MASTER

Living envelop for comfort
design of living façade for a school building to enhance students' visual comfort

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Design of Living façade for a School building to enhance students' visual comfort

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Executive summary

Façade as outer skin of the building is supposed to provide a pleasant indoor environment for its occupants. One of the indicators of enhanced indoor environment is comfort which itself has got several sub-indicators including; thermal, visual, acoustic comfort and indoor air quality. The goal of this research is design of a façade product for an elementary school which could enhance students' visual comfort. However, further studies shows that, visual comfort has got two main requirements which are both variable; users' lighting requirements and contextual requirements which is daylight availability. Daylight availability at specific location depends on several factors which determine its components' type (skylight or sunlight), color Spectrum, direction, and Sky luminance. Moreover, the lighting requirements of users depend on type of activity they perform and change both in lighting qualitative and quantitative aspects.

The outcome of two requirements set the design requirements. As a result, the designed façade product should be designed in a way that could response to changes in daylight availability and users' lighting requirement. This led the design approach to come up with kind of living façade product which could adjust itself to those changes. After analysis of available daylighting systems, the appropriate daylighting systems were integrated into a heterogeneous fenestration façade concept which makes it possible to assign different tasks to each part of fenestration. After completion of design concept the product is simulated in Ecotect software to examine its daylighting performance in different selected situations. Due to wide range of daylight qualitative and quantitative factors, this study is focused on one of those factors namely; illuminance.

Table of content

1. Introduction- What, why & how?

1.1. Importance of Living façade

Façade in traditional building system is a shield against external environment which is considered as a variable and unknown quantity that cannot be controlled. On the other hand, the internal environment, with use of air conditioning, can be highly controlled. As a result, a traditional building's facade becomes a sealed skin, a barrier between the variable outdoor climate and the highly controlled indoor climate. In such a system, the efficiency of the facade is measured by its ability to shield from the outdoor environment so that the air conditioning system can cool as efficiently as possible [18].

This system has got several disadvantages. Since such a façade system is solid and fixed it has no interaction with climatic changes or occupant requirements. The maximum interfere of occupants would be to open a window or adjust the sunshades. Since the façade condition is the same for different situations of outdoor and indoor air environment and building spaces different functions, this may lead to high building operation cost and energy consumption. To overcome the problem caused by conventional façade systems, it is proposed that, there must be an active system of façade which can adjust itself according to climate and occupants' requirements. Such a system would be like a living creature which may adapt itself in response to functional and environmental demands, namely a living façade system.

1.2. Research goal and scope

The main goal of this research is to design a living façade for a elementary school building to improve users' performance. According to researches there is a direct relation between performance of the students and teachers in schools and physical environment (Table-1.1). Having this in mind the main aim of this research is to provide a better indoor environment for an elementary school to improve users' performance. To illustrate the link between living façade which was mentioned and the preceding statement about research goal, it can be referred to Figure-1.1, which indicates the hierarchy of research focus and how the research subject has been narrowed through wide range of influential aspects.

As it is shown in Figure-1.1 the research focus is to design of a living façade which can provide visual comfort for users. However it must be noticed that, in comfort field there are several indicators of comfort which sometimes overlap each other (their overlap area might accent or contradict each other). So, it is almost impossible to reach a certain comfort thoroughly without studying other fields. For example, to reach visual comfort might result in maximizing use of daylight and glazing in façade, while this might cause overheating and thermal discomfort. Due to limitations of this research, it is focused on visual comfort, and its impact on other comfort indicators is not studied thoroughly. So it must be noted that, all diagrams and analysis of daylighting are done with visual comfort orientation (specially analysis in chapter-5) and to reach comfort in other fields further studies are required which are not in frame work of this research.

Figure-1.1. Hierarchy of research focuses from physical environment to Visual comfort, which is the focus of this research.

Users' performance and Attendance:

- Socio-economic factors
- Physiological factors
- Environmental factors
- Individual Competences
- **Physical Environment :**
    - Building compatibility with educational requirements
    - School design/ Educational environment standards; Class size, etc.
    - **Building indoor environment:**
        - Safety
        - Health
        - Spatial configuration
        - **Comfort:**
            - Electromagnetic Fields
            - Water quality
            - Greens
            - Vibration
            - Acoustical Comfort
            - Thermal Comfort
            - Indoor Air Quality
            - **Visual Comfort :**
                - Illuminance
                - Discomfort situations
                - Uniformity and contrast
                - Color aspects
                - **Daylighting**

There are a number of researches which show a link between physical environment, especially indoor environment, and performance of users. Some of these researches have been studied and their outcome has been categorized in a table to illustrate the possible effects of physical environment and users' performance (table-1.1). As it may be concluded from this summary, although the focus and final result of these researches are slightly different, they all do agree that there is a direct link between occupant performance in school and buildings physical environment, specifically indoor environment. Research 1, 3 and 5, mainly focus on influences of indoor environment of school occupants' performance and requires educational spaces to provide a healthy and comfortable environment. This finding may be found also in research 2 with more detailed investigation and explores two main aspects of indoor environment; Indoor air quality and daylighting. However, it goes beyond that and concludes that having personal control in lighting also affects students' progress. Research 4, mostly explores the effect of thermal comfort in tropics on students health, which has a direct influence on students performance. Regardless of slight differences between the focus and result of these researches, they all emphasize on:

- School physical environment, especially indoor environment influence both students and teachers performance.

- Having control on lighting of indoor spaces also effect students' progress.

This result is used as a start point for research and its focus narrowing as it was described in preceding chapter.

Table-1.1. Summary of articles about relation between performance of students and physical environment

number	Author	Subject	Aim/Purpose	Conclusion
1	Schneider, M. 2002	Do School Facilities Affect Academic Outcomes?	To investigate the effect of school built environment in on learning.	Spatial configurations, noise, heat, cold, light, and air quality bear on **students' and teachers' ability to perform.** Learning environment needs; clean air, good light, quiet, comfort, and safety.
2	Olson, S. L. & Kellum, S. 2003	The Impact of Sustainable Buildings on Educational Achievements.	To investigate the relation between: Indoor Air Quality and Student Performance Daylighting and Student Performance	The physical environment provided by school facilities affects **learning**. Spatial configurations, noise, heat, cold, light, and air quality bear on **students' and teachers' ability to perform.** Sustainable schools provide a well-lit, healthy, comfortable environment conducive to learning and student achievement while **saving money, energy, and resources**. Sustainable schools give students and teachers: **comfortable, healthy learning** environments contributing to **academic success and the achievement**. **Personal lighting controls** in schools affects students progress.

Table-1.1. Summary of articles about relation between performance of students and physical environment

number	Author	Subject	Aim/Purpose	Conclusion
3	Heath, G.A., & Mendell, M.J. 2000	Do Indoor Environments in Schools Influence Student Performance?	• The influences of IEQ factors, measured or qualitative, on health • The influence of adverse health on performance or attendance • The influence of absenteeism on performance	Some aspects of **IEQ**(including low ventilation rate and less daylight or light) and **HVAC systems**, may reduce the **attendance** of students and affect their **performance.**
4	Prescott, K. 2001	Thermal comfort in school buildings in the tropic		Adaptive approach in school building design, have major implications for: • Sizing of mechanical plant, equipment, electricity supply mains • Running/life cycle costs of buildings • Immediate health issues • Future health if student retain or lose adaptability to the natural climatic environment.

Table-1.1. Summary of articles about relation between performance of students and physical environment

number	Author	Subject	Aim/Purpose	Conclusion
5	Earthman, Glen I. October 2002	School Facility Conditions and Student Academic Achievement	Impact of school facilities on student Performance and teacher effectiveness.	School building design features and components (those impacting temperature, lighting, acoustics and age) have been proven to have a measurable influence upon student learning. Student attending schools in better condition outperform students in substandard buildings by several percentage points. Poor school facilities negatively impact teacher effectiveness and performance, and therefore students'. School overcrowding also makes it harder for students to learn; this effect is greater for students from families of low socioeconomic status. Class size reduction leads to higher student achievement.
6	EPA	Indoor Air Quality & Student's Performance	To find out how Indoor Air Quality affects a Child's Ability to Learn?	Managing potential IAQ hazards and maintaining the indoor environment quality of a school facility will assist students performance

1.2.1. Comfortable Indoor environment quality indicators

According to researches (table -1.1) the physical environment should provide a healthy, safe, and comfortable environment for its occupants. On one hand each of these achievements may urge different requirements for design of school building and focuses on different aspects of educational environment. And on the other hand, it seems that it is really difficult to make a clear distinction between them, since they might have some overlaps in some areas. For instance, a comfortable environment requires a good ventilated indoor air, which also essential for a healthy environment. This research would put emphasize on comfort and would attempt to provide a comfortable environment (from building technology viewpoint). So, it is needed to define the comfortable indicators of indoor environment quality.

The term comfort has a broad definition; however, when related to the indoor built environment it refers to a state of mind that expresses satisfaction with that environment. In the built environment domain different indicators of comfort are introduced, the holistic one introduces 8 sub-headings including [4]:

- Thermal comfort
- Visual Comfort
- Indoor air quality
- Acoustic comfort
- Green
- Water quality
- Vibration
- Electromagnetic fields

The first four of above mentioned comfort indicators are related to the building façade, which is the focus of this research. These indicators are related to each other and how building indoor environment is affected by each of them might influence other comfort indicators also. For example the amount of light entering the building which is one of aspects of visual comfort, also might influence the thermal comfort by heating the indoor environment. To be able to accomplish a detailed research within the frame work of this research, it is decided to focus on one of these comfort indicators, specifically visual comfort; however, the result of that is needed to be studied to examine how it affects other comfort indicators.

1.2.2. Visual comfort

Visual comfort can be defined as following:

"Generally, the function of lighting in a building can be subdivided in three domains; health, safety, visual performance, and aesthetics. First of all, the lighting of an area should be adequate to ensure that people can live safely, and it should not in itself be a health hazard. Assessment of the visual environment can provide information as whether or not these criteria are met. Second, the visual performance defines whether the lighting solution in a room is suitable for the performed task(s). Compliance to the standards is critical for the performance of the visual task and thus fulfilling the required activities. Third, aesthetics defines the positive effects of the lighting in a room upon human well-being, both psychologically and biologically. The lighting contributes to the users' well-being, has activating effects, and adapts to the desired luminance levels. The visual comfort has been characterized by seven performance indicators" [22]:

- Illuminance
- Discomfort glare
- Disability glare and reflections
- Uniformity and contrast
- Flicker
- Color aspects: color rendering and color temperature
- Daylight

Each performance indicator is dependent of the specific indicators or parameters. Moreover, guidelines and target values for each indicator or parameter are defined by the standards and regulations for lighting design, depending on the lighting tasks performed in the space. This research is focused on daylighting.

Table-1.2. Summary of literature study about Indicators of Comfort of indoor environment

number	Author	Subject	Aim/Purpose	Conclusion
1	PERFECTION	Coordination action for performance indicators for health, comfort and safety of the indoor environment	A coordination action for which the main objective is the development of a framework and a set of indicators concerning the overall quality of the indoor environment of buildings	Acoustic comfort Visual comfort Indoor air quality Quality of drinking water Thermal comfort.
2	Chiang, C. M. & Lai, C. M. 2002,	A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan	Presents the methodology of developing the comprehensive indicator for indoor-environment assessment. It intends to provide the occupants with the measures of indoor-environment quality	**Thermal Comfort** **Visual Comfort** **Indoor Air quality** **Acoustic comfort** Water quality Green Vibration Electromagnetic fields
3	Aries, M.B.C. & Zonneveldt, L. ,	Daylight and Comfort in the indoor environment	Visual comfort and its interaction with other comfort variables. In this respect, other comfort variables are acoustical comfort, thermal comfort, indoor air quality, ergonomic comfort, and psychosocial comfort.	Next to assessment of the physical parameters, take personal and environmental aspects such as **age, behavior, state of mind, prior experience, culture, frequency, duration, or timing** into account during comfort assessment Rank concept of the comfort scale: **Comfort, inconvenience, discomfort, unhealthy, illness**

1.3. Research Question

According to research goal, it seems that the main challenge of this research would be choosing consistent criteria façade system which can provide visual comfort for its users. To answer this main question of the research it is needed to answer a few sub questions. As a result, it seems that the main research question might be within a living façade concept for a school building:

Main Research Question

What are the characteristics of a living façade system for a school building which provides visual comfort?

- What are the lighting requirements of users?
- What are the contextual requirements?
- What are the requirements lighting design?
- Which façade system can meet the requirements of the program?
- What are the criteria of choosing appropriate daylighting systems?

1.4. Research method

The literature review chapter is divided in two main sections:

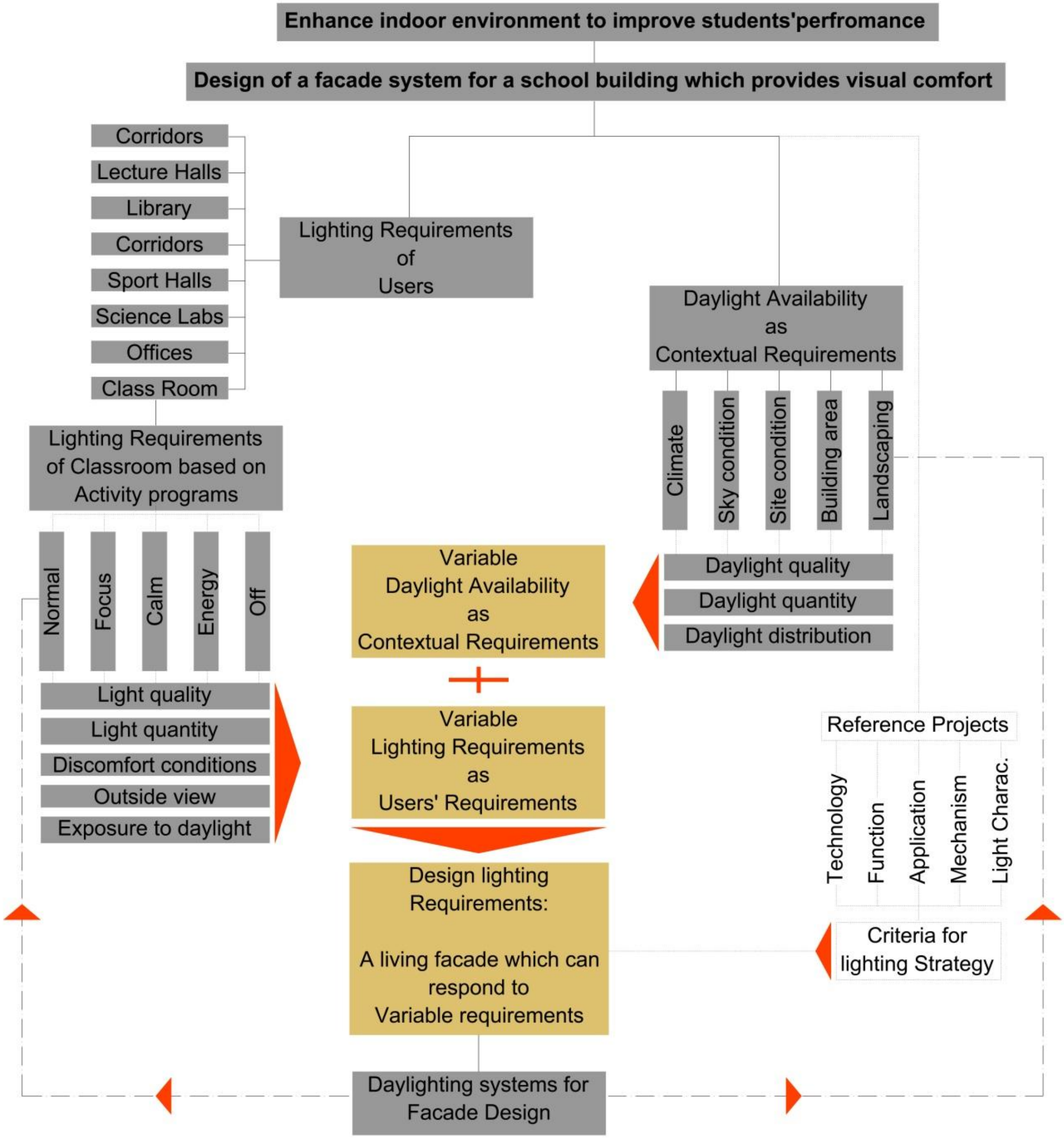
- **Users' requirements:** This part of research focuses on lighting characteristics and lighting requirements for different spaces in school. Since the lighting requirements for different spaces in school may differ from other spaces, the research is focused more on lighting requirements of classroom specifically. And by studying the quantitative and qualitative characteristics of lighting for classroom, determines lighting requirements.

- **Contextual requirements**: The contextual requirements which is mostly the availability of daylighting is studied.

- **Daylighting systems**: which different daylighting systems are studied to see which system can be used for façade design.

The outcome of these requirements has leaded to design requirements. This section is followed by study of several reference projects which have used different daylighting systems. By summarizing the characteristics of these projects some criteria are derived which based on the appropriate technical solutions of daylighting systems for façade are chosen later. This step is followed by Design process which involves the conceptualization, analysis, and implementation of different daylighting systems into façade. The aim is to design and conceptualize ideas for a new façade system, using existing technologies and techniques.

