from the loggers in the same graph.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of the lighting and thermal analyses of alternative fenestration compositions, the results of the data validation and discussion of these results with respect to the study objectives are presented. The results are grouped under three sections where the first covers illuminance data, second covers luminance data and third covers monthly discomfort times data. The derived data are given both in tabular format and in charts.

4.1 Illuminance Data

Light levels on the analysis grid over school desks and white board were calculated both for overcast sky and for intermediate sky with sun on 21 March 12:00 for each fenestration composition. Thus, 88 sets of light level analysis results were collected for south facing windows and 48 sets were collected for north facing windows. These results are given in iso-lux contour line format in Appendix A.

Below are the summarized results of light levels separately for south facing and north facing windows. The summarized results for south facing windows under overcast sky conditions are given in Table 4.1 while under intermediate sky conditions are given in Table 4.3. In addition, the summarized results for north facing windows under overcast sky conditions are given in Table 4.2 while under intermediate sky conditions are given in Table 4.4. The light level threshold values for classrooms used in the analysis are 300 lux for horizontal tasks and 500 lux for vertical tasks. These values were taken from CIBSE (1994) recommendations. In the results; diversity found by the division of the maximum illuminance to the minimum illuminance in accordance with the description of CIBSE (1994) was used to represent the illuminance range over the analysis grid.

Table 4.1 Illuminance Data over the School Desks and the Whiteboard for South Facing Windows under Overcast Sky Condition

Window Types	Analysis Grid Values Over the School Desks				Analysis Grid Values Over the Whiteboard			
	Average Illuminance (Lux)	Percentage Above 300 Lux (%)	Min. Illuminance (Lux)	Diversity	Average Illuminance (Lux)	Percentage Above 500 Lux (%)	Min. Illuminance (Lux)	Diversity
WS1	299.33	33.30%	138.81	4.76	211.48	0.00%	146.98	2.25
WS2	338.04	50.00%	170.56	3.66	260.42	0.00%	178.04	2.09
WS3	235.56	33.30%	106.06	3.83	165.90	0.00%	105.16	2.37
WS4	241.05	33.00%	130.98	2.63	202.42	0.00%	130.07	2.37
WS5	234.88	33.30%	101.52	4.84	156.91	0.00%	97.71	2.59
WS6	253.41	33.30%	115.43	3.82	188.40	0.00%	111.92	2.48
WS7	209.56	16.70%	78.02	6.91	139.30	0.00%	90.94	2.55
WS8	219.72	20.00%	94.75	5.10	152.86	0.00%	104.03	2.20
WS9	258.96	30.00%	126.18	3.85	204.23	0.00%	131.94	2.26
WS10	233.15	30.00%	102.22	4.46	164.71	0.00%	108.73	2.33
WS11	266.36	30.00%	120.86	3.88	204.81	0.00%	133.94	2.26
WS12	216.05	16.70%	87.36	5.54	149.26	0.00%	101.20	2.35
WS13	245.91	30.00%	104.72	4.91	177.07	0.00%	116.65	2.22
WS14	102.92	0.00%	53.78	3.08	94.07	0.00%	56.97	2.45
WS15	146.58	0.00%	87.77	2.39	137.69	0.00%	85.29	2.68
WS16	107.38	0.00%	57.39	3.34	84.16	0.00%	51.98	2.52
WS17	121.74	0.00%	53.97	3.92	99.64	0.00%	61.58	2.52
WS18	124.28	3.30%	41.13	7.61	76.16	0.00%	44.80	3.09
WS19	115.35	0.00%	56.29	3.67	94.18	0.00%	48.61	2.98
WS20	134.47	0.00%	67.72	2.89	118.86	0.00%	73.51	2.67
WS21	132.79	0.00%	42.51	6.98	86.76	0.00%	51.27	2.94
WS22	153.20	0.00%	62.76	4.74	109.95	0.00%	68.19	2.41

Table 4.2 Illuminance Data over the School Desks and the Whiteboard for North Facing Windows under Overcast Sky Conditions

Window Types	Analysis Grid Values Over the School Desks				Analysis Grid Values Over the Whiteboard			
	Average Illuminance (Lux)	Percentage Above 300 Lux (%)	Min Illuminance (Lux)	Diversity	Average Illuminance (Lux)	Percentage Above 500 Lux (%)	Min Illuminance (Lux)	Diversity
WN1	562.90	0.63	185.83	7.84	297.79	0.06	189.09	2.75
WN2	426.39	0.50	146.86	6.81	222.59	0.00	131.27	2.75
WN3	424.23	0.50	135.20	8.15	211.62	0.00	130.30	2.74
WN4	367.05	0.33	107.85	10.05	181.68	0.00	115.90	2.87
WN5	411.54	0.47	126.87	8.44	213.58	0.00	137.87	2.89
WN6	399.22	0.43	118.99	9.23	201.61	0.00	122.03	2.96
WN7	444.39	0.50	141.40	7.96	228.99	0.00	140.46	2.81
WN8	217.40	0.33	69.95	5.93	125.91	0.00	73.65	2.89
WN9	223.47	0.33	63.61	8.81	113.33	0.00	67.57	3.10
WN10	222.35	0.17	49.27	15.21	96.28	0.00	56.51	3.55
WN11	241.81	0.33	68.71	8.57	128.10	0.00	74.00	2.80
WN12	239.45	0.30	48.44	14.47	112.71	0.00	58.84	3.56

Table 4.3 Illuminance Data over the School Desks and the Whiteboard for South Facing Windows under Intermediate Sky Conditions

	Analysis Grid Values Over the School Desks				Analysis Grid Values Over the Whiteboard			
Window Types	Average Illuminance (Lux)	Percentage Above 300 Lux (%)	Min Illuminance (Lux)	Diversity	Average Illuminance (Lux)	Percentage Above 500 Lux (%)	Min Illuminance (Lux)	Diversity
WS1	992.63	100.00%	448.88	4.99	670.01	88.90%	467.85	2.12
WS2	1201.05	100.00%	588.73	3.79	893.43	100.00%	571.42	2.25
WS3	771.04	100.00%	373.32	3.39	542.02	55.60%	365.62	2.14
WS4	902.94	100.00%	477.14	2.65	709.62	94.40%	450.06	2.37
WS5	777.47	100.00%	344.62	4.67	507.45	44.40%	332.94	2.40
WS6	913.29	100.00%	410.39	3.76	641.86	83.30%	404.35	2.44
WS7	698.67	96.70%	259.61	7.01	437.32	27.80%	268.78	2.80
WS8	731.29	96.70%	298.86	5.26	482.95	38.90%	315.23	2.25
WS9	915.93	100.00%	418.04	3.93	667.90	77.80%	445.05	2.09
WS10	786.29	100.00%	353.75	4.26	518.54	50.00%	380.83	2.02
WS11	974.21	100.00%	460.01	3.58	686.46	77.80%	443.50	2.33
WS12	715.29	96.70%	292.72	5.61	460.18	27.80%	303.66	2.47
WS13	842.76	100.00%	371.47	4.76	580.34	61.10%	374.11	2.29
WS14	342.08	50.00%	197.72	2.52	306.20	0.00%	203.04	2.38
WS15	589.10	100.00%	310.84	2.68	512.23	50.00%	334.14	2.63
WS16	358.35	60.00%	179.08	3.55	269.23	0.00%	157.87	2.82
WS17	424.21	66.70%	213.45	3.49	340.54	5.60%	221.47	2.65
WS18	417.40	50.00%	147.67	7.05	239.26	0.00%	141.91	3.31
WS19	382.69	63.30%	190.77	3.54	303.88	0.00%	188.29	2.42
WS20	515.95	90.00%	245.61	3.01	442.98	22.20%	288.69	2.37
WS21	439.44	60.00%	169.59	5.34	274.29	0.00%	147.93	3.12
WS22	526.34	70.00%	202.05	4.96	359.28	55.60%	216.79	2.38

Table 4.4 Illuminance Data over the School Desks and the Whiteboard for North Facing Windows under Intermediate Sky Conditions

	Analysis Grid Values Over the School Desks				Analysis Grid Values Over the Whiteboard			
Window Types	Average Illuminance (Lux)	Percentage Above 300 Lux (%)	Min Illuminance (Lux)	Diversity	Average Illuminance (Lux)	Percentage Above 500 Lux (%)	Min Illuminance (Lux)	Diversity
WN1	604.47	83.30%	264.28	4.93	431.86	27.80%	296.35	2.12
WN2	442.26	63.30%	181.32	4.88	303.04	0.00%	211.41	2.14
WN3	444.90	56.70%	183.01	5.43	303.14	0.00%	205.21	2.35
WN4	402.61	50.00%	165.48	6.02	281.51	0.00%	198.53	2.10
WN5	441.70	56.70%	182.43	5.55	310.95	0.00%	216.49	2.07
WN6	432.18	50.00%	179.01	5.79	305.07	0.00%	213.35	2.12
WN7	462.02	63.30%	189.75	5.30	317.93	0.00%	199.75	2.38
WN8	226.42	33.30%	85.49	4.70	165.36	0.00%	100.27	2.59
WN9	233.64	33.30%	86.53	5.67	157.34	0.00%	96.39	2.64
WN10	228.64	20.00%	75.50	7.94	145.52	0.00%	84.56	2.71
WN11	245.79	33.30%	96.46	5.31	171.96	0.00%	115.29	2.32
WN12	247.59	30.00%	83.29	7.14	164.96	0.00%	104.67	2.36

4.2 Luminance Data

Luminance images were Generated for Classrooms Configured with intermediate sky with sun on 21 March 16:00, with the camera position described in the method section, for each fenestration configuration. Thus, 22 images were collected for south facing windows and 12 images were collected for north facing windows. One example of the luminance images is given below. The maximum luminance values, i.e. the maximum window luminances and the luminances of the task, i.e. the white board luminances were collected from these images and are given below in Table 4.5 as a luminance ratio to compare the possibility of glare between different configurations.

Table 4.5 Luminance Ratios for South and North Facing Windows

Window Types	Luminance Ratio	Window Types	Luminance Ratio
WS1	47.87	WN1	8.73
WS2	36.83	WN2	10.80
WS3	61.96	WN3	11.90
WS4	48.98	WN4	15.22
WS5	62.69	WN5	11.84
WS6	52.97	WN6	12.70
WS7	70.35	WN7	11.23
WS8	64.44	WN8	18.64
WS9	50.91	WN9	21.22
WS10	63.36	WN10	27.20
WS11	48.10	WN11	18.75
WS12	68.15	WN12	21.60
WS13	55.12		
WS14	112.43		
WS15	5.78		
WS16	115.09		
WS17	94.83		
WS18	132.12		
WS19	108.03		
WS20	81.57		
WS21	118.29		
WS22	93.21		

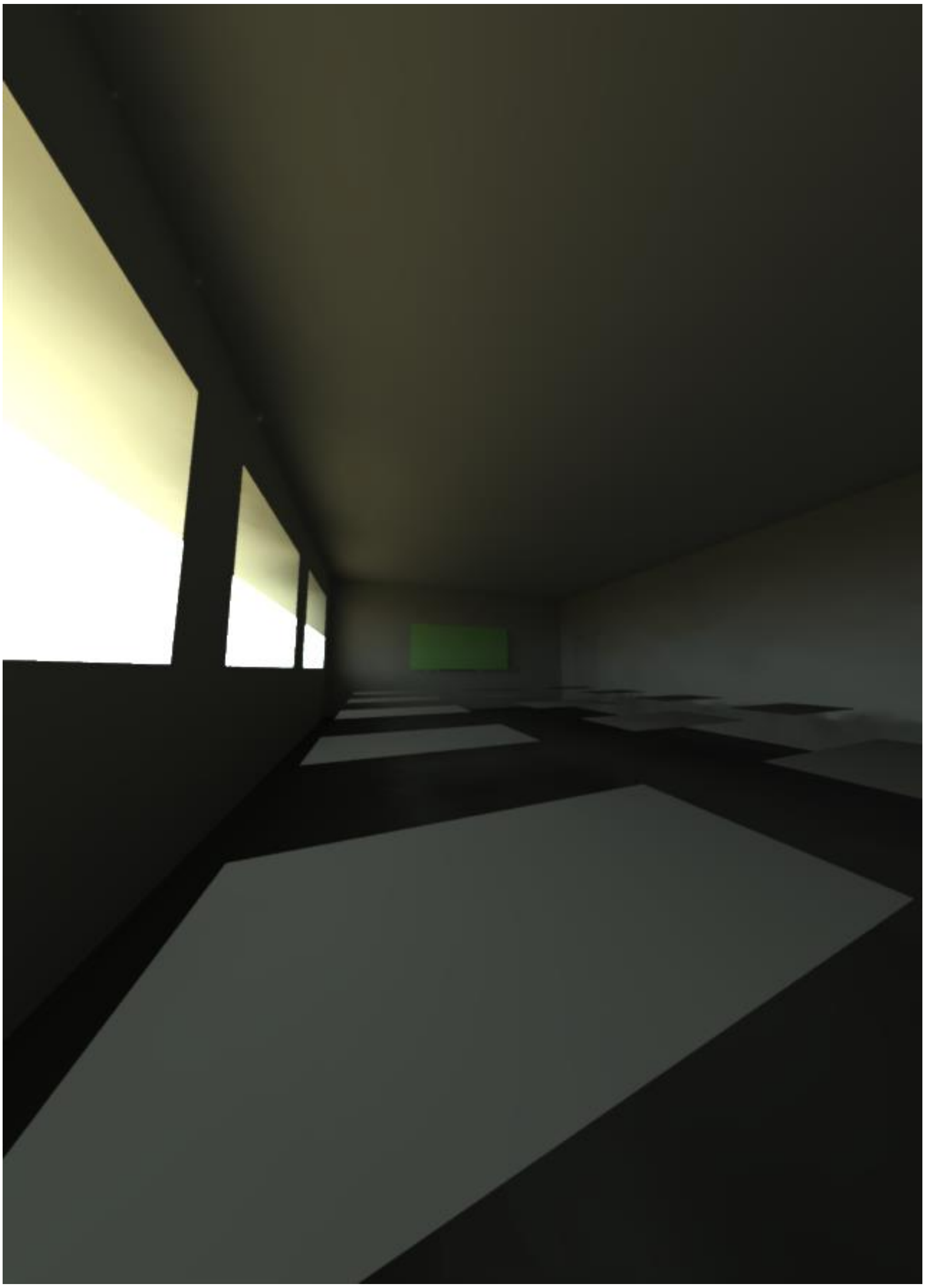


Figure 4.1 Luminance Image of WS10

4.3 Discomfort Degree Hours

The discomfort degree hours for both “too cool” and “too hot” periods which are given in Appendix B, were collected monthly for each fenestration configuration. The total yearly discomfort degree hours (DDH) for a year are given below for each fenestration configuration in Table 4.6. On the other hand, to compare the windows having same areas between each other, four different column charts were produced. The DDH for larger (2.73 m²) windows facing south are shown in Figure 4.1 and for smaller (1.47 m²) windows facing south are shown in Figure 4.2. Those for north facing larger and smaller windows are given in Figure 4.3 and 4.4 respectively.

Table 4.6 Total Yearly DDH for South and North Facing Windows

Window Types	Too Hot (DegHrs)	Too Cool (DegHrs)	Discomfort Degree Hours	Window Types	Too Hot (DegHrs)	Too Cool (DegHrs)	Discomfort Degree Hours
WS1	4308.1	4994.3	9302.40	WN1	4274.6	5070.0	9344.60
WS2	4324.8	4981.1	9305.09	WN2	6348.5	2814.5	9163.10
WS3	6385.4	2758.6	9143.90	WN3	6348.5	2814.5	9163.10
WS4	6404.5	2749.6	9154.00	WN4	6348.5	2814.5	9163.10
WS5	6385.8	2758.3	9144.20	WN5	6347.9	2815.1	9163.00
WS6	6399.9	2751.8	9151.60	WN6	6351.1	2812.3	9163.40
WS7	6389.8	2756.5	9146.30	WN7	6351.1	2812.3	9163.40
WS8	6385.4	2757.2	9142.50	WN8	9920.9	853.9	10774.90
WS9	6401.2	2749.7	9150.90	WN9	9920.9	853.9	10774.90
WS10	6385.3	2757.7	9142.70	WN10	9920.9	853.9	10774.90
WS11	6397.0	2752.0	9151.90	WN11	9920.5	854.0	10774.60
WS12	6385.2	2757.5	9143.00	WN12	9920.5	854.0	10774.60
WS13	6402.4	2749.5	9149.00				
WS14	9966.6	834.7	10801.40				
WS15	9986.1	831.7	10817.70				
WS16	9968.5	834.6	10801.40				
WS17	9981.3	832.4	10813.70				
WS18	9967.5	834.6	10802.10				
WS19	9975.6	832.9	10808.40				
WS20	9986.4	831.1	10817.60				
WS21	9968.2	834.1	10802.30				
WS22	9979.2	832.4	10811.60				

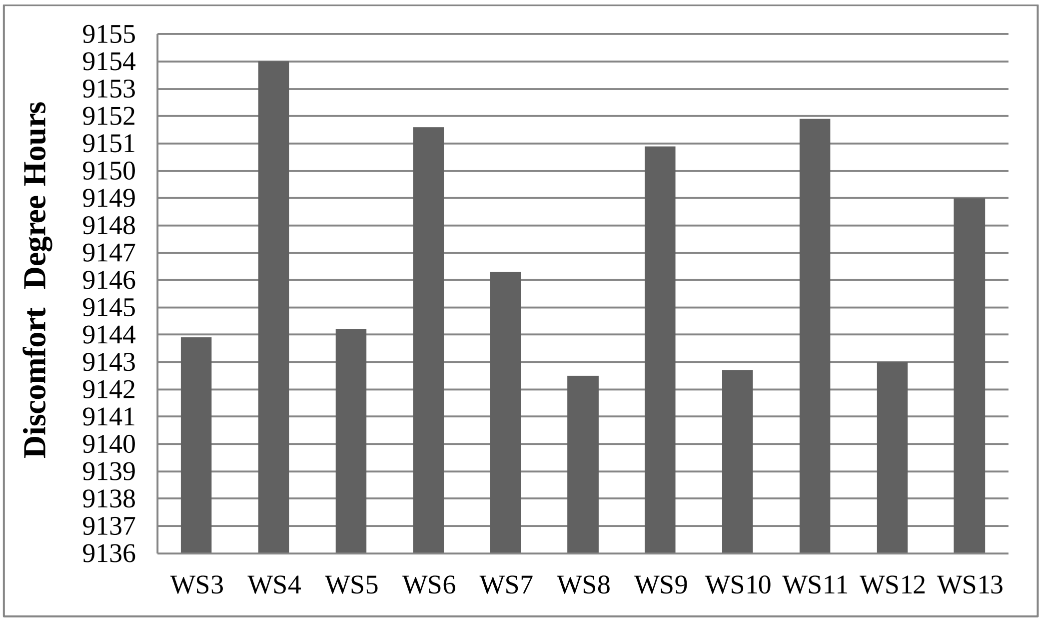


Figure 4.2 Total Yearly Discomfort Degree Hours for South Facing 2.73 m² Windows

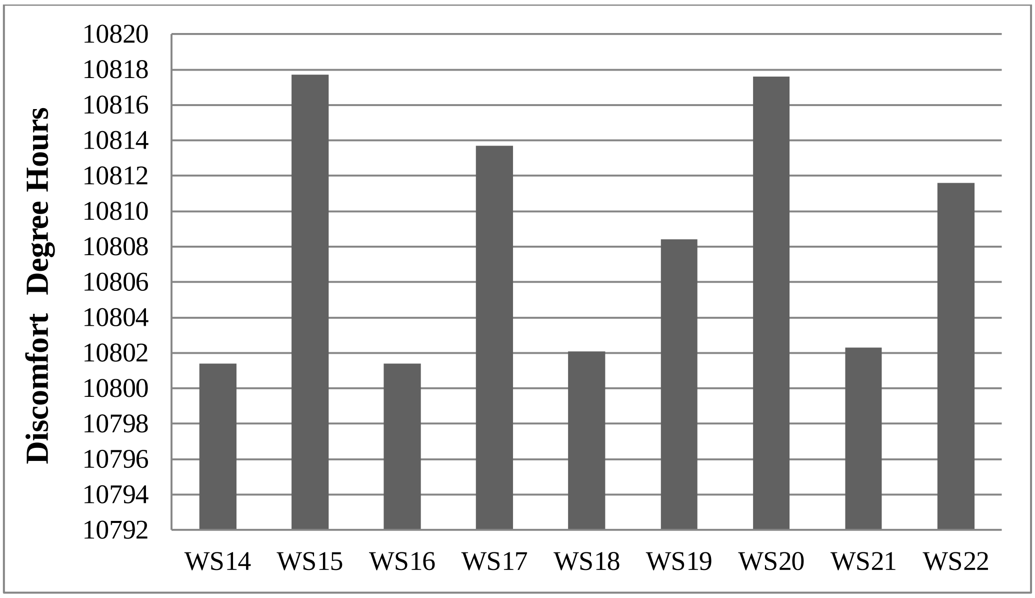


Figure 4.3 Total Yearly Discomfort Degree Hours for South Facing 1.47 m² Windows

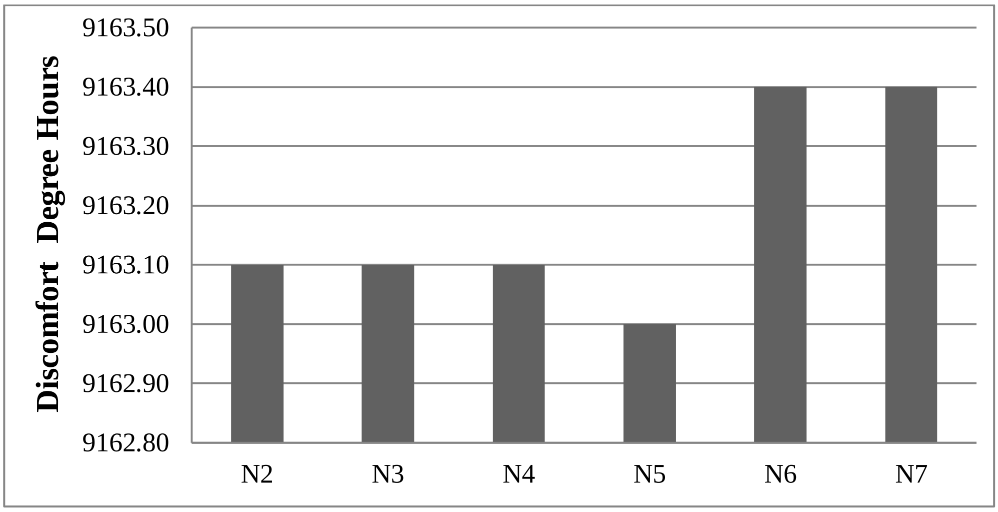


Figure 4.4 Total Yearly Discomfort Degree Hours for North Facing 2.73 m² Windows

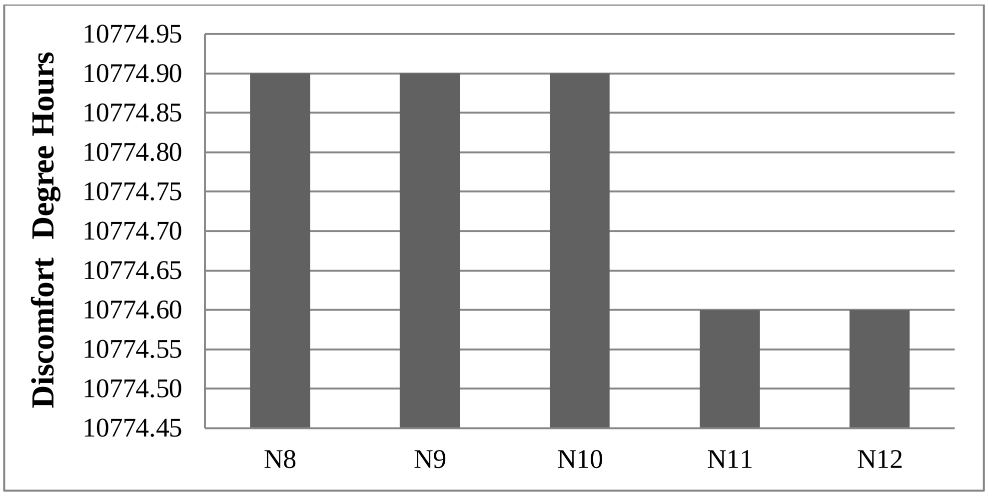


Figure 4.5 Total Yearly Discomfort Degree Hours for North Facing 1.47 m² Windows

4.4 Results of Data Validation

The recorded illuminance data and the corresponding simulated illuminance data over the desks of the two classrooms of the school located in Çankaya district of Ankara were overlaid in the comparison graphs. The data between 08:00 to 18:00 at 30 minutes intervals on 21 September were used in the graphs. In Figure 4.6 and 4.7, data belonging to the window side and the wall side of the classroom facing south-east are given respectively. On the other hand, in Figure 4.8 and 4.9, data belonging to the window side and the wall side of the classroom facing north-west are given respectively. In addition, data are given in tabular format in Appendix C.

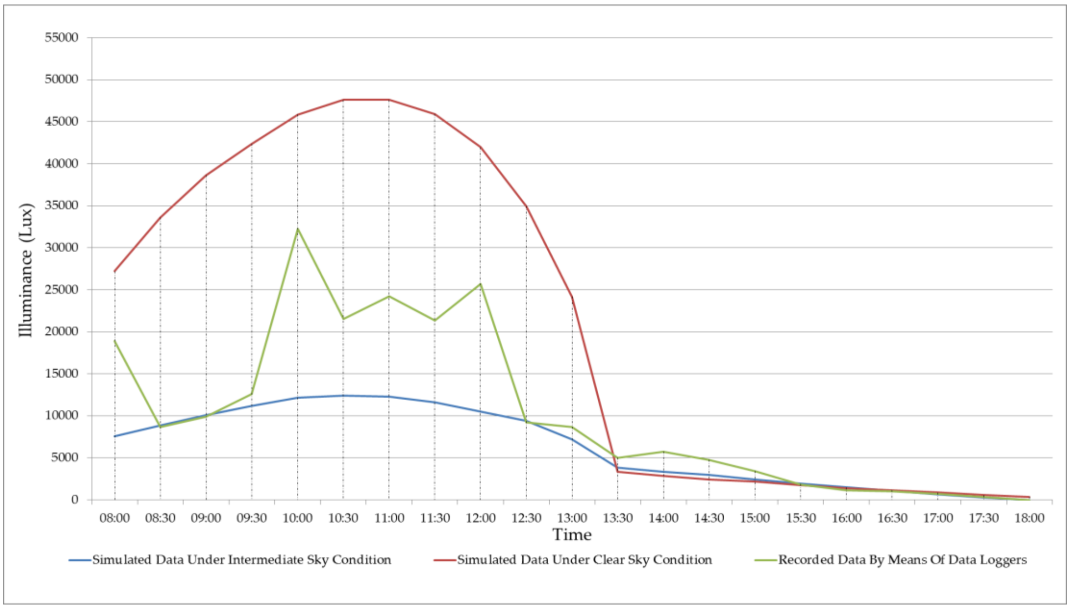


Figure 4.6 Recorded and Simulated Illuminance Data over School Desk in Window Side of the Classroom Facing South-East

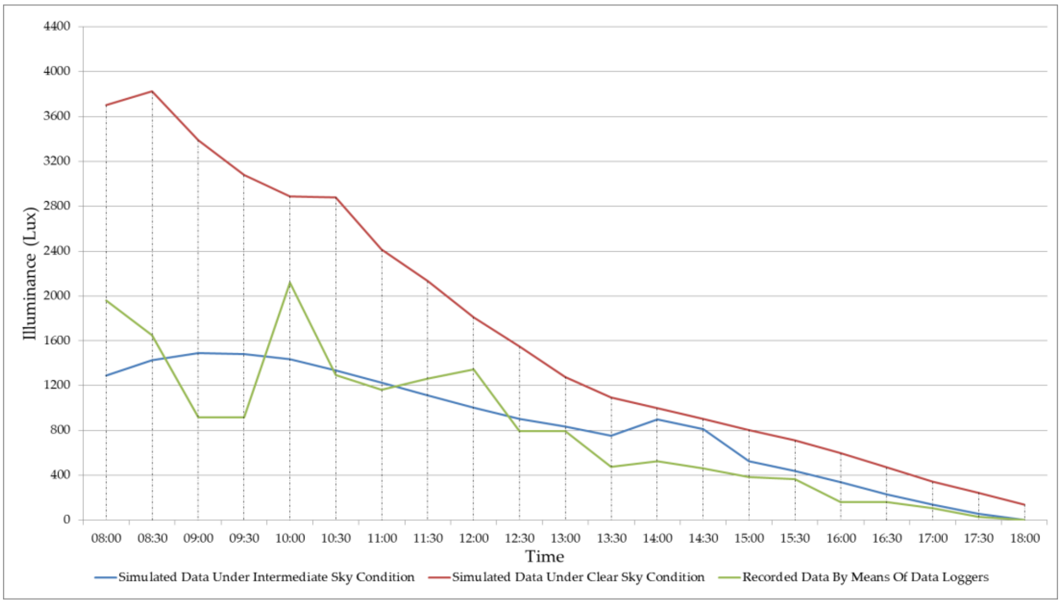


Figure 4.7 Recorded and Simulated Illuminance Data over School Desk in Wall Side of the Classroom Facing South-East

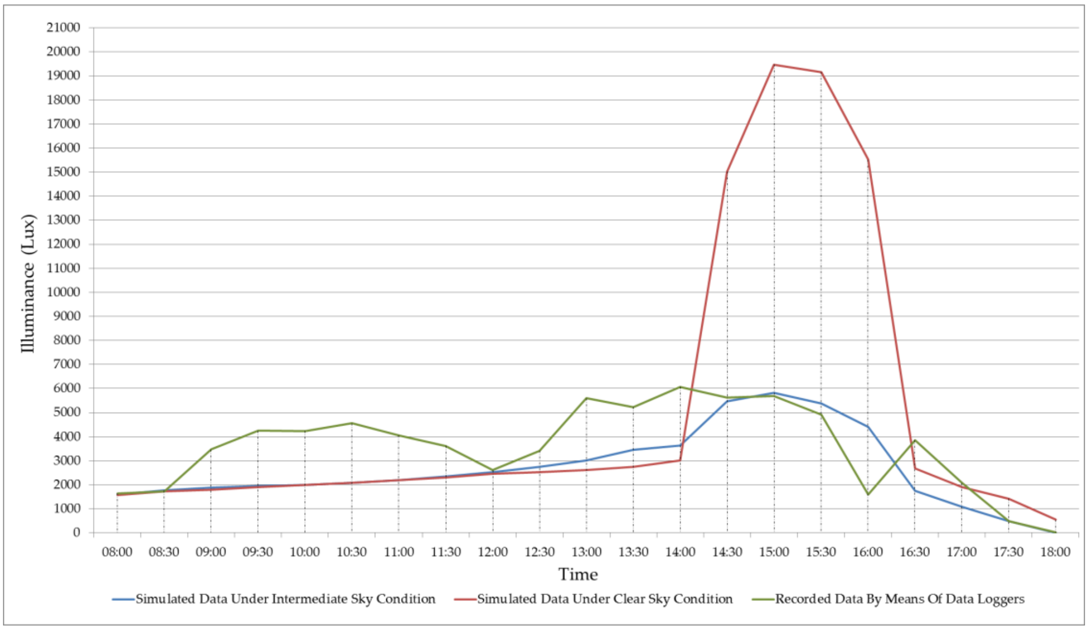


Figure 4.8 Recorded and Simulated Illuminance Data over School Desk in Window Side of the Classroom Facing North-West

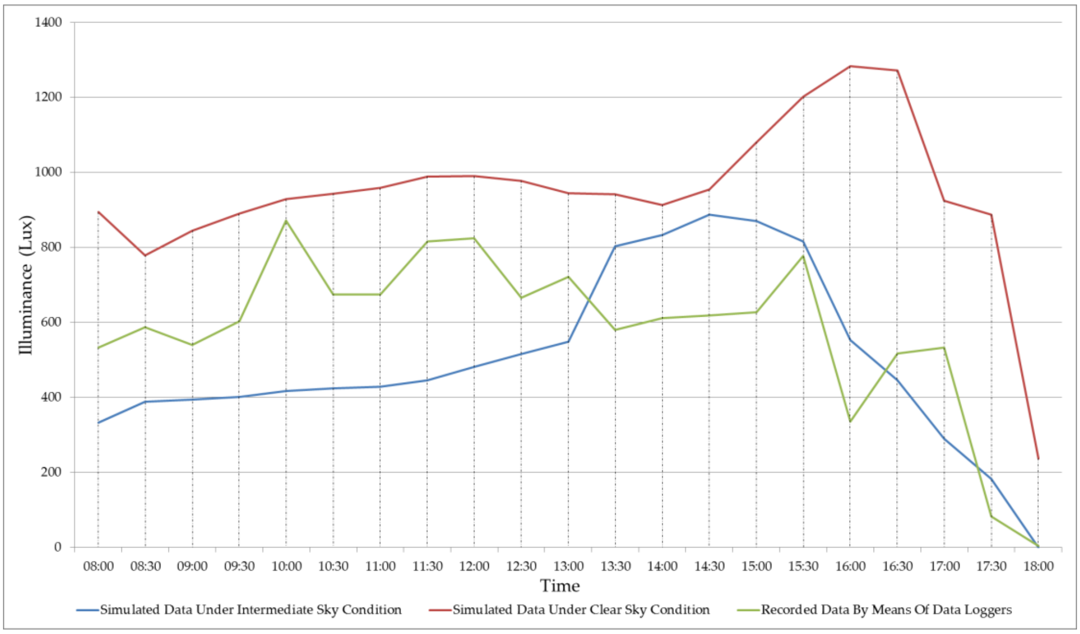


Figure 4.9 Recorded and Simulated Illuminance Data over School Desk in Wall Side of the Classroom Facing North-West

4.5 Discussion

The figures in this section are produced for comparison. The Figure 4.10 and 4.11 depict the illuminance values while Figure 4.12 and 4.13 show diversity variations for south and north facing windows respectively. On the other hand, the figure 4.14 and 4.15 show the luminance ratio range of different fenestration configurations for south and north facing windows respectively. The windows having same dimensions, which were grouped as small, medium and large area windows, were pointed out in the horizontal axis of the all line charts. In addition, windows with lightshelf were marked with black dots in the line charts.