Figure-1.2. Research model and its sequential phases.



2. Literature review

2.1. Contextual requirements

Design of a physical environment which provides visual comfort using daylight is based on availability of daylight. However, the quality and quantity of daylight and its distribution direction, ratio between diffuse and direct light and color is constantly changing. All of these variations are the result of the position of the sun and the weather conditions. To have a clear idea about daylight availability it is needed to know daylight characteristics and how it changes through different situations. Generally, the daylight availability is based on several factors including [23]:

- Climate
- Sky Condition
- Site condition
- Building area
- Landscaping

These factors determine daylight **quality, quantity** and its **distribution** as following [23]:

- Sunlight or Skylight
- Daylight color Spectrum
- Sky luminance
- Daylight direction

2.1.1. Daylight components

Daylight has two main components [22]:

a) **Sunlight:** the directional beam emitted by the sun which is:

- Directional
- Piercing and very strong,
- Warmer in both temperature and color
- Gives shape to a building
- Need to control its direct penetration into critical visual task areas
- Spaces illuminated by the rays of eastern and western sunlight radically change on a daily, hour by hour basis and are extremely difficult to adapt for critical visual task environments.

b) **Skylight:** the diffuse reflection of light particles in the atmosphere which is:

- Can be diffuse light of the clear, cloudy, or overcast sky
- Can be similar in all orientations

- Is soft, cool in both temperature and color
- Spaces illuminated with diffuse southern sunlight change on a seasonal basis and are adaptable to critical visual tasks [22].

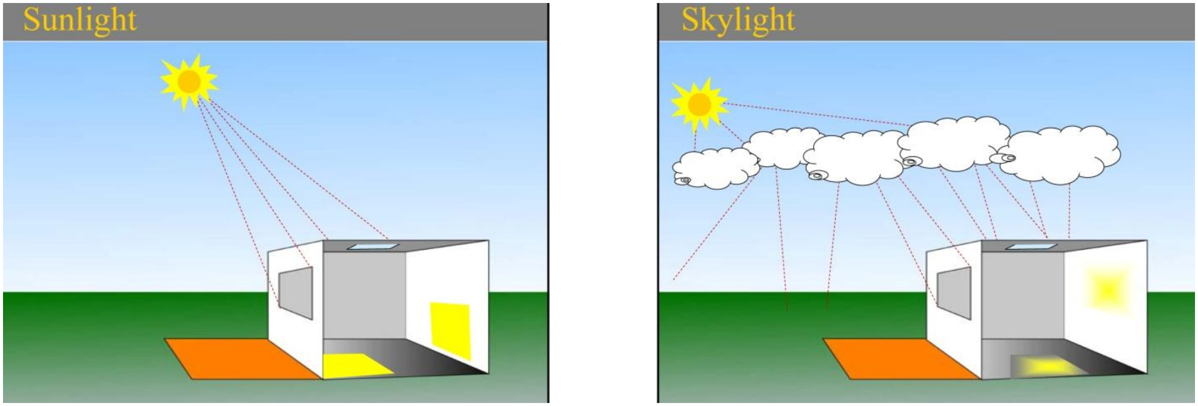


Figure-2.1. Difference between sunlight and skylight.

2.1.2. Daylight availability

Due to changes in availability of daylight by seasonal and day timing changes in sun position and also climatic changes, the contextual situation, which is based on the quality and quantity of daylight and its distribution, is not fixed. Therefore, it is needed to consider the application of designed cladding for classroom in different critical times of the year and day. To do so, it is suggested firstly, to analyze which characteristics of sunlight change through time, and then make decision about those critical times which are needed to be considered. To achieve that, those factors which may affect daylight availability will be investigated.

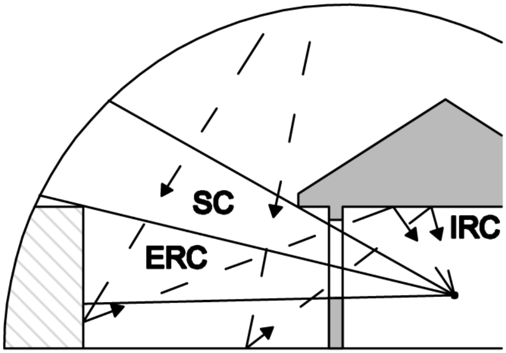


Figure-2.2. Sky Component, External Reflected Component, Internal Reflected Component

a) Climate

"Climate is related to the prevailing weather conditions including: temperature, humidity, precipitation, cloud cover, wind speed, and direction at a specific location or region. Since the corresponding data are different, these data are averaged over a period of time to calculate and predict probable expectations during a typical year. There are two different climate: macro-climate which is region specific, and micro-climate which is specific to a particular site or sub-area of a site. Climate is considered as essential guidelines for daylighting design of a building. Prevailing sky conditions set priorities for a response primarily to clear skies or to the overcast. Temperature ranges can help set priorities for aperture area and window glazing types. The relationship between sun position, sky conditions, and outdoor air temperature can help designers to decide when to provide solar shading or glare control inside or outside the building envelope" [23].

b) Sky condition

Generally, sky condition refers to the character of the sky at a particular point in time relative to percentage of cloud cover. This depends on sun position, weather, and atmospheric conditions including the presence of water vapor and other particulate in the atmosphere [23].

Cloud cover (CLD), sunshine hour (SH), clearness index (Kt) and diffuse fraction (K) are the four common climatic parameters indicating the prevailing sky conditions. The frequency of occurrence and cumulative frequency distribution of these four parameters determine the sky condition [23].

Table-2.1. Technically sky conditions are defined by percentage of cloud cover.

Sky Condition	Percentage of Cloud Cover
Clear	Less than 10%
Partly Cloudy	10-50%
Mostly Cloudy	50-90%
Overcast	Greater than 90%

The two primary sky types are clear skies and overcast. Clear skies allow for direct beam sunlight, cast sharp shadows, and generally produce levels of illumination from 50,000 to 200,000 Lux at horizontal unobstructed surface during daylight hours (depending on time and location). Distributions of light under clear skies are highly dependent on sun position and orientation. Overcast skies tend to deliver diffuse light, dominantly from overhead, and provide a range of 6,000 to 50,000 Lux at noon (depending on latitude), however illumination ranges can vary widely due to cloud density. Generally the brightest source of illumination under overcast skies is the zenith (directly overhead) [23].

c) Site condition

Site conditions refer to the specifics of a building site including: climate, prevailing sky conditions, landscape, and other specific constraints including the zoning envelope of a building. Key site conditions that influence daylight are solar exposure and sky conditions, and landscape, which includes site topography, vegetation, surrounding structures, and surfaces [23].

d) Building area

The buildable area of a site can have a significant impact on a daylighting design. Buildable area can be constrained by planning or zoning requirements which can limit the buildable area of a site in both the horizontal and vertical direction via height limits, setbacks, and other zoning envelope restrictions. Floor area ratio (FAR) requirements can limit the amount of gross square footage of a building. Height limits and setback requirements can have a substantial impact on a daylighting design. All of these issues shape building massing and therefore can influence daylight availability within a building [23].

e) Landscaping

"Common elements of landscape that influence patterns of diffuse daylight and skylight include topography, site surfaces and vegetation. Some of these elements such as topography remain static throughout the year, while others are dynamic and must be considered on a seasonal basis. Two examples of this include the change in ground reflectance during periods of snow cover, or variations in tree canopy density when a deciduous tree loses its leaves for the winter. Building landscape geometry and surface characteristics can dramatically shape the external reflected component of a daylight source. Obstructions such as; large trees, landforms on and around a building site can change both the character and intensity of daylight illumination at any given point within the site area" [23].

Figure-2.3. Left: before Right: after solar shading with vegetation at east façade of the Pierce Co. Environmental Services Building, Architect: The Miller Hull Partnership, 2003.

2.1.3. Daylight variation

a) Color Spectrum

Color temperature has been described most simply as a method of describing the color characteristics of light, usually either warm (yellowish) or cool (bluish), and measuring it in degrees of Kelvin (°K). Sunlight changes its color as it crosses the sky (or more accurately, as the Earth rotates in relation to it). At dawn & sunset the sun appears more reddish, due to the filtering nature of the denser atmospheric layer its rays are passing thru at that angle. It has a correlated color temperature of approximately 2000°K at sunrise/sunset, and 5600°K when directly overhead. The daylight color temperature ranges from sunrise to the middle of the day [3]:

3200 K	sunrise / sunset
5500 K	Normal daylight
	sunny day around 12 o'clock
6500-7500 K	cloudy sky dome
8000 K	misty sky dome
9000-12000 K	blue sky
20000 K	deep blue clear sky

Figure-2.4. Color Temperature ranges thru day.

b) Sky luminance

The so-called CIE overcast sky is the most common simplification for the brightness distribution of the sky under cloudy sky condition, even though it depends on the position on earth: Clear sky, Intermediate sky, Overcast sky, Uniform sky [28].

c) Daylight direction

Daylight direction is dependent on the geographical position on earth (latitude), and the orientation of building. Netherlands lies between latitudes 51 ° N and 53.5 ° N (and between 4 ° E and 7 "E). The sun path diagram shows some information about daylight availability in the Netherlands [20]:

- The sun reaches its highest position on the south and stands up about 62 degrees high in June at noon (that's 13.40 pm winter time and 12.40 pm summer time).
- In December, the sun reaches a maximum height of 15 degrees at 12.00 noon on the south.
- East and West mainly, have to deal with low solar energy, ranging between 0 and 30 degrees during the year. The north orientation receives direct sunlight, just from 23 March to 22 September at sun height of 0 - 30 degrees. At this sun height, the sun is parallel to the facade and sometimes solar energy enters inside the building.

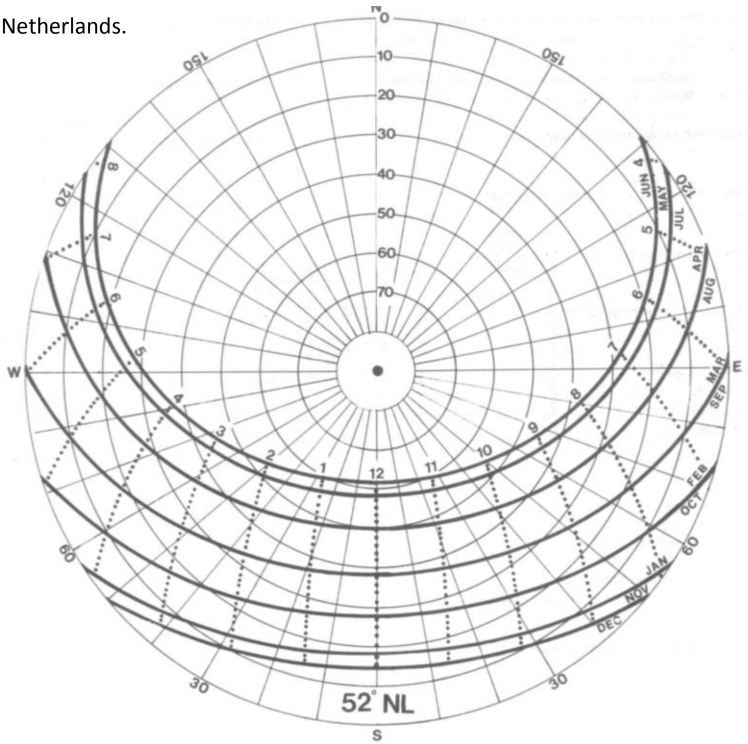


Figure-2.5. Sun path diagram in the Netherlands.

2.2. Users' Lighting Requirements

Since the demands of required lighting for different spaces within school buildings differ from each other (based on the different tasks' lighting requirements) daylighting design for each space should be done separately. This requires carefully study of task and occupants demands. In this research, the focus of designing of a façade system would be focused on classroom and related activities inside that space to provide desired visual comfort. Therefore, it is needed to define the activities in the classroom and users' requirements in detail. It is assumed that, this classroom would function as a classroom for an elementary school for students between ages of 7 to 11. The reason is that due to kind of education at these ages, students spend most of school time at school classroom and indoor spaces. And their activities include different kind of intellectual and physical activities which meets the requirements of this research.

2.2.1. Activity programs in the classroom

The main activities within a classroom are reading and writing (either on paper or on computer, either close or distant). However, these are not the only tasks done within a classroom. Student in classroom based on the time of the day, their program, and type of education perform different activities. For example they might be involved in group activities which requires active environment while they are discussing and doing physical activities during their courses. To have a clear understanding of all different kind of tasks and possible conditions inside the classroom, they are categorized in 4 main groups of activities which each of them consist of a scenario of tasks done and their requirements. As it is shown in the table-2.2 the lighting the need for lighting differs during each day according to task requirements [27].

Figure-2.6. The four different activity programs during school hours in the classroom proposed by Philips.

Table-2.2. Categorizing class activities regarding their need for daylighting

Activity category		Characteristics of lighting and requirements of tasks	Duration/Frequency of activity
Normal	How	Standard intensity + Standard color tone	Priority-1
	When	Normal Class lessons when need an average concentration level: • Subjects in world orientation and comprehensive reading • Instructions for all courses	The most frequent activity
	What	Reading and writing close and distant	Lasts for very long time
Focus	How	High intensity cool color tone	Priority-4
	When	when children perform a concentrated task or when the teacher believes that children need to be more concentrated: •Technical reading, arithmetic, grammar, spelling, Exams and tests	The least frequent activity
	What	Reading and writing close	Lasts for long time
Energy	How	Very High intensity + very cool color tone	Priority-2
	When	During moments Students are sleepy or find it hard to get concentrated: •The start of the day, After lunch break when concentration is required • At times that the students' concentration level declines	The 2nd. most frequent activity
	What	Relaxing, physical activities, communication	Lasts for long time
Calm	How	Standard intensity + warm color tone	Priority-3
	When	calm down a class and when children conduct collaborative or creative courses: • Calming when overactive, Creative, collaborative subjects, free tasks • Reading together • In breaks, after exams, Social time	The 3rd.most frequent activity
	What	Normal activities	Lasts for short time
Off	How	No daylighting	Priority-5
	When	Leaving the class, Watching video	The 5th.most frequent activity
	What	-	Lasts for long time

2.2.2. Lighting requirements of activity programs

To have a better idea about what are the characteristics of lighting for each category of class activity, they would be analyzed according to their demand for lighting and daylighting. It is needed to mention that most of references and directives introduce lighting norms and standards for education systems, provide the technical information for classrooms based on normal program. This is due to the fact that, mostly this technical information is based on space functions instead of activities. So, to achieve the lighting requirements the approach of research was based on searching for lighting requirements for classroom based on activity types. That is, based on the type of activity which is defined in the timing program in the classroom, the research looks for lighting requirements of that activity and assimilates the lighting requirements for that activity in the classroom.

It is needed to mention that some of these lighting qualities do not have a scaled measurement unit. For instance, about flicker or veiling reflection, it is hardly possible to fine any numeric information; most of references which discuss about these kinds of lighting qualities just introduce the importance degree of that lighting aspect based on the type of activity or space function. For example IESNA reference book, provides a scale of importance ranging from very important to less important. So, the approach of this research follows the same strategies about these lighting qualities. Moreover, about those lighting quality and quality aspects which are measured with numeric scales, different lighting guides introduce a range of requirements which may slightly differ from other references. This is partly because of the fact that this technical information is based on the visual comfort, which does not have a rigid status, and differs based on occupants' age, mental status, activity time, and other similar factors. To have the best and the most accurate technical information, several references were studies and compared together, and then an average result has been taken (technical data of table-2.4~7 have been taken from [8] and [14]).

Table 2-3. IESNA design guide provides a scale of importance ranging from very important to less important.

I. INTERIOR LOCATIONS AND TASKS	Very Important	Important	Somewhat important	Blank = Not important or not applicable																			
Design Issues	Appearance of Space and Luminaires	Color Appearance (and Color Contrast)	Daylighting Integration and Control	Direct Glare	Flicker (and Strobe)	Light Distribution on Surfaces	Light Distribution on Task Plane (Uniformity)	Luminances of Room Surfaces	Modeling of Faces or Objects	Point(s) of Interest	Reflected Glare	Shadows	Source/Task/Eye Geometry	Sparkle/Desirable Reflected Highlights	Surface Characteristics	System Control and Flexibility	Special Considerations	Notes on Special Considerations	Illuminance (Horizontal)	Category or Value (lux)	Illuminance (Vertical)	Category or Value (lux)	Notes on Illuminance - see end of section	Reference Chapter(s)

a) Category-1: Normal program

This program is the most dominant occurring program during school hours. The major task is reading and writing both in near and far distance. High illuminance, both horizontal and vertical uniformity are required. Moreover, discomfort conditions must be limited. That is, there must be as less glare, flicker, shadow and veiling reflection as possible to avoid distracting students. Since, this program occupies most of school time, it is essential to provide day lighting to some extent to get benefits of day lighting both on its environmental and health effect. Color rendering and contrast must be kept at the normal standard, which requires normal rendering for all colors and 3D objects must be rendered thoroughly. Plus, since this program lasts for long run, view should not be obstructed completely, providing controlled view can prevent students from being fatigued.

Table-2.4 Activity category- **Normal:** lighting requirements

Visual comfort conditions	**Lighting quantity**	Illuminance	350 LUX
		Reflectance	Walls: 40-60% Ceiling: 70-90% Floor: 30-50 % Board: up to 20%
		Luminance ratio	1/2 X<Luminance ration<3X X= Task luminance
	Lighting quality	Color rendering	Minimum of 80
		Color contrast	Minimum 7:1
		Source/Task/Eye geometry	Eliminate glare, shadow see figure 4.6
		Modeling of face or objects	combination of diffuse and directional light
		Vertical illuminance	Very important
		Horizontal illuminance	Very important
		Light distribution on Surface Uniformity ratio	0.9
		Light distribution on Task plane Uniformity ratio	0.9
		Reflected Glare	X<0.3 X=Ratio illuminance on task from the mirror angle /total illuminance on the task
		Direct Glare	
	Discomfort conditions	Flicker	Eliminated completely
		Limiting Glare rating	19
		Shadows	Eliminated completely
		Veiling reflection	Eliminated completely
	Visual privacy	Outside view	Controlled view
Health	**Need of exposure to day lighting**		Normal need to be exposed to day lighting-Grade3

b) Category-2: Focus program:

During focus program, the prominent task is reading and writing in close distance. Most of lighting requirements are similar to normal program; however, since students need high focus and concentration, more illuminance is required compared to normal program and less discomfort conditions can be tolerated. That is, flicker, glare, shadows and veiling reflections must be eliminated completely. It is recommended to use electrical lighting which is more controllable and can provide more horizontal luminance and task surface uniformity. Moreover, it is less crucial for students to be exposed to daylight during this program. Color rendering and contrast must be kept at the normal standard, which requires normal rendering for all colors and 3D objects must be rendered thoroughly. Also, it is recommended to use cool color tone which provides more concentration. Outside view, can be obstructed to prevent student from distracting.

Table-2.5 Activity category- **Focus:** lighting requirements

Visual comfort condition	**Lighting quantity**	Illuminance	500 LUX
		Reflectance	Walls: 40-60% Ceiling: 70-90% Floor: 30-50 % Board: up to 20%
		Luminance ratio	1/2 X<Luminance ration<3 X X= Task luminance
	Lighting quality	Color rendering	>80
		Color contrast	Minimum 7:1
		Source/Task/Eye geometry	Eliminate glare, shadow see figure 4.6
		Modeling of face or objects	combination of diffuse and directional light
		Vertical illuminance	Important
		Horizontal illuminance	Very important
		Light distribution on Surface Uniformity ratio	Not less than 0.8
		Light distribution on Task plane Uniformity ratio	0.9
		Reflected Glare	X<0.3 X=Ratio illuminance on task from the mirror angle /total illuminance on the task
		Direct Glare	
	Discomfort conditions	Flicker	Eliminated completely
		Limiting Glare rating	19
		Shadows	Eliminated completely
		Veiling reflection	Eliminated completely
	Visual privacy	Outside view	Highly controlled view
Health	**Need of exposure to day lighting**		No need to be exposed to day lighting - Grade4

c) Category-3: Energy program:

This program occurs during moments Students are a bit sleepy or find it hard to concentrate, the start of the day and during lunch. Therefore, in contrast other programs, this program has got determined occurring time. It is expected that students gather energy to start course hours after these times. Since no serious task is done during this program, lighting situation can be flexible. Students relax, communicate and do physical and social activities during these times, and wider range of discomfort conditions can be tolerated. Although their activity might need less intense illuminance compared to all other programs, they illuminance should be higher to help them boost their mood and energy. So, being exposed to direct day light is essential due to its direct effect of students' alertness and health. Regarding low concentration and focus need, it is recommended to provide outside view openly to remove students' fatigue.

Table-2.6 Activity category- **Energy:** lighting requirements

Visual comfort conditions	**Lighting quantity**	Illuminance	500 LUX
		Reflectance	Walls: 40-60% Ceiling: 70-90% Floor: 30-50 % Board: up to 20%
		Luminance ratio	1/3X<Luminance ration<5X X= Task luminance
	Lighting quality	Color rendering	>90
		Color contrast	Minimum 9:1
		Source/Task/Eye geometry	Eliminate glare, shadow see figure 4.6
		Modeling of face or objects	combination of diffuse and directional light
		Vertical illuminance	Important
		Horizontal illuminance	Normal
		Light distribution on Surface Uniformity ratio	Minimum 0.8
		Light distribution on Task plane Uniformity ratio	0.8
		Reflected Glare	X<0.3 X=Ratio illuminance on task from the mirror angle /total illuminance on the task
		Direct Glare	
	Discomfort conditions	Flicker	Limited rate accepted
		Limiting Glare rating	19
		Shadows	Limited rate accepted
		Veiling reflection	Limited rate accepted
	Visual privacy	Outside view	Completely open view
Health	**Need of exposure to day lighting**		High need to be exposed to day lighting-Grade1

d) Category-4: Calm program:

During calm program, which occurs frequently but shortly, between normal programs, students do communicate with each other, do practical assignments or take short breaks. Students need less focus and concentration, as a result required illuminance is less than normal program and more discomfort conditions can be tolerated. That is, flicker, glare, shadows and veiling reflections can be tolerated to some extend which does not cause any discomfort and still is in comfort situation range. Horizontal and vertical luminance has the same importance, and color rendering and 3D object recognition is highly required since students are involved in activities which require them to interact with other students and objects. Moreover, they need to be exposed to daylight more and warm color tones must be used. Also, outside view may be provided to some extent.

Table-2.7 Activity category- **Calm:** lighting requirements

Visual comfort conditions	**Lighting quantity**	Illuminance	300 LUX
		Reflectance	Walls: 40-60 % Ceiling: 70-90% Floor: 30-50 % Board: up to 20%
		Luminance ratio	1/3X<Luminance ration<5X X= Task luminance
	Lighting quality	Color rendering	>80
		Color contrast	Minimum 9:1
		Source/Task/Eye geometry	Eliminate glare, shadow see figure 4.6
		Modeling of face or objects	combination of diffuse and directional light
		Vertical illuminance	Normal
		Horizontal illuminance	Normal
		Light distribution on Surface Uniformity ratio	0.8
		Light distribution on Task plane Uniformity ratio	0.8
		Reflected Glare	X<0.3 X=Ratio illuminance on task from the mirror angle /total illuminance on the task
		Direct Glare	
	Discomfort conditions	Flicker	Limited rate accepted
		Limiting Glare rating	19
		Shadows	Limited rate accepted
		Veiling reflection	Limited rate accepted
	Visual privacy	Outside view	Open view
Health	**Need of exposure to day lighting**		Need to be exposed to day lighting-Grade2

2.2.3. Analysis of Lighting requirements of activity programs

Now that there is a clear idea about lighting requirements of each activity program, it is needed to translate these requirements to design strategies and executive solutions. This can be achieved through knowing the characteristics of daylighting and electrical lighting and their effect on visual activities, which was discussed earlier in this chapter. It is needed to mention that visual comfort includes both daylighting and electrical lighting, so in this part the role and effect of each lighting category would be discussed. Especially it is crucial to notice that in a successful design these categories should be integrated together, in a way which can provide uniformity. However, since this research is going to focus on daylighting aspect, detailed electrical lighting design would not be discussed here.

a) Category-1: Normal program

- Combination of electrical lighting and daylighting is needed. It is recommended to provide as much required lighting as possible by using daylighting. However, it is obvious that due to seasonal and climatic situations it might not possible to answer all lighting requirements just by daylighting, as a result, electrical lighting must be designed as supplementary lighting to fulfill all the requirements.
- Since high uniformity ratio both on surface and task plane is required, it is important to choose appropriate daylighting strategy, regarding to using correct position (skylight or sidelight) system of daylighting (uni-lateral or bilateral). Additional task plane luminance might be provided by using sky-lighting.
- Day lighting must be controlled to eliminate probable discomfort aspects of daylighting including; glare, shadows, veiling reflection. Absence of flicker in Daylighting is a strong point; however, it must be noticed to control flicker in electrical lighting also.
- Since daylighting provides good color contrast, 3D object rendering and color rendering, these requirements would be met by providing enough daylighting. And design of electrical lighting must meet this requirement so that it does not affect color rendering, color contrast in negative way.
- Required Standard color tone may be achieved by daylighting and its natural light spectrum.
- It is recommended to provide controlled outside view (The outside scene which classrooms are going to face must be considered in school design so that avoid placing classrooms to views which might distract their attention). This view does not need to be complete open view.

b) Category-2: Focus program

- Similar to category-1 combination of electrical lighting and daylighting is needed; however it must be noted that electrical lighting has got more role in this program. Because task plane uniformity and horizontal luminance ration has got more importance here, and these are characteristics which can be provided by electrical lighting. Moreover, it must be noted that in contrast to normal program which occurs every day on a scheduled program, focus program occurs by teacher decisions. Since it does not last for so long time, daylighting may be limited during this program and electrical lighting may be replaced instead to take advantage of its controllable lighting characteristics.
- Considering very high uniformity ratio on task plane and high horizontal illuminance, in design of daylighting strategy attention should be paid to choose correct position (skylight or sidelight) and system of daylighting (uni-lateral or bilateral).
- Both Day lighting and electrical lighting must be controlled restrict-ly to eliminate all discomfort aspects of daylighting including; glare, shadows, veiling reflection and flicker. It must be mentioned that due to activity characteristics the least discomfort situation may be tolerated during this program.
- Required cool color tone may be achieved by electrical lighting.
- Since daylighting has got less importance in this program and major part of lighting would be provided by electrical lighting, careful attention should be paid to enough color contrast, 3D object rendering and color rendering. Also, use of indirect controlled day lighting may provide desired lighting.
- It is recommended to limit outside view to prevent distractions and interruptions.

c) Category-3: Energy program

- Happening in two specific parts of day time (early in the morning and during lunch break), with high demand of being exposed to daylight, makes day lighting as very important of lighting source for this program. In sever situations when present daylighting does not meet the needs of the program electrical lighting with similar characteristics to natural daylighting must be available to compensate the lack of enough day lighting.
- Regarding lower uniformity ratio requirements both on task plane and surface, and on the other hand higher presence of daylighting , which provides good uniformity on all surfaces, position (skylight or sidelight) and system of daylighting (uni-lateral or bilateral) can accept wider possible options.

- Having high tolerance to discomfort situations, these situations can be tolerated to some extent. That is, filtered shadows are acceptable; however, glare and veiling reflection must be studied thoroughly, since high amount of them still might cause discomfort. As, daylighting is major lighting source, so flicker will not be an important problem to deal with.
- Regarding very high importance of good color contrast, 3D object rendering and color rendering, which are essential for physical and social activities, it is expected that this characteristics would be achieved by devised daylighting.
- Required very cool color tone may be achieved using supplementary limited electrical lighting.
- Outside view may be provided openly without any restriction.

d) Category-4: Calm program

- Occurring between courses or as short breaks this program requires more daylighting than normal program. Regarding less luminance demand, it is possible to switch off electrical lighting or dim them, and increase daylighting.
- Having more daylight in the classroom compared to focus and normal program, while highly controlled lighting situation is required, it is crucial to use correct position (skylight or sidelight) and system of daylighting (uni-lateral or bilateral).
- Discomfort situations must be kept within the same level for normal program. However, since activities require less concentration, low contrast filtered shadows might be acceptable. Still careful attention should be paid to glare and veiling reflection.
- Like energy program, calm situation requires good color contrast, color rendering and 3D object rendering, which can be achieved by provided amount of daylighting.
- Less controlled outside view is recommended.

2.2.4. Variation of Users' lighting requirements

According to analysis of lighting requirements of timing program it might be concluded that:

I. Despite some similarities, the timing programs which are based on the type of activities in the classroom have got different lighting quality and quantity requirements and outside view demands.

a) Different lighting aspects:

- Illuminance rate is among one of critical factors which changes from one program to another. The need for illuminance decreases through energy, focus, normal, calm program.
- Luminance ration is among those factors which depend on type of activities. That is in energy and calm program which students do not need much focus, they can accept wider range of luminance ratio on different surfaces. In contrast, during normal and focus program, which students need high concentration, the luminance ration should not differ a lot to prevent their eye from major adjustments to light which might cause eye fatigue.
- Source/task/eye geometry depending on position of task and its changes over task time differs in focus and normal program, with energy and calm program. In the first group since students take seated and still situation, the source direction and angle can be designed according to predictable eye/task geometry. However, in energy and calm program which students take movements and the visual direction changes constantly, light source should be designed according that.
- Modeling of face or objects (3D rendering) in calm and energy program is more important than two other programs, which means that those energy and calm program combination of diffuse and directional light is more critical.
- Horizontal luminance and Light distribution on Task plane uniformity ratio in focus and normal program should be higher. Meanwhile during energy and calm program luminance for vertical and horizontal surfaces and uniformity ration are almost similar.
- Need for outside views in programs with less concentration (energy and calm) are higher than others.

- Need for exposure to daylight depends on the type and the duration of program. That is during energy and calm program students may be exposed to more daylight for short periods, while during normal and focus program they might be exposed to less daylight for a longer period. Focus program does not require exposure to daylight since its frequency is not so often.

b) Similar lighting aspects:

- Reflectance ratio, does not differ that much.
- Color rendering, color contrast requirements is almost the same timing programs.

- Discomfort conditions including veiling reflection, glare, and flicker should be controlled carefully during all programs. However, in programs which require less focus, slight shadows are acceptable.

II. The frequency and duration of each timing program is different, which means that the requirements of lighting quality and quantity changes over school time in the classroom.

III. Lighting quality and quantity requirements during different timing programs, do contradict each other in some cases, while they do accent each other in some cases. For instance, focus program which requires high illuminance, needs controlled outside view and less exposure to daylight. That is, lighting strategy should take into account all those opposite requirements while sometimes there are similar requirements.

IV. Lighting of the classroom needs different lighting sources. In other words, considering type of activities and availability of daylight (regarding to the time of the day, season, location of the building, end etc.) either electrical or day lighting (or combination of both of them) might be required. That is, for some programs one of these lighting sources might be enough, like energy program which seems that daylight can provide most of lighting requirements. While for other programs, like focus program, it seems that combination of daylight and electrical lighting might be required. This is because of the fact that, daylight cannot meet all the lighting requirements of that program.

2.3. Daylighting systems and strategies

2.3.1. Daylighting systems

Daylighting systems can be defined as following:

"A daylighting system combines simple glazing with some other element that enhances the delivery or control of light into a space" [10].

Daylighting systems have three major functions: Solar shading, Protection from glare, Redirection of daylight. Windows need protection from glare and solar shading in order to create acceptable interior conditions. The redirection of daylight can save energy but is not an indispensable function. The view to the outside is not a function of a daylighting system but a primary function of the window itself; the impact of daylighting systems on the view to the outside needs to be considered carefully. There are two major categories of daylighting systems [6]:

a) Daylighting Systems With Shading

Two types of daylighting systems with shading are covered: systems that rely primarily on diffuse skylight and reject direct sunlight, and systems that use primarily direct sunlight, sending it onto the ceiling or to locations above eye height. Conventional solar shading systems, such as pull-down shades, often significantly reduce the admission of daylight to a room. To increase daylight while providing shading, advanced systems have been developed that both protect the area near the window from direct sunlight and send direct and/or diffuse daylight into the interior of the room[6].

b) Daylighting Systems Without Shading

Daylighting systems without shading are designed primarily to redirect daylight to areas away from a window or skylight opening. They may or may not block direct sunlight. These systems can be divided into four categories [6]:

- **Diffuse light-guiding systems**

Redirect daylight from specific areas of the sky vault to the interior of the room. Under overcast sky conditions, the area around the sky zenith is much brighter (around three times) than the area close to the horizon. For sites with tall external obstructions (typical in dense urban environments), the upper portion of the sky may be the only source of daylight. Light-guiding systems can improve daylight utilization in these situations [6].

- **Direct light-guiding systems**

Send direct sunlight to the interior of the room without the secondary effects of glare and overheating [6].

- **Light-scattering or diffusing systems**

They are used in sky-light or top-light apertures to produce even daylight distribution. If these systems are used in vertical window apertures, serious glare will result [6].

- **Light transport systems**

Collect and transport sunlight over long distances to the core of a building via fiber-optics or light pipes.

Based on the building conditions and daylight availability, required daylighting might be provided using side-light or top-light. Each of daylighting systems might be used alone or alongside other systems. However, using appropriate side-light and top-light systems together can provide, even and better light distribution in the space. Moreover, since top-light can provide daylighting from brightest zone of the sky, it is the only way to get daylighting in conditions when there is not enough daylight (for example in overcast situation).