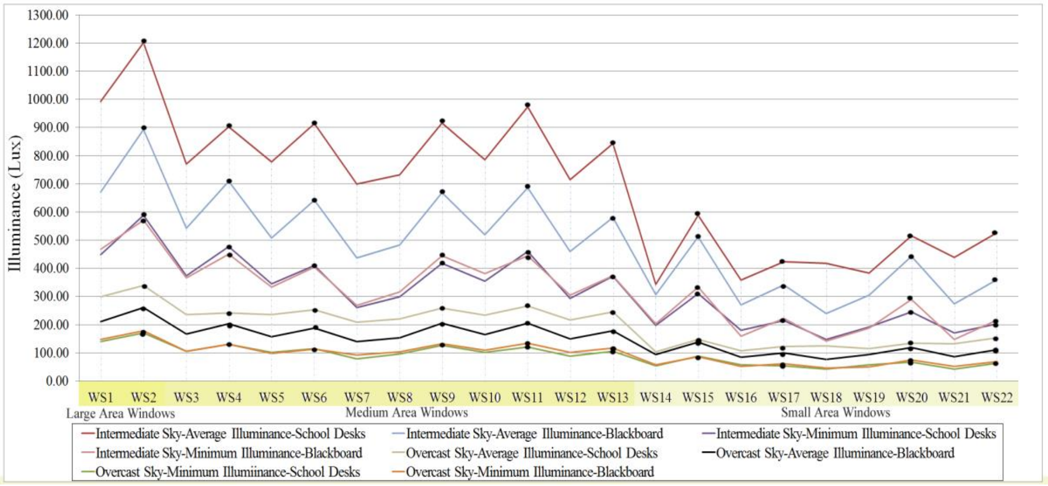


Figure 4.10 Average and Minimum Illuminance over the School Desks and the Whiteboard under Both Sky Conditions for South Facing Windows

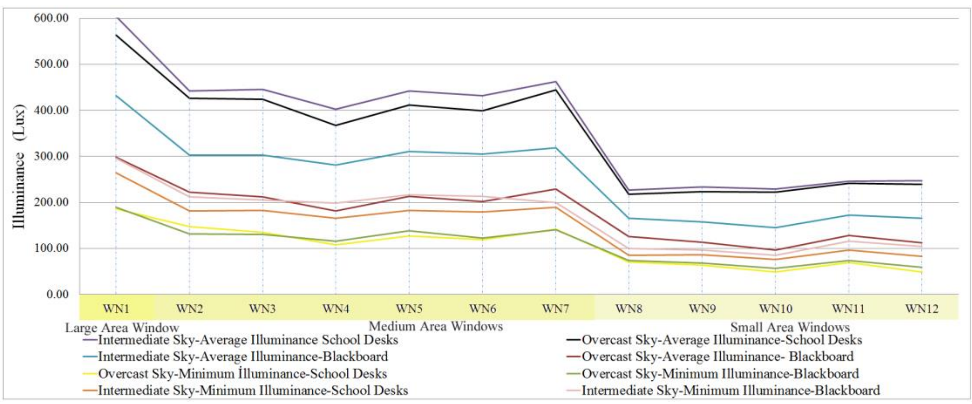


Figure 4.11 Average and Minimum Illuminance over the School Desks and the Whiteboard under Both Sky Conditions for North Facing Windows

Through Figure 4.10, it can be stated that a lightshelf enhance the performance of windows in terms of the amount of light provided inside in comparison with an overhang. In addition, in Figure 4.10 the rise and falls is steeper for intermediate sky than the overcast sky which may be due to the increase in the performance of lightshelves under direct sunlight. According to Figure 4.10 and 4.11, while school desks receive more average light than the white board, the minimum lighting levels are more or less the same. This can stem from the difference in the orientation, the size and the distance to windows between school desk surface and the white board surface. In Figure 4.10, there is also a considerable difference in the amount of light provided inside between the intermediate sky and overcast sky. For instance, the minimum light levels over the analysis grids under intermediate sky are even greater than the average light levels over the analysis grids under overcast sky. However, In Figure 4.11, there is not a considerable difference in the amount of light provided inside between the intermediate sky and overcast sky especially over the school desks. This indicates that the influence of the sky conditions on the performance of windows regarding amount of illuminance provided inside change radically with the window orientations. On the other hand, from Figure 4.10 and 4.11, it can be concluded that the difference in the performances of the same window under overcast and intermediate sky conditions become smaller as the area becomes smaller which implies that the decrease in the window area decrease the impact of sky conditions on the performance of windows in this regard.

For both south facing and north facing windows, it can be generalized that the amount of light received inside has a direct relation with the area of the windows. The increase in the area of the windows increase the amount of light received inside. However, there are exceptions only observed in the performance of south facing windows under the intermediate sky conditions over the white board such that WS4 and WS11 outperform WS1 as well as, WS15 outperforms WS7, WS8, WS12 and WS20 outperforms WS7. WS4, WS11, WS15, WS20 are the windows with a lightshelf whereas WS1, WS7, WS8, WS12 are the ones with an overhang. This shows that the use of a lightshelf is more critical for the white board than the school desks. This also shows that a south facing window having smaller area can outperform another window with an overhang and having larger area with the help of a lightshelf.

The highest diversity for north facing windows is found over the school desks under overcast sky conditions while there is a similarity in the diversity found over the same task under different sky conditions for south facing windows which can be followed through Figure 4.12 and 4.13 This clearly exhibits the shading effect of both an overhang and a lightshelf. Through Figure 4.12 and 4.13, a relation cannot be established between the area of a window and diversity. On the other hand, diversity found over the white board is smaller than and has a smaller range than the diversity found over school desks. Narrow range results from the smallness of the area of the white board and the distance of white board from window. Figure 4.12 also shows that lightshelf decrease the diversity found over school desks in general when compared to overhang. However, a lightshelf sometimes increase the diversity found over the white board especially under intermediate sky with sun which may be explained by the orientation of the task. Figure 4.13 also exhibits that the rise and falls become sharper in the smaller area windows which have the highest diversities.

This implies that the aspect ratio or parapet height have greater influence on smaller areas than larger areas in terms of diversity.

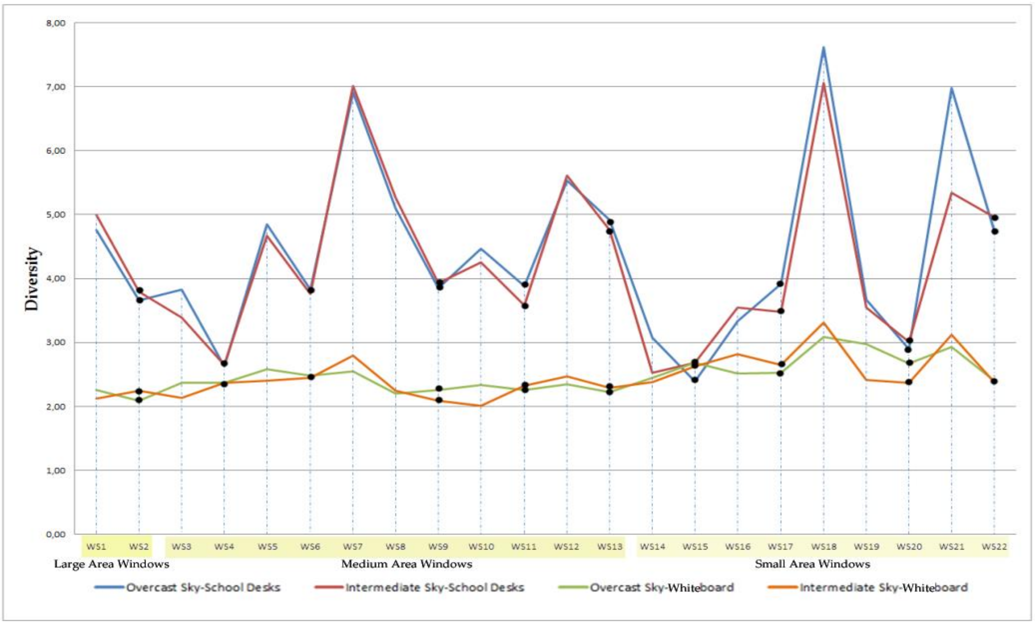


Figure 4.12 Comparison Chart for diversity over the School Desks and the Whiteboard under Both Sky Conditions for South Facing Windows

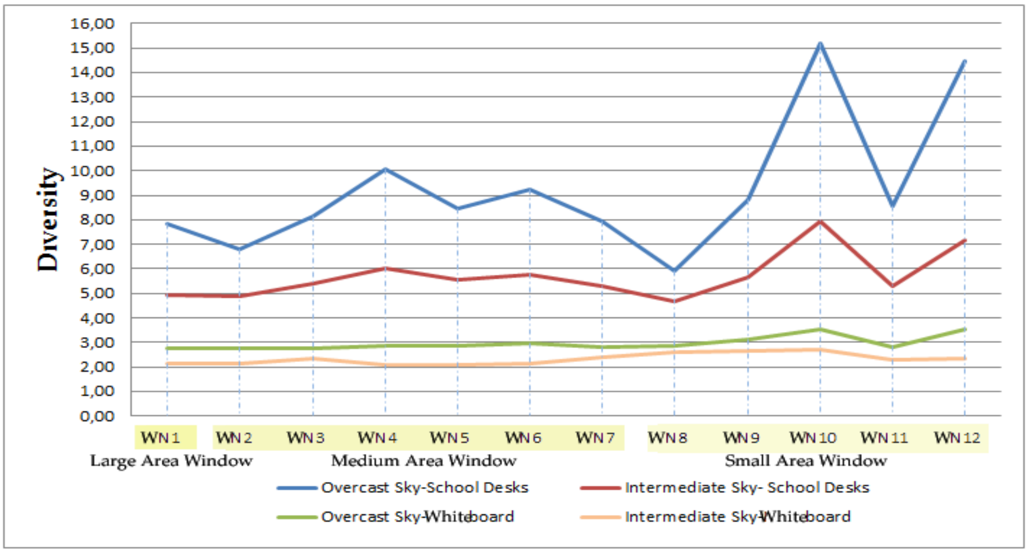


Figure 4.13 Comparison Chart for Diversity over the School Desks and the Whiteboard under Both Sky Conditions for North Facing Windows

According to Figure 4.14, except WS15, and Figure 4.15, luminance ratio has a direct relation with the area that is the decrease in the area increases the luminance ratio. For south facing windows, lightshelf decrease the luminance ratio in comparison with the same window configured with an overhang.

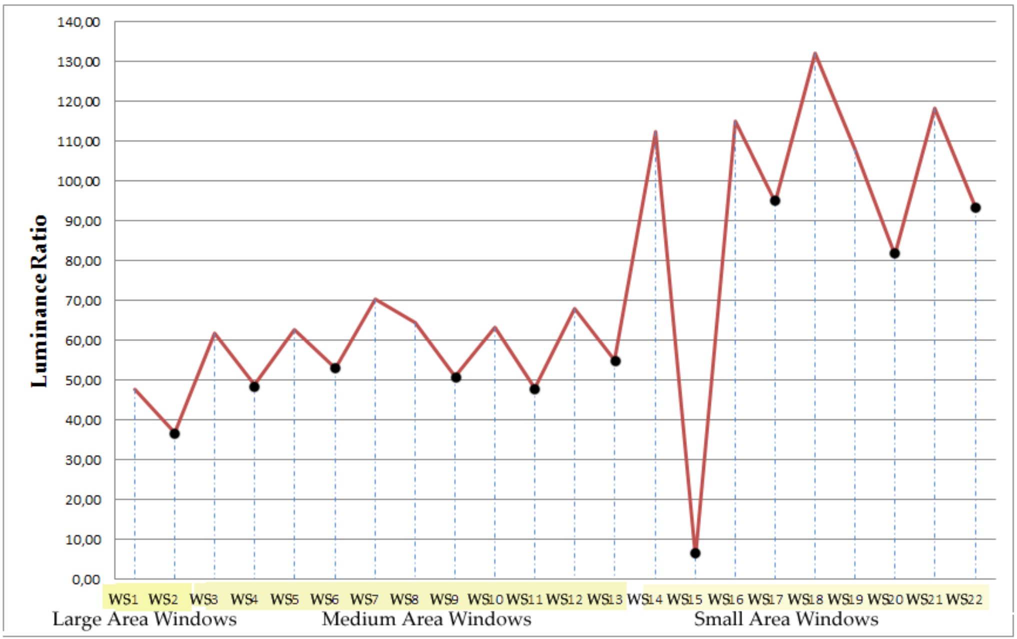


Figure 4.14 Luminance Ratio for South Facing Windows

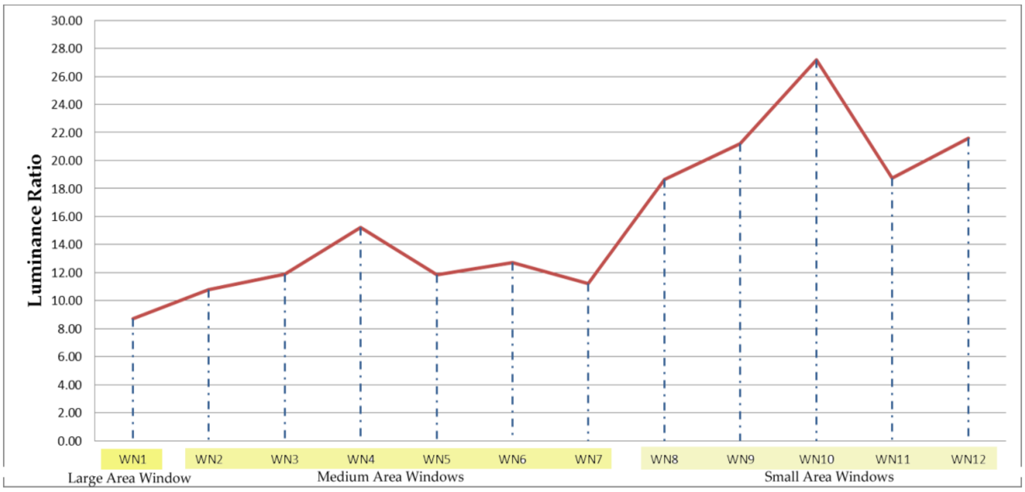


Figure 4.15 Luminance Ratio for North Facing Windows

For both north and south facing windows, the best thermal performers are the medium area windows while the least thermal performers are the smaller area ones in terms of DDH. This implies that after a certain point, the decrease in the area of the window worsen the thermal performance rather than making better. This can result from the fact that the occupancy loads is static while fabric, infiltration and solar loads changes with the window area, therefore, the fabric and infiltration losses become much smaller when compared to occupancy loads after a certain point, then the inside becomes “too hot”. In addition, from Table 4.6, it can be generalized that mostly “too cool” value is smaller than the “too hot” which can be due to the effect of occupancy loads and high insulation. Moreover, windows having smaller area perform better at north than south regarding the DDH which is due to the fact that the solar loads relatively less affected than the fabric loads by the decrease in the area and the solar loads is considerably less for north facing windows than the south facing windows. On the other hand, through Figure 4.2 and 4.3, it can be stated that an overhang enhance the performance of windows in comparison with a lightshelf regarding DDH.

According to Figure 4.6 and 4.7, it can be stated that the graphical patterns show similar characteristics and to a greater extent, the recorded data either roughly overlap with the simulated data or found in between data simulated under intermediate sky and clear sky conditions which exhibits that the real sky condition was also somewhere between the intermediate sky and clear sky. The rise and falls in the graphic of the recorded data could be due to the change of the sky condition which can be easily followed through the graphics. In Figure 4.8, in the forenoon, the recorded illuminance values are above the simulated ones which can be due to fact that the model was produced without surrounding environment resulting in a disregard of the effect of the reflected solar component. According to Figure 4.8 and Figure 4.9, it can be realized that the sky is much cloudier in the afternoon resulting in a fall in the graphics.

According to the simulated data verification, it can be stated that due to the fact that the sky condition changes instant to instant and the model was produced without surrounding environment, the recorded illuminance data by means of data loggers does not totally overlap with the simulated illuminance data produced in Ecotect Analysis 2011 with Desktop Radiance, but still to a greater extent, either it approximately and partly overlaps with the simulated data or the graphical patterns show similar characteristics presenting the reliability of the simulated data. It can further be stated that the instant change in the sky condition is a compelling factor in the evaluation of the results.

Below are the average illuminance, luminance, diversity and DDH performance ranking tables of different fenestration configurations according to either parapet height or aspect ratio. The windows having same area and aspect ratio and the windows having same area and parapet height were grouped. The windows with lightshelves and the windows with overhangs were compared among themselves and were ranged according to their performance from higher to lower. The diversity over the school desks under both sky conditions and the average illuminance over the white board under both sky conditions show the same performance ranking, therefore they are arranged in a single column in the tables.

Table 4.7 Illuminance, Luminance Ratio, Diversity and DDH Performance Ranking from Highest to Lowest According to Parapet Height for South Facing Windows Having Same Area and Aspect Ratio and According to Aspect Ratio for South Facing Windows Having Same Area and Parapet Height

Fenestration Grouping					Performance Ranking					
	Area (m^2)	Aspect Ratio	Parapet Height (cm)	Types	According To Avg. Illuminance Under Intermediate Sky Condition Over School Desks	According To Avg. Illuminance Under Overcast Sky Condition Over School Desks	According To Avg.Illuminance Under Both Sky Conditions Over Whiteboard	According To Diversity Under Both Sky Conditions Over School Desks	According To Luminance Ratio	According To DDH
Windows having same area and aspect ratio	2.73 m^2	1.62	140	WS3	WS5	WS3	WS3	WS3	WS3	WS3
			120	WS5	WS3	WS5	WS5	WS5	WS5	WS5
			80	WS7	WS7	WS7	WS7	WS7	WS7	WS7
			140	WS4	WS6	WS6	WS4	WS4	WS4	WS6
			120	WS6	WS4	WS4	WS6	WS6	WS6	WS4
		1.11	112.84	WS10	WS10	WS10	WS10	WS10	WS10	WS10
			80	WS12	WS12	WS12	WS12	WS12	WS12	WS12
			112.84	WS11	WS11	WS11	WS11	WS11	WS11	WS13
			80	WS13	WS13	WS13	WS13	WS13	WS13	WS11
	1.47m^2	3	200	WS14	WS18	WS18	WS14	WS14	WS14	WS14=WS
			160	WS16	WS16	WS16	WS16	WS16	WS16	WS18
			120	WS18	WS14	WS14	WS18	WS18	WS18	
			200	WS15	WS15	WS15	WS15	WS15	WS15	WS17
			160	WS17	WS17	WS17	WS17	WS17	WS17	WS15
		1.11	154.68	WS19	WS21	WS21	WS19	WS19	WS19	WS21
			120	WS21	WS19	WS19	WS21	WS21	WS21	WS19
			154.68	WS20	WS22	WS22	WS20	WS20	WS20	WS22
			120	WS22	WS20	WS20	WS22	WS22	WS22	WS20
		Parapet Height (cm)	Aspect Ratio							
Windows having same area and parapet height	2.73m^2	80	0.76	WS8	WS8	WS8	WS8	WS8	WS8	WS8
			1.11	WS12	WS12	WS12	WS12	WS12	WS12	WS12
			1.62	WS7	WS7	WS7	WS7	WS7	WS7	WS7
			0.76	WS9	WS9	WS9	WS9	WS9	WS9	WS13
			1.11	WS13	WS13	WS13	WS13	WS13	WS13	WS9
	1.47m^2	120	1.11	WS21	WS21	WS21	WS21	WS21	WS21	WS21
			3	WS18	WS18	WS18	WS18	WS18	WS18	WS18

Table 4.8 Illuminance, Luminance Ratio, Diversity and DDH Performance Ranking from Highest to Lowest According to Parapet Height for North Facing Windows Having Same Area and Aspect Ratio and According to Aspect Ratio for North Facing Windows Having Same Area and Parapet Height

Fenestration Grouping					Performance Ranking					
	Area (m^2)	Aspect Ratio	Parapet Height (cm)	Window Types	According To Avg. Illuminance Under Intermediate Sky Condition Over School Desks	According To Avg. Illuminance Under Overcast Sky Condition Over School Desks	According To Avg.Illuminance Under Both Sky Conditions Over Whiteboard	According To Diversity Under Both Sky Conditions Over School Desks	According To Luminance Ratio	According To DDH
Windows having same area and aspect ratio	2.73m^2	1.62	140	WN2	WN3	WN2	WN2	WN2	WN2	Same Perfromance
			120	WN3	WN2	WN3	WN3	WN3	WN3	
			80	WN4	WN4	WN4	WN4	WN4	WN4	
		1.11	112.84	WN7	WN7	WN7	WN7	WN7	WN7	Same Perfromance
			80	WN6	WN6	WN6	WN6	WN6	WN6	
	1.47m2	3	200	WN8	WN9	WN9	WN8	WN8	WN8	Same Perfromance
			160	WN9	WN10	WN10	WN9	WN9	WN9	
			120	WN10	WN8	WN8	WN10	WN10	WN10	
		1.11	154.68	WN11	WN12	WN11	WN11	WN11	WN11	Same Perfromance
			120	WN12	WN11	WN12	WN12	WN12	WN12	
		Parapet Height (cm)	Aspect Ratio							
Windows having same area and parapet height	2.73m^2	80	0.76	WN5	WN5	WN5	WN5	WN5	WN5	WN5
			1.11	WN6	WN6	WN6	WN6	WN6	WN6	WN4
			1.62	WN4	WN4	WN4	WN4	WN4	WN4	WN6
	1.47m2	120	1.11	WN12	WN12	WN12	WN12	WN12	WN12	WN12
			3	WN10	WN10	WN10	WN10	WN10	WN10	WN10

For both north and south facing windows, the performances of windows having same area and aspect ratio regarding the amount of light provided over the white board, diversity over the school desks and luminance ratio increases with the increase in the parapet height. The performances of these windows regarding the amount of light provided over school desks sometimes increase sometimes decrease with the increase in the parapet height. In addition, for south facing windows, DDH performance of windows with overhangs increases with the increase in the parapet height while DDH performance of windows with lightshelves increase with the decrease in the parapet height. This is due to the fact that, the solar gain through a window with a lightshelf increase mostly with the increase in the distance between the lightshelf and window head. On the other hand, for north facing windows, the performances of windows regarding the DDH remain same with the change in the parapet height.

On the other hand, for both north and south facing windows, the performances of windows having same area and parapet height regarding the amount of light provided over both tasks and both sky conditions, diversity over the school desks and luminance ratio increases with the decrease in the aspect ratio. For south facing windows, DDH performance of windows with overhangs increases with the decrease in the aspect ratio while DDH performance of windows with lightshelves increase with increase in the aspect ratio which is, as stated above, related to the distance between lightshelf and window head. On the other hand, for north facing windows DDH performance is mostly increase with the decrease in the aspect ratio.

Below are the ranking tables between fenestration configurations in general. Windows were ranged according to their performance from higher to lower. 5 was accepted as a threshold value for diversity which was recommended by CIBSE (1994) as well as, 40 was accepted as a threshold value for luminance ratio which was cited in literature review chapter as the highest accepted level. The values below the thresholds were painted in the tables.

Table 4.9 Illuminance, Luminance Ratio, Diversity and DDH Performance Ranking for South Facing Windows from Highest To Lowest in General

Under Overcast Sky Condition			Under Intermediate Sky Condition				
Performance Ranking According to Diversity over School Desks	Performance Ranking According to Percantage above 300 Lux	Performance Ranking According to Average Illuminance over Whiteboard	Performance Ranking According to Diversity over School Desks	Performance Ranking According to Percentage above 300 Lux	Performance Ranking According to Percantage above 500 Lux	Performance Ranking According to Luminance Ratio	Thermal Performance Ranking According to DDH
WS15	WS2	WS2	WS14	WS4	WS2	WS15	WS8
WS4	WS1	WS1	WS4	WS15	WS4	WS2	WS10
WS20	WS4	WS11	WS15	WS3	WS1	WS1	WS12
WS14	WS6	WS9	WS20	WS11	WS6	WS11	WS3
WS16	WS3	WS4	WS3	WS6	WS9	WS4	WS5
WS2	WS5	WS6	WS17	WS2	WS11	WS9	WS7
WS19	WS9	WS13	WS19	WS9	WS13	WS6	WS13
WS6	WS11	WS3	WS16	WS10	WS3	WS13	WS9
WS3	WS13	WS10	WS11	WS5	WS22	WS3	WS6
WS9	WS10	WS5	WS6	WS13	WS10	WS5	WS11
WS11	WS8	WS8	WS2	WS1	WS15	WS10	WS4
WS17	WS12	WS12	WS9	WS8	WS5	WS8	WS1
WS10	WS7	WS7	WS10	WS12	WS8	WS12	WS2
WS22	WS18	WS15	WS5	WS7	WS12	WS7	WS14
WS1	WS15	WS20	WS13	WS20	WS7	WS20	WS16
WS5	WS20	WS22	WS22	WS22	WS20	WS22	WS18
WS13	WS14	WS17	WS1	WS17	WS17	WS17	WS21
WS8	WS16	WS19	WS8	WS19	WS14	WS19	WS19
WS12	WS19	WS14	WS21	WS16	WS19	WS14	WS22
WS7	WS17	WS21	WS12	WS21	WS16	WS16	WS17
WS21	WS22	WS16	WS7	WS14	WS21	WS21	WS20
WS18	WS21	WS18	WS18	WS18	WS18	WS18	WS15

Table 4.10 Illuminance, Luminance Ratio, Diversity and DDH Performance Ranking for North Facing Windows from Highest to Lowest in General

Under Overcast Sky Condition			Under Intermediate Sky Condition				
Performance Ranking According to Diversity over School Desks	Performance Ranking According to Percantage above 300 Lux	Performance Ranking According to Average Illuminance over Whiteboard	Performance Ranking According to Diversity over School Desks	Performance Ranking According to Percentage above 300 Lux	Performance Ranking According to Average Illuminance over Whiteboard	Performance Ranking According to Luminance Ratio	Thermal Performance Ranking According to DDH
WN8	WN1	WN1	WN8	WN1	WN1	WN1	WN5
WN2	WN2	WN7	WN2	WN7	WN7	WN2	WN2
WN1	WN7	WN5	WN1	WN2	WN5	WN7	WN3
WN7	WN3	WN2	WN7	WN3	WN6	WN5	WN4
WN3	WN5	WN3	WN11	WN5	WN2	WN3	WN7
WN5	WN6	WN6	WN3	WN6	WN3	WN6	WN6
WN11	WN4	WN4	WN5	WN4	WN4	WN4	WN1
WN9	WN8	WN11	WN9	WN11	WN11	WN8	WN11
WN6	WN11	WN8	WN6	WN9	WN8	WN11	WN12
WN4	WN9	WN9	WN4	WN8	WN12	WN9	WN8
WN12	WN12	WN12	WN12	WN12	WN9	WN12	WN9
WN10	WN10	WN10	WN10	WN10	WN10	WN10	WN10

The average illuminance data is not a reasonable measure alone in the determination of visual performance of these windows. The reasonable measure can be the percentage of space above the required illuminance level due to the fact that there is no difference between the performance of two windows providing different amount of light inside if both meet the required illuminance level. In this respect, for south facing windows, the required illuminance level is never met under overcast sky while it was met over the school desks for 11 windows and it was met only for a window over the white board under intermediate sky. For north facing windows, the required illuminance level is never met under both sky conditions. From Table 4.9 and 4.10, it is stated that the least performer windows regarding diversity remain same under both sky conditions which have varying aspect ratios with lower parapet heights. This implies that the parapet height have more influence on the performance regarding diversity over school desks than the aspect ratio. In addition, for north facing windows the diversity requirement is only met under intermediate sky conditions by three windows which show the positive effect of solar control devices on the performance of windows regarding diversity.