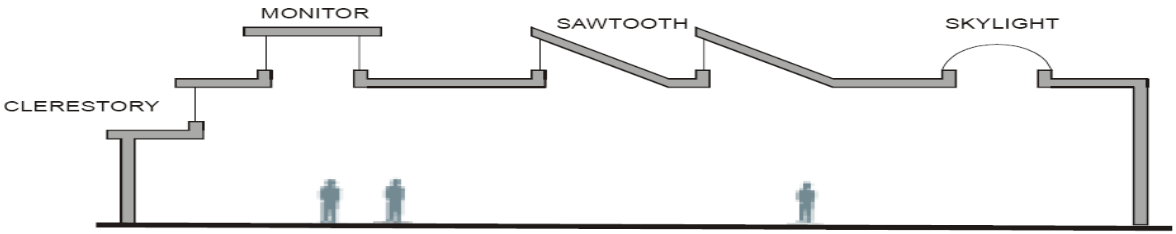


Figure-2.7. Examples of different top-light daylighting systems.

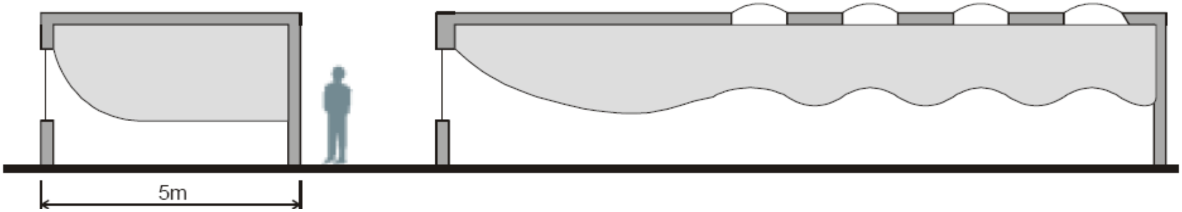


Figure-2.8. Use of top-light in combination to side-light, contributes to better and even light distribution.

2.3.2. Strategies for different light conditions

a) Strategies for Skylight

Strategies for diffuse skylight apply for either clear or cloudy skies. However, dealing with direct sunlight is the most significant characteristic of them. In all facades except north façade solar shading always is an issue for daylighting. Solar shading is a thermal function that primarily protects from direct sunlight, while glare protection is a visual function that moderates high luminance in the visual field. Although solar shading and glare protection are different functions that require individual design consideration, in situations which solar shading is not critical, a system to protect from glare can be applied for solar shading as well. Systems to protect from glare address not only direct sunlight but skylight and reflected sunlight as well [6].

b) Strategies for Cloudy Skies

To distribute skylight to interior spaces leads to windows which are relatively large and located high on the walls. Although, large openings can be a weak point, since under sunny condition they may cause overheating and glare. As a result, protecting from glare and sun shading are critical parts of these systems. Usually moveable or other innovative daylighting systems are applied to compensate decreasing daylight levels under overcast sky conditions or to control sunlight to some extent. Although the application of simple architectural measures may be an opportunity to enhance daylight penetration, the design of the window is the most influential factor on the performance of this type of strategy under cloudy conditions [6].

c) Strategies for Clear Skies

Shading of direct sunlight is part of the continuous operating mode of this strategy. Openings for clear sky strategies do not need to be sized for the low daylight levels of overcast skies. Shading systems that allow the window to depend primarily on diffuse skylight are applicable [6].

d) Direct Sunlight

Since sunlight is a parallel source, direct sunlight can be easily guided and piped. Optical systems for direct light guiding and systems for light transport are applicable in this case. Because beam daylighting requires only small apertures, it can be applied as an added strategy in an approach that otherwise focuses on cloudy skies [6].

2.3.3. Strategies for fenestration

Due to limited ability of facades to distribute daylight to deep space, especially under cloudy skies, appropriate fenestration strategy should be decided regarding using side-lighting or top-lighting, unilateral or multilateral daylighting strategies. A heterogeneous design makes it possible to apply different daylighting systems to different parts of the window, or similar systems may be operated separately for different areas of the window. Here are a summary of fenestration strategies [16]:

- **Increase exposure to daylight:** This can be achieved by North and south exposure to daylight. Also higher Skin to volume ratio can increase provides greater the percentage of floor space available for daylighting. However, it should be noted that larger windows require more control, so glazing selection and shading effectiveness should be considered carefully.

- **Take a deep facade approach:** A facade with some depth which has got shading elements creates a buffer zone that can filter glare and block sun.

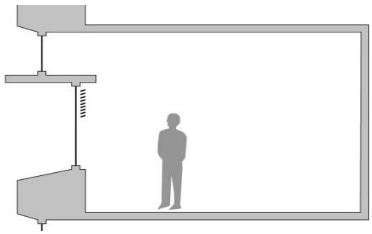


Figure-2.9. Deep wall section provides self-shading, allows easy integration of light shelf, creates surfaces that reduces glare.

- **Use separate apertures for view and daylight:** By separation of view and light windows, it is possible to use high transmission, clearer glazing in clerestory windows, and lower transmission glazing in view windows to control glare.

- **Keep private rooms somewhat shallow:** It is recommended to keep the Keep depth of rooms within 1.5-2.0 times window head height for sufficient illumination levels and balanced distribution.

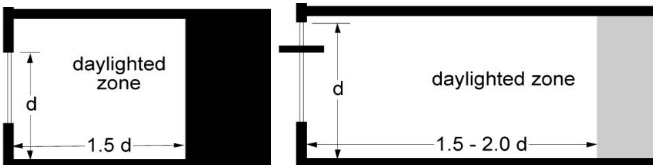


Figure-2.10. Use of light shelf can increase daylight transmission up to 2 times of window head height.

- **The higher the window, the deeper the daylighting zone**: Higher window head and using techniques like light shelves, can increase depth of a delighted zone up to 2.5 times the window head height.

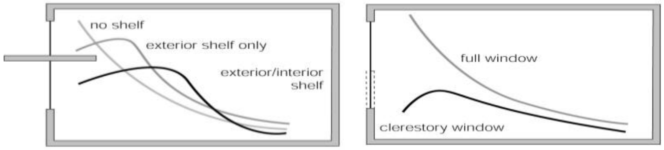


Figure-2.11. High windows provide better distribution. And light shelf improves distribution of daylight.

- **Strip windows provide more uniform daylight**. Continuous strip window can provide adequate, even daylighting, while the breaks between punched windows can create contrasts of light and dark areas.

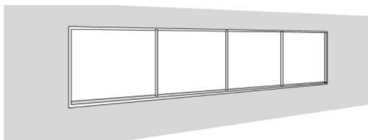


Figure-2.12. Strip windows are an easy way for uniform daylighting.

3. Reference project

In this chapter a number of projects have been studied and the used daylighting systems are analyzed to get the required criteria for assessment of daylighting systems. It is needed to mention that, in some cases the reference projects have been failed to response the program lighting requirements and specially from visual comfort view point some of them have got critical disadvantages; however, the purpose is to analyze these weak points and gat lessons from the to be considered for this research design purpose.

3.1. Reference Projects Data

3.1.1. Arab world Institute (1987)

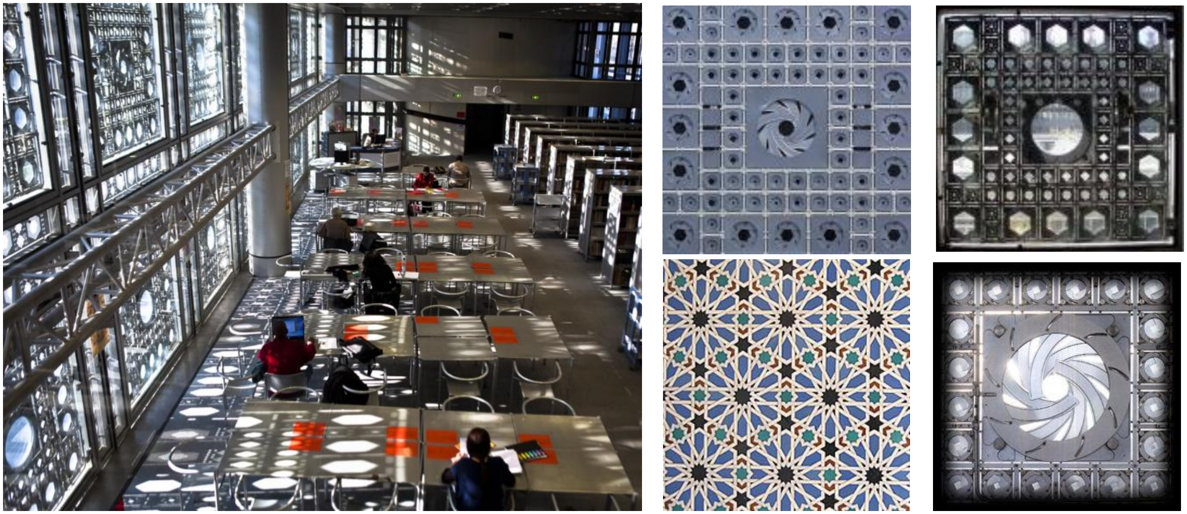


Figure-3.1. Adjustable photoelectric cells of Façade elements which can be adapted according daylight availability.

Country	France, Paris
Climate	Temperate: Typical Western European, Oceanic climate
Architect	Jean Nouvel
Function	Cultural center, mixed use
System	Operable shutter system

Construction System	Frame, glass curtain wall
Context	Urban plaza, near river
Application	Southern façade/ Vertical
Possible application	Façades, Vertical, Exterior
Concept	The building reinforces archetypal elements of traditional Arabic architecture: the interior, the treatment of light and filters through racks and overlapping frames. The southern front is the best example of this dual loyalty because it reinterprets a number of commonly used geometric figures in the Arab culture, giving them a contemporary form of mobile lenses, very similar to those of a camera.
Façade Technology	The most interesting windows are those of the IMA south facade. The size and shape of the crystals is exactly like the facade of the north, but in this case, each glass square has a number of photoelectric cells similar to a camera lens that open outside receive less light and vice versa. In each window there is a central photo detector larger than the rest, and smaller, of two different sizes, geometrically arranged in the glass. The opening and closing of these elements gives rise to a shape very similar to those found in the decoration of Arab buildings and was very well received by the Arab owners of the institute. Above the glass-clad storefront, a metallic screen unfolds with moving geometric motifs. The motifs are actually 240 motor-controlled apertures, which open and close every hour. They act as brise (Breeze) soleil to control the light entering the building.
Characteristics	Kinetic architecture Climate oriented strategy Filtered lighting

3.1.2. Simons Center, SUNY Stony Brook (2010)

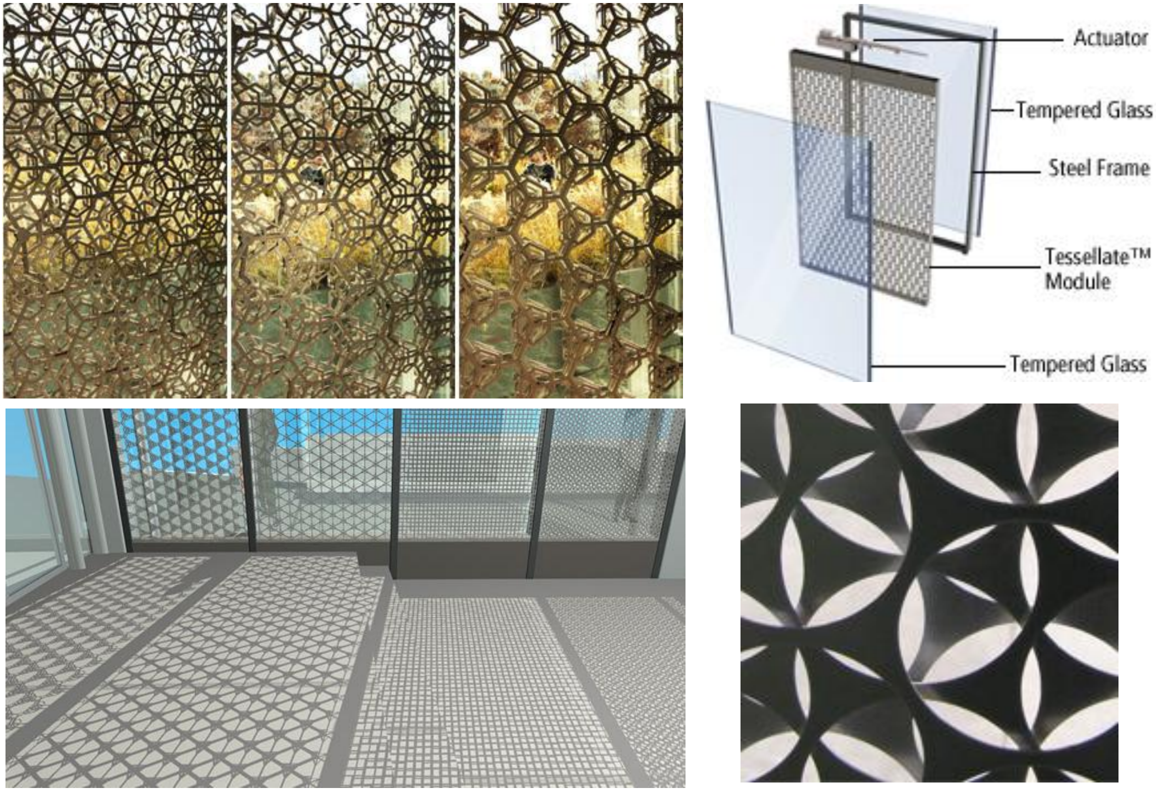


Figure-3.2. Perforated patterns of Tessellate surface modules.

Country	USA/ NY
Climate	Humid subtropical climate
Architect	Perkins Eastman
Function	State University of New York
System	Tessellate: Continually evolving surface, pattern and opacity
Construction System	Adaptive Shading Coverage: 38 sq. meters Material: Waterjet-cut stainless steel, glass

Dimensions: 5.6m Wide x 6.7m Tall

Context	Campus, Center for Geometry and Physics
Application	Southern façade / Vertical
Possible applications	Façades, roofs, awnings Vertical / Horizontal Exterior / Interior / Integrated into glazing
Concept	Tessellate surface modules are self-contained, framed screens with perforated patterns that can continually shift and evolve; they create a dynamic architectural element that regulates light and solar gain, ventilation and airflow, privacy, and views. Tessellat consists of a series of stacked panels that can be constructed of various metals or plastics. As these layers overlap, the result is a kaleidoscopic visual display of patterns aligning and then diverging into a fine, light-diffusing mesh.
Façade Technology	As these patterns align and diverge, the visual effect is of sparse geometric patterns—hexagons, circles, square, and triangles—that blossom into an opaque mesh. The result is a kinetic surface that spans 38 square meters and imbues the building with the functional capacity to dynamically change its opacity. Each Tessellate module runs on a single motor. These modules are controlled by a single computer processor, which can be programmed for various purposes.
Characteristics	Fully variable shading control, Reduced solar gain and glare Privacy control Ventilation and airflow control

3.1.3. POLA Ginza building façade, Tokyo, Japan (2009)

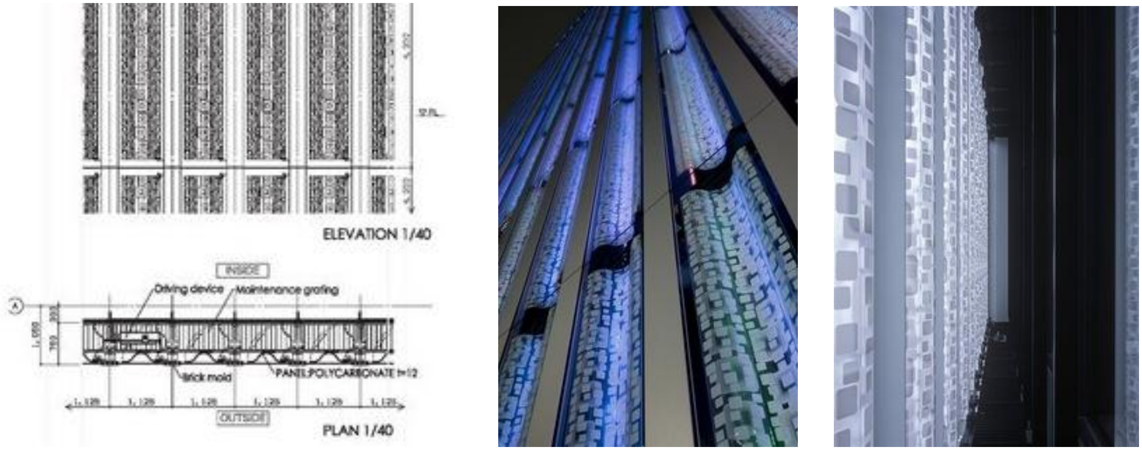


Figure-3.3. Double glazing façade with kinetic panels

Country	Japan, Tokyo
Climate	Humid subtropical climate
Architect	Nikken Sekkei + Yasuda Atelier
Function	Shopping
System	Double glazing façade with kinetic panels
Construction System	Adaptive Shading Coverage: 500 sq. meters Number of operable units: 185 Material: Acrylic
Context	District with accumulation of International super brands
Application	Southern Facade
Possible applications	Façades, Vertical Exterior / Integrated into glazing

Concept

This double glazing façade with kinetic panels has not only the attractive effect toward the Ginza street but also the ecological effect to decrease the thermal disturbance for the building itself. In summer, kinetic panels receive the sunlight and heated air is discharged from the top by its chimney effect. They improve the effect of sun cut and minimize the interior thermal disturbance. For this purpose, windows were put at the top and openings at the bottom. The window of the top opens and closes automatically in accordance with the temperature inside the double grazing. In winter, the warmed air inside the double glazing works as insulation by closing the top windows. Natural fresh air can be taken in the middle floor by opening the inner sash in spring and autumn. It actualizes comfortable work space without using HVAC equipment. The calculation shows this double glazing system reduces its annual consumption of HVAC energy by 30% compared with the single curtain wall system. The kinetic panels also defuse the sunlight to bring in light deeper inside. By installing the daylight sensor, energy for the artificial lighting is automatically cut back.

Façade Technology

The 14-story building has 185 shutter mechanisms that are housed within the double glazing of the façade. Each shutter has dimensions of approximately one by three meters, and is made of an acrylic sheet that has been formed into a curved surface.

The kinetic panels, having variety of scaled patterns that remind us of an image of the cells of life, change their appearance like a breathing life by the mechanical and luminous movement.

They are operated in maximum 14 panels a group by the automatic hinges placed on their tops and the horizontal shaft with rollers that push the panels along their curved profile. Panels and the shaft are not connect directly each other but related indirectly so that the panels move in a deferent timing gradually and escape from the different movement caused by the possible severe earthquake.

Characteristics

Ecological effect to decrease the thermal disturbance

3.1.4. AHHAA Science Centre | Tartu, Estonia (2011)

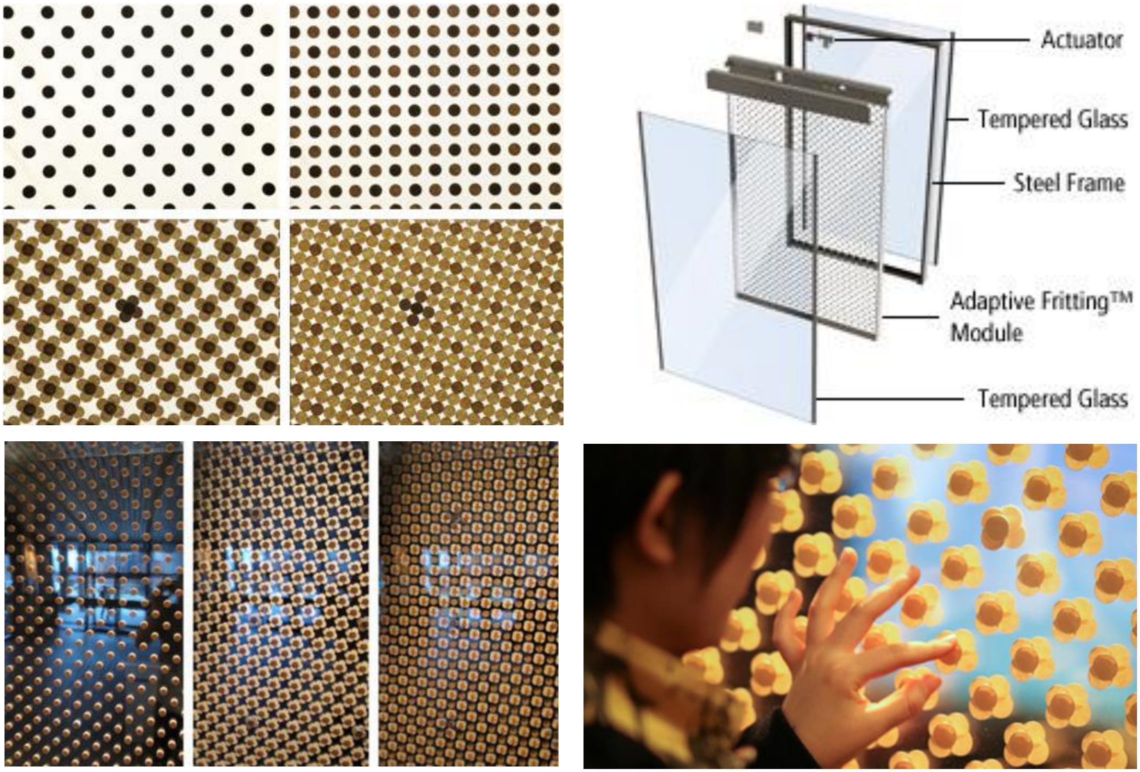


Figure-3.4. The glass panels with pattern that moves and changes to control heat gain and light.

Country	Estonia, Tartu
Climate	Temperate seasonal climate
Function	Conference room
System	Adaptive fritting
Construction System	8.6 sq. meters of adaptive surfaces Dimensions: 3.6m x 2.4m Materials: Acrylic, Aluminum Control System: Each panel driven by a servo motor with custom array control

Number of operable units: 3

Context — A glass conference room wall with adjustable opacity

Application — Interior space divider

Possible applications

Vertical façades

Integrated into glazing (IGU)

Interior space dividers

Concept — The glass panels employ a pattern that moves and changes to control heat gain and light while still allowing transparency for the viewing in and out.

Façade Technology — Adaptive Fritting is an integrated glass unit with a custom moveable graphic pattern that can modulate its transparency to control transmitted light, solar gain, privacy, and views.

While conventional fritting relies on a fixed pattern, Adaptive Fritting can control its transparency and modulate between opaque and transparent states. This performance is achieved by shifting a series of fritted glass layers so that the graphic pattern alternately aligns and diverges. Glass fritting is an established architectural treatment for passive solar control; Adaptive Fritting imbues this treatment with the expanded functionality of movement.

This system offers opportunity for complete design flexibility and architectural integration. Panels can be composed of fritted glass or plastics, at scales ranging from .5 to 3 meters. Patterning options are infinite: geometric grids, color variations and images, non-uniform fields or gradients, even organic and non-repeating patterns are possible.

Characteristics

Fully variable shading control

Reduced solar gain and glare

Privacy control

3.1.5. Adaptive Shading Esplanade, Building center Trust (2010)

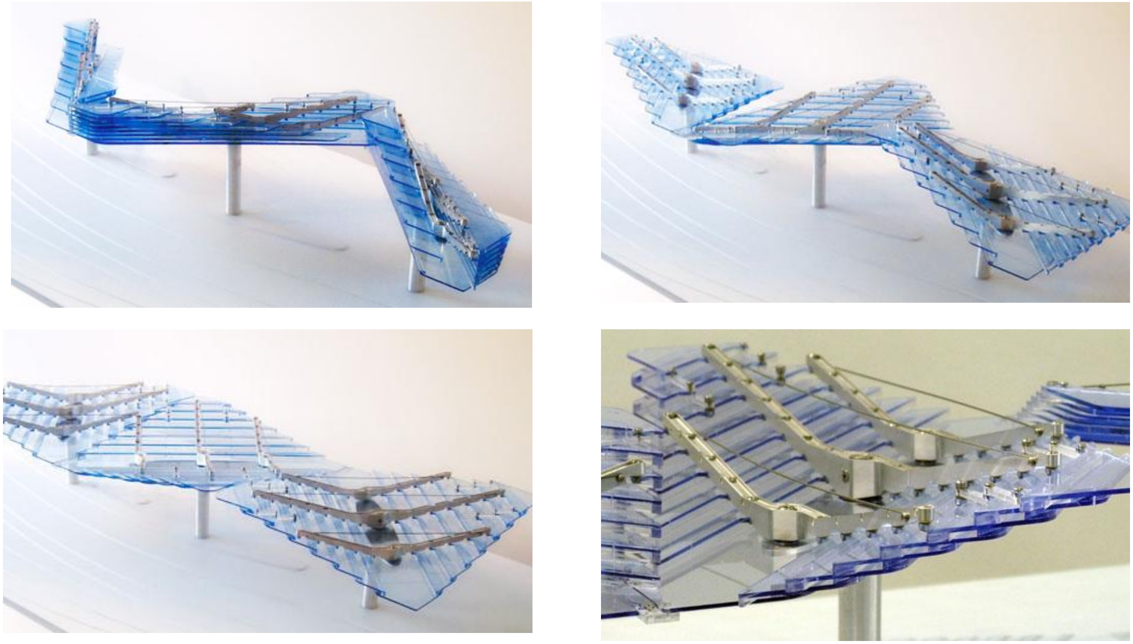


Figure-3.5. Strata systems with kinetic shades.

Project	Building center Trust
Country	UK, London
Climate	Temperate: Typical Western European, oceanic climate
Architect	ABI (Adaptive Building Initiative)
Function	Shelter
System	Strata
Application	Roof/ Horizontal

Possible application

Awnings/ Horizontal

Description

Originally commissioned for an exhibit titled '100 Years of Construction Innovation' by the Building Centre Trust, Adaptive Shading Esplanade is a scale model demonstrating a new generation of adaptive shading designs.

Concept

Three freestanding kinetic shades, each with a square plan, retract into a slender profile, their transformation enabled by utilizing the Adaptive Building Initiative's Strata system. The shading surfaces are treated in transparent blue glass; the structural members are constructed of aircraft quality aluminum.

These units can be arranged in a variety of ways—as a rectilinear esplanade, for example, or a square configuration. They can be either freestanding or integrated into the building structure, creating a courtyard that can transform from indoor to outdoor use.

3.1.6. Helio Trace/ USA, NY, 2010, Center of Architecture (2010)

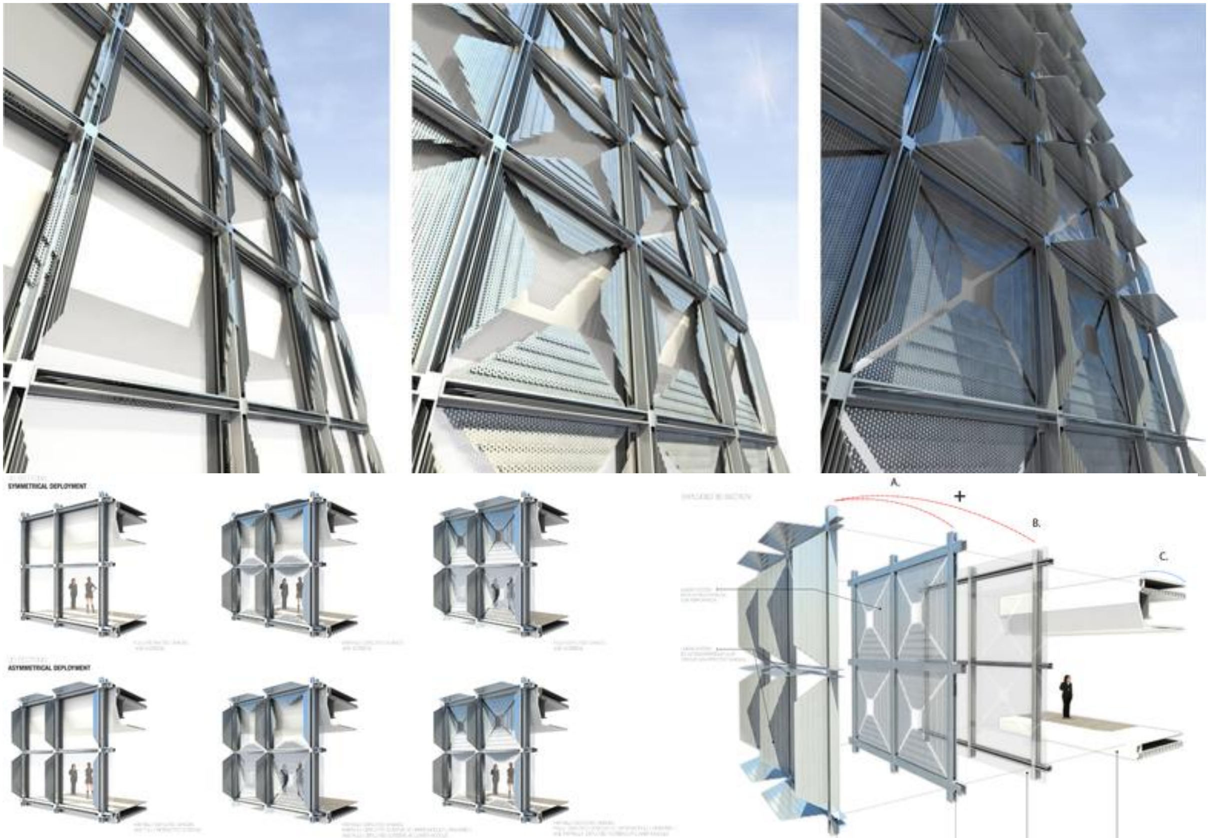


Figure-3.6. Kinetic, solar-responsive curtain wall system that trace the sun’s path.

Project	Helio Trace
Country	USA/ NY
Climate	Humid subtropical climate
Architect	Skidmore, Owings and Merrill LLP
Function	Office building

System	Strata
Construction System	Kinetic, solar-responsive curtain wall system that trace the sun's path
Application	Exterior wall
Possible application	Façades, roofs, awnings Vertical / Horizontal Exterior / Integrated into glazing
Concept	As a kinetic curtain wall system, HelioTrace can literally trace the path of the sun over the course of a day and over the course of a year. In conjunction with other system components, this will significantly increase daylighting while reducing solar heat gain effects for building occupants. The system maintains high-quality daylight at the perimeter zone while eliminating glare, reducing a building's peak solar gains by as much as 81% on an annual basis.
Façade Technology	Helio Trace's optimized, universal design is programmed to perform anywhere in the world by adapting to site characteristics, orientation, and sun path. It can be applied to any rational building geometry by calibrating individual curtain wall panels. Three components comprise the system: kinetic shades on the exterior of the building are attached to a prefabricated, thermally-efficient building envelope, which in turn allows the use of interior chilled ceiling panels that are far more energy efficient than more typical air conditioning solutions.
Characteristics	Reduction of solar gains on buildings by Kinetic, solar-responsive curtain wall system Ensures the right balance of shade and sun Reduce the daytime use of electric lights with daylight, and air-conditioning with natural airflow Respond to ecology, form and function

3.1.7. Aldar Central Market (2010)

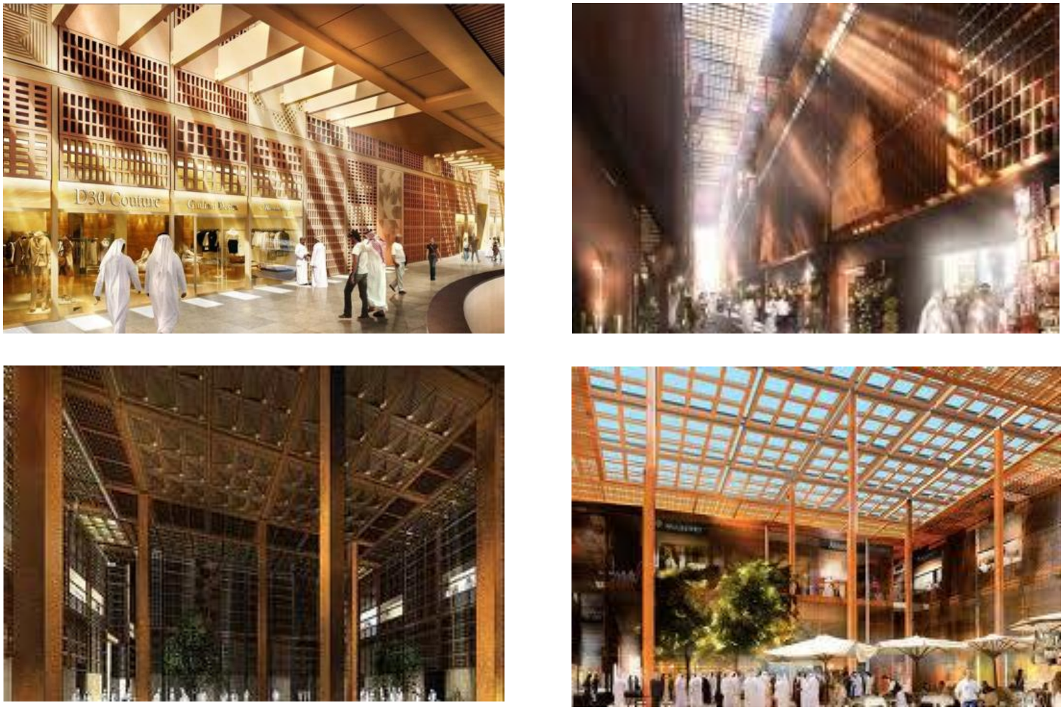


Figure-3.7. Adaptive Building Initiative's Permea system.

Project	Aldar Central Market
Country	UAE , Abu Dhabi
Climate	Hot Arid climate
Architect	Foster + Partners
Function	Shopping center
System	Permea
Construction System	Adaptive Shading Coverage: 1,000 sq. m. Number of operable units: 8

Materials: Aluminum, Steel

Control System: Each unit driven by a servo motor with custom array control

Context: Public squares within the retail complex

Application: Roof/ Horizontal

Possible Application:

Façades, roofs, awnings, building skins

Vertical / Horizontal

Exterior / Interior

Freestanding structural shades

Concept:

Using the Adaptive Building Initiative's Permea system, Hoberman Associates developed several exterior shading roofs in three public squares within the retail complex. The kinetic design works off of an operable grid. In its covered configuration, the shading roof resembles a traditional coffered Islamic roof. When retracted, the roof becomes a slender lattice that complements the Foster team's designs for fixed shading.