According to Table 4.9 and 4.10, the requirement for the luminance ratio is met by all north facing windows whereas it is met by only two south facing windows which is related to the effect of the sun in the sky. The existence of sun in the sky is very much affected the window luminance, i.e. the glare source luminance, for south facing windows while it not affected the window luminance for north facing windows resulting in smaller luminance ratios for that façade. For south facing windows, the luminance ratio of WS15, which belongs to small area window group and has highest parapet height and aspect ratio, is relatively much smaller than the rest due to the position of the camera at which the sky view is almost prohibited by the interior lightshelf.

According to Table 4.9 and 4.10, the best performer windows with respect to DDH are WS8 and WN5. They belong to medium are window group and they have the lowest aspect ratio in comparison with the others in their group indicating that aspect ratio has more influence on the DDH performance than the parapet height.

WS2, which belongs to large area window group configured with lightshelf, is the best performer among south facing windows in terms of daylight performance and is the one which only meets all the visual requirements, while its DDH perfromance is the mid-rank among others.

CHAPTER 5

CONCLUSION

This study focused on the effects of the area, shape, location and orientation of windows as well as the effects of lightshelf and overhang on the daylight and thermal performance of the typical school building which was assumed to be located in Ankara. The study was conducted through the collection of the illuminance, luminance and discomfort degree hours data of a typical classroom of the school which was predetermined with the directive named as "Eğitim Yapıları Mimari Proje Hazırlanması Genel İlkeleri" with different fenestration configuration for north and south orientations by simulation software, namely Ecotect Analysis 2011. In addition, the simulated data is validated through the daylight analysis of the classrooms of a school building located in Çankaya District of Ankara with data loggers. The results of the validation study present the reliability of the simulated data.

The study reemphasizes the importance of the orientation and the size of the task as well as the proximity of the task to window regarding the daylight design. It also reveals that the white board is the more critical task requiring careful consideration in terms of daylight design. On the other hand, it shows that the influence of the different sky conditions on the daylight performance of windows change radically with the window orientations and with the area of a window. For instance, north facing windows show similar performance under both overcast and intermediate sky conditions in comparison with the south facing windows.

According to the analyses, the window area has the most considerable effect on the daylight and thermal performance of windows in comparison with the shape and location of windows. With the consideration of the performance criteria of this study, the daylight performance, except diversity, generally increases with the increase in the area while there is an optimum area of a window found between the largest and smallest window areas regarding the thermal performance. The diversity is mostly related with a solar control device and a parapet height. On the other hand, the results of the analysis reveal that a south facing window having smaller area can outperform another one having larger area with the help of a lightshelf. According to settings of this study, a lightshelf is generally superior over an overhang in terms of daylight performance while an overhang is superior to a lightshelf in terms of thermal performance. On the other hand, uses of both enhance the performance of windows in terms of diversity found over the task surfaces whereas they decrease the amount of light inside under overcast sky conditions in comparison with a window configured without them. In addition, the use of a lightshelf is more critical for the white board than the school desks.

According to the study, it can be stated that in order to provide a uniform illuminance distribution, to prevent glare and to avoid unwanted solar gains in a classroom of the schools, windows should be designed with solar control devices with careful consideration not to decrease the amount of light inside under overcast sky conditions. On the other hand according to the results, even with the use of solar control devices glare is very critical and probable for classrooms facing south whereas even without the use of solar control devices, it is not critical as much for classrooms facing north. However the amount of illumination is very critical for classrooms facing north.

The directive fails for both north and south orientations for the setting of this study. However with the use of a lightshelf, only a window which has the largest area as indicated in the directive, meets all the visual requirements for south while its thermal perfromance is the mid-rank among others. Thus it can be concluded that windows should be configured with solar control devices especially for south orientation. In addition, classrooms facing north should be avoided unless the classroom width is decreased or the ceiling height is increased. In addition, it can be concluded that it is not appropriate to order an ordinary typical window design for all orientations and climates.

The study reveals that there is an interrelation between the performance parameters and a more detailed analysis is required to optimize the fenestration of these buildings with respect to thermal and daylight performances. On other hand, with the use of dynamic solar control devices optimization can be reached due to the fact that they can adapt to the changing outside conditions.

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APPENDIX A

ILLIMUNANCE DATA SET IN ISO-LUX CONTOUR LINE FORMAT

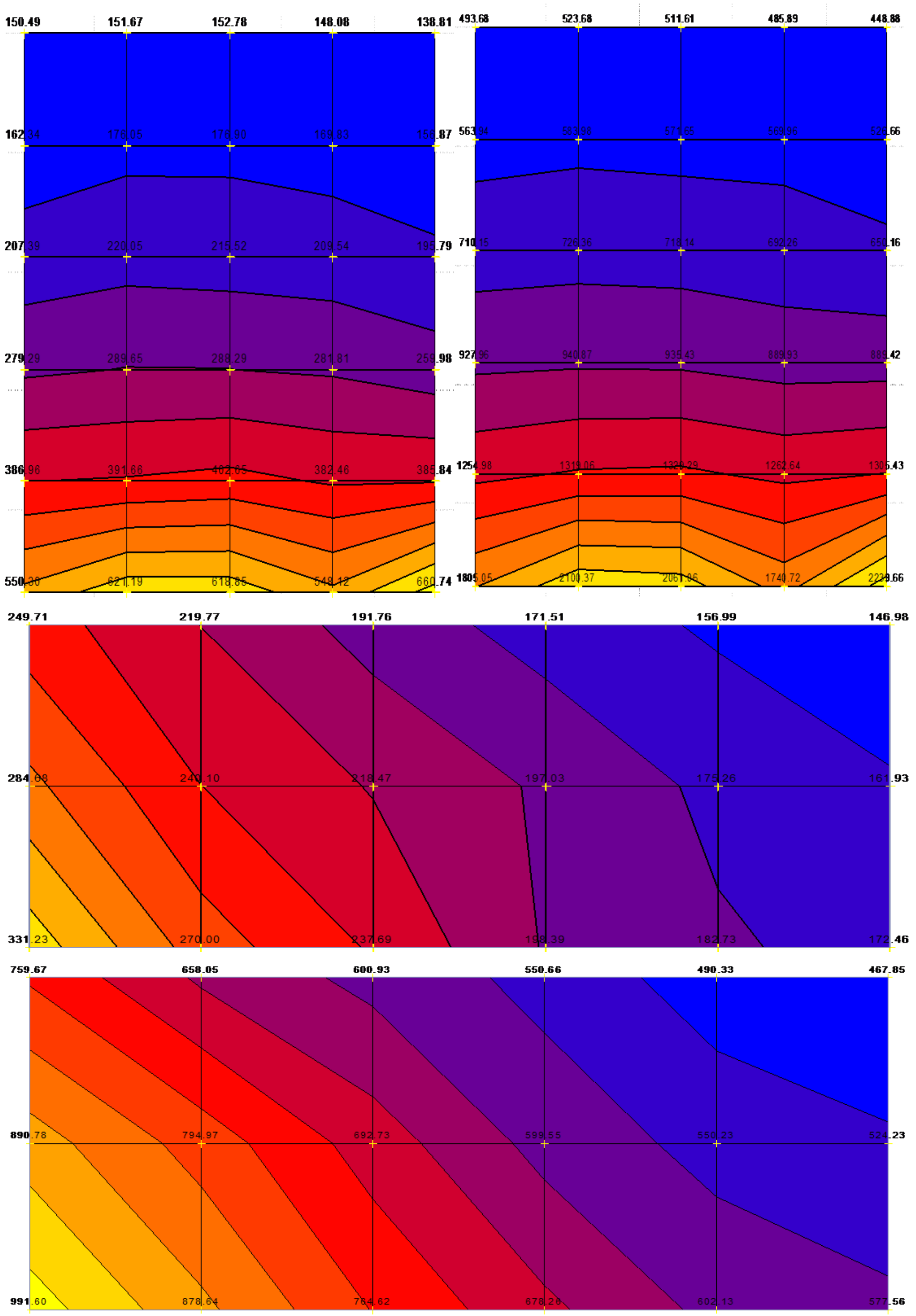


Figure A.1 Illuminance Values for WS1 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

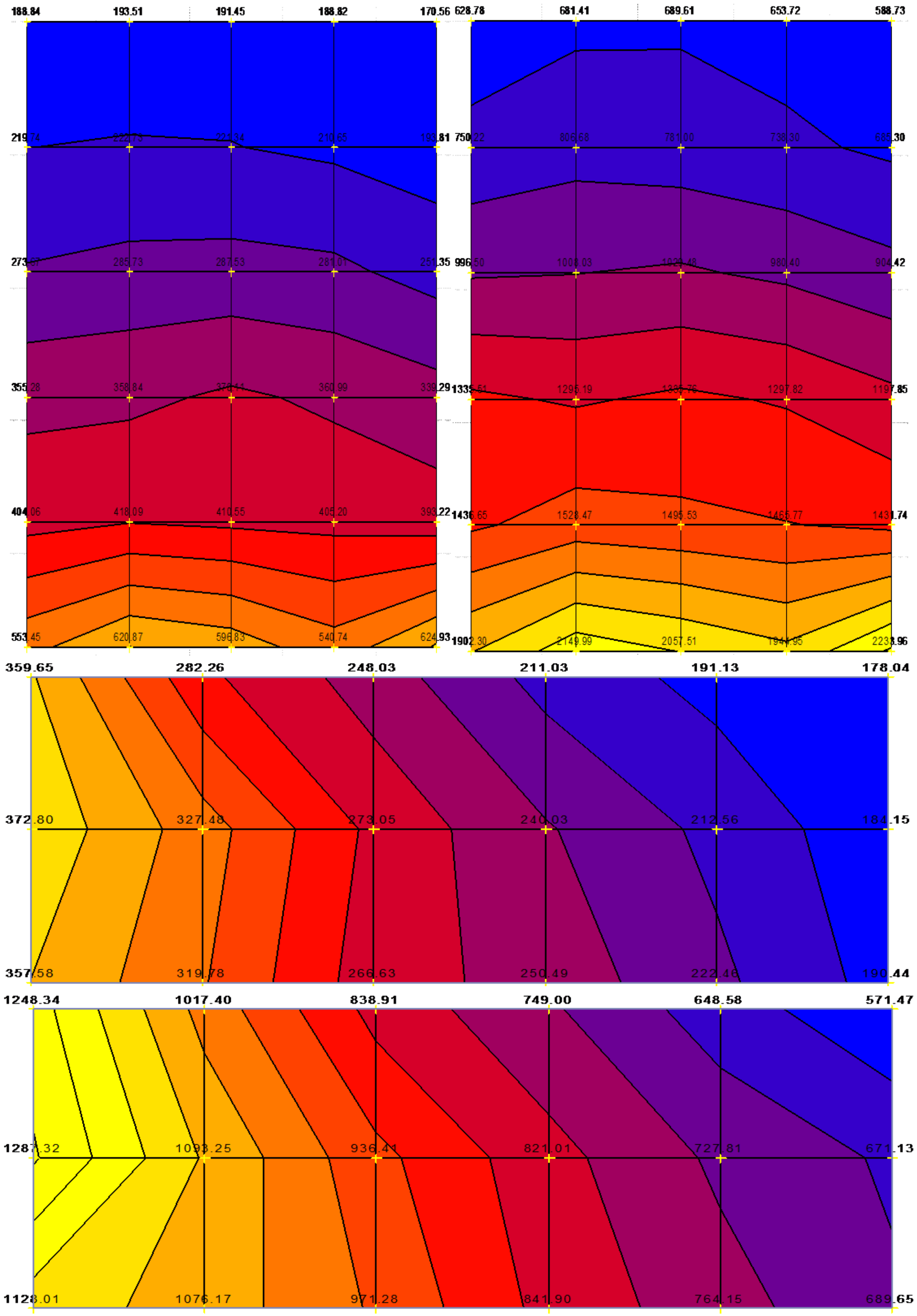


Figure A.2 Illuminance Values for WS2 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

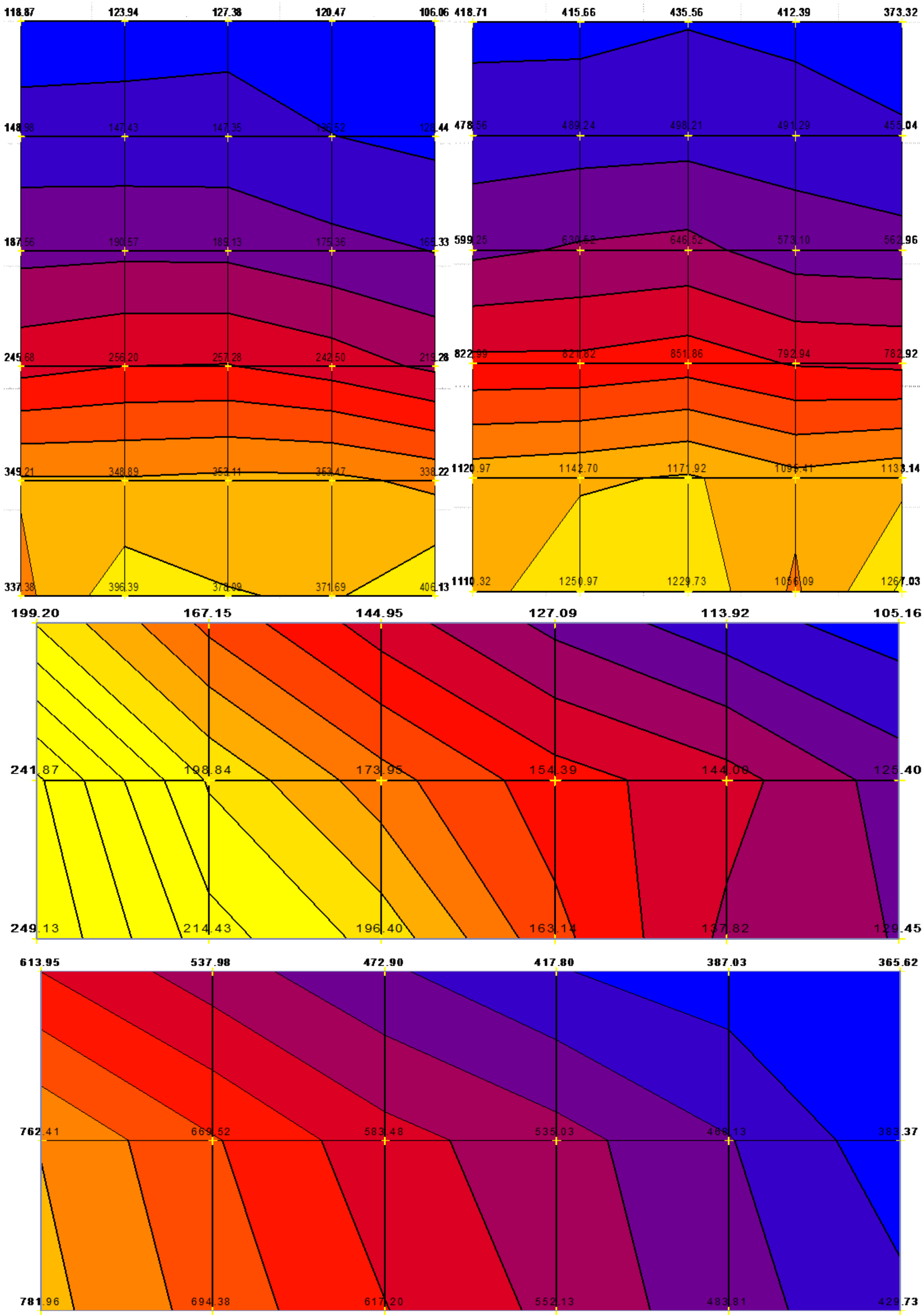


Figure A.3 Illuminance Values for WS3 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

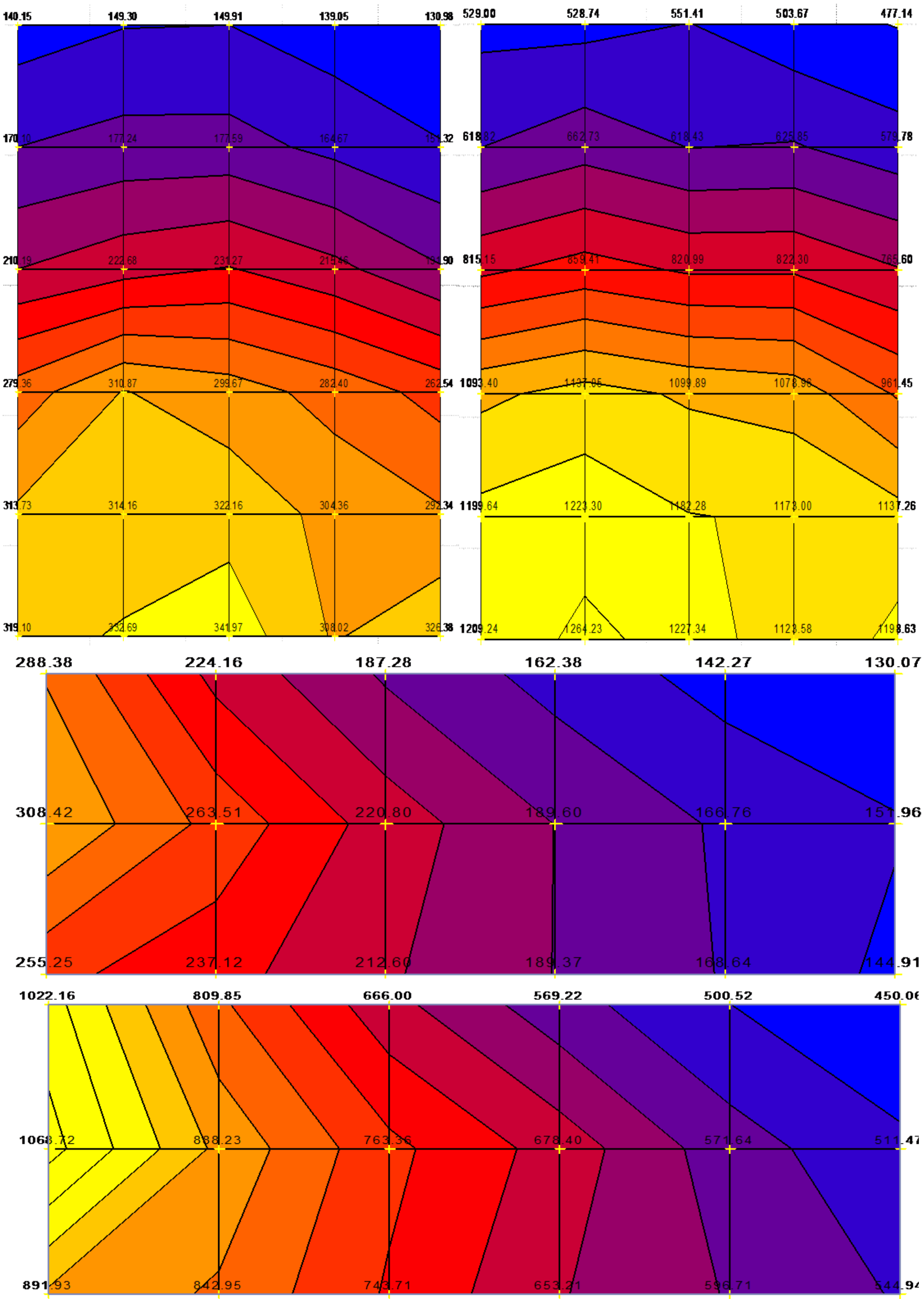


Figure A.4 Illuminance Values for WS4 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

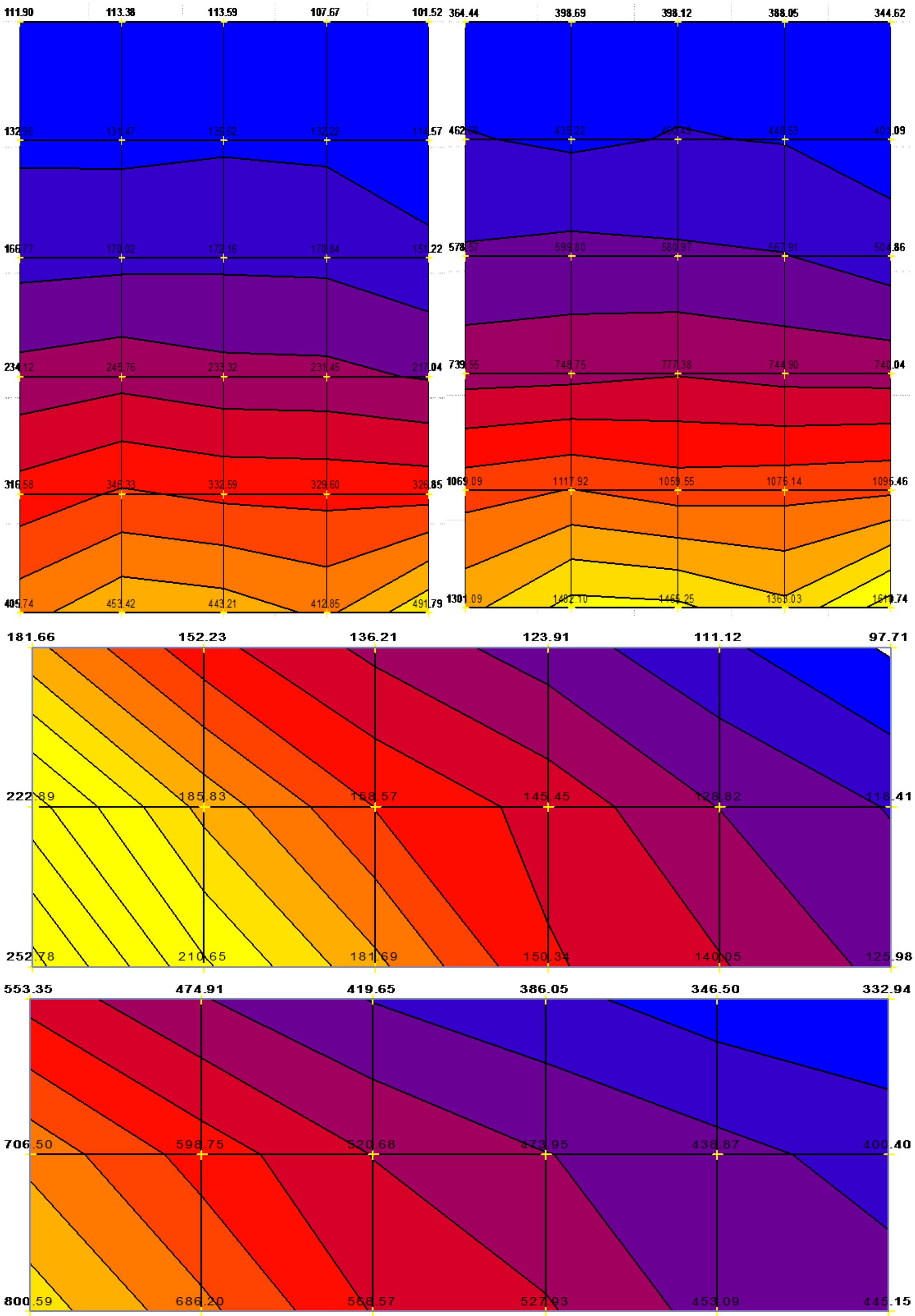


Figure A.5 Illuminance Values for WS5 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

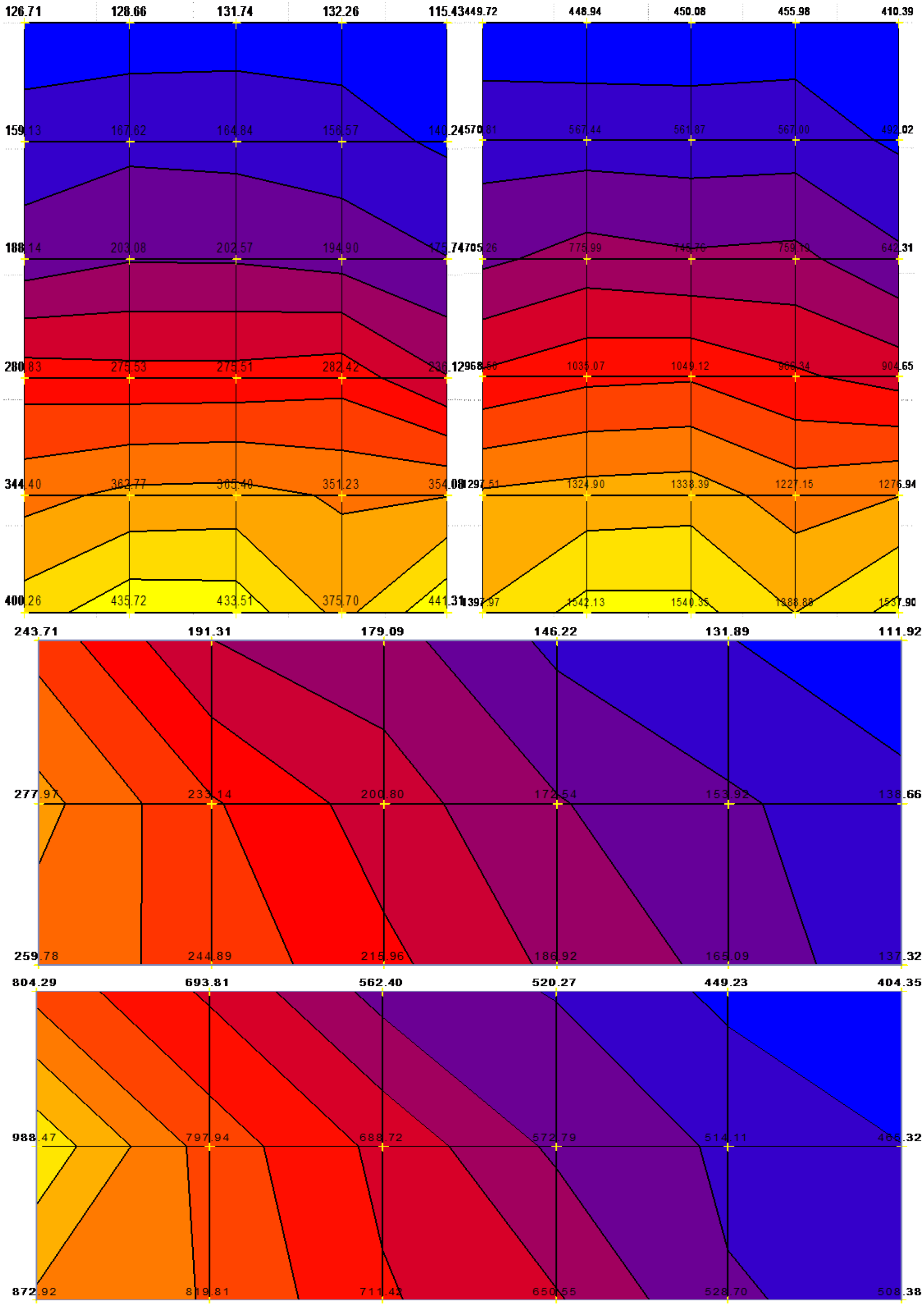


Figure A.6 Illuminance Values for WS6 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

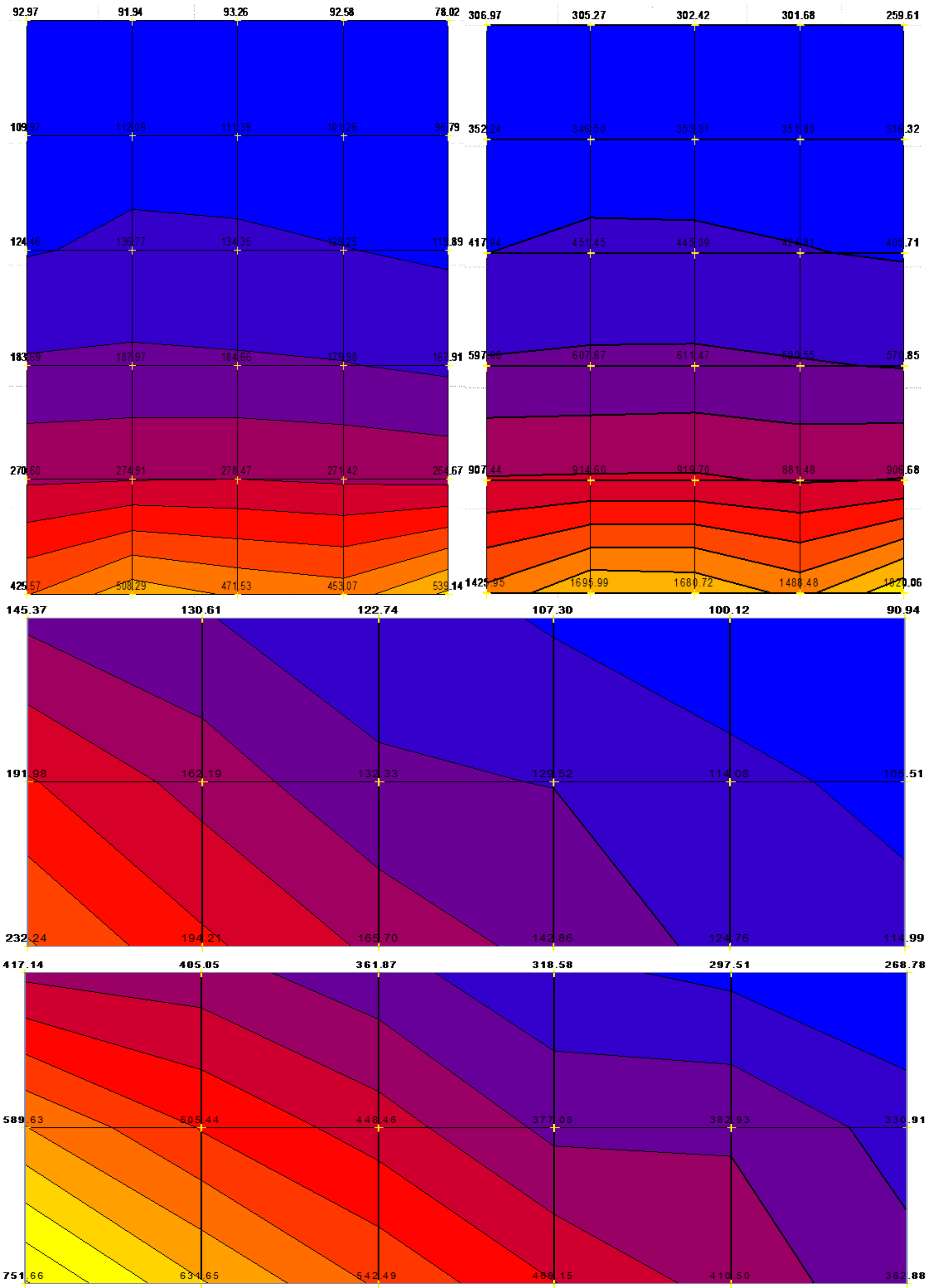


Figure A.7 Illuminance Values for WS7 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