Façade Technology:

Permea is a unitized, self-contained system that controls its permeability, varying smoothly between a completely covered and a largely open state. It can be configured to create a seal to protect against dust and debris over large areas; and customized for non-rectangular shapes and installed in a non-vertical orientation.

Permea panels move parallel to the building's surface, allowing its layers to be completely hidden when retracted. Additional benefits include unitized integration with the building, and an unprecedented level of control over patterning. For special situations, Permea can be engineered to function as a protective blast shield.

Characteristics:

Ventilation and airflow control

Dust and debris protection

Reduced solar gain and glare

Shading control, Privacy control

3.1.8. Alexandria library (2003)

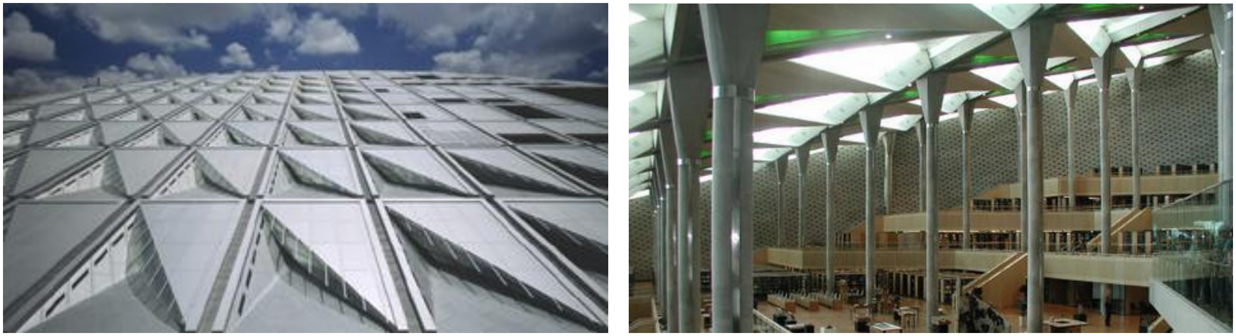


Figure-3.8. Daylighting system used in Alexandria library.

Project	Alexandria Library
Country	Egypt/ Alexandria
Climate	Arid desert climate
Architect	Snøhetta Architects with Hamza Associates
Function	Library
Context	Harbor facing the sea on the north, and Alexandria University Complex on its southern.
Description	Library design comprises a simple circle inclined towards the sea and partly submerged in a pool of water. The inclined roof lets in daylight indirectly and allows for an uninterrupted view of the Mediterranean. The building is surrounded by a wall clad with granite engraved with calligraphy and inscriptions representative of the world's civilizations.
Concept	The open reading room, occupies more than half of the library volume and is stepped over seven terraces. Indirectly lit by vertical, north facing skylights in the roof, the spacious room is not exposed to direct sunlight that is harmful to books and manuscripts. The terraced reading room design reduces book retrieval time considerably, compared to traditional library planning employed in many recently completed projects. Reading

areas and stacks are arranged at close proximity at the same level, the stacks being placed at each terrace level, underneath the next higher terrace. This way, the readers who are sitting at the terrace edge, enjoy maximum exposure to natural light and grand views of the space while being in close proximity to the associated book storage area. This concept is repeated throughout the room and creates a large amphitheater with a large variety of evenly lit reading facilities. The building is further augmented by up-to-date digital information facilities and planned to accept a wide range of changing technologies in the future.

Façade Technology

The roof / facade have associations with contemporary technology such as the modern micro-chip making it a connection between nature and science. Composed of 9 x 14 meter modules, many of which are split in two with one half being a skylight to allow northern light into the reading area, the roof has a very 'high tech' appearance yet is actually very nearly hand crafted. Set into the metal panels are small glass pieces that send colors onto the floor and walls of the reading area.

3.2. Reference projects’ analysis:

After gathering and classification of the all data and information about reference project, their façade and daylighting systems were being analyzed. This analysis can provide the criteria needed for choose of appropriate daylighting system. This is done by making a mind map using all outstanding features of reference projects, and then by categorizing and organizing those features the following criteria were noted:

Table-3.1. Analysis of reference projects- **Arab world institute**

Technology	High performance dynamic	Integrations of advanced technology to glazing Pure concept using existing technology Technology focused on controlling one aspect of daylighting: lighting quantity
Function	Energy save	Providing inadequate daylighting, need of electrical lighting
	Spatial configuration	Create new experience of lighting
	Comfort	No comfort aspect except visual privacy, has been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity according timing program
	Lighting quality	No control over lighting quality except
	Task visibility	Inappropriate lighting characteristics
	Color consideration	With high illumination contrast not even color rendering
	Light distribution	No uniformity, high illumination contrast, shadows
Mechanism	Change stimulus	Tracking sun, not considering users task requirements
	Pace of changes	Rather noticeable reaction pace, which might cause distraction
Location Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Incompatible with occupants' activity requirements

Table-3.2. Analysis of reference projects- **Simons Center**

Technology	High performance dynamic	Using existing technology; Tessellate Continually evolving surface, pattern and opacity Technology focused on controlling one aspect of daylighting: lighting quantity
Function	Energy save	Not achieved
	Spatial configuration	Create new experience of lighting
	Comfort	No comfort aspect has been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity according to sun position
	Lighting quality	No control over lighting quality
	Task visibility	Inappropriate lighting
	Color consideration	With high illumination contrast not even color rendering
	Light distribution	No uniformity, high illumination contrast, shadows
Mechanism	Change stimulus	Tracking sun, not considering users task requirements
	Pace of changes	Rather noticeable reaction pace, which might cause distraction
Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Incompatible with occupants' activity requirements

Table-3.3. Analysis of reference projects- **POLA Ginza building façade**

Technology	High performance dynamic	Integrations of advanced technology to glazing Pure concept using existing technology controlling several aspect of daylighting: lighting quantity and quality
Function	Energy save	Decreasing lighting and cooling load of building
	Spatial configuration	Create new experience of lighting , Visual privacy is provided
	Comfort	visual comfort aspect achieved to some extent
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity
	Lighting quality	Provide diffused light
	Task visibility	Compatible with function activity
	Color consideration	Appropriate color rendering for commercial function
	Light distribution	No uniformity, which is not critical for commercial function
Mechanism	Change stimulus	Tracking sun, not considering users task requirements
	Pace of changes	Rather noticeable reaction pace, which does not conflict with building function
Location Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Compatible with occupants' activity requirements

Table-3.4. Analysis of reference projects- **AHHAA Science Centre**

Technology	Kinetic system	Using existing technology; Adaptive fritting Technology focused on controlling one aspect of daylighting: lighting quantity
Function	Energy save	Not achieved
	Spatial configuration	Create new experience of lighting
	Comfort	No comfort has been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity according timing program
	Lighting quality	No control over lighting quality
	Task visibility	Inappropriate lighting characteristics
	Color consideration	With high illumination contrast not even color rendering
	Light distribution	No uniformity, high illumination contrast, shadows
Mechanism	Change stimulus	User timing program
	Pace of changes	Rather noticeable reaction pace, which might cause distraction
Application	Environmental req.	Interior application only
	Functional req.	Incompatible with occupants' activity requirements

Table-3.5. Analysis of reference projects- **Adaptive Shading Esplanade**

Technology	High performance dynamic	Integrations of advanced technology to glazing Pure concept using existing technology Controlling several aspect of daylighting: lighting quantity and quality
Function	Energy save	Decreasing cooling and lighting load
	Spatial configuration	-
	Comfort	Some aspects of Visual, thermal comfort has been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity
	Lighting quality	Control and adjust lighting quality
	Task visibility	Appropriate lighting for required activity
	Color consideration	With high illumination contrast not even color rendering
	Light distribution	Uniformity, high illumination, No shadows
Mechanism	Change stimulus	Tracking sun, not considering users task requirements
	Pace of changes	Appropriate change pace
Location Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Compatible with occupants' task requirements

Table-3.6. Analysis of reference projects - **Helio Trace**

Technology	High performance Dynamic	Integrations of advanced technology to glazing Controlling several aspect of daylighting: lighting quantity and quality
Function	Energy save	Decreasing cooling and lighting load
	Spatial configuration	From viewpoint of daylighting and built environment has been achieved
	Comfort	Visual, thermal comfort has been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity according to sun position
	Lighting quality	Control over lighting quality
	Task visibility	Compatible lighting characteristics for function requirement
	Color consideration	Even color rendering
	Light distribution	Illuminance Uniformity, low illumination contrast, no shadows
Mechanism	Change stimulus	Tracking sun, considering users task requirements
	Pace of changes	Appropriate reaction pace
Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Compatible with occupants' task requirements

Table-3.7. Analysis of reference projects- **Aldar Central Market**

Technology	High performance Dynamic	Integrations of advanced technology to glazing Pure concept using existing technology Controlling several aspect of daylighting: lighting quantity and quality
Function	Energy save	Decreasing cooling and lighting load
	Spatial configuration	Create new experience of lighting
	Comfort	Some aspects of Visual, thermal comfort has been achieved
Lighting characteristics	Lighting quantity	Control and adjust amount of daylighting entering the building
	Lighting quality	Provide diffused daylight and control lighting quality
	Task visibility	Appropriate lighting for commercial function
	Color consideration	Not even color rendering, but compatible with building function
	Light distribution	Acceptable illuminance uniformity
Mechanism	Change stimulus	Tracking sun and available daylight
	Pace of changes	Rather noticeable reaction pace, which might cause distraction
Location Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Incompatible with occupants' task requirements

Table-3.8. Analysis of reference projects - **Alexandria library**

Technology	High performance	Pure concept using existing technology Controlling several aspect of daylighting: lighting quantity and quality
Function	Energy save	Decrease lighting and cooling load of building
	Spatial configuration	Create new experience of lighting
	Comfort	Visual comfort and some aspects of thermal comfort have been achieved
Lighting characteristics	Lighting quantity	Control and adjust lighting quantity
	Lighting quality	Control over lighting quality
	Task visibility	Appropriate lighting for reading and writing
	Color consideration	With high illumination uniformity and even color rendering
	Light distribution	Illuminance uniformity, low luminance ration, no shadows
Mechanism	Change stimulus	Static system adjust light according to received light rays
	Pace of changes	Static system, no changes
Application	Environmental req.	Compatible with environmental requirements
	Functional req.	Compatible with occupants' task requirements

3.3. Conclusion

After classification and analysis of reference projects, the main criteria were extracted. These criteria will be used later to analyze the daylighting systems and to evaluate which daylighting system can match the lighting requirements of the program:

3.3.1. Technology

The technology used in the daylighting system, is an important factor; either it is adaptive or static façade system. That depends on the demands of program and expectations from façade, how the required daylighting is provided. According to analyzed reference projects the systems are either high performance or kinetic façade systems.

3.3.2. Function

The function of daylighting system in façade might be different according to program demands. The most significant functions are including:

- **Energy save:**
  - Reduction of electrical lighting by taking advantage of day lighting
  - Use of photovoltaic panels for energy needed for Actuator
  - Reduction of mechanical cooling and heating load
- **Spatial configuration/ Aesthetic**
  - Create exclusive experience of light and spatial perception
- **Comfort**

a. Visual comfort

- Filtering light
- Glare control
- Provide required daylight regarding user’s health and comfort need
- Shading control
- Visual privacy

b. Other comfort aspects

- Indoor air quality: Ventilation and airflow control
- Thermal comfort: Reduced solar gain
- Aural comfort

3.3.3. Mechanism

Either the daylighting systems are static or dynamic, the mechanism is among the influential factors; how the system works to provide desired daylighting, under different conditions. In dynamic systems, the mechanism of changes, pace of change and the stimulus factors are critical. On the other hand in static systems, the desired daylighting is provided by a system which is fixed. So under different daylight available, this system must b able to provide desired daylighting:

- **Static**
- **Dynamic**
    - Pace of changes: Gradually or Drastically
    - Changes stimulus
        - Sun tracing
        - Environmental requirements: wind, etc
        - Functional requirements
        - Users: Timing, scheduled program, manual, etc
    - Response mechanism

3.3.4. Location Application

Application of daylighting systems are also should be considered, since some of them can be applied either on vertical or horizontal surfaces. Also, whether the system can be applied interior.

4. Design Lighting requirements

4.1. Lighting requirements of classroom

The characteristic of daylighting which comes through the system is related to which aspects of light is controlled or affected by daylighting system. Whether the system influence quantitative or qualitative aspects of light (or both of them), resulted daylight get different characteristics, which should be according to program demands. Lighting characteristics regarding task requirements, Visibility, Distraction, etc are among those factors which must be considered thoroughly. Considering those criteria driven from sample projects' analysis, daylighting approach is outlined as following;

I. Normal program which is the most dominant and frequent activity program and also requires optimal lighting requirements, might be considered as the default lighting situation, and the requirements of other programs would be provided by changing the lighting source, quality and quantity. That is, façade, and classrooms design and lighting would be designed in a way which can adapt itself to those requirements. In other words, according to different activity programs, different lighting programs would be defined which would require some changes in façade and lighting of the classroom.

II. Those lighting quality and quantity aspects which are similar through different activity programs would be considered as fixed requirements. While other aspects which change through school time might requires the design of the façade and classroom to be flexible toward those requirements so that it may adapt itself according to lighting demands.

III. Design of façade should take into account both lighting quality and quantity aspects and outside view. This can be achieved either by choosing strategies or technologies which control different aspects of lighting quality and quantity or by combining different technologies or strategies together, which each of them control specific aspect.

IV. The mechanism of changes (speed and the way of changes) in façade should be selected in regard to task requirements. For instance if some changes in illuminance are required for a short period during normal class time (like more illuminance requirement for an exam time), the mechanism which provides that higher illuminance should not interrupt or distract class normal activity.

V. Applied strategies and technologies, should take into account contextual consideration including; building environment (its location and climate), building function, and the place where it is going to be applied (façade, roof, and etc).

VI. Although providing visual comfort is the main goal of the research, enough consideration should be given to other comfort aspects including; thermal, acoustic and indoor air quality. That is, although other comfort aspects are not the focus of this research, the result of designed façade system should not result in thermal, acoustic and indoor air qualities discomfort condition.

Figure-4.1 illustrates a comparison between lighting aspects among four activity programs. The lighting situation in normal program has been taken as a reference so that it may be compared with lighting aspects in other programs (in grey color). Figure-4.2 shows an analysis of lighting aspects in 4 activity program. There are three categories of lighting aspects:

- Variable lighting aspects;
- Minor changes;
- Fixed lighting aspects.