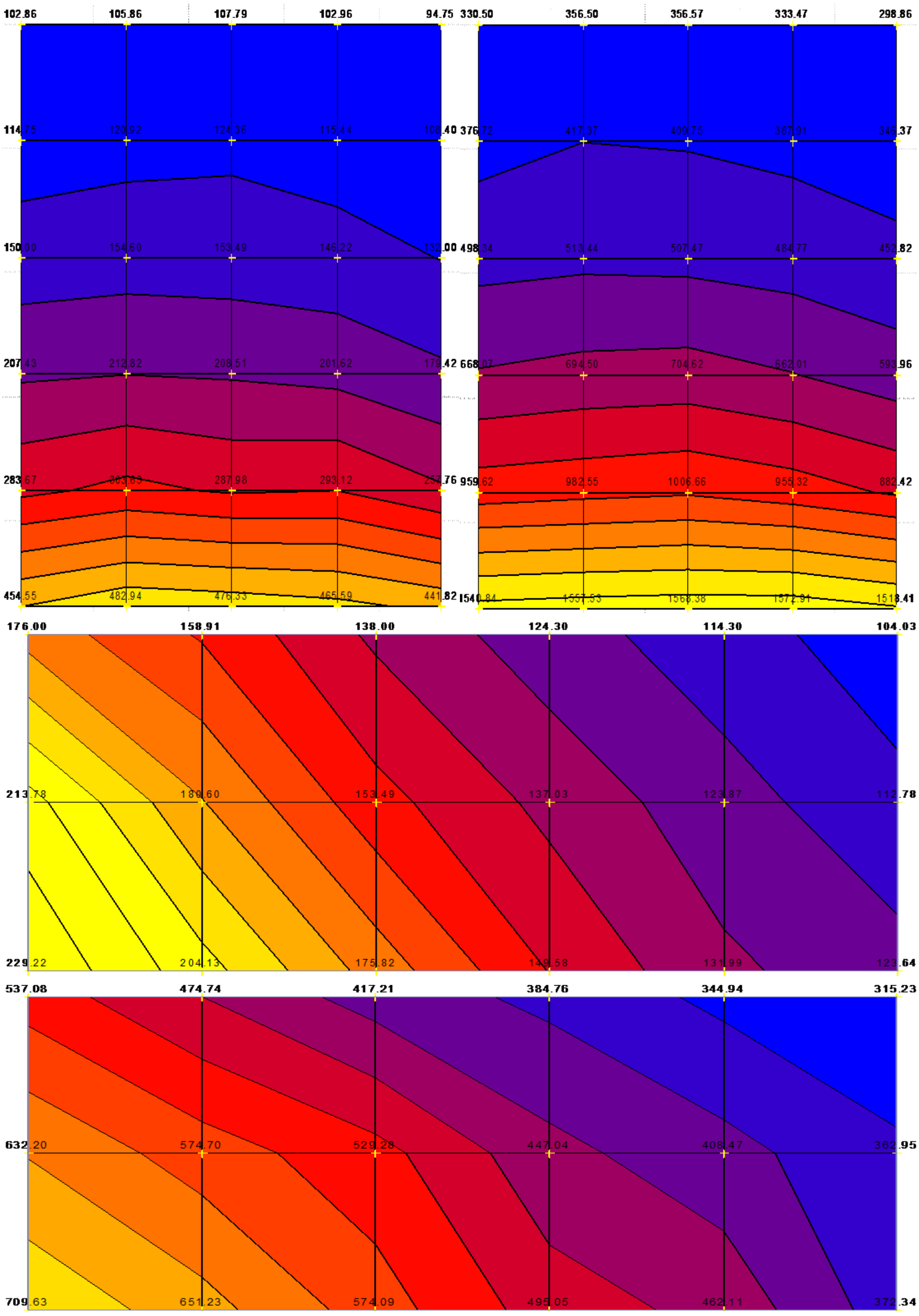


Figure A.8 Illuminance Values for WS8 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

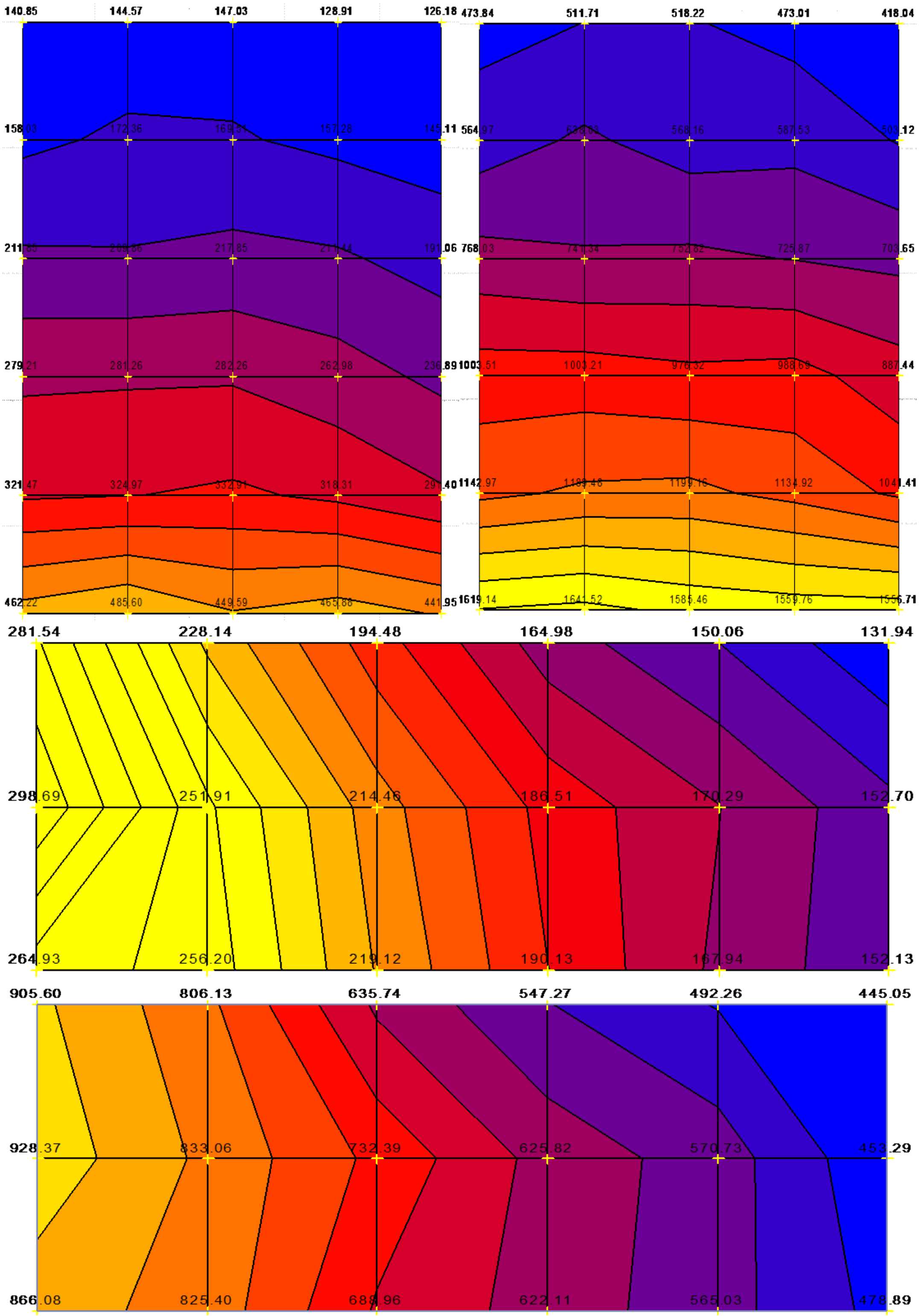


Figure A.9 Illuminance Values for WS9 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

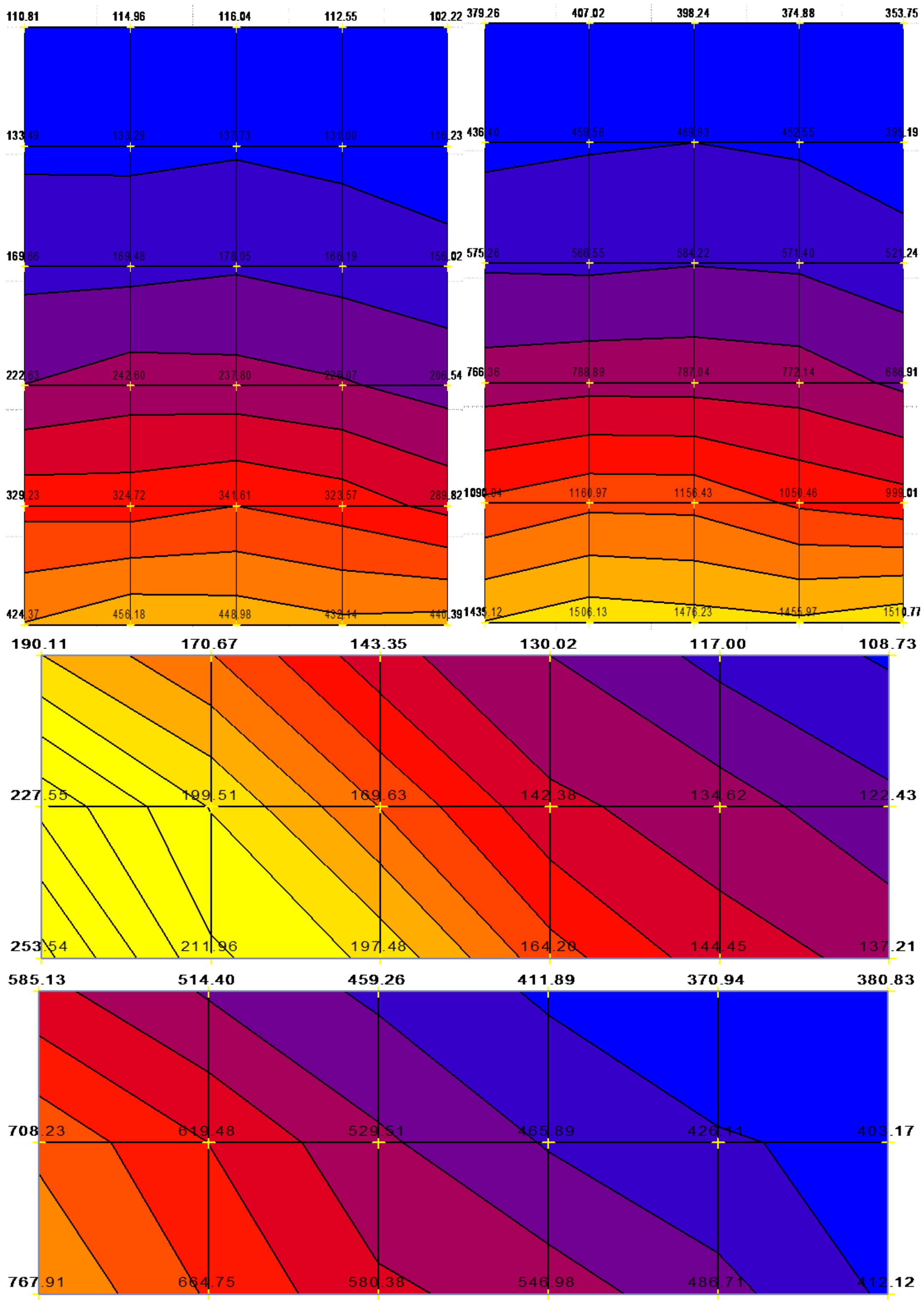


Figure A.10 Illuminance Values for WS10 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

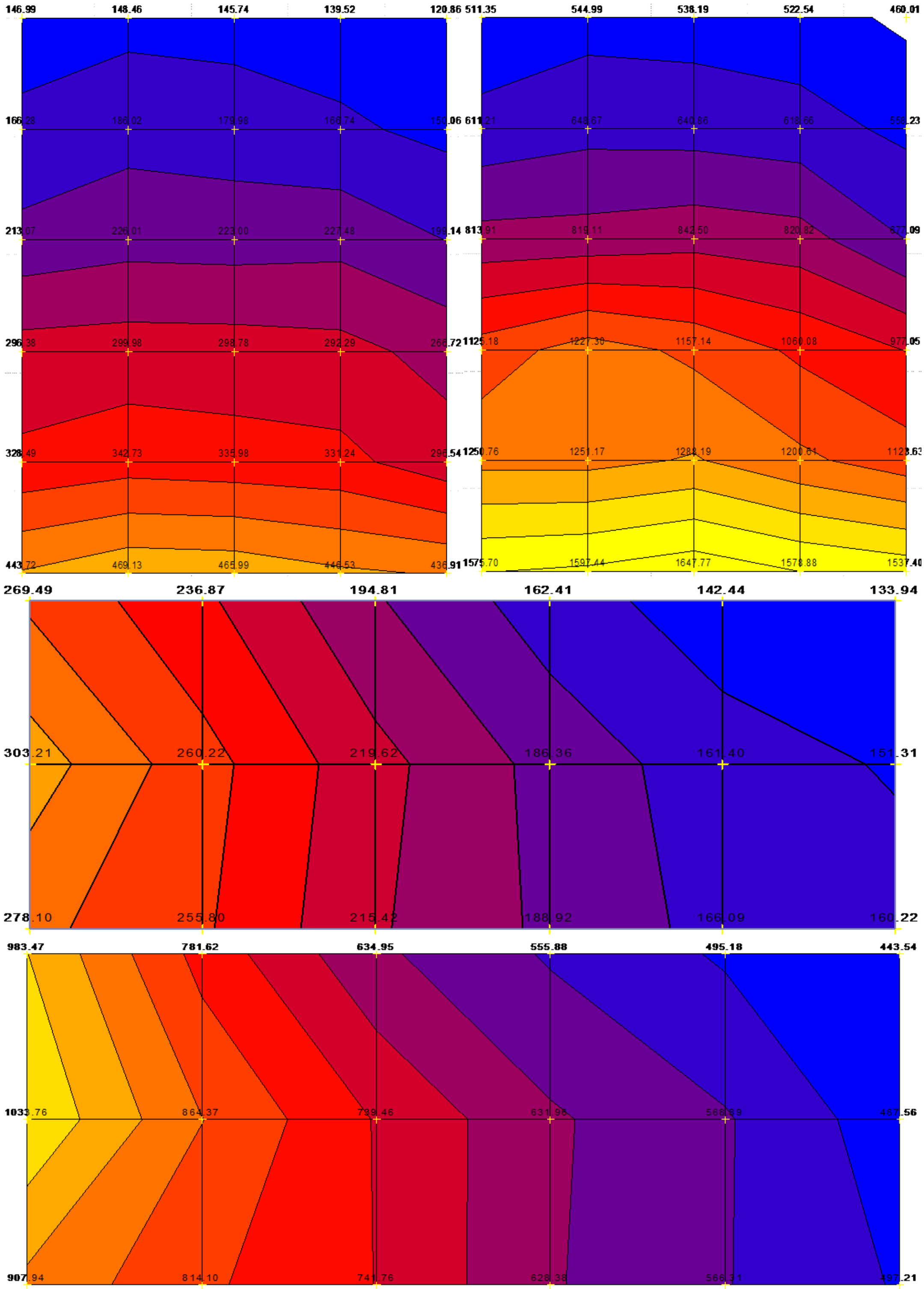


Figure A.11 Illuminance Values for WS11 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

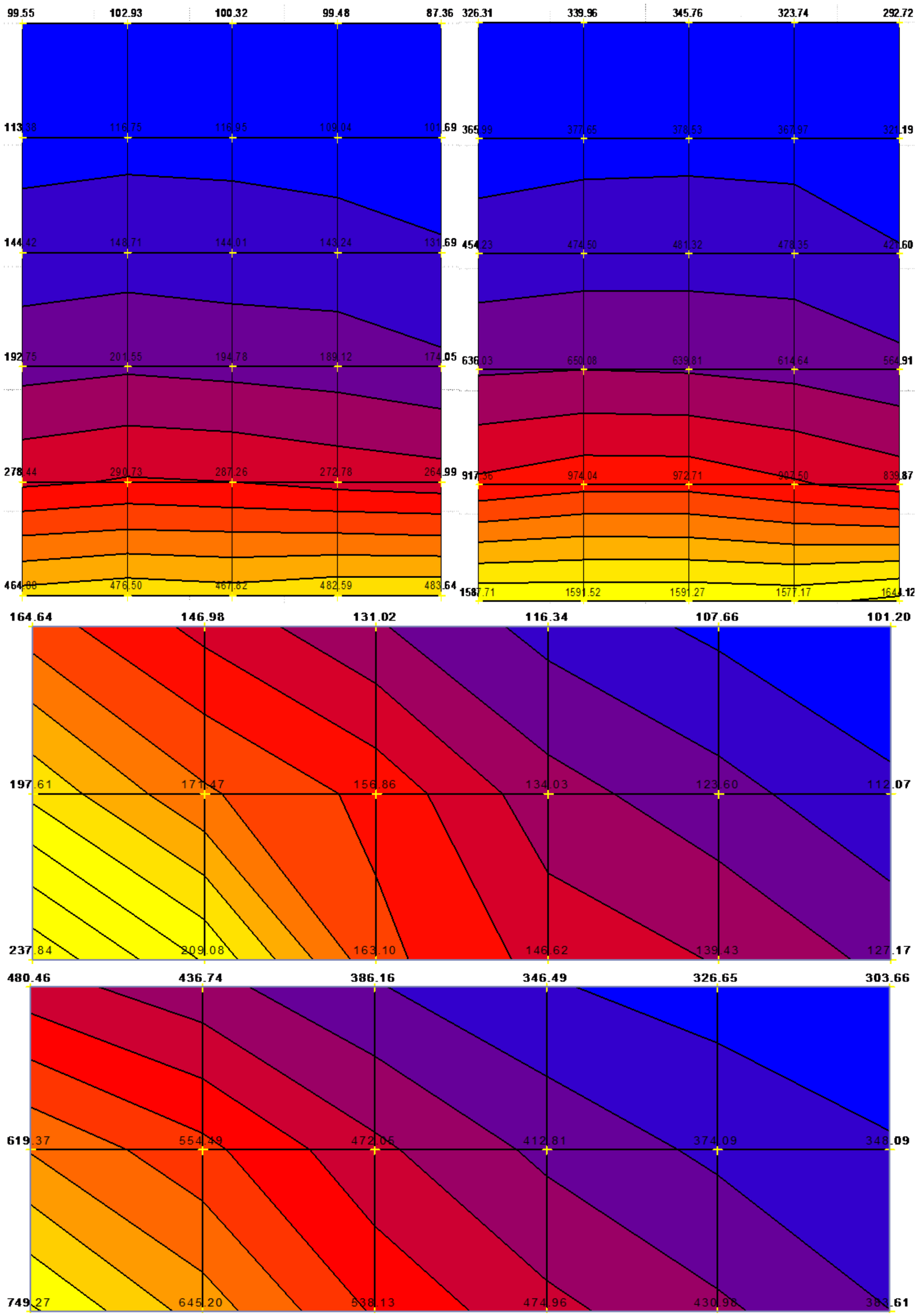


Figure A.12 Illuminance Values for WS12 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

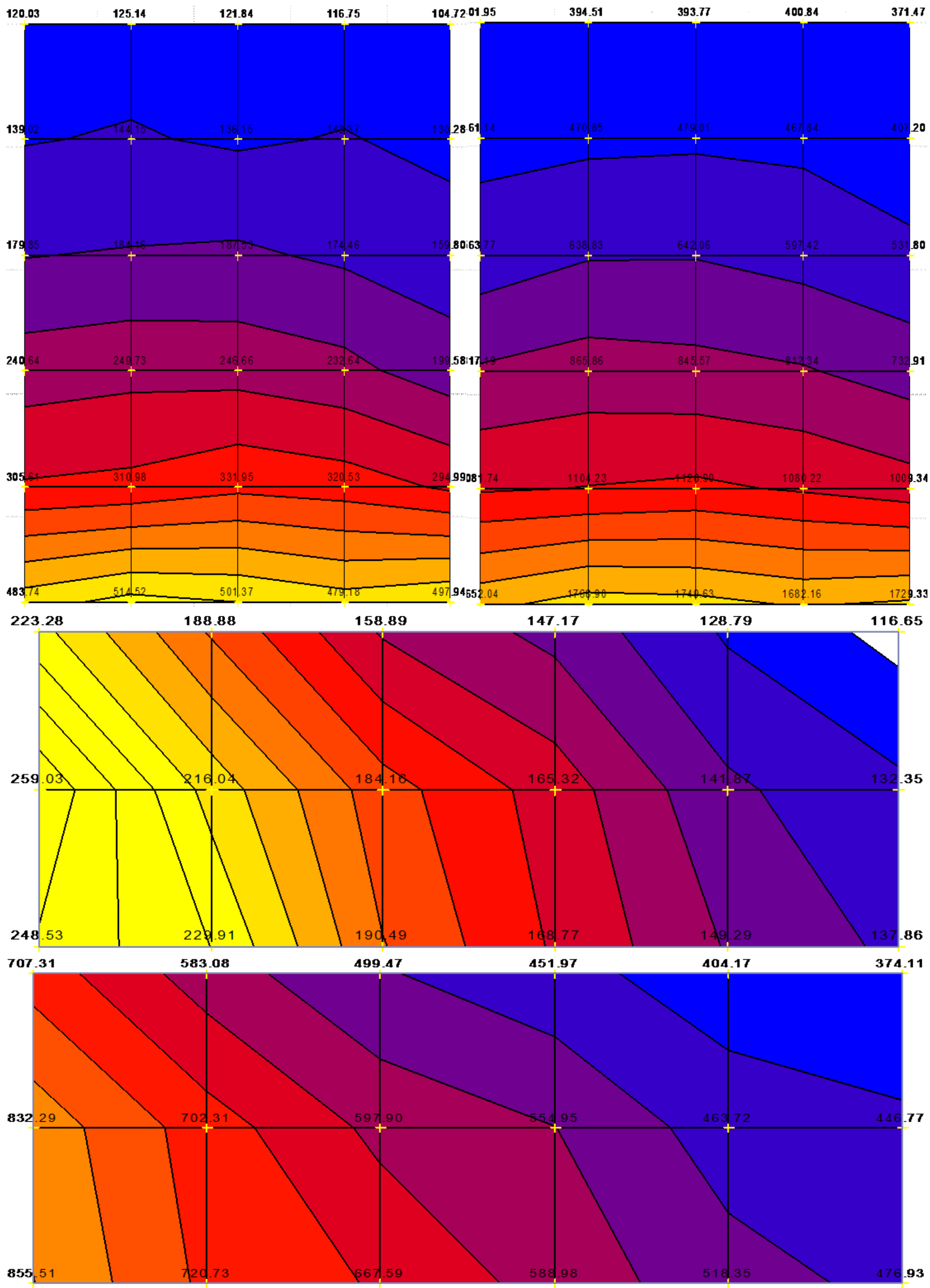


Figure A.13 Illuminance Values for WS13 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

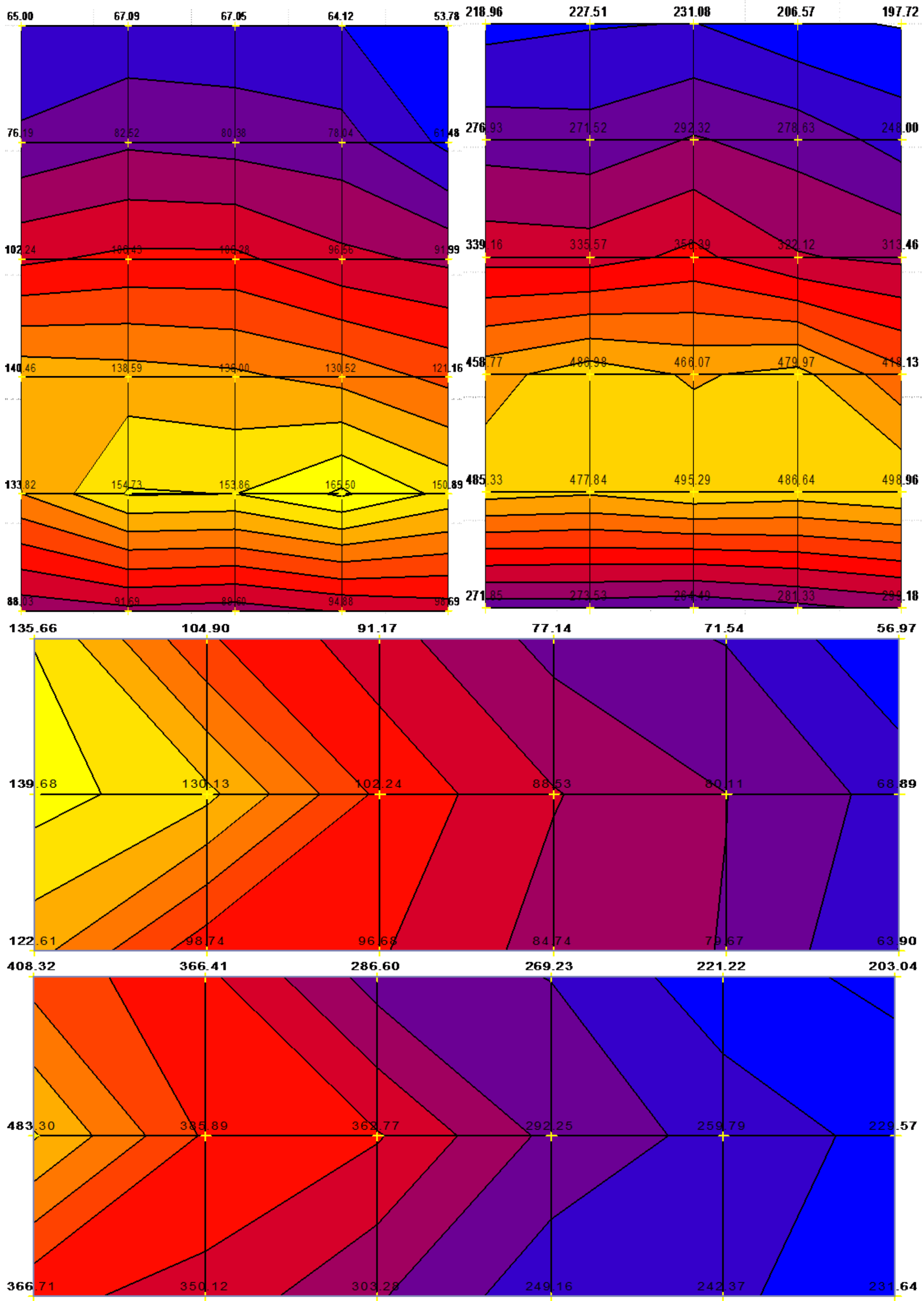


Figure A.14 Illuminance Values for WS14 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

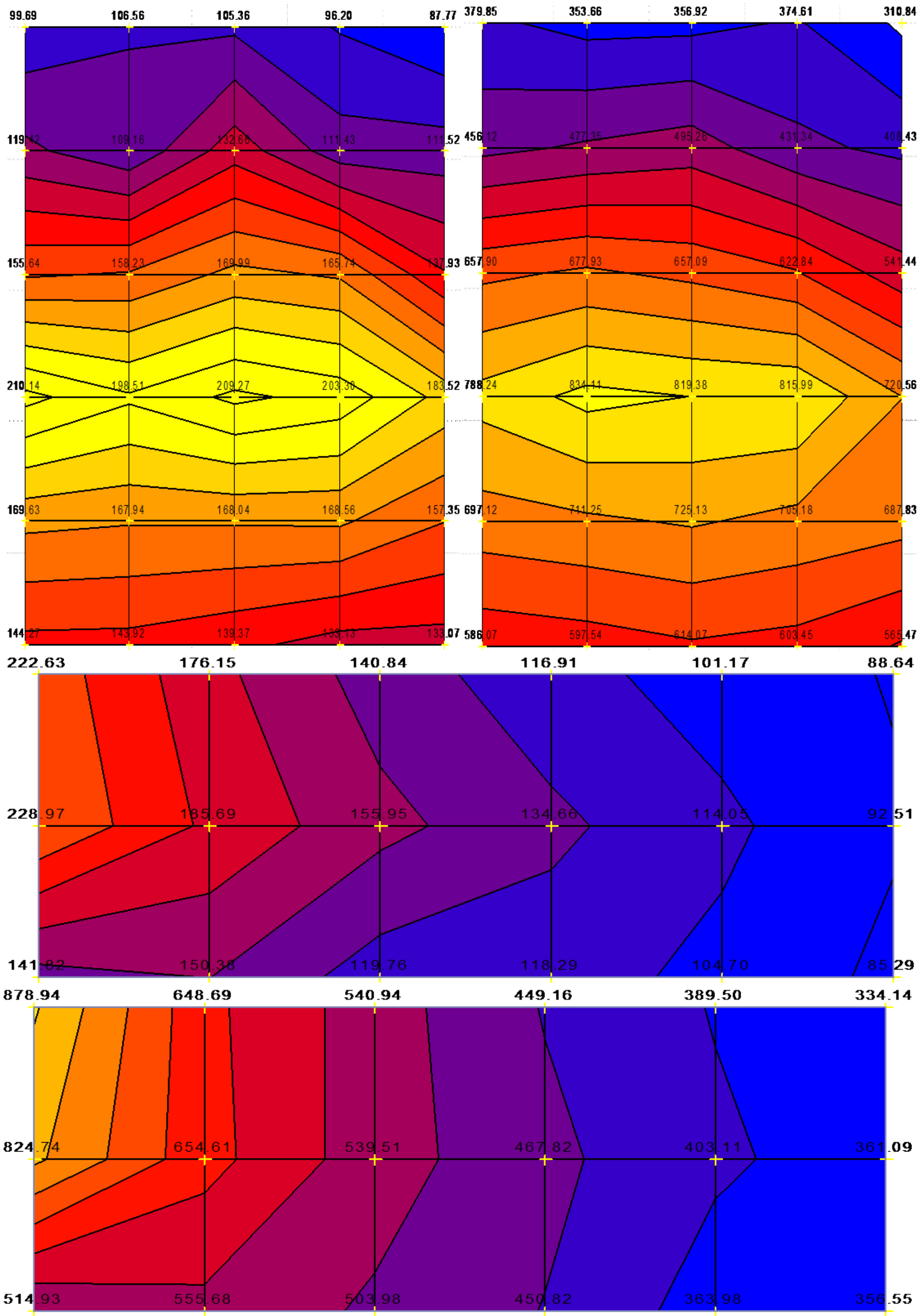


Figure A.15 Illuminance Values for WS15 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

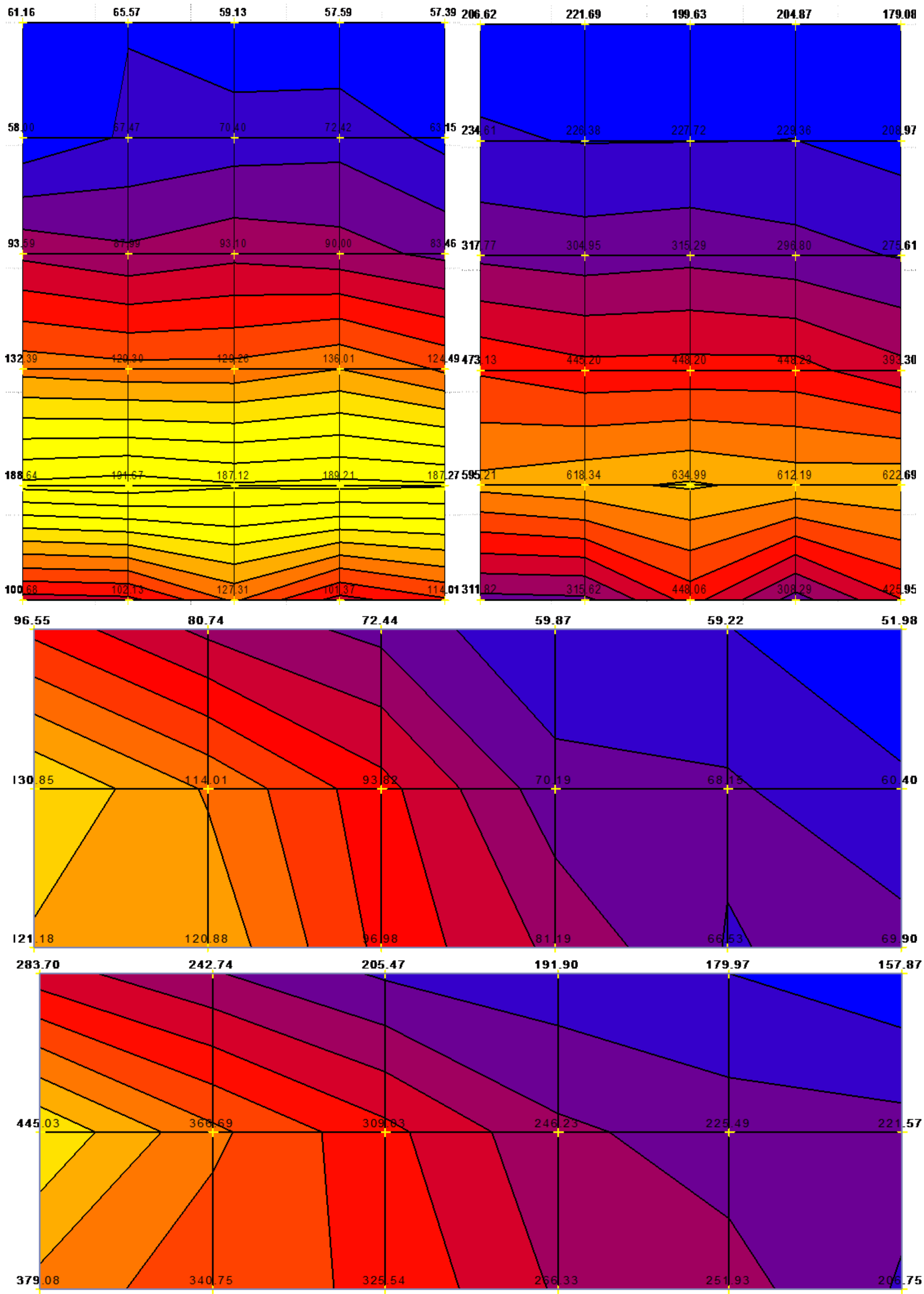


Figure A.16 Illuminance Values for WS16 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

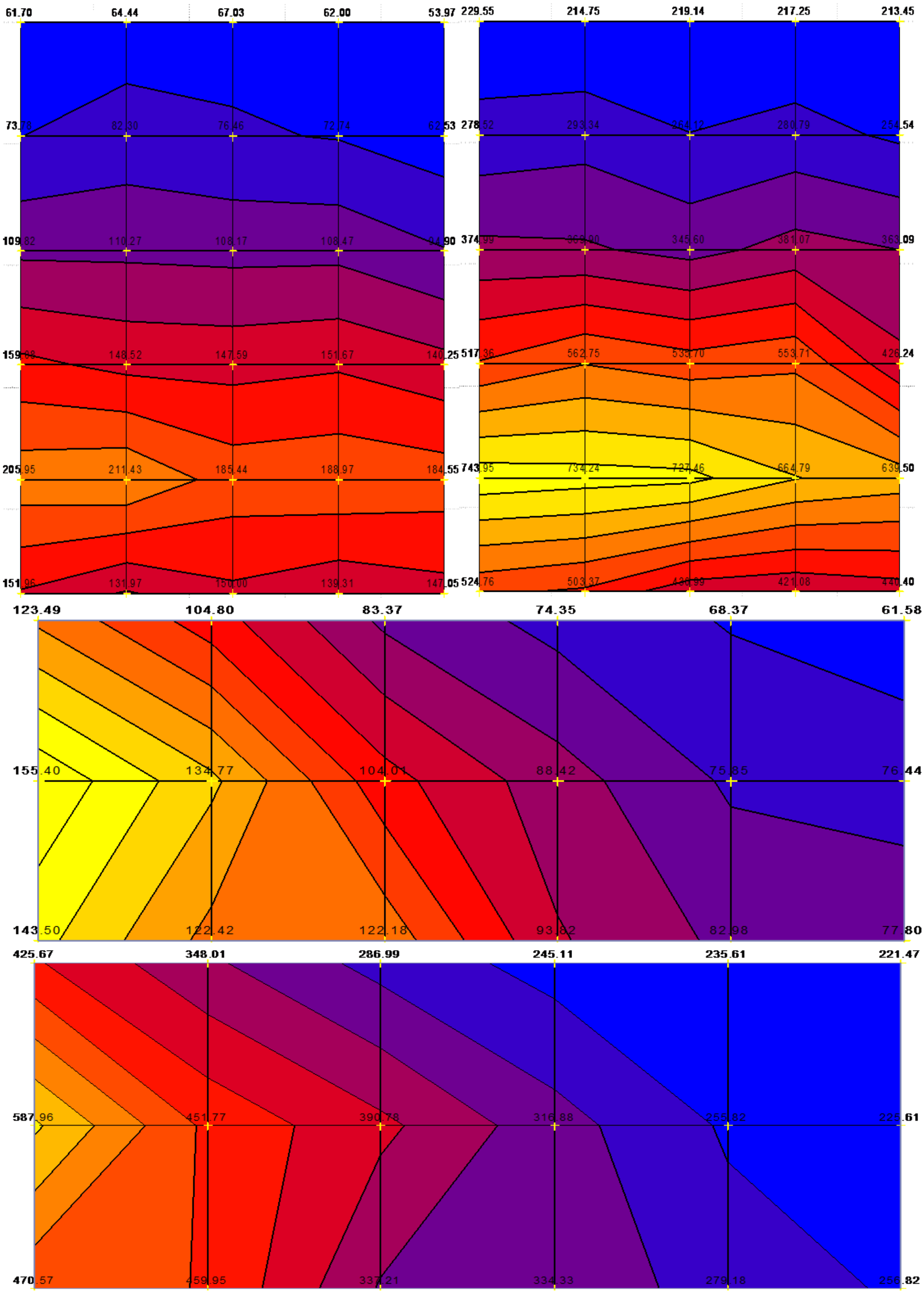


Figure A.17 Illuminance Values for WS17 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

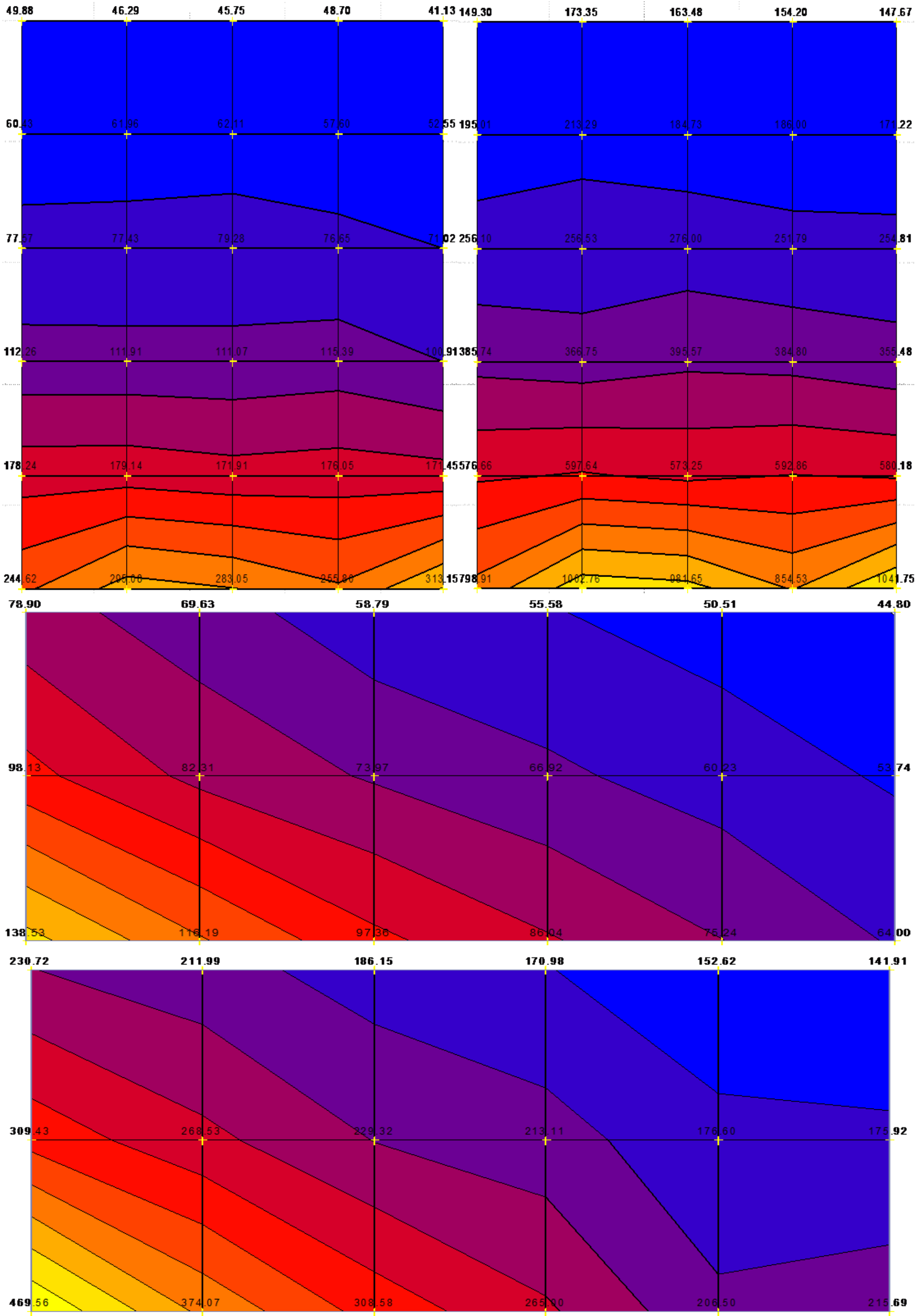


Figure A.18 Illuminance Values for WS18 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

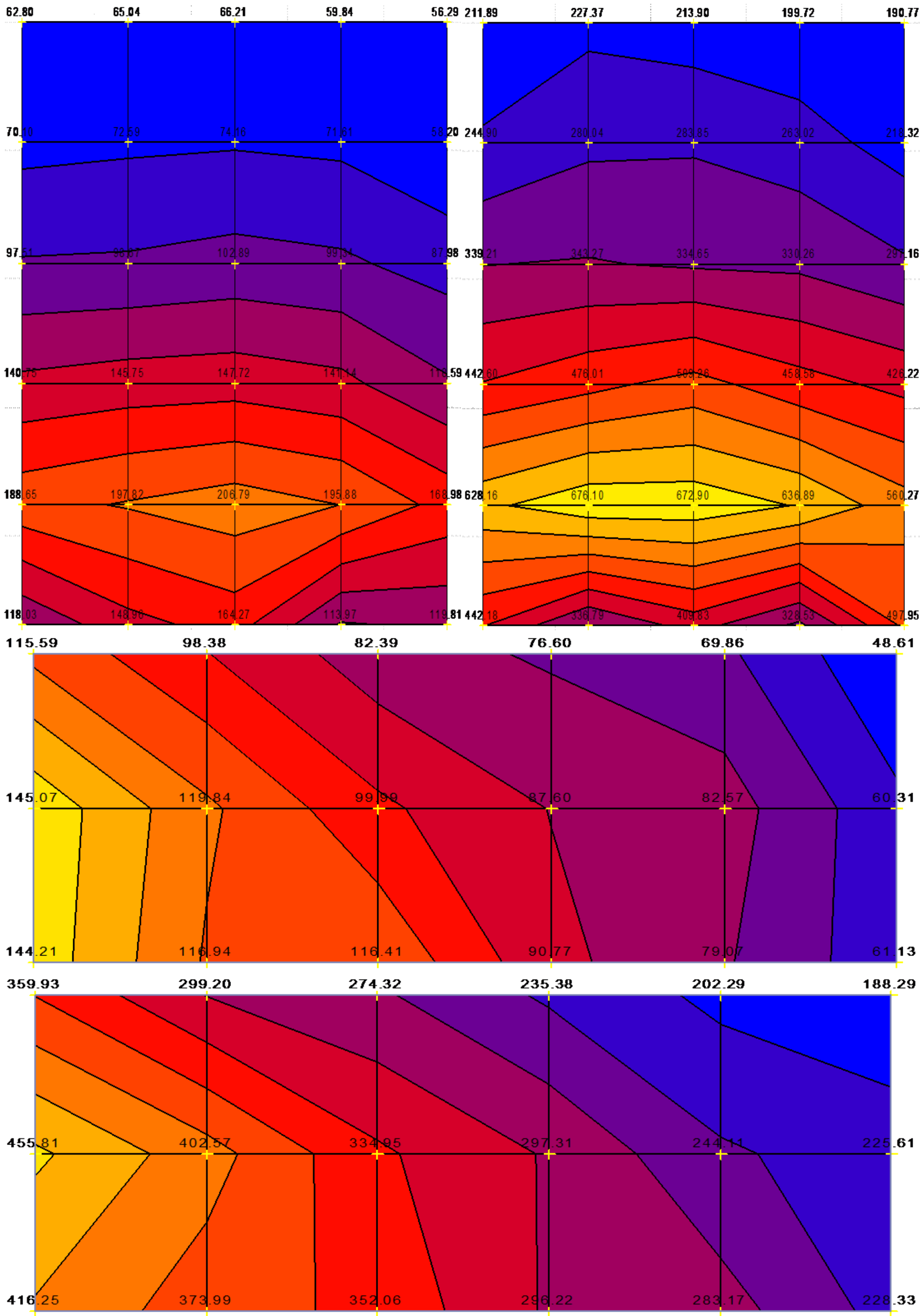


Figure A.19 Illuminance Values for WS19 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

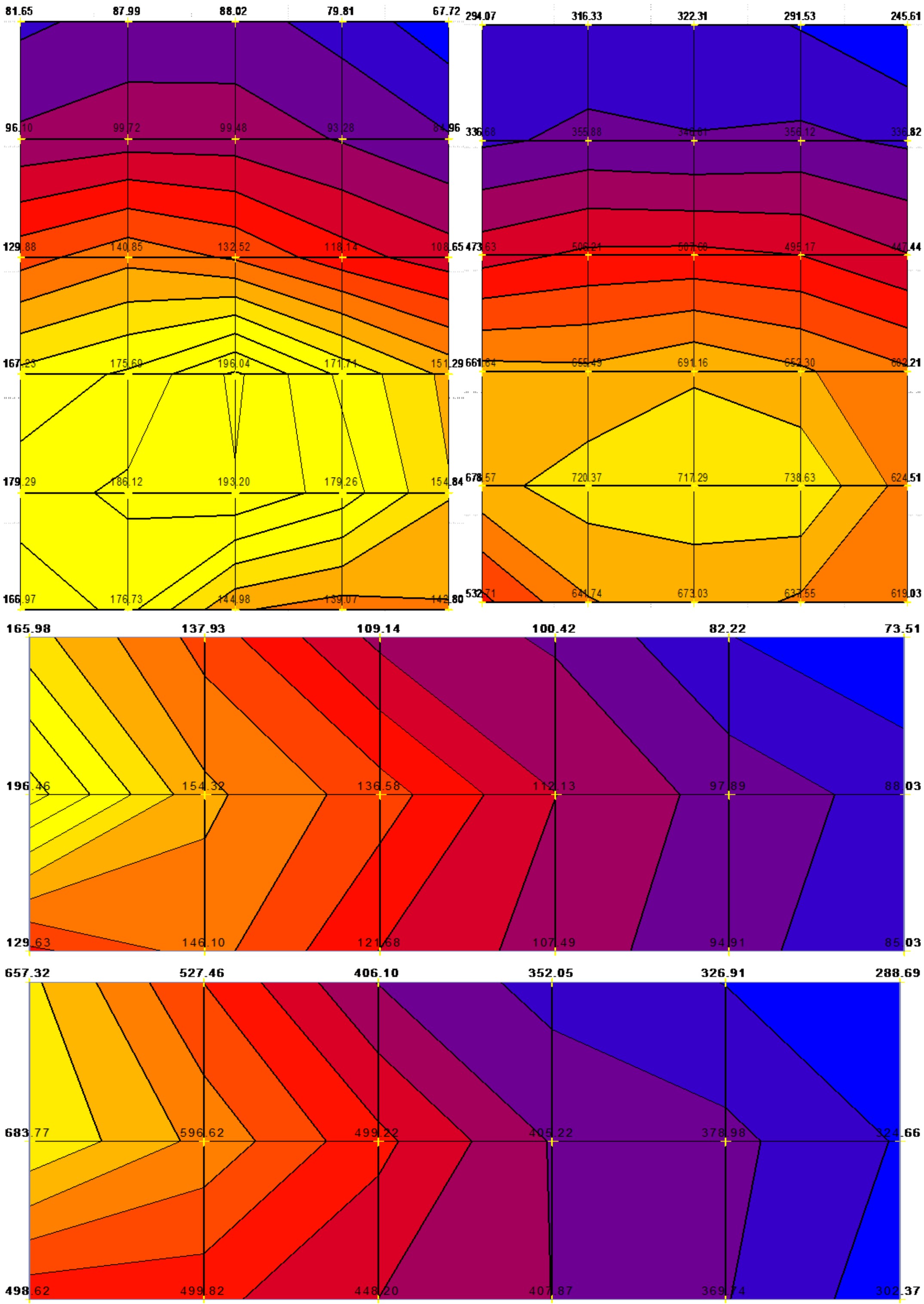


Figure A.20 Illuminance Values for WS20 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

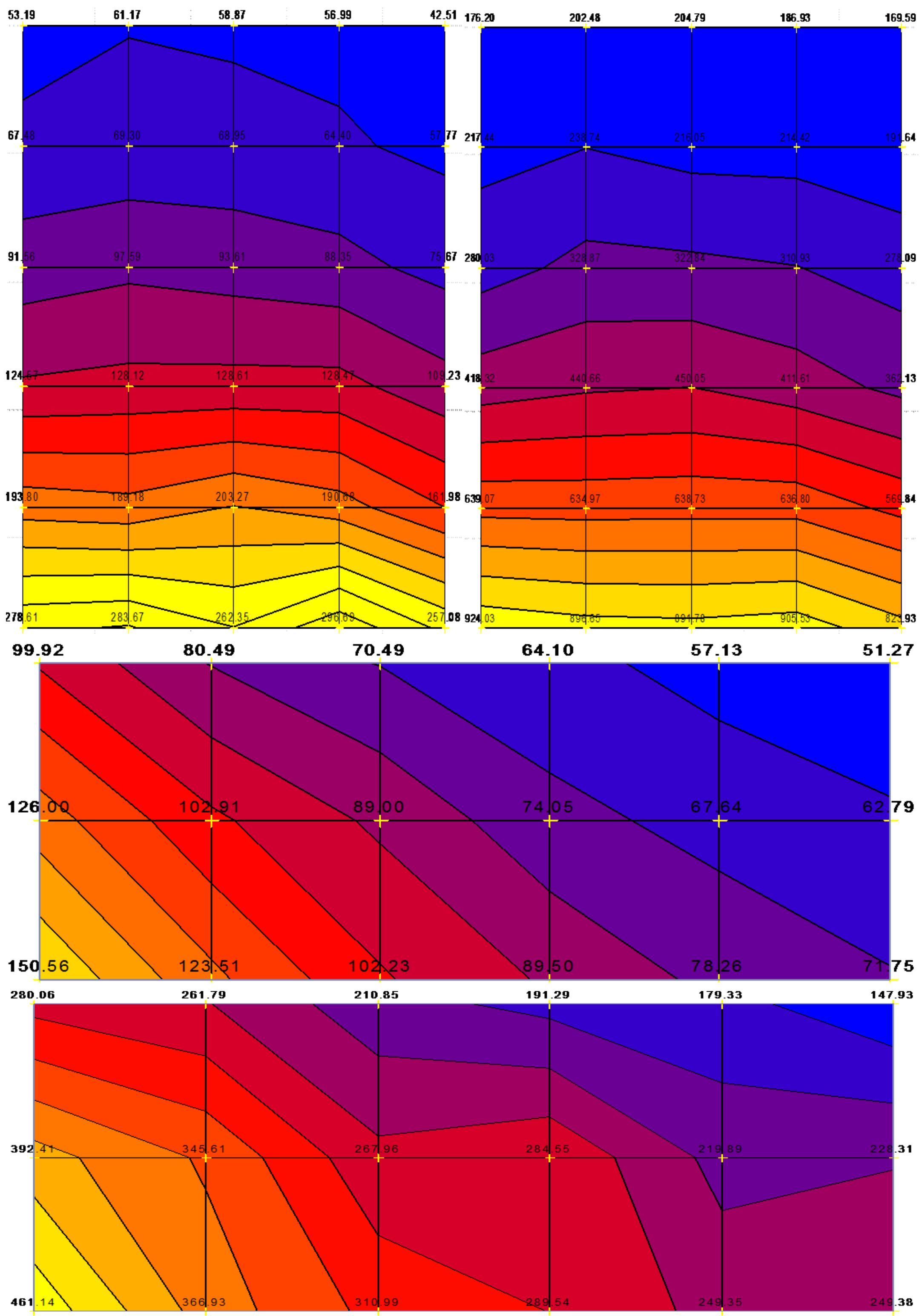


Figure A.21 Illuminance Values for WS21 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

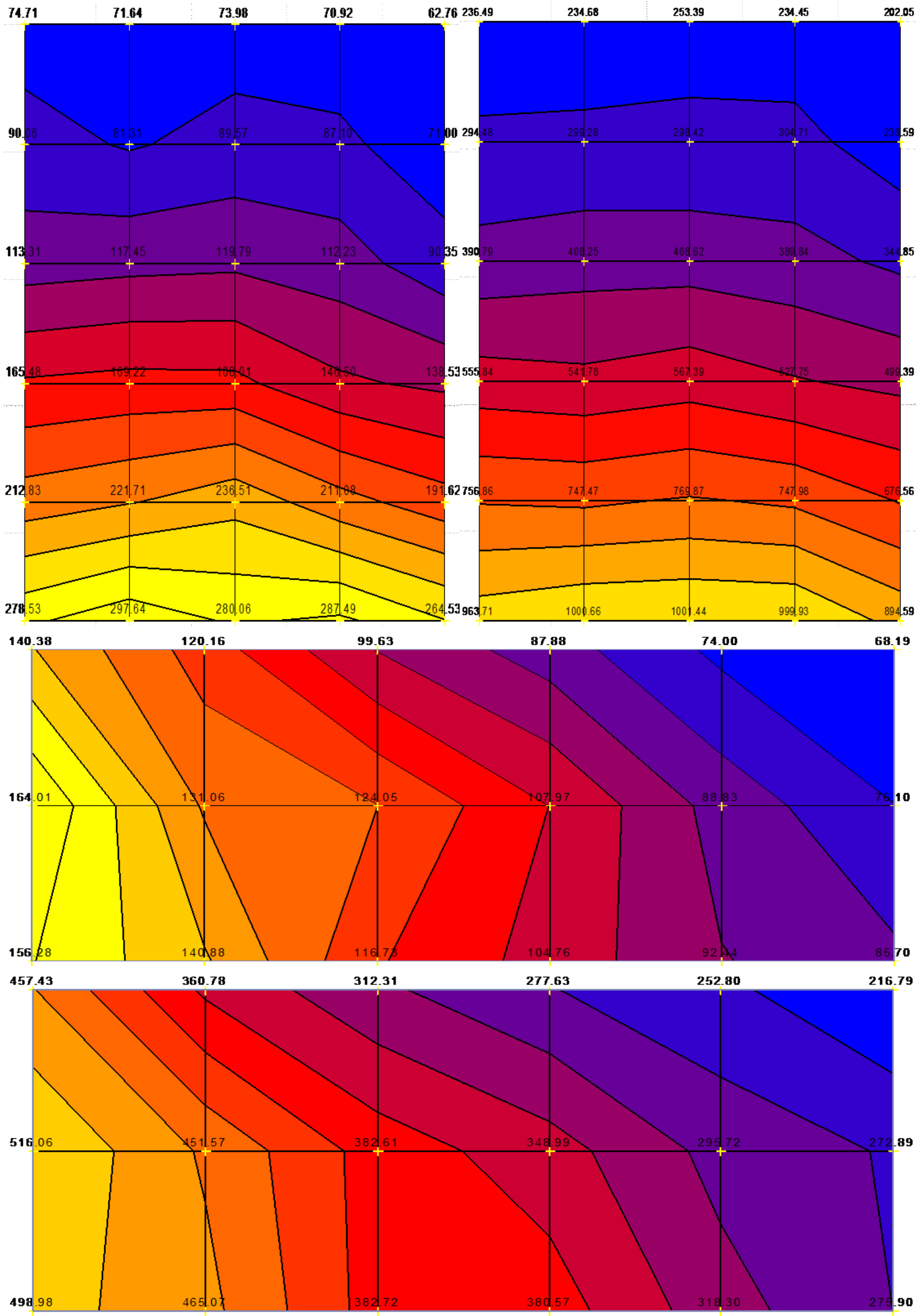


Figure A.22 Illuminance Values for WS22 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

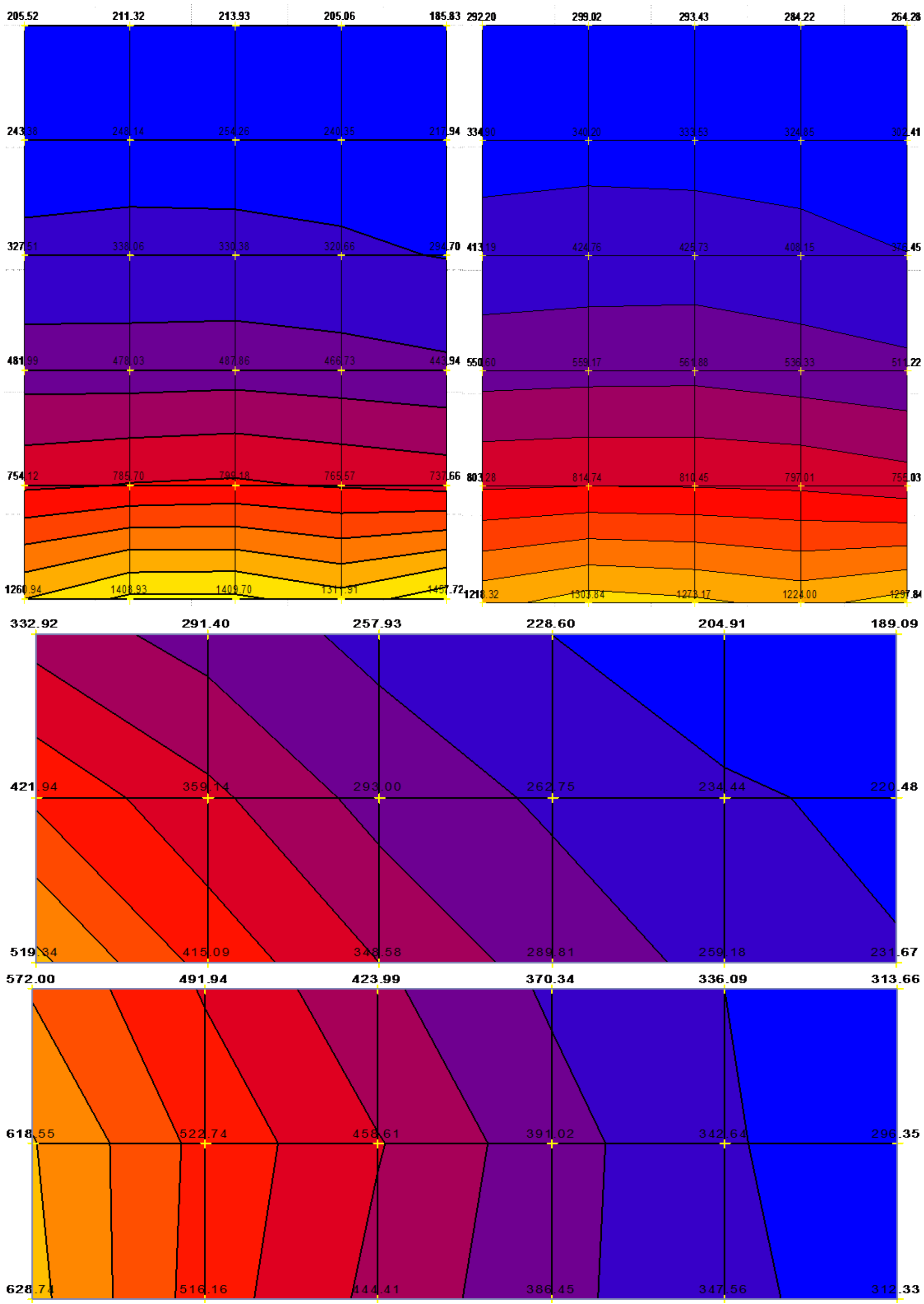


Figure A.23 Illuminance Values for WN1 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