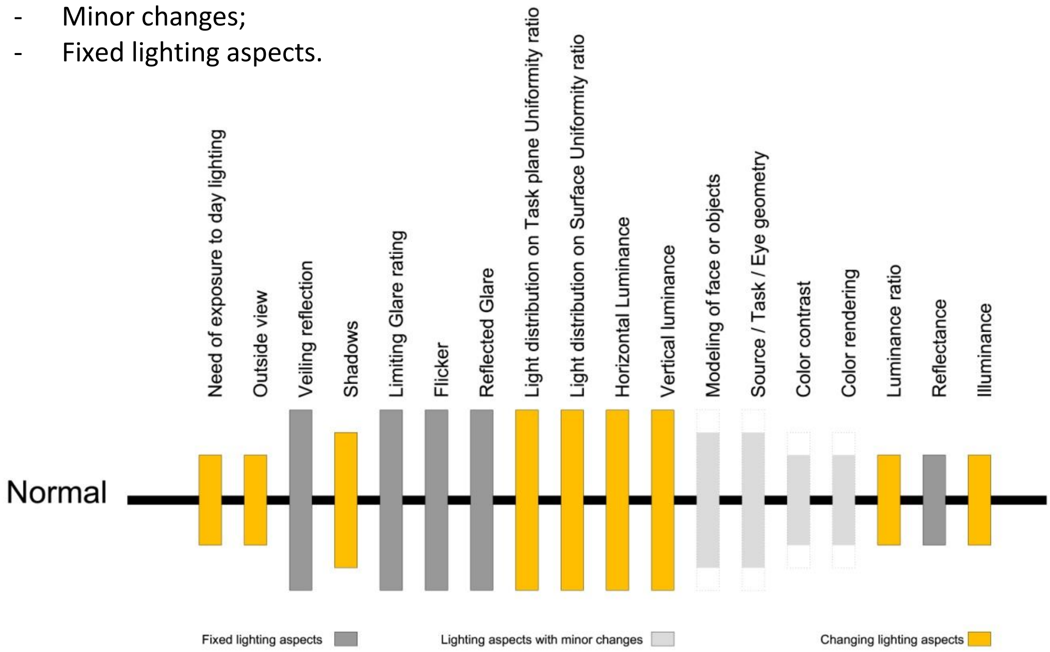
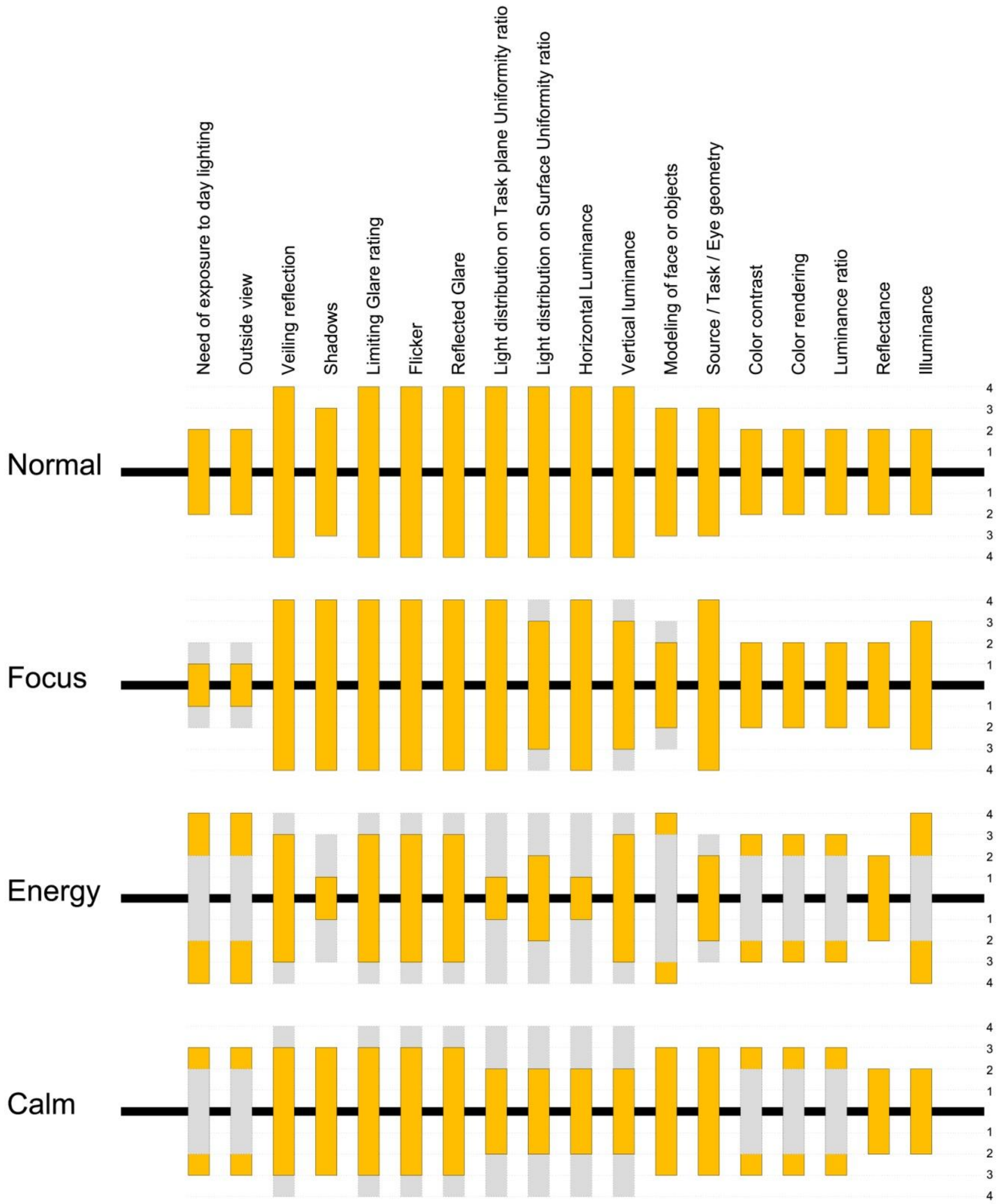


Figure 4.2- Three different category of lighting aspects in normal activity program as default lighting condition

Figure 4.1- Comparison of lighting aspects among four activity programs.



4.2. Conclusion

Regarding daylighting main requirements which were discussed before, and the result of comparing different activity program lighting requirements, it may be concluded that, lighting strategies should meet following principles:

I. The cladding of the classroom should be designed in a way that, provide different lighting quality and quantity aspects including; Luminance, vertical and horizontal luminance, uniformity on both task plane and surface, outside view and exposure to daylight based on the classroom timing and activity program.

II. Lighting aspects related to color rendering and contrast, modeling of faces and objects, and source-task-eye geometry should be designed in optimal range according to requirements of normal program and meet also the requirements of focus program, which is lower than normal situation. However, since in calm and energy programs the requirements are slightly higher than normal situation, changes in lighting aspects of group-I can meet and provide these higher requirements.

III. Reflectance and discomfort aspects of lighting including; flicker, veiling reflection, and Glare, would be design according to requirements if normal program and it applies for other activity programs. However, for calm and energy program acceptable shadows are higher than normal program.

5. Design approach

5.1. Design pre-conditions

Defining the contextual conditions of the classroom requires considering both general design situation and defining its location. The classrooms selected for this research is a Primary School classroom for students between 7-11 years old. The working plane is situated at a height of 70 cm above floor level. The classroom is usually occupied from 8:00 a.m. to 4:00 p.m. locating on the first floor, facing the south, it is side-lit with unilateral windows, and use of top-lit is possible in the case of need. Using the general daylighting strategies and contextual assumptions, here are the classroom contextual pre-assumptions;

- The school is located in Eindhoven, latitude 51.4°N, longitude 5.4°E, with a moderate maritime climate [20].

- To maximize day lighting, School building would be oriented toward South-north which provides the best day lighting in northern hemisphere.

- The class room, which requires high exposure to daylight, would be lit by side-light facing south; however, use of top-light can be an option when or where side-light does not meet the lighting requirements of activities. Also Combination of using side light and top light makes it possible to switch between illuminance uniformity from horizontal to vertical.

- Due to prevailing sky condition regarding the project location, which is overcast and cloudy, it is recommended to maximize glazing area on southern façade; however, careful attention should be paid to control possible discomfort aspects of direct sunlight.

Also, it is assumed that there is no direct light obstruction building in the neighborhood, which might block the entering light from the windows. This information may be used for the computer simulation.

5.2. Lighting requirement of Activities

Now that the contextual condition of classroom is determined, next step is to go through daylighting strategies of classroom cladding. To do so, all the lighting requirements of classroom activity are summarized and categorized according to their occurrence and variation through time:

i. Illuminance and its uniformity both on horizontal and vertical surface, luminance ratio, outside view, and daylight presence in the classroom are those aspects of lighting which are variable. That is, lighting strategies and technologies should provide flexibility in these aspects.

ii. Discomfort conditions including glare, veiling reflection and shadows must be eliminated thoroughly, and lighting adjustment should not bring about or increase discomfort condition. However, shadows are expected to some extent in some times.

iii. Lighting aspects for color and object rendering should be provided according to requirements and should be kept the same through different lighting situations.

iv. Need of being exposed to daylight and also the color spectrum which stimulates students' alertness should be taken into account.

Due to wide range of visual comfort indicators (light quality, quantity, and view characteristics), priority will be given to the most important aspects. So, This Research will focus on the most important indicators of visual comfort.

a. Light quantity: Illuminance and its uniformity (includes luminance ratio)
b. Light quality: Color spectrum
c. Discomfort: Glare
d. View

So, although visual comfort is achieved when all its aspects are consider thoroughly, in this research the focus of design will be given to the above mentioned factors. An analysis of daylighting function of different parts of façade might be seen later in Figure-5.1.

5.3. Cladding component

To have better understanding of cladding system which, the whole cladding system of the classroom is divided in four main components based on its function and situation. This division will make it possible to assign appropriate lighting system for each cladding component to achieve program requirements. It is needed to examine how and which systems can be combined together to provide desired lighting requirements. To do so, first the role and function of each component will be determined:

a) Top light

Due to its position, it can provide the best possible horizontal lighting, which is important for normal and focus program. Moreover, in overcast conditions, top light can provide the most available daylight. As a result lighting systems which are used for this cladding component should provide lighting with high illuminance uniformity, also color rendering and 3D object rendering should be in acceptable range. Since this opening is located high in the ceiling, the discomfort effect is not so critical; however, discomfort situations like glare and shadows should studied carefully to avoid discomfort (Figure-5.2).

b) Side light- upper

Since it is located above eye level, view is not necessary for this part. The main function is to provide vertical illuminance. Because of its location, being placed high in vertical windows, it can provide good available daylight. Also, being above eye level, some aspects of discomfort conditions like shadows or glare are acceptable. Although, careful attention should be paid to direct light coming from this part which might cause glare at back part of class. The light passing through this window part can be enhanced on its color tone, to provide required light color spectrum according to students' activity (Figure-5.2).

c) Side light- view

This part has got two main functions: lighting and view. Since the amount of view and required illuminance for all activity programs are not identical, this part should provide different availability in view and illuminance. In one hand, since this opening is at eye level and the lighting coming through it affects students' activity directly, light coming through this façade part, should not bear any discomfort effect, which means it should provide diffused and enhanced lighting instead of direct light. On the other hand, this part of façade is the only part which can provide direct lighting for students' health need to be exposed to direct daylight during boosting times. So, it is suggested to design this façade component in a heterogonous way, which allows each part to have different function (Figure-5.2).

d) Side light- lower

This part of façade will provide just lighting for enhancing space perception. Due to its location, it is of the less importance for lighting the task surface. Because the light coming from such low height cannot provide suitable light illuminating task surface. However, that light can be used to enhance light characteristics, including color spectrum to enhance space perception. Since this enhanced colored light will be lower than surface task, it will not affect natural color light required for task surface. Also using lighting systems which increase light transmission it can be transferred deeper into space. As a result light coming through this part should be diffused enhanced color light with high transmission (Figure-5.2).

Figure-5.1. Light transmission through normal side light without light shelf and top light effect.

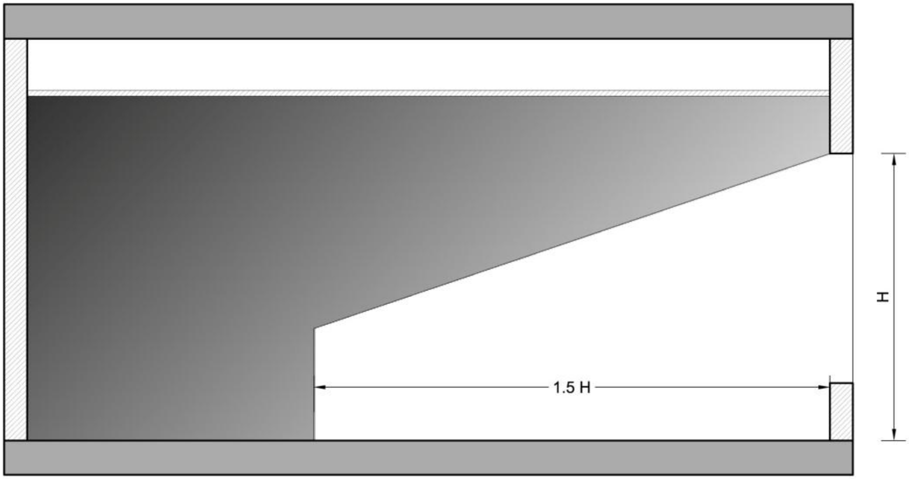
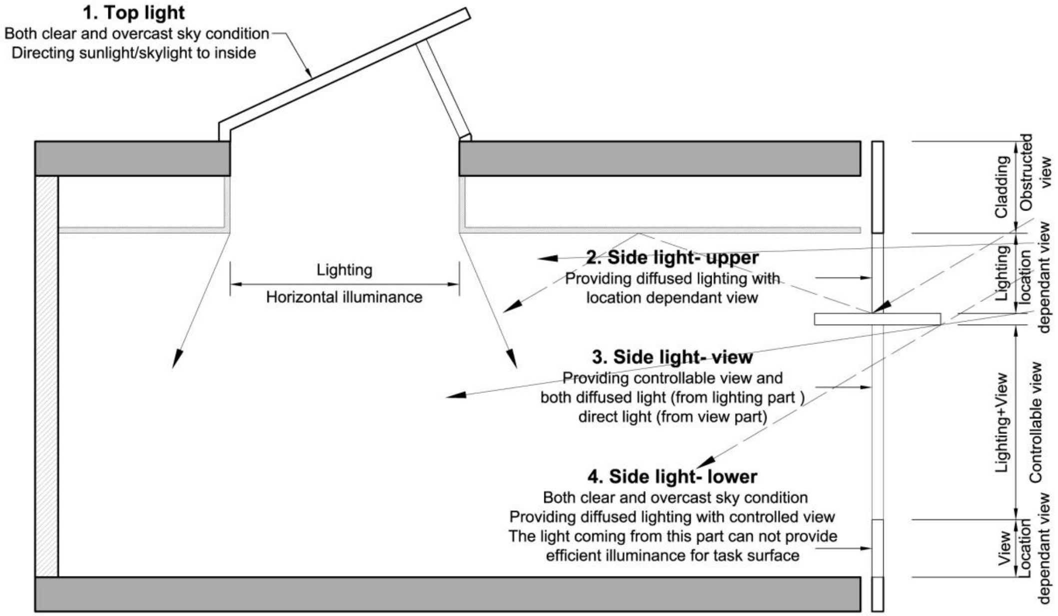


Figure-5.2. Division of classroom cladding according to each component's function and situation.



5.4. Analysis of daylighting systems based on cladding components

In this part, available daylighting systems (see [6] and [14] for more information about daylighting systems) are analyzed based on the criteria derived by study of reference projects including: Application, Technology, Function, Lighting characteristics, and Mechanism. This analysis will provide a guide to choose the appropriate daylighting system for each part of façade product, based on its situation.

So, next step would be to examine how these several systems can be combined together, considering the main purpose of the program, which is to provide variant lighting situations based on variant requirements. That is, by having a number of systems which may fit in the program requirements, design process will go through choosing appropriate systems which will act together to accomplish program goal (Table-5.1~3). Also in table-5.4 a summary of analysis of all the daylighting systems is illustrated. This summary shows which daylighting systems are suitable with lighting requirements of façade components.

AA= **A**ppropriate **A**pplication

Daylighting system fulfills all the requirements (have some advantages with no disadvantages).

A= **A**pplicable

Meets some parts of the requirements (have some advantages but might cause few disadvantages which can be managed).

CA= **C**an **A**pplied

Using daylighting system does have neither any advantages nor disadvantages.

NA= **N**ot **A**pplicable

Using daylighting system causes some serious disadvantages, no noticeable advantages.

Table-5.1 Analysis of Daylighting systems with shading based on the criteria of reference projects.

category	Type	Application situation	Location	Technology	Function view+lighting	Lighting characteristic	Mechanism	Conclusion	Threats
1A Primary using diffuse skylight	Prismatic panels	Toplight	AA	AA	A	AA	CA	☺	Glare
		Sidelight-upper	AA	AA	A	A	AA	☺	Glare
		Sidelight-view	AA	AA	A	A	AA	☺	Glare+ View
		Sidelight-lower	AA	AA	A	AA	CA	☺	
	Prisms and Venetian blinds	Toplight	NA	NA	A	CA	AA	-	
		Sidelight-upper	AA	AA	AA	AA	A	☺	Tracking
		Sidelight-view	AA	AA	A	A	A	-	Tracking
		Sidelight-lower	CA	CA	NA	CA	CA	-	
	Sun protecting mirror elements	Toplight	AA	AA	AA	AA	A	☺	
		Sidelight-upper	NA	-	-	-	-	-	
		Sidelight-view	NA	-	-	-	-	-	
		Sidelight-lower	NA	-	-	-	-	-	
	Anidolic zenithal opening	Toplight	AA	CA	AA	AA	CA	☺	
		Sidelight-upper	NA	-	-	-	-	-	
		Sidelight-view	NA	-	-	-	-	-	
		Sidelight-lower	NA	-	-	-	-	-	
	Directional selective shading system with concentrating Holo-graphic optical element	Toplight	AA	CA	AA	AA	CA	-	
		Sidelight-upper	NA	-	-	-	-	-	
		Sidelight-view	NA	-	-	-	-	-	
		Sidelight-lower	NA	-	-	-	-	-	
	Transparent shading system with HOE based on total reflection	Toplight	AA	AA	AA	AA	AA	☺	
		Sidelight-upper	A	AA	AA	A	AA	☺	
		Sidelight-view	A	AA	A	AA	AA	☺	
		Sidelight-lower	A	AA	NA	A	CA	-	View
1B Primary using direct sunlight	Light guiding shade	Toplight	NA	-	-	-	-	-	
		Sidelight-upper	AA	AA	AA	AA	CA	☺	
		Sidelight-view	NA	-	-	-	-	-	
		Sidelight-lower	NA	-	-	-	-	-	
	Louvers and blinds	Toplight	NA	-	-	-	-	-	
		Sidelight-upper	A	CA	CA	NA	CA	-	
		Sidelight-view	A	CA	CA	CA	CA	-	
		Sidelight-lower	CA	CA	NA	NA	NA	-	

Table-5.2 Analysis of Daylighting systems based on the criteria of reference projects.