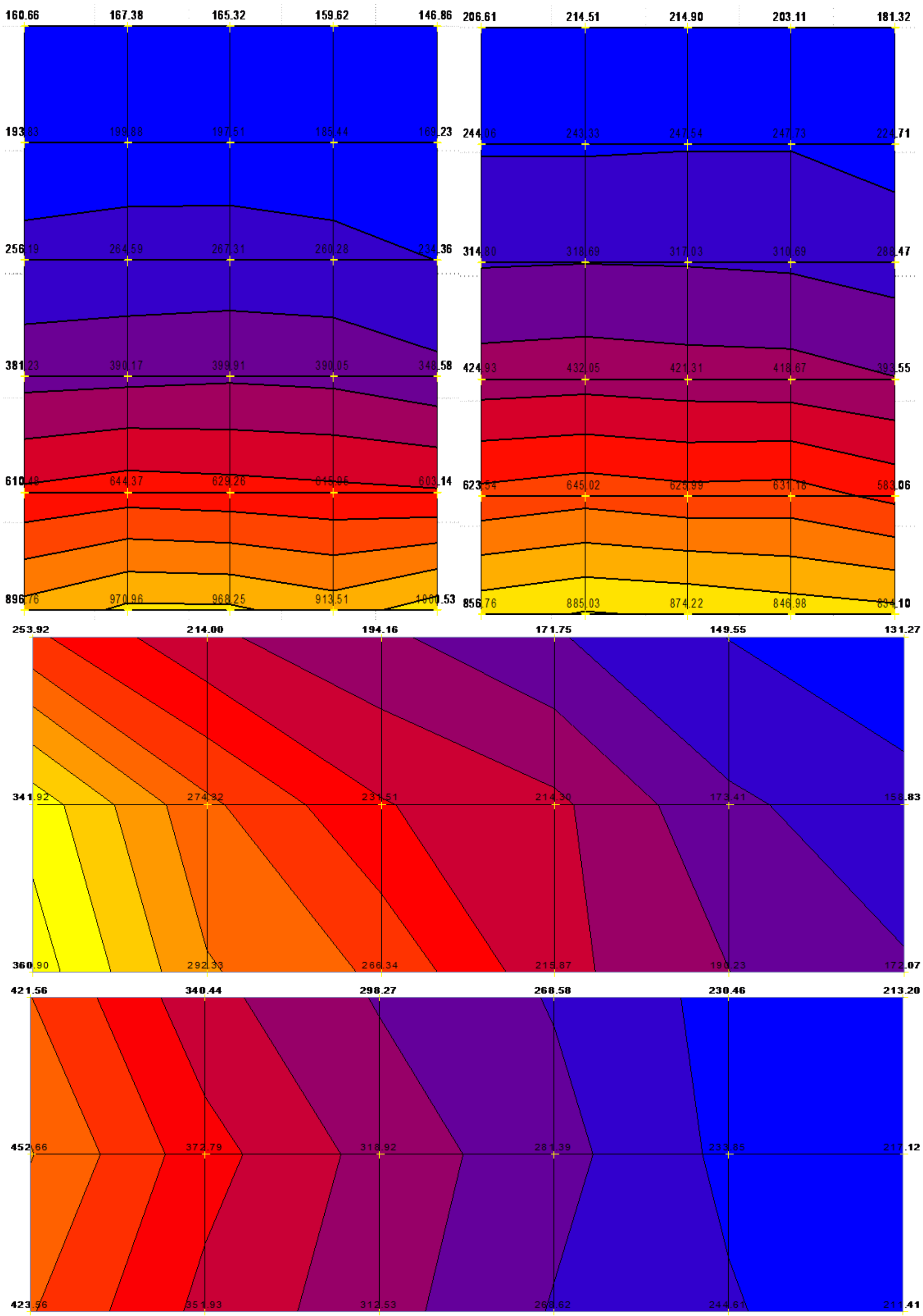


Figure A.24 Illuminance Values for WN2 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

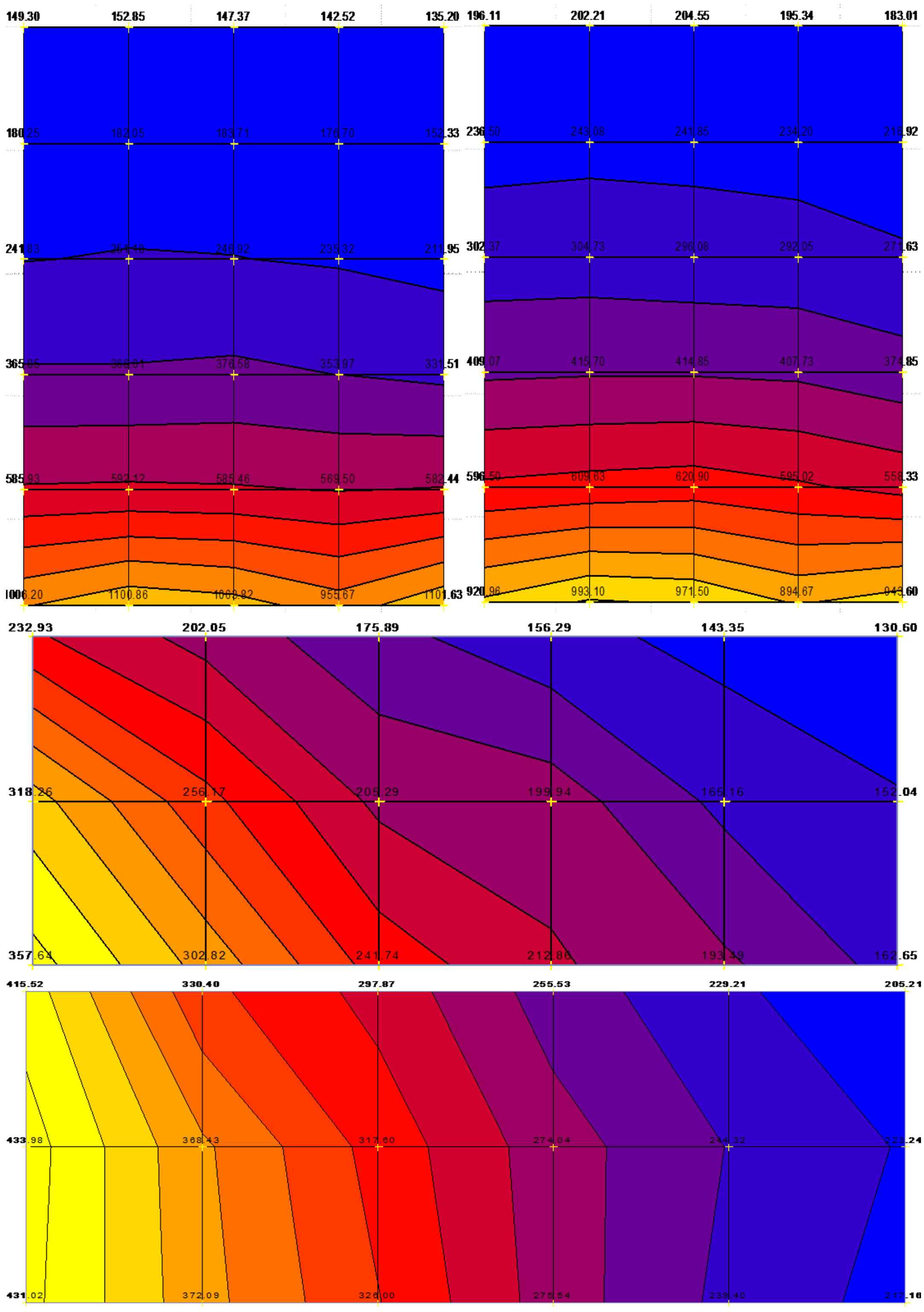


Figure A.25 Illuminance Values for WN3 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

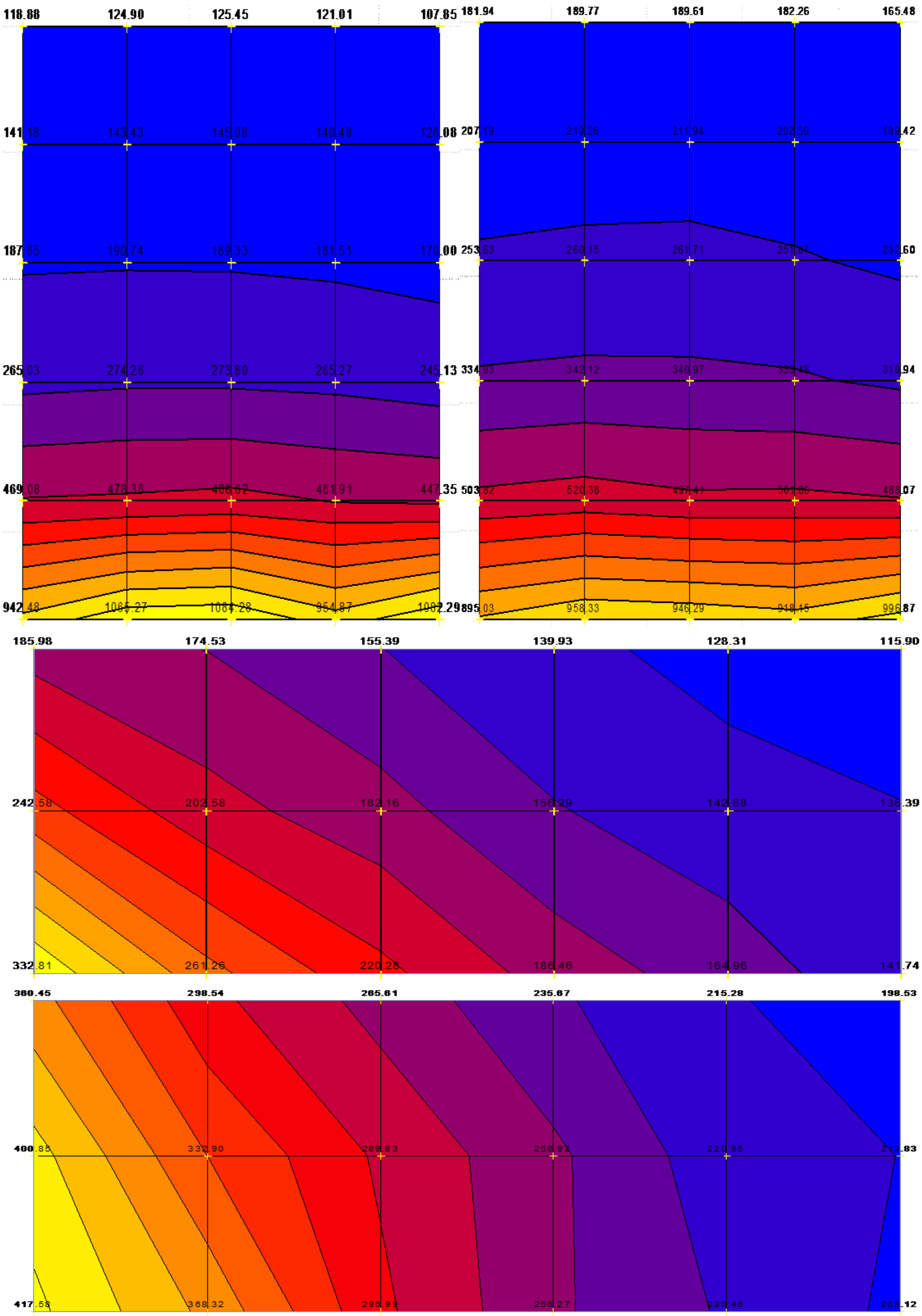


Figure A.26 Illuminance Values for WN4 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

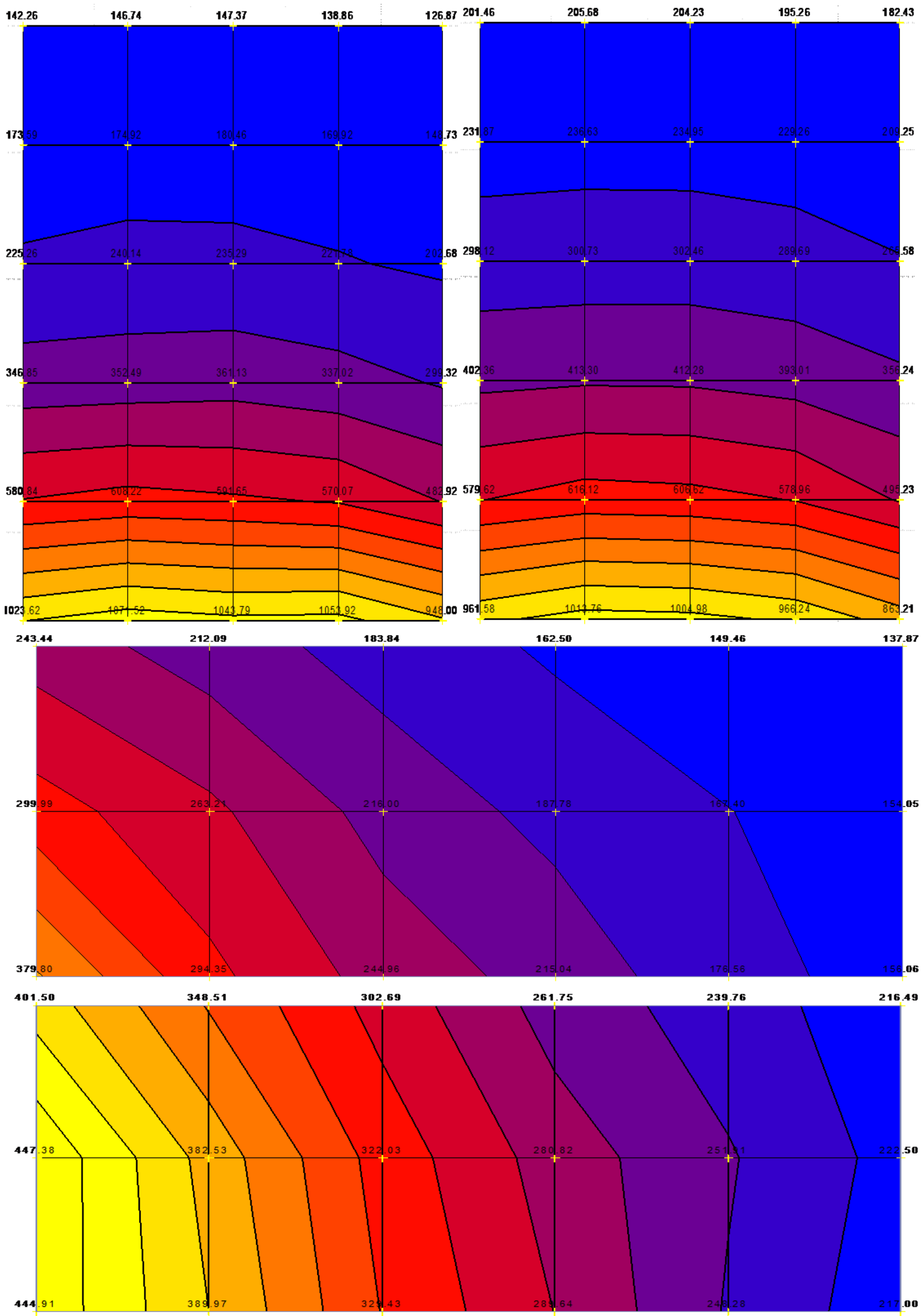


Figure A.27 Illuminance Values for WN5 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

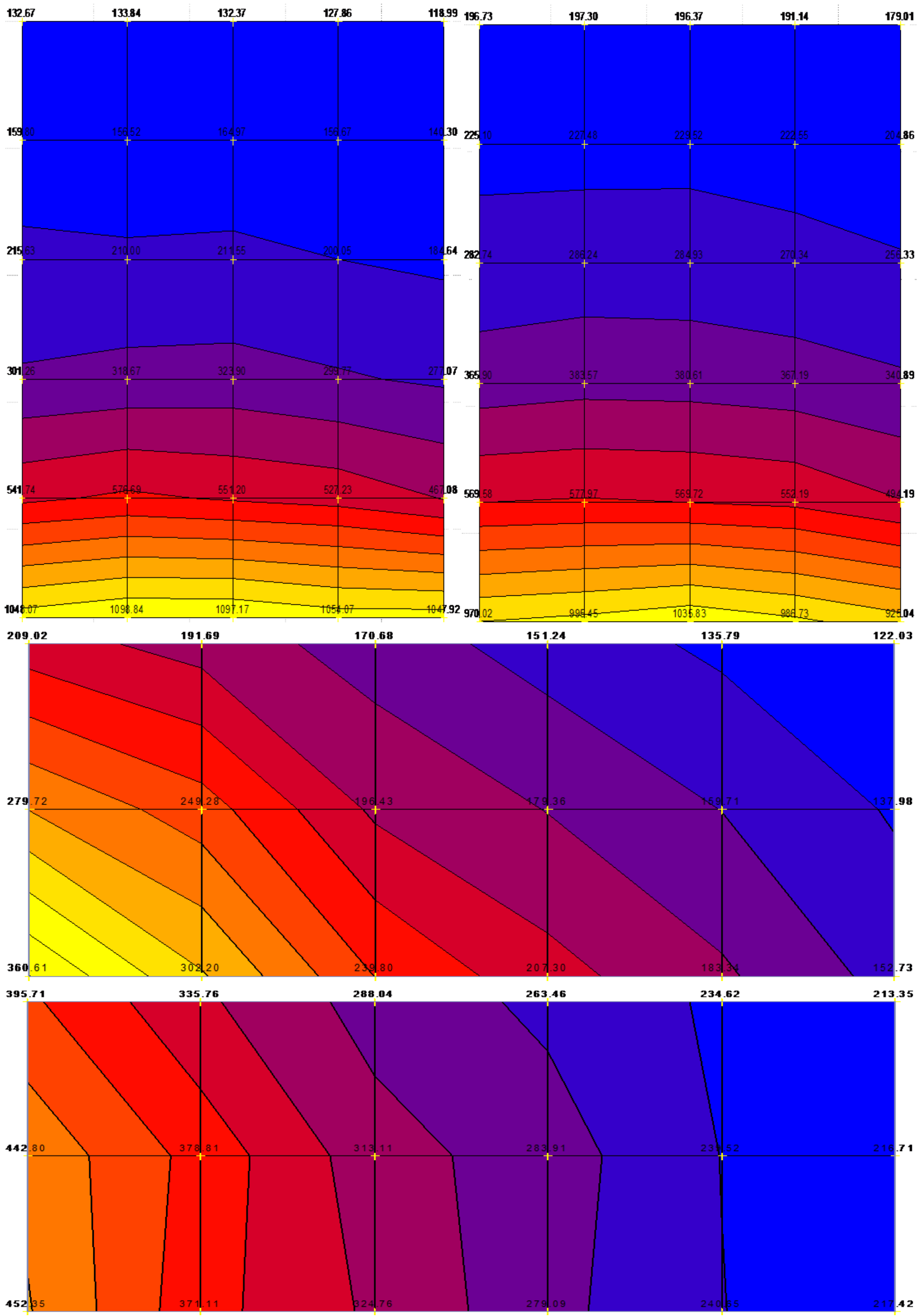


Figure A.28 Illuminance Values for WN6 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

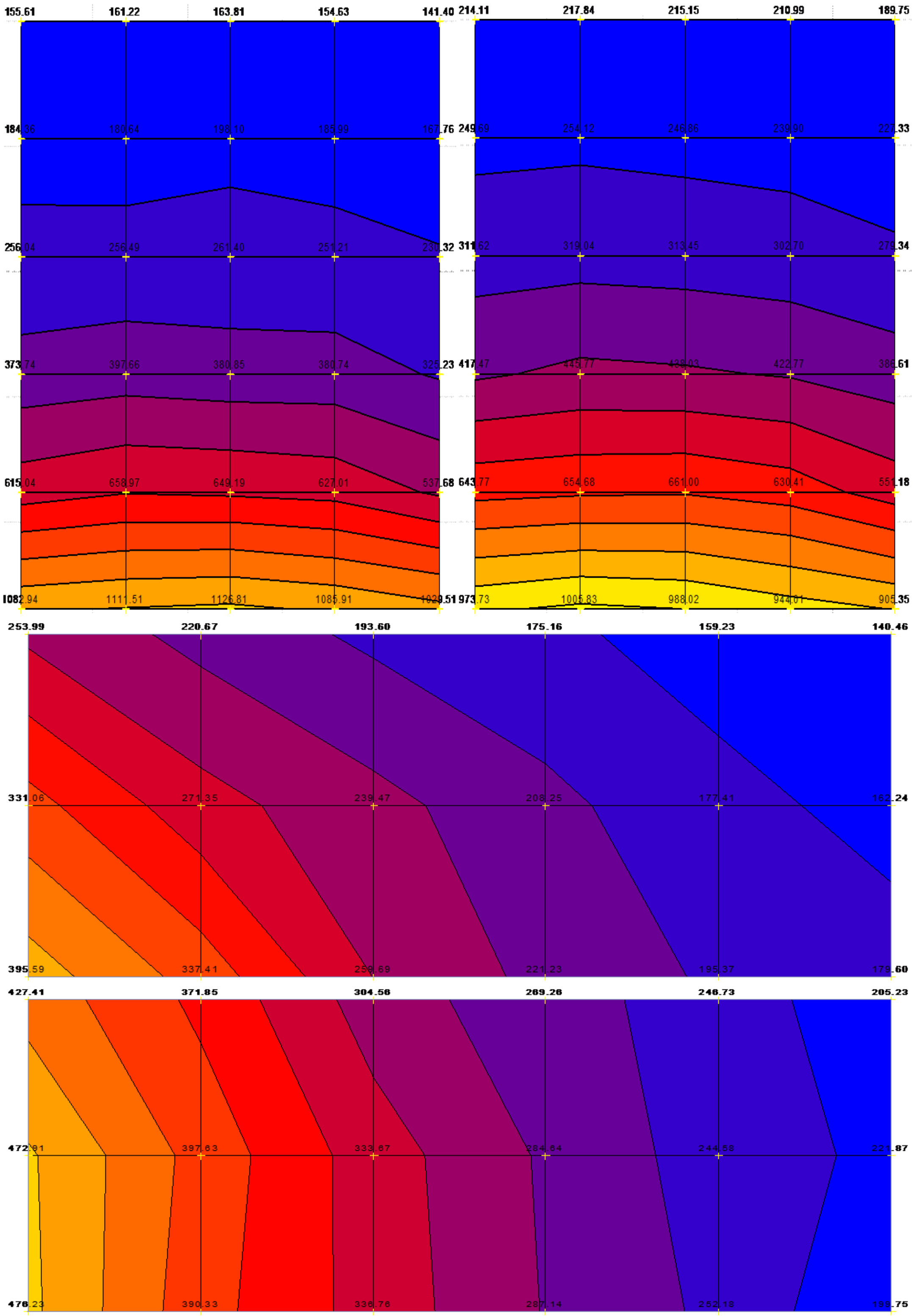


Figure A.29 Illuminance Values for WN7 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

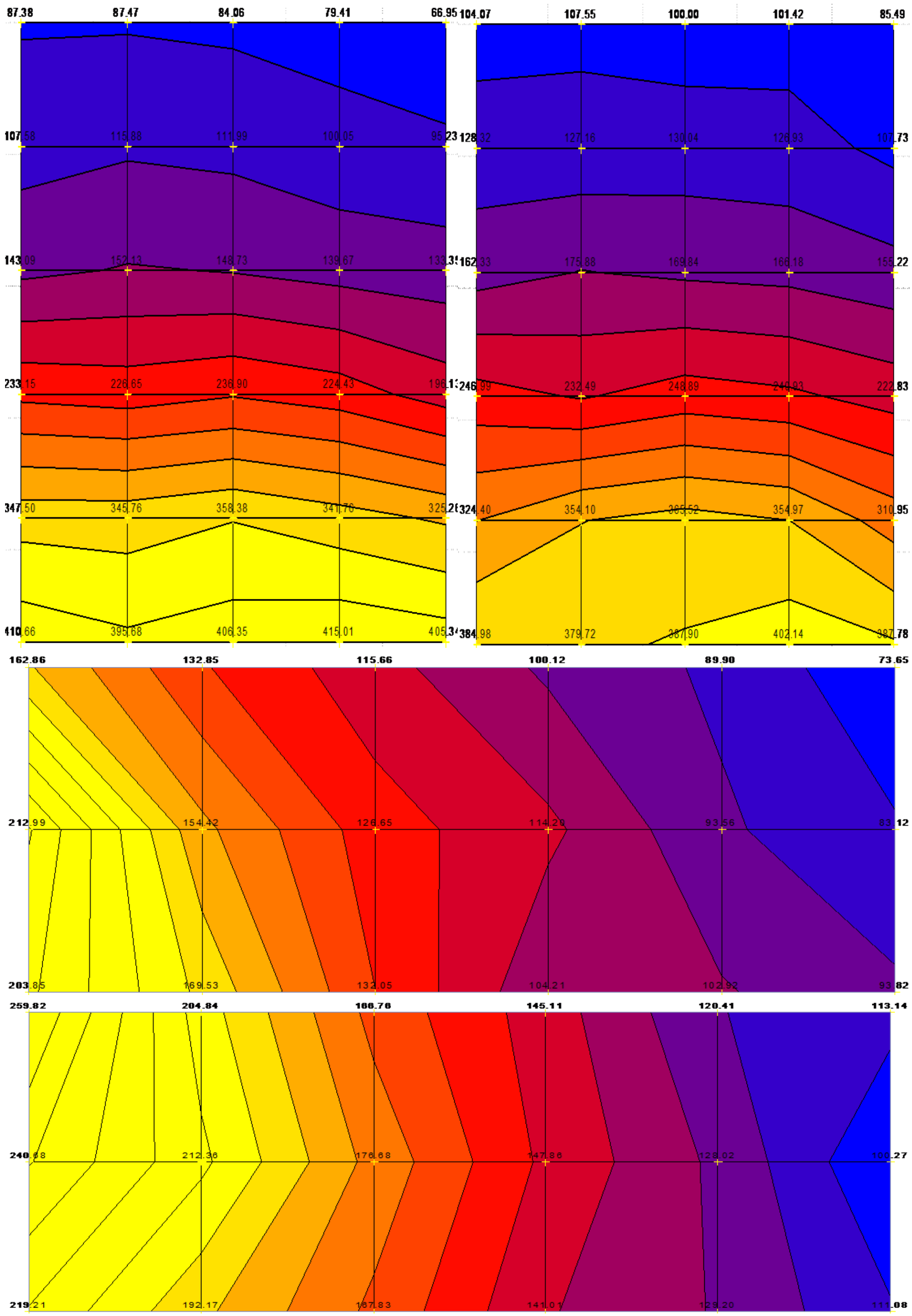


Figure A.30 Illuminance Values for WN8 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

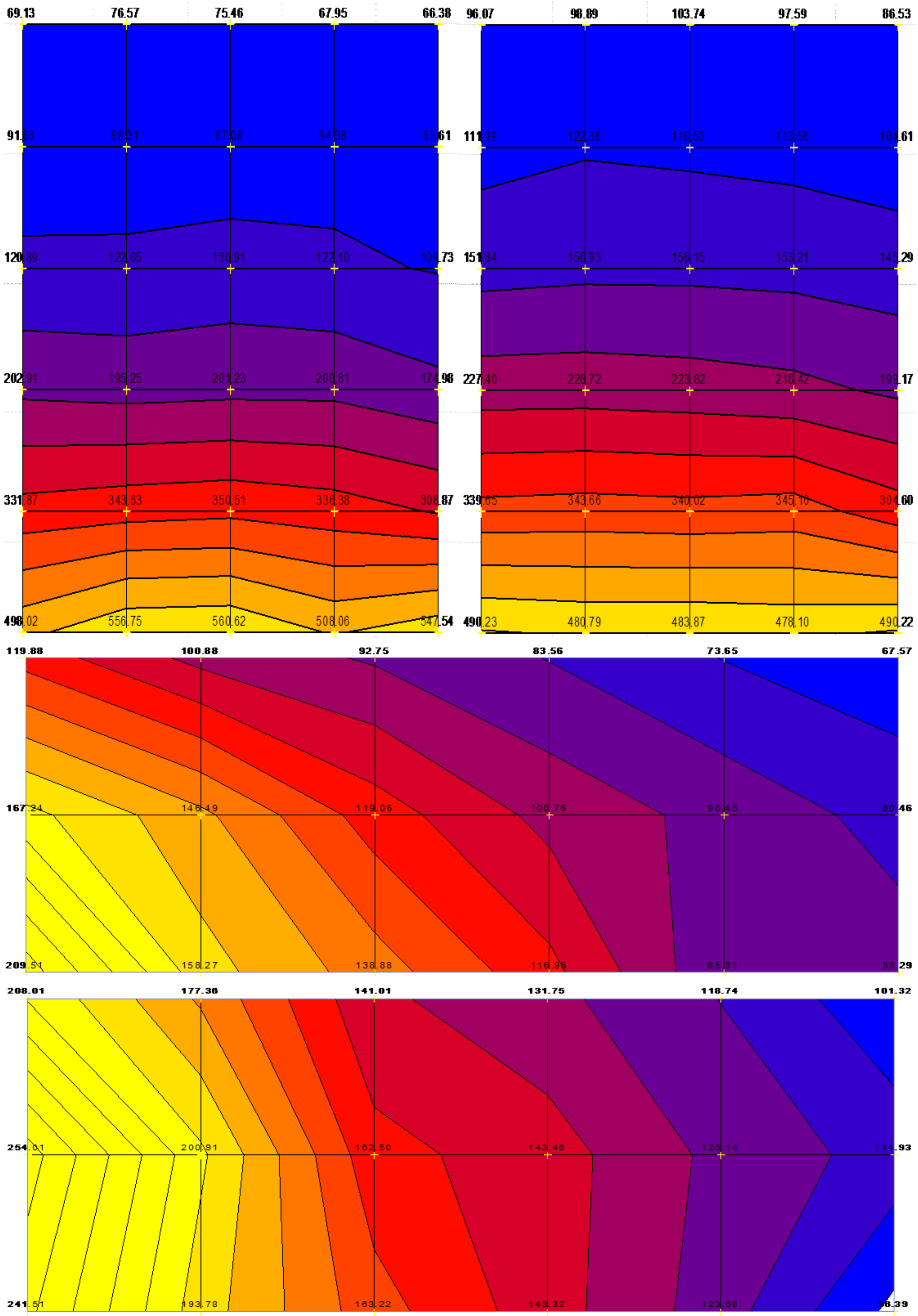


Figure A.31 Illuminance Values for WN9 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

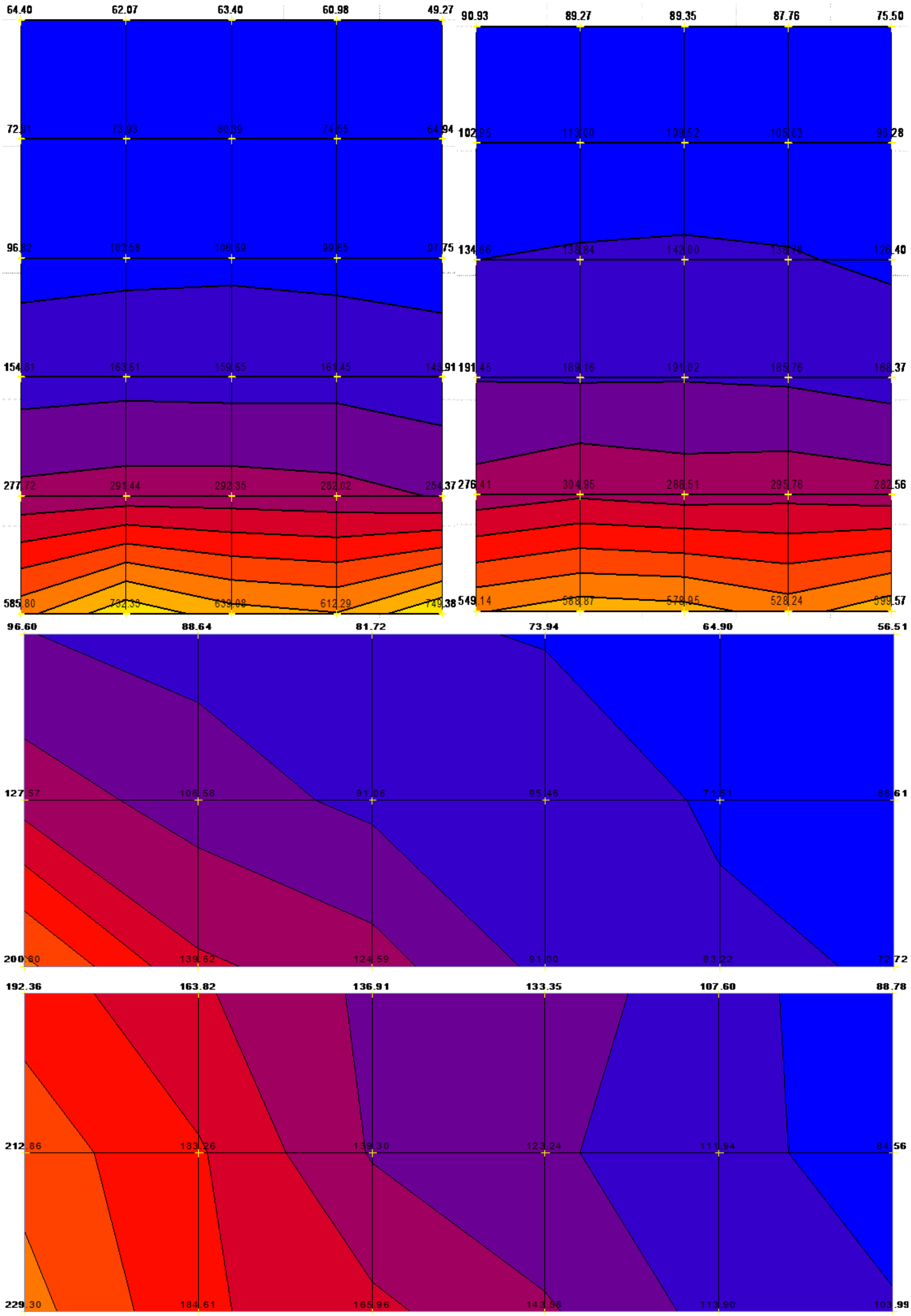


Figure A.32 Illuminance Values for WN10 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

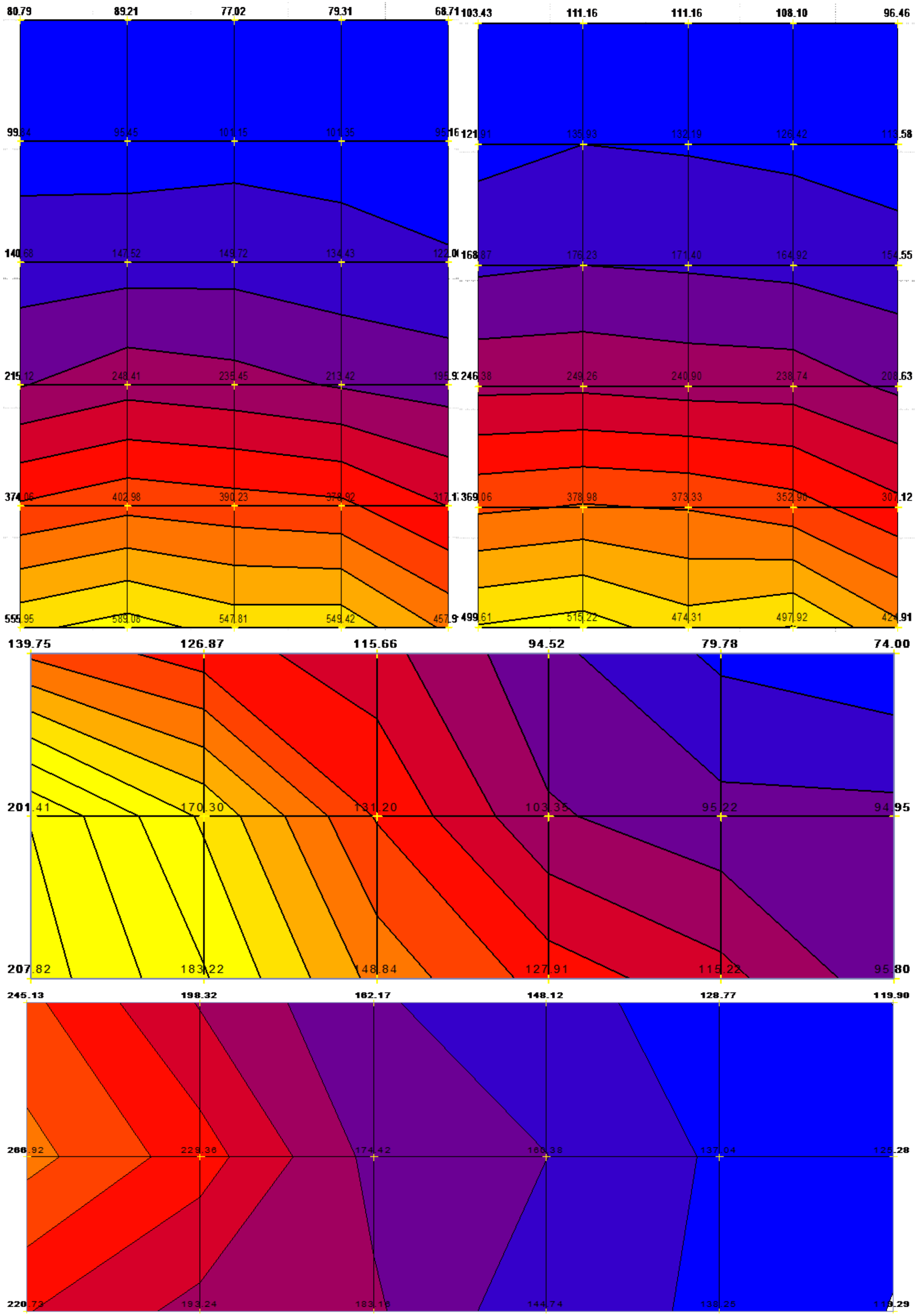


Figure A.33 Illuminance Values for WN11 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

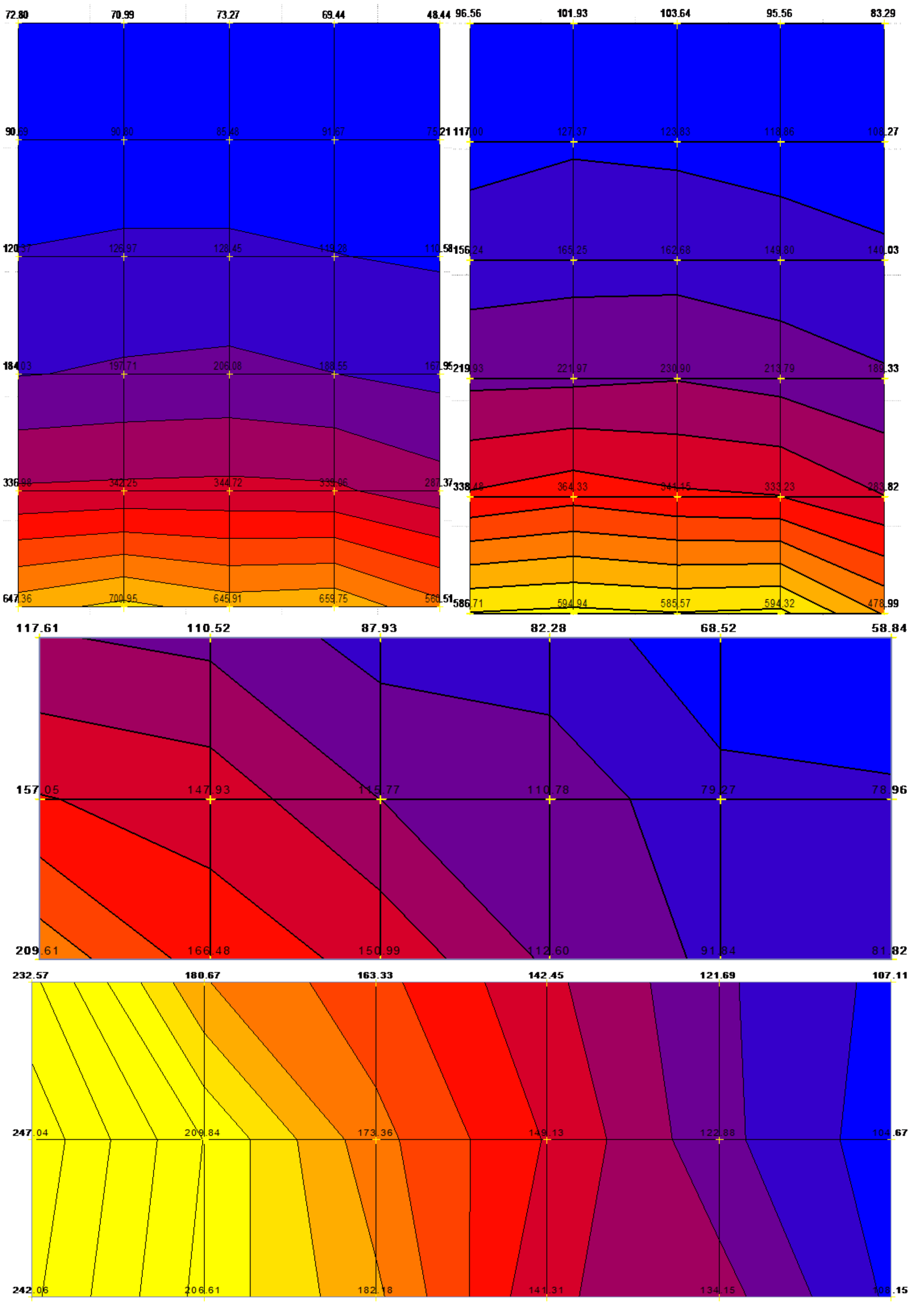


Figure A.34 Illuminance Values for WN12 over School Desks under Overcast Sky (Top Left), under Intermediate Sky (Top Right); over Whiteboard under Overcast Sky (Middle), under Intermediate Sky (Bottom)

APPENDIX B

MONTHLY DISCOMFORT DEGREE HOURS DATA SET

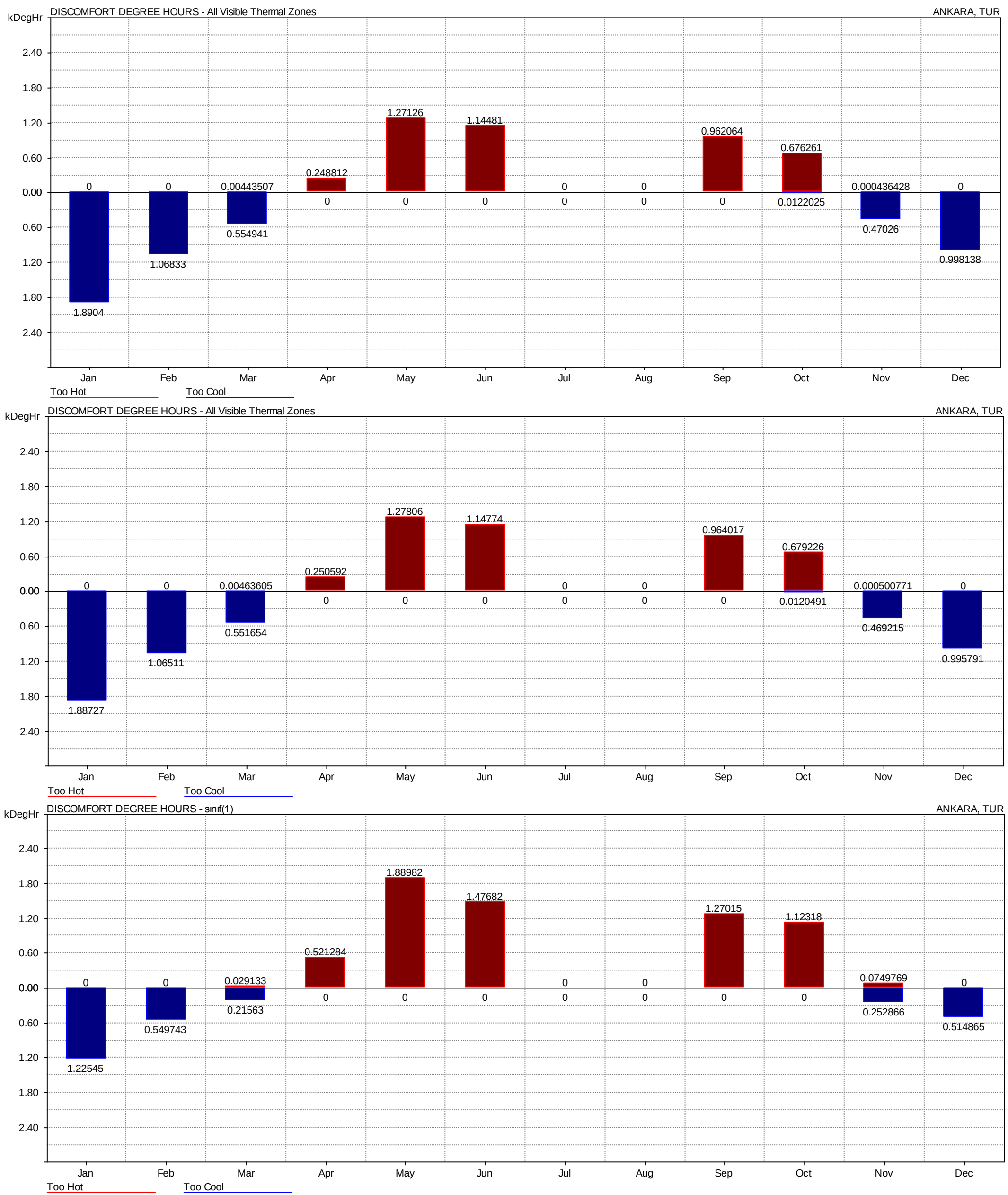


Figure B.1 DDH for the Classroom with WS1 (Top), WS2 (Middle) and WS3 (Bottom)

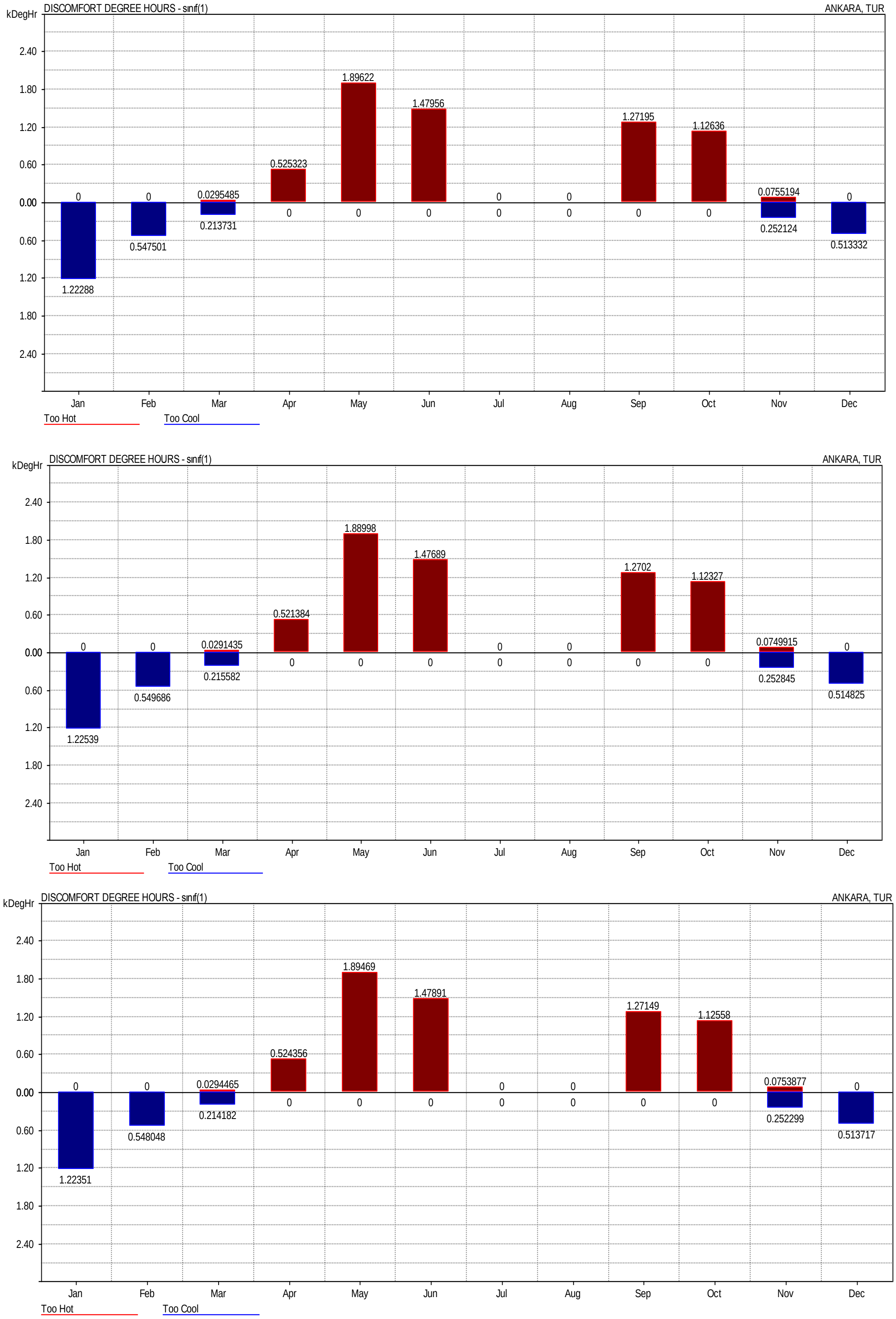


Figure B.2 DDH for the Classroom with WS4 (Top), WS5 (Middle) and WS6 (Bottom)

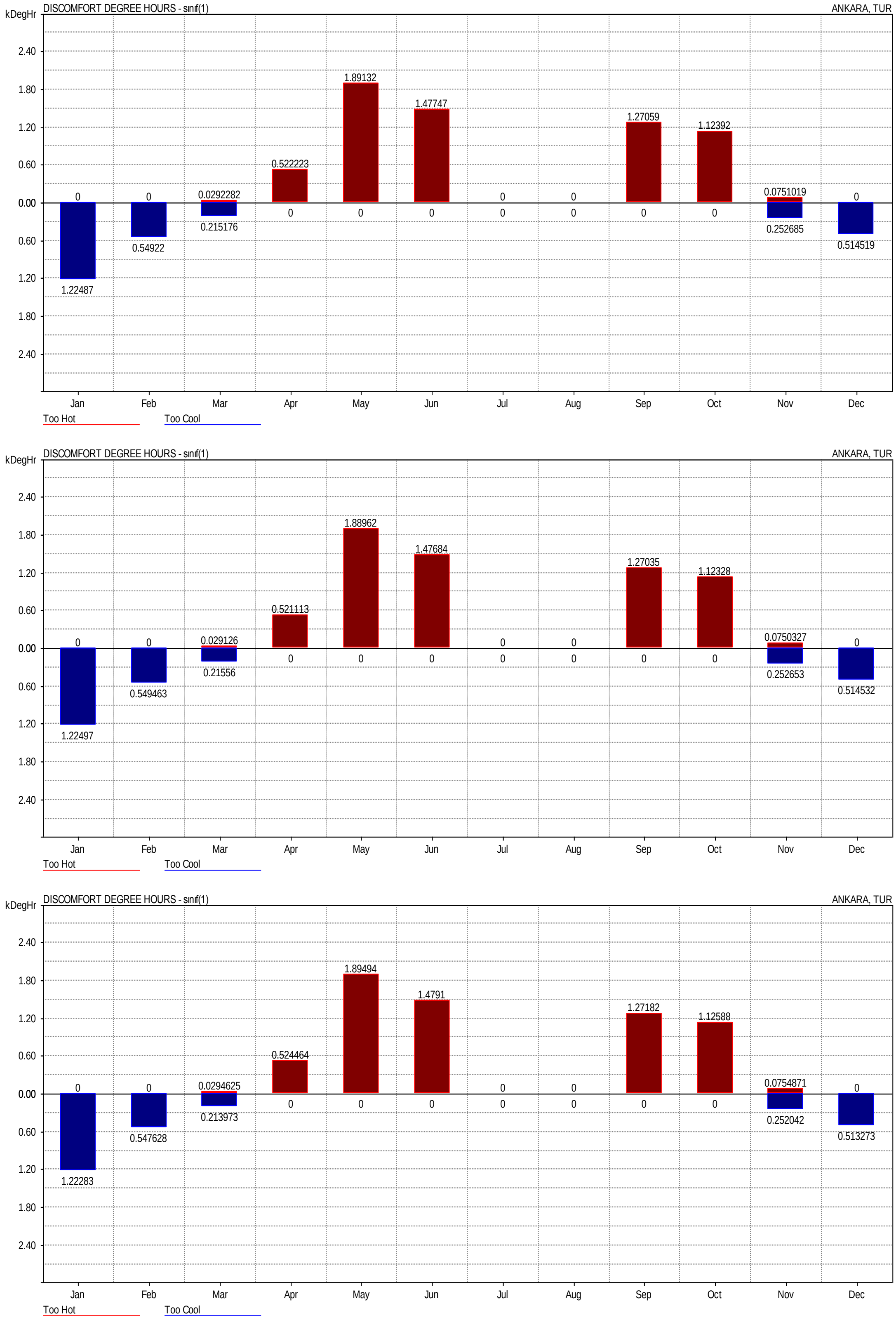


Figure B.3 DDH for the Classroom with WS7 (Top), WS8 (Middle) and WS9 (Bottom)

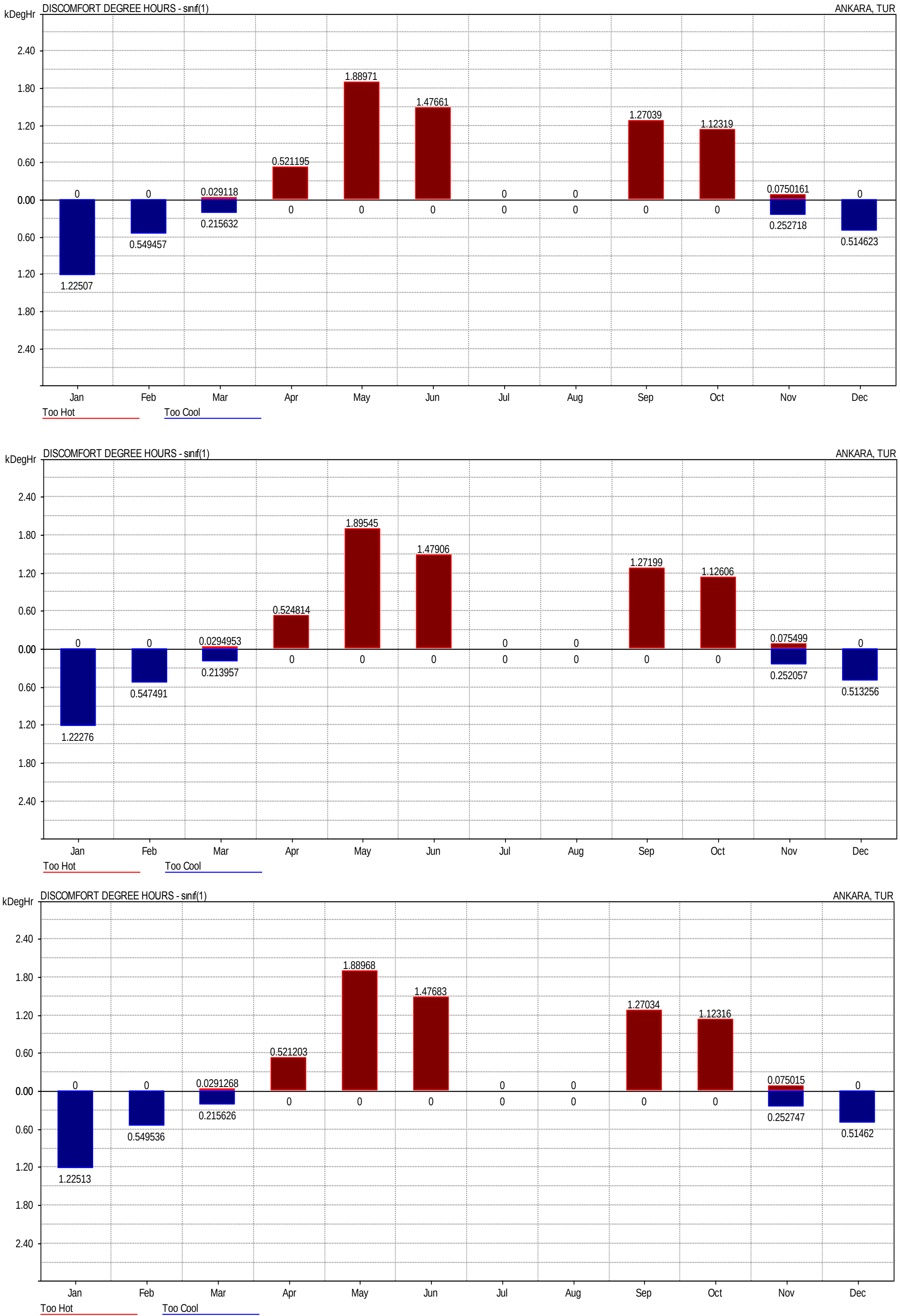


Figure B.4 DDH for the Classroom with WS10 (Top), WS11 (Middle) and WS12 (Bottom)

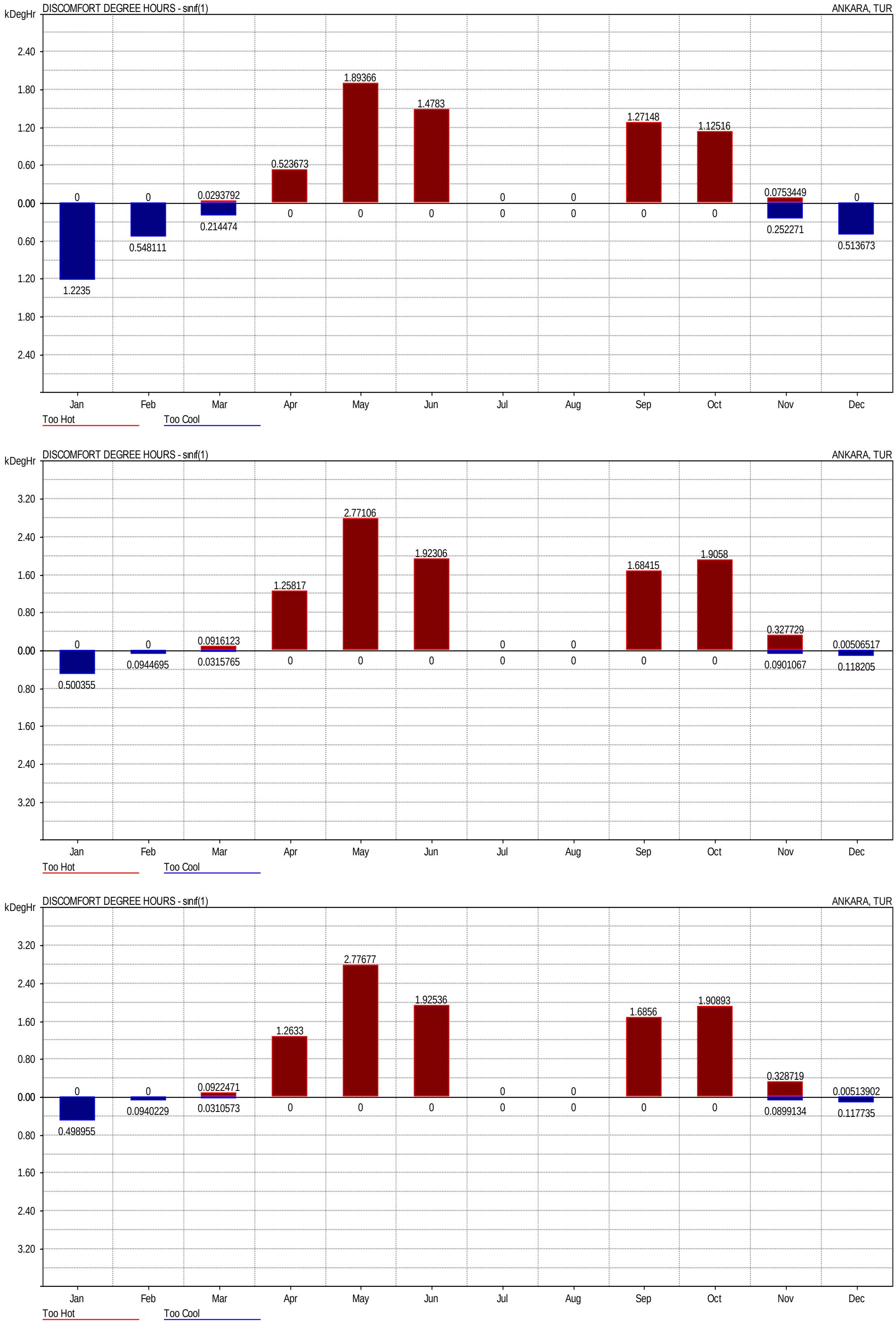


Figure B.5 DDH for the Classroom with WS13 (Top), WS14 (Middle) and WS15 (Bottom)

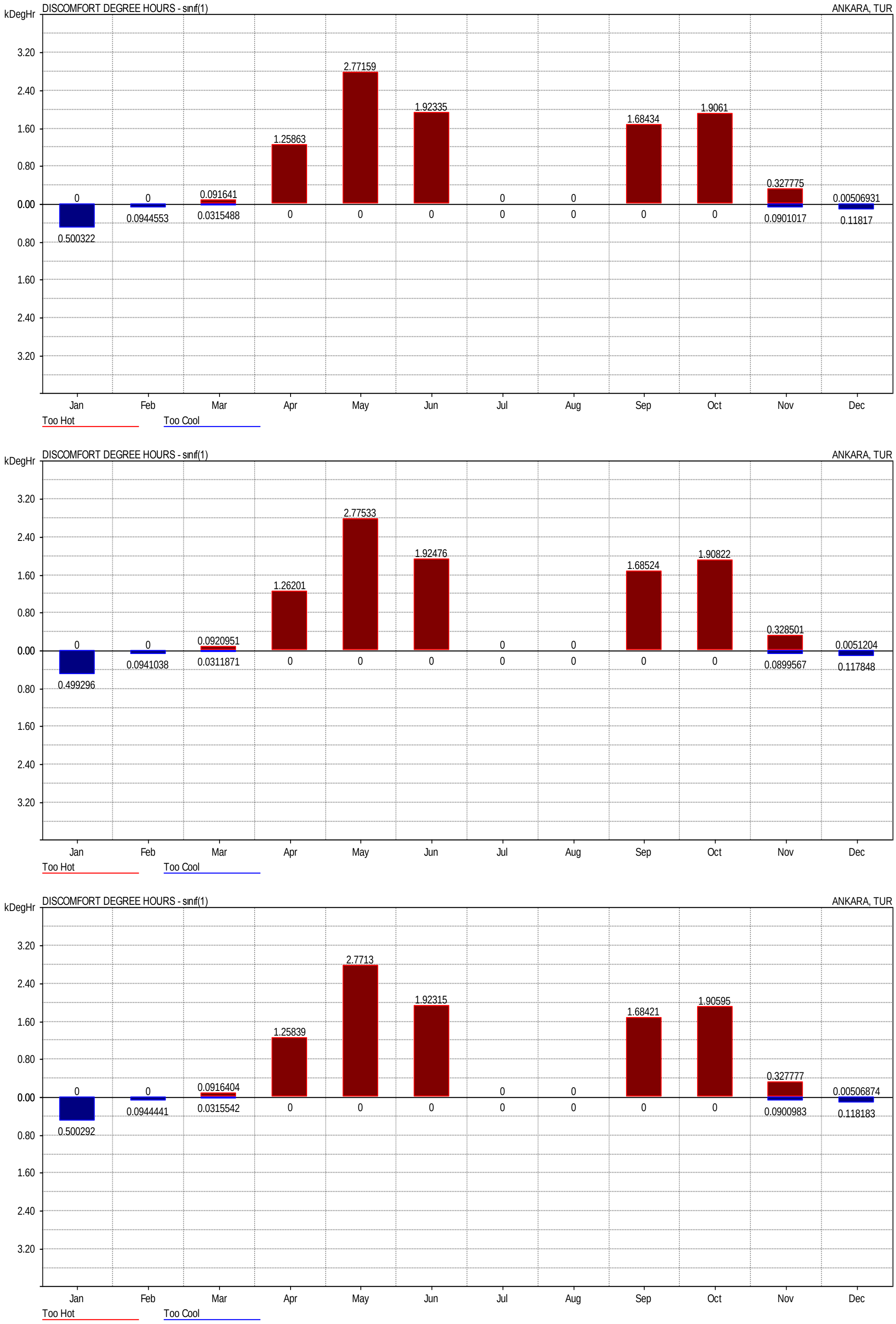
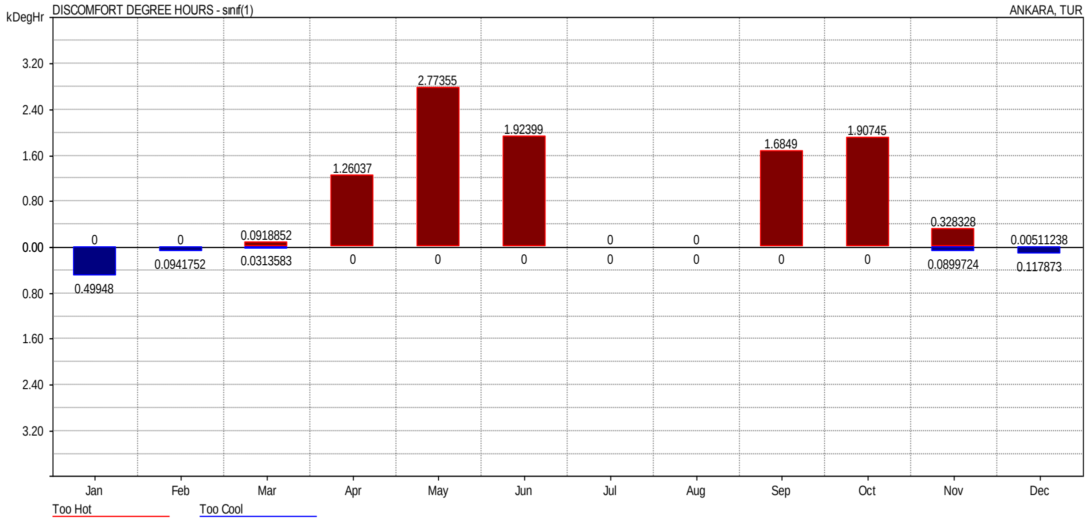
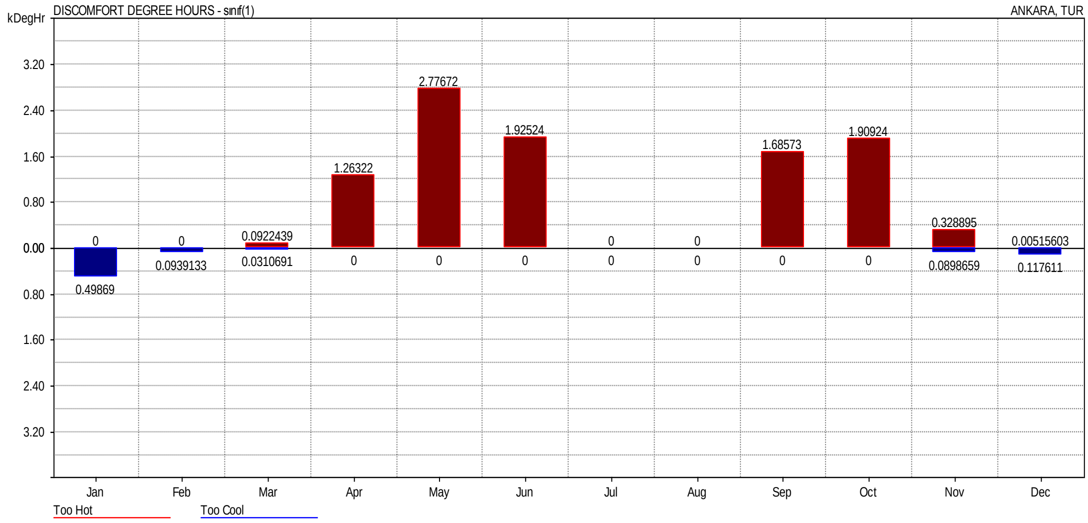


Figure B.6 DDH for the Classroom with WS16 (Top), WS17 (Middle) and WS18 (Bottom)





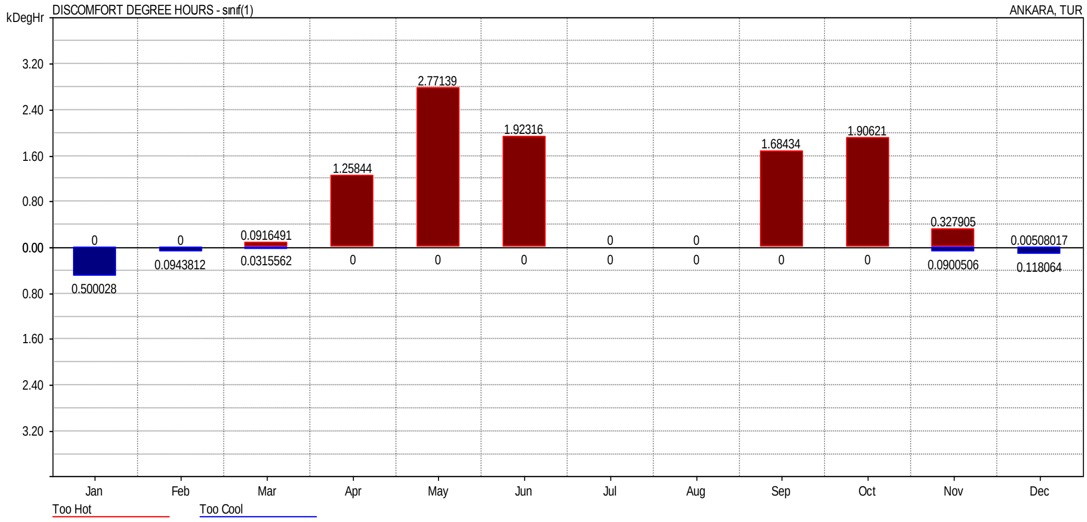


Figure B.7 DDH for the Classroom with WS19 (Top), WS20 (Middle) and WS21 (Bottom)

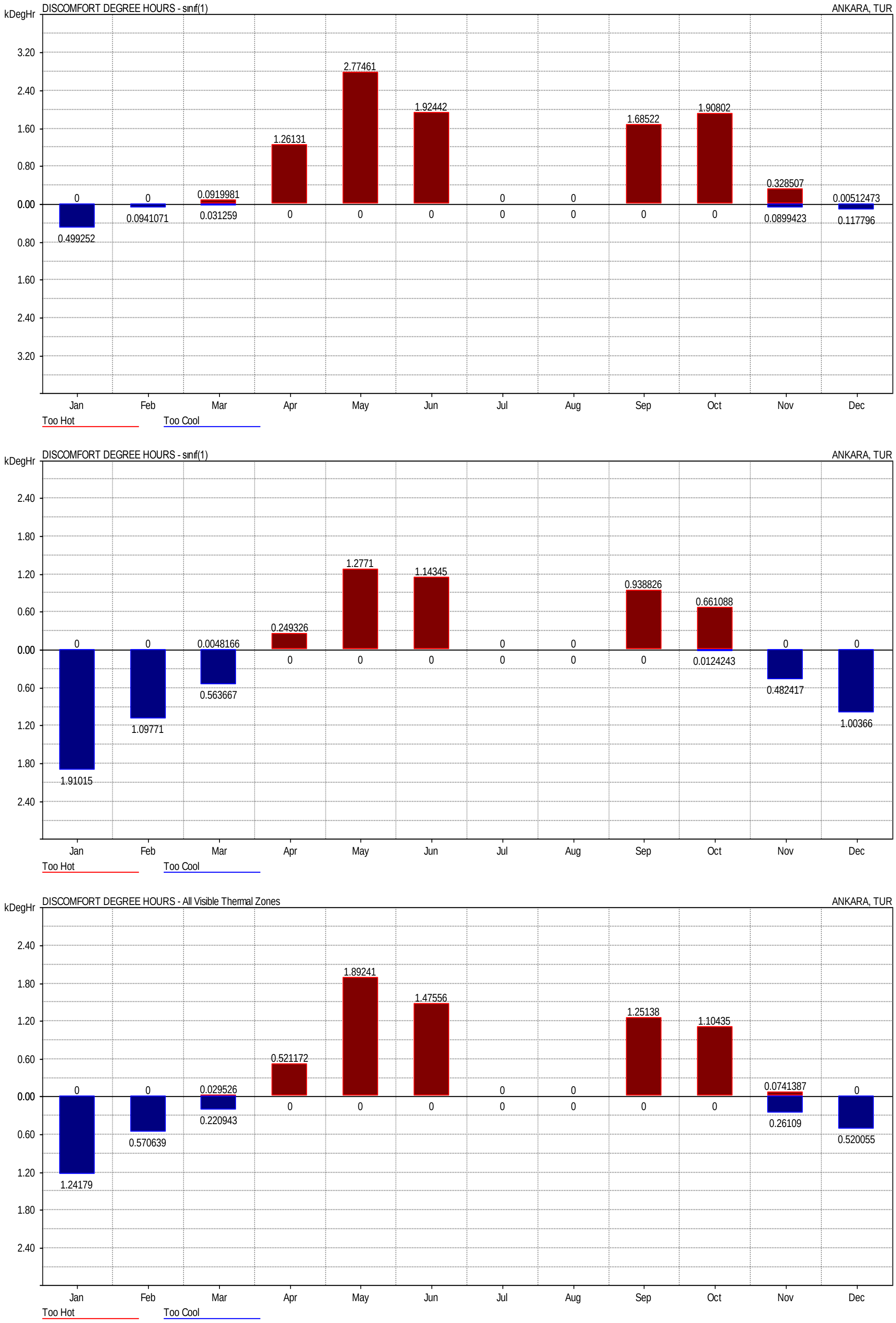


Figure B.8 DDH for the Classroom with WS22 (Top), WN1 (Middle) and WN2 (Bottom)

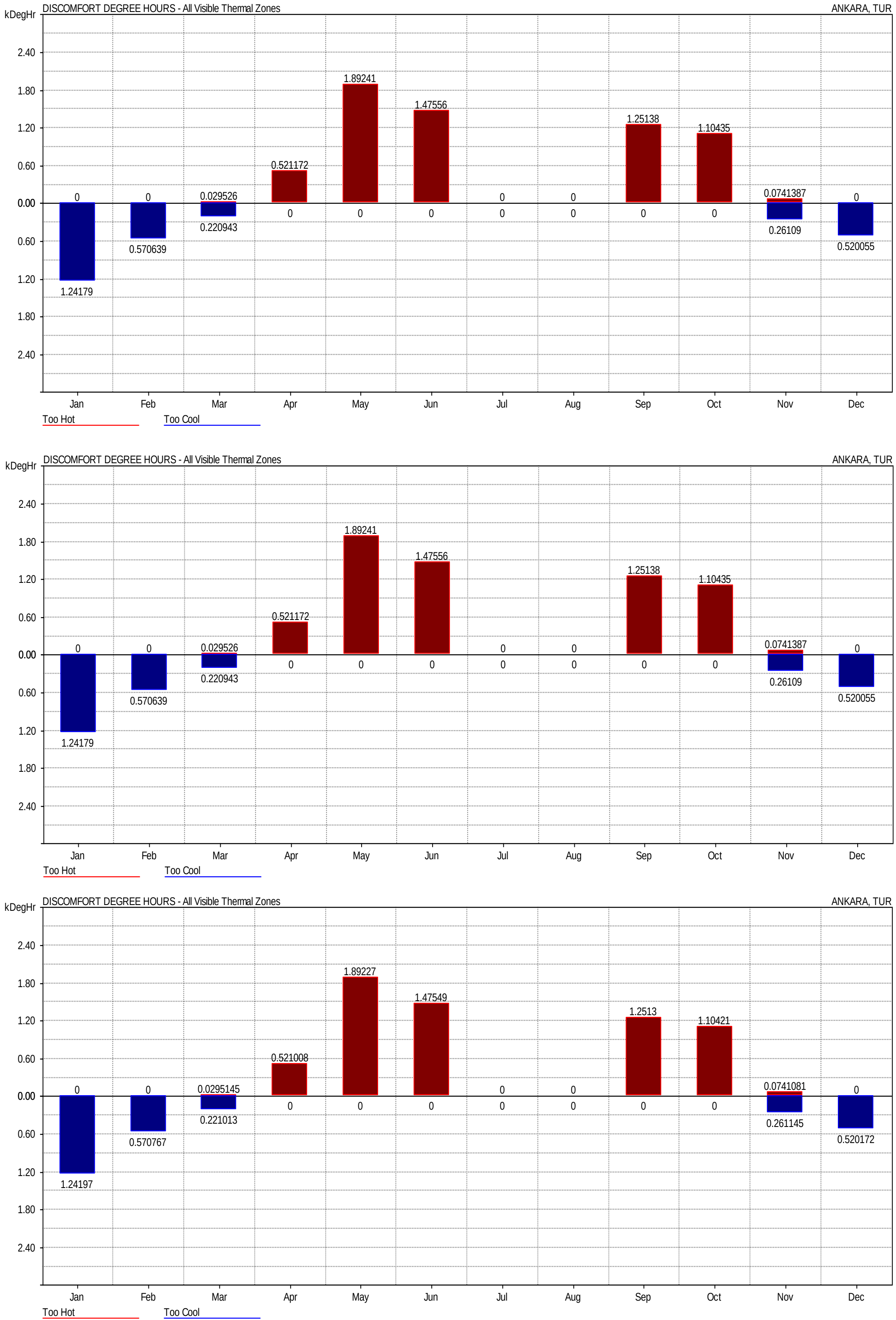


Figure B.9 DDH for the Classroom with WN3 (Top), WN4 (Middle) and WN5 (Bottom)

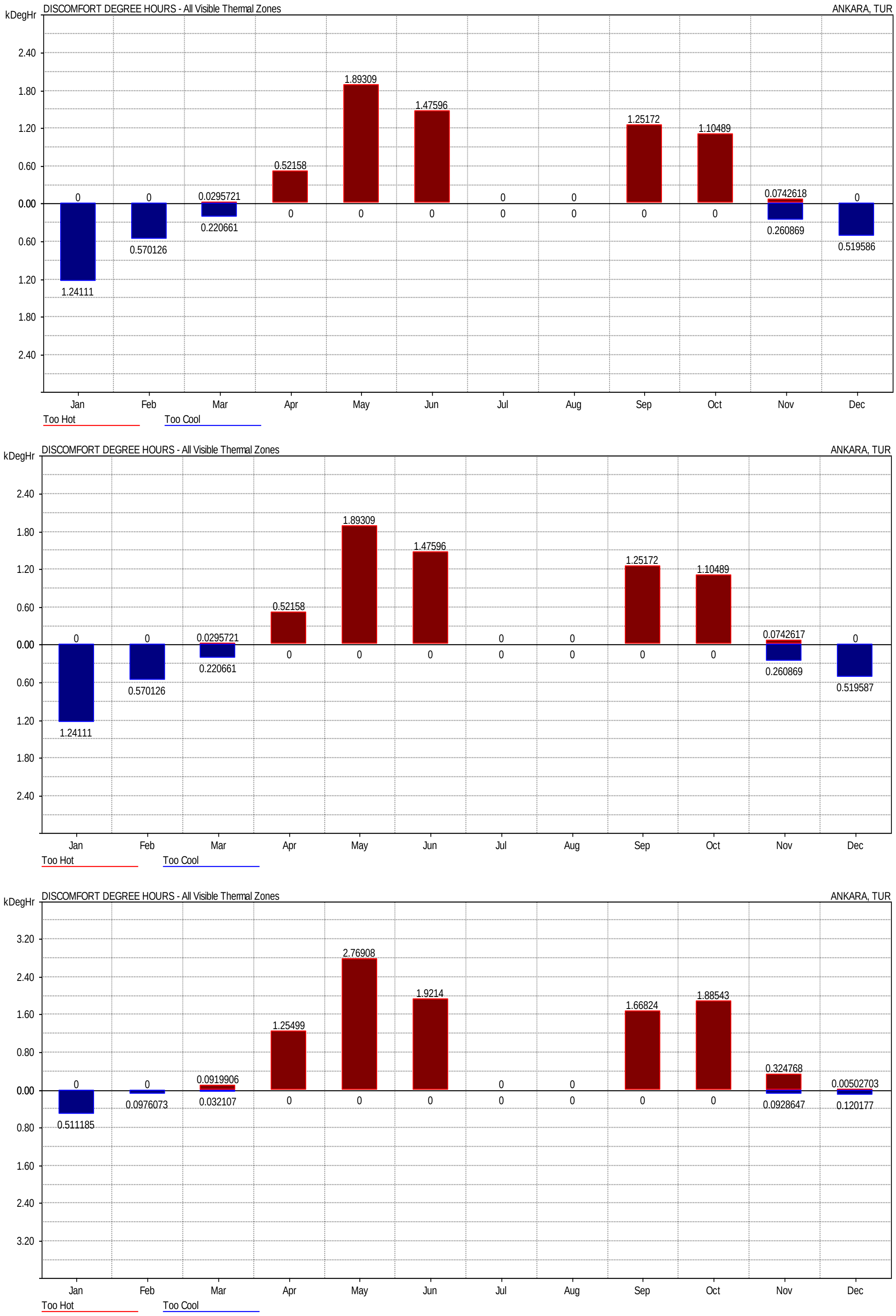
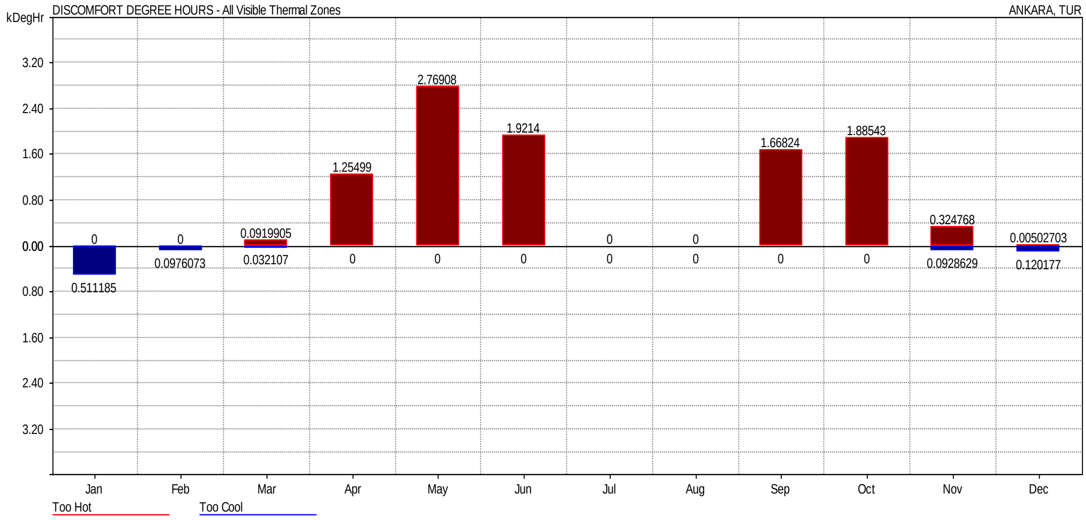
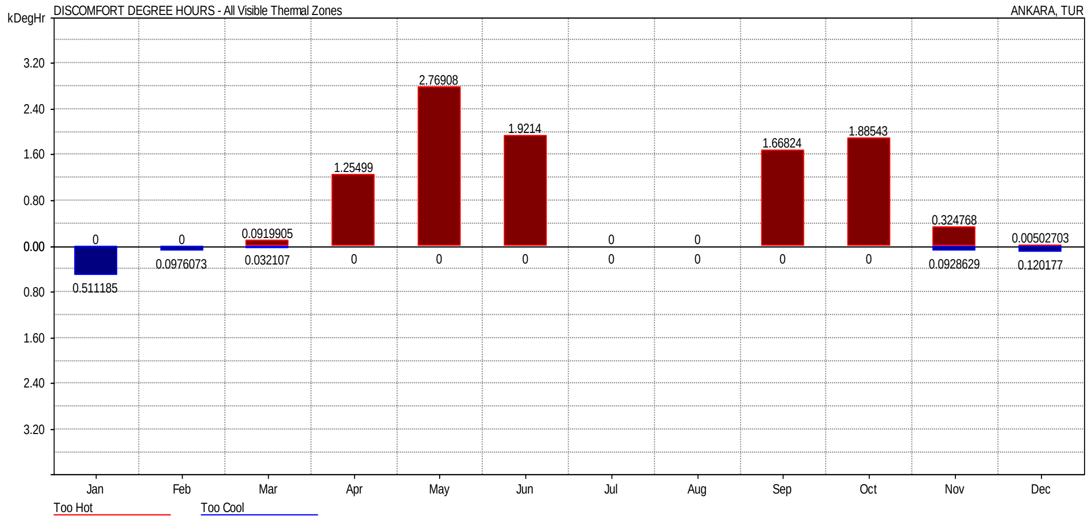


Figure B.10 DDH for the Classroom with WN6 (Top), WN7 (Middle) and WN8 (Bottom)





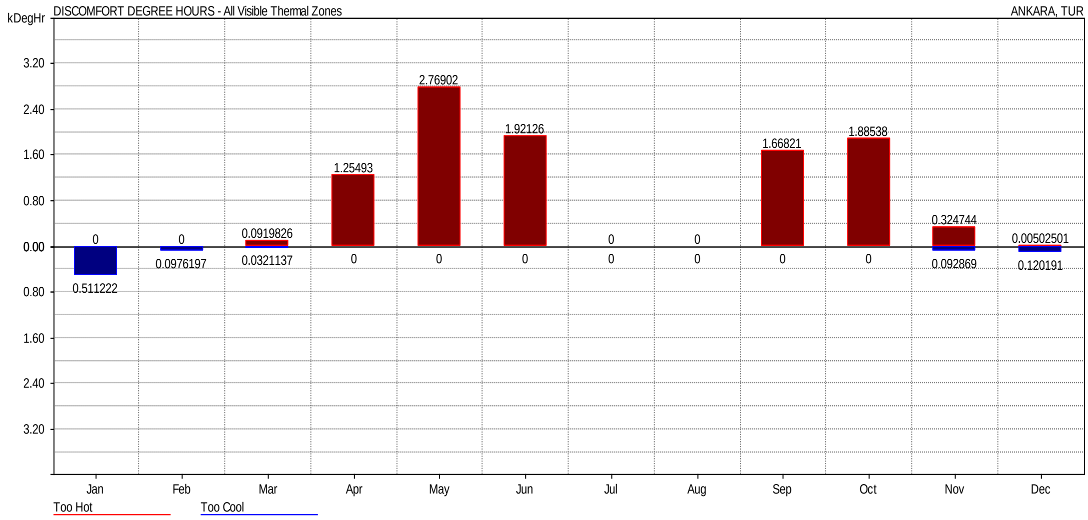


Figure B.11 DDH for the Classroom with WN9 (Top), WN10 (Middle) and WN11(Bottom)

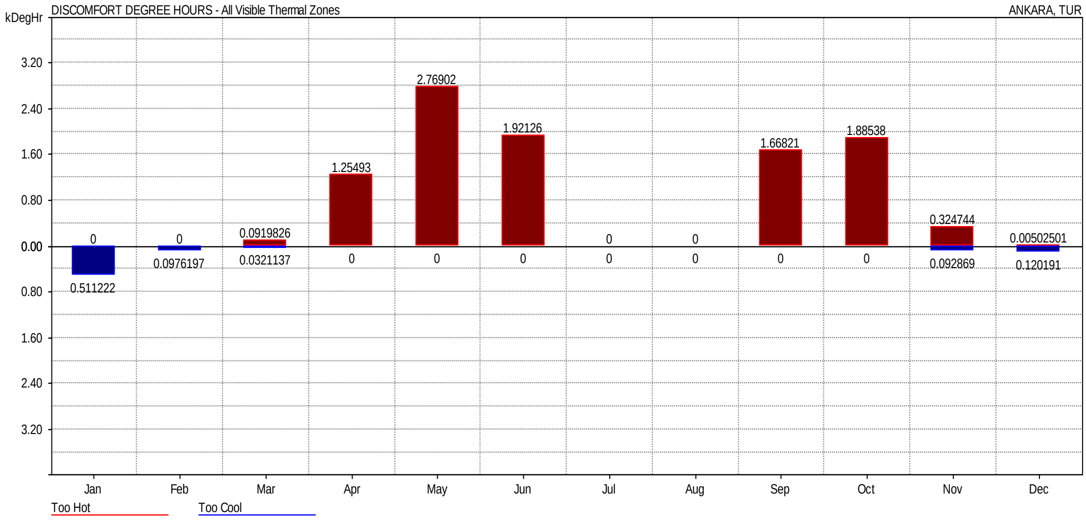


Figure B.12 DDH for the Classroom with WN12

APPENDIX C

ILLUMINANCE DATA SET FOR VALIDATION

Table C.1 Simulated and Recorded Illuminance Data over School Desks in Window Side (Left) and in Wall Side (Right) of the Classroom Facing South-East

Time	Simulated Illuminance Data Under Intermediate Sky Condition (Lux)	Simulated Illuminance Data Under Clear Sky Condition (Lux)	Recorded Illuminance Data (Lux)	Time	Simulated Illuminance Data Under Intermediate Sky Condition (Lux)	Simulated Illuminance Data Under Clear Sky Condition (Lux)	Recorded Illuminance Data (Lux)
08:00	7559.09	1292.3	18901.3	08:00	27211.3	3702.85	1959.1
08:30	8861.83	1428.9	8660.3	08:30	33616.62	3825.37	1651.6
09:00	10092.07	1491.91	9913.8	09:00	38639.3	3389.23	918.5
09:30	11193.22	1483.8	12610.1	09:30	42376.25	3078	918.5
10:00	12193.95	1435.05	32280.1	10:00	45881.13	2888.37	2116.8
10:30	12417.83	1333.81	21518.7	10:30	47612.87	2880.8	1296.9
11:00	12297.88	1228.53	24222.9	11:00	47628.36	2413.73	1162.9
11:30	11606.62	1113.55	21353.2	11:30	45934.65	2131.1	1265.3
12:00	10481.31	1002.75	25705	12:00	41969.98	1810.05	1344.2
12:30	9422.25	903.8	9235.8	12:30	34963.07	1548.48	792.3
13:00	7180.25	833.43	8652.4	13:00	24175.23	1278.38	792.3
13:30	3802.32	754.41	5002.2	13:30	3353.71	1092.74	477
14:00	3347.26	898.35	5759.1	14:00	2868.41	997.89	524.3
14:30	2948.03	813.82	4781.5	14:30	2443.98	901.75	461.2
15:00	2430.35	524.07	3409.7	15:00	2159.32	804.38	382.4
15:30	1922.37	438.52	1809.3	15:30	1755.37	711.31	366.6
16:00	1477.27	338.33	1115.6	16:00	1413.23	598.37	161.6
16:30	1101.84	231.48	1028.8	16:30	1138.6	470.4	161.6
17:00	657.44	138.58	689.8	17:00	864.66	343.2	106.4
17:30	277.75	58.42	311.4	17:30	578.07	244.45	27.6
18:00	0.03	0.03	3.9	18:00	342.63	138.25	3.9

Table C.2 Simulated and Recorded Illuminance Data over School Desks in Window Side (Left) and in Wall Side (Right) of the Classroom Facing North-West

Time	Simulated Illuminance Data Under Intermediate Sky Condition (Lux)	Simulated Illuminance Data Under Clear Sky Condition (Lux)	Recorded Illuminance Data (Lux)	Time	Simulated Illuminance Data Under Intermediate Sky Condition (Lux)	Simulated Illuminance Data Under Clear Sky Condition (Lux)	Recorded Illuminance Data (Lux)
08:00	1597.39	1575.79	1635.9	08:00	332.86	894.17	532.2
08:30	1756.73	1720.33	1730.5	08:30	388.42	778.84	587.3
09:00	1875.23	1797.79	3464.9	09:00	394.21	845.08	540
09:30	1950.5	1890.58	4237.5	09:30	401.43	889.71	603.1
10:00	1998.58	1997.12	4229.6	10:00	417.21	928.28	871.2
10:30	2084.62	2076.96	4552.9	10:30	423.88	943.3	674.1
11:00	2193.31	2194.49	4056.2	11:00	428.87	958.31	674.1
11:30	2345.79	2298.18	3606.8	11:30	445.98	989.47	816
12:00	2522.4	2455.94	2605.6	12:00	480.84	989.55	823.9
12:30	2731.13	2529.36	3409.7	12:30	515.2	978.03	666.2
13:00	3010.45	2613.85	5593.5	13:00	548.33	943.88	721.4
13:30	3439.49	2743.45	5223	13:30	803.09	941.34	579.5
14:00	3632.16	3014.44	6074.4	14:00	833.02	913.34	611
14:30	5464.59	15022.39	5617.2	14:30	887.23	954.47	618.9
15:00	5827.37	19474.25	5688.1	15:00	870.29	1080.97	626.8
15:30	5382.02	19165.62	4907.6	15:30	815.25	1201.83	776.6
16:00	4412.65	15513.63	1580.7	16:00	552.28	1282.71	335.1
16:30	1754.96	2667.46	3851.2	16:30	445.83	1271.37	516.4
17:00	1084.92	1899.9	2069.5	17:00	288.94	924.53	532.2
17:30	476.82	1415.16	477	17:30	182.8	887.89	82.8
18:00	0.03	545.92	11.8	18:00	0.03	237.01	3.9