category	Type	Application situation	Location	Technology	Function view+lighting	Lighting characteristi	Mechanism	Conclusion	Threats
1B Primary using direct sunlight	**Light shelf for redirection of sunlight**	**Toplight**	**NA**	-	-	-	-	-	
		Sidelight-upper	**AA**	**AA**	**AA**	**A**	**AA**	☺	Glare
		Sidelight-view	**NA**	-	-	-	-	-	
		Sidelight-lower	**NA**	-	-	-	-	-	
	Glazing with reflecting profiles	**Toplight**	**AA**	**A**	**AA**	**A**	**AA**	☺	
		Sidelight-upper	**A**	**A**	**AA**	**A**	**AA**	☺	
		Sidelight-view	**A**	**CA**	**CA**	**NA**	**CA**	-	
		Sidelight-lower	**A**	**CA**	**CA**	**NA**	**CA**	-	
	Skylight with laser cut panels	**Toplight**	**AA**	**AA**	**AA**	**A**	**CA**	☺	Glare
		Sidelight-upper	**NA**	-	-	-	-	-	
		Sidelight-view	**NA**	-	-	-	-	-	
		Sidelight-lower	**NA**	-	-	-	-	-	
	Turnable lamellas	**Toplight**	**AA**	**AA**	**A**	**AA**	**A**	☺	Glare
		Sidelight-upper	**AA**	**AA**	**A**	**AA**	**A**	☺	Glare
		Sidelight-view	**AA**	**AA**	**A**	**A**	**A**	-	View+ Glare
		Sidelight-lower	**AA**	**AA**	**CA**	**NA**	**A**	-	
	Anidolic solar blinds	**Toplight**	**NA**	-	-	-	-	-	
		Sidelight-upper	**CA**	**CA**	**A**	**A**	**CA**	-	
		Sidelight-view	**CA**	**CA**	**NA**	**NA**	**NA**	-	
		Sidelight-lower	**CA**	**AA**	**AA**	**A**	**CA**	☺	
2A Diffuse light guiding systems	**Light shelf**	**Toplight**	**NA**	-	-	-	-	-	
		Sidelight-upper	**AA**	**AA**	**AA**	**AA**	**AA**	☺	
		Sidelight-view	**NA**	-	-	-	-	-	
		Sidelight-lower	**NA**	-	-	-	-	-	
	Aniodolic integrated system	**Toplight**	**NA**	-	-	-	-	-	
		Sidelight-upper	**AA**	**AA**	**AA**	**A**	**AA**	☺	Glare
		Sidelight-view	**NA**	-	-	-	-	-	
		Sidelight-lower	**NA**	-	-	-	-	-	
	Aniodolic ceiling	**Toplight**	**NA**	-	-	-	-	-	
		Sidelight-upper	**AA**	**AA**	**AA**	**AA**	**CA**	☺	Glare
		Sidelight-view	**NA**	-	-	-	-	-	
		Sidelight-lower	**NA**	-	-	-	-	-	

Table-5.3. Analysis of Daylighting systems without shading based on the criteria of reference projects.

category	Type	Application situation	Location	Technology	Function view+lighting	Lighting characteristic	Mechanism	Conclusion	Threats
2A Diffuse light guiding systems	Fish system	Toplight	NA	-	-	-	-	-	
		Sidelight-upper	AA	A	A	A	CA	-	
		Sidelight-view	A	A	A	NA	CA	-	
		Sidelight-lower	A	A	A	NA	A	-	
	Zenith light guiding elements with HOEs	Toplight	AA	A	A	NA	CA	-	Color dispersion
		Sidelight-upper	AA	A	A	A	CA	-	Color dispersion
		Sidelight-view	AA	A	A	NA	CA	-	
		Sidelight-lower	A	A	NA	NA	CA	-	
2B Direct light guiding systems	Laser cut panels	Toplight	AA	AA	AA	A	AA	☺	Glare
		Sidelight-upper	AA	AA	AA	A	AA	☺	Glare
		Sidelight-view	AA	A	A	NA	A	-	Glare
		Sidelight-lower	AA	CA	NA	NA	A	-	View
	Prismatic panels	Toplight	AA	AA	A	AA	CA	☺	
		Sidelight-upper	AA	AA	A	A	AA	☺	Glare
		Sidelight-view	AA	AA	A	A	AA	☺	View+ Glare
		Sidelight-lower	AA	AA	A	AA	CA	☺	
	HOEs in the skylight	Toplight	AA	AA	A	AA	CA	-	Color dispersion
		Sidelight-upper	NA	-	-	-	-	-	
		Sidelight-view	NA	-	-	-	-	-	
		Sidelight-lower	NA	-	-	-	-	-	
	Sun directing glass	Toplight	A	A	AA	AA	AA	☺	Glare
		Sidelight-upper	A	A	AA	AA	AA	☺	Glare
		Sidelight-view	A	CA	NA	NA	A	-	
		Sidelight-lower	A	CA	AA	NA	AA	-	
2C Scattering systems		Toplight	AA	A	A	A	AA	☺	Glare
		Sidelight-upper	AA	A	A	A	AA	☺	Glare
		Sidelight-view	A	A	NA	NA	CA	-	
		Sidelight-lower	A	A	A	NA	CA	-	

Table-5.4. Summary of analysis of all the Daylighting systems

category	Type	Toplight	Sidelight-upper	Sidelight-view	Sidelight-lower
1A Primary using diffuse skylight	**Prismatic panels**	☺	☺	☺	☺
	Prisms and Venetian blinds	-	☺	-	-
	Sun protecting mirror elements	☺	-	-	-
	Anidolic zenithal opening	☺	-	-	-
	Directional selective shading system with concentrating Holo-graphic optical element	☺	-	-	-
	Transparent shading system with HOE based on total reflection	☺	☺	☺	-
1B Primary using direct sunlight	**Light guiding shade**	-	☺	-	-
	Louvers and blinds	-	-	-	-
	Light shelf for redirection of sunlight	-	☺	-	-
	Glazing with reflecting profiles	☺	☺	-	-
	Skylight with laser cut panels	☺	-	-	-
	Turnable lamellas	☺	☺	-	-
	Aniodolic solar blinds	-	-	-	☺
2A Diffuse light guiding systems	**Light shelf**	-	☺	-	-
	Aniodolic integrated system	-	☺	-	-
	Aniodolic ceiling	-	☺	-	-
	Fish system	-	-	-	-
	Zenith light guiding elements with HOEs	-	-	-	-
2B Direct light guiding systems	**Laser cut panels**	☺	☺	-	-
	Prismatic Panels	☺	☺	☺	-
	HOEs in the skylight	-	-	-	-
	Sun directing glass	☺	☺	-	-
2C Scattering systems		☺	☺	-	-

Now that, there is a clue that, which daylighting systems can meet the lighting requirements of cladding parts, next step is to examine which of these selected systems and how they can be integrated into each other to consist a united cladding system which all the cladding parts complement each other. As it can be concluded from this analysis of available daylighting systems, the appropriate systems which can meet the requirements of all cladding parts is the prismatic panels. Also this system can be matched easily with other glazing systems which are needed to improve lighting characteristics including Dichroic glass, Smart Energy Glass [29].

To conclude, considering the requirements of façade components, the appropriate daylighting systems and products are as following:

- Prismatic panels will be used for side light-view and side light-lower, which shading, glare control and limited view is required. Also it should be noticed that since it produced diffused light, it provides uniformity, low contrast shadow and even distribution of light.

- Light shelf will be used for side light-upper part which increased the light transmission into room space and also can provide redirected and diffused daylight.

- To enhance the color tone of side light-upper and side-light-lower, Dichroic glass can be integrated with daylighting system which is used in these parts.

- Need of adjustment of façade elements should be considered when it is needed considering the function of the façade elements, daylight availability and the lighting requirements.

So, these daylighting systems will be put into practice to see how they can performance within different façade concepts. First the daylight direction variation (seasonal and daily) is analyzed. Direction and angle of sunlight varies from maximum 62 degree in June to minimum 15 degree in December (Figure-5.3). Also the daylight availability ranges from 8am till 4pm in December to 4 am till 8 pm in June (Figure-5.4). It must be noted that daylight availability in southern façade during June starts from 7 am till 5 pm, which reaches the façade with a parallel angle from east at 7 am and reaches the maximum angle at noon with a perpendicular angle, and then continues its direction to a parallel angle 5 pm. Figure-5.5 illustrates daylight angle changes through year.

Figure-5.3. The minimum and maximum Daylight availability in the Netherlands and its effect on Southern facade.

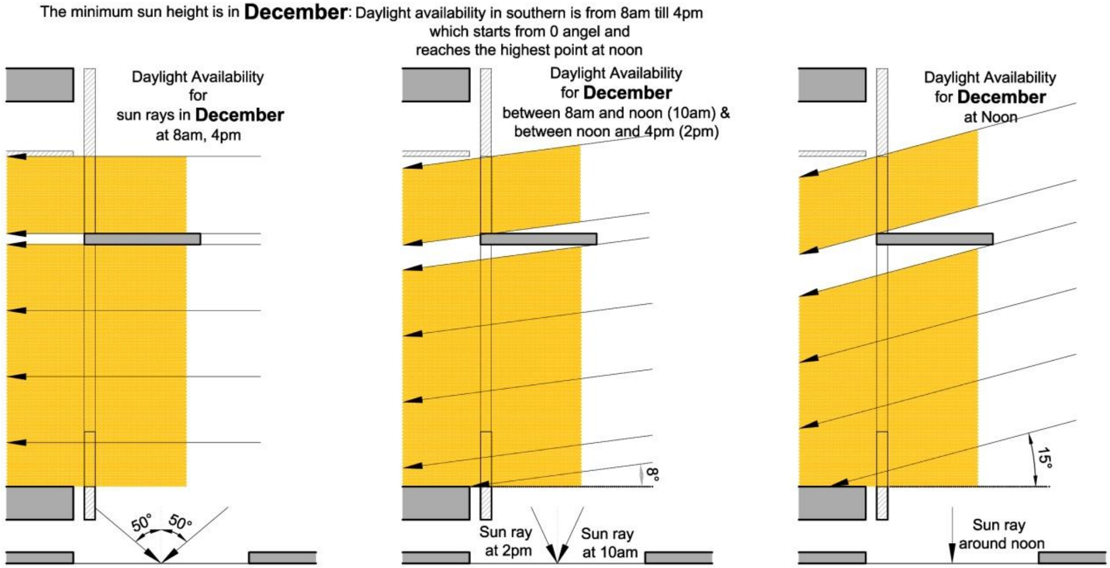


Figure-5.4. The maximum Daylight availability in June in the Netherlands and its effect on Southern façade.

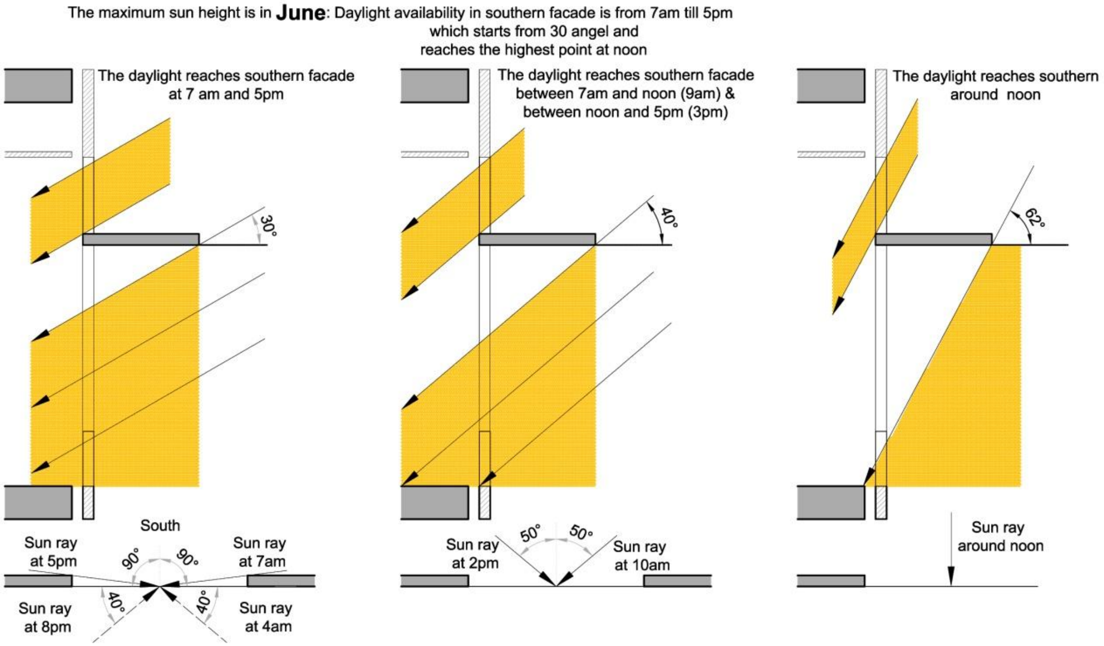
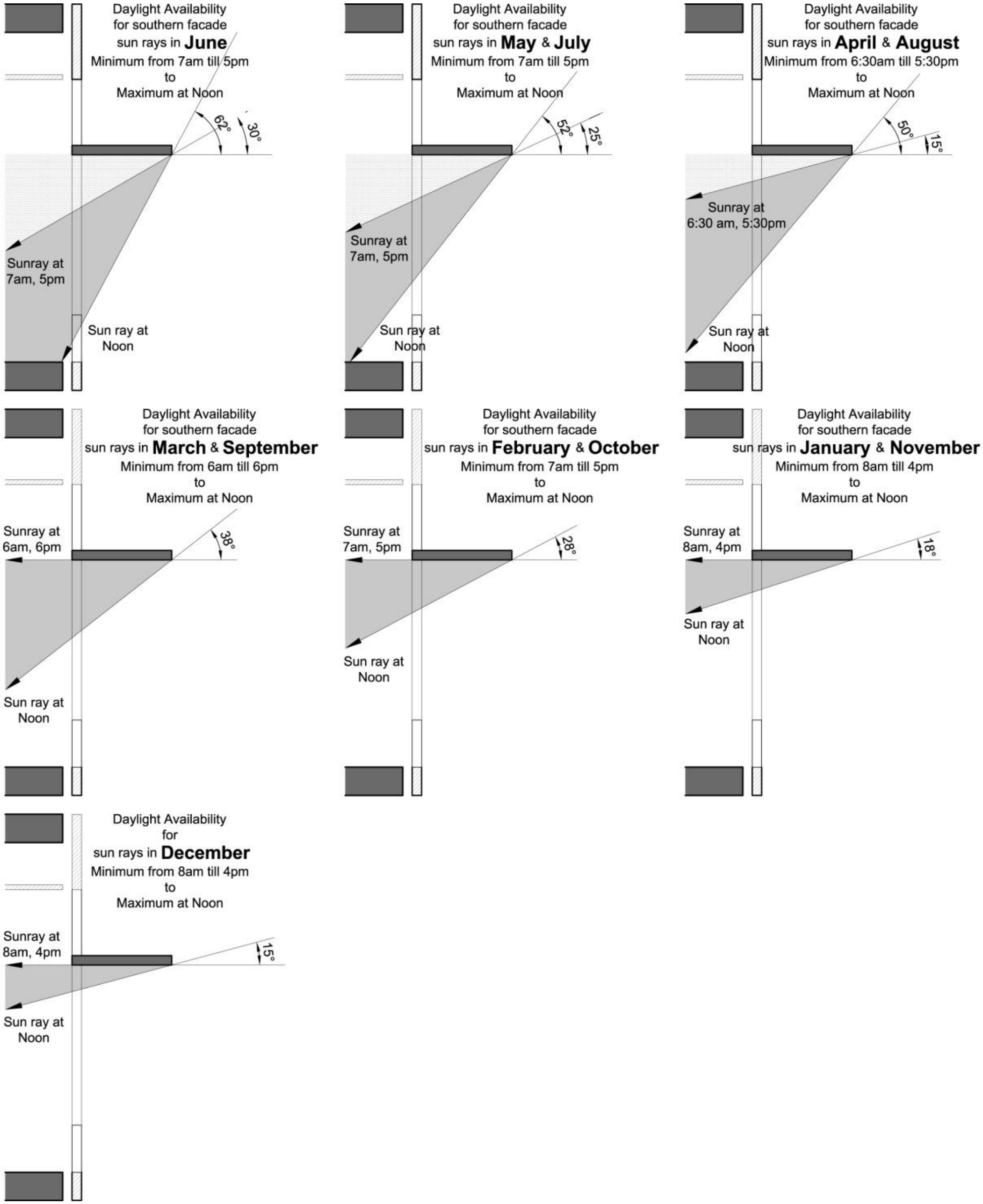


Figure-5.5. The Daylight availability variation through year in the Netherlands and its effect on southern facade.



So, it can be concluded that direction and angle of sunlight changes both in horizontal and vertical direction. This can affect the design of façade in several ways:

- Since prismatic panels are based on the direction of sunlight, they should b designed in a way that can adapt track sun position and be adjusted (both vertically and horizontally) to provide desired orientation.

- Also, this might affect the sun shading system (light shelf) and the orientation of reflecting surface (Figure-5.6).

As it was discussed before the façade system is supposed to enhance and control specific aspects of daylighting quality quantity and view. Having this in mind, and considering the façade heterogeneous division, the daylighting function expectations of the façade components are translated into several functional layers (Figure-5.7).

So, as it can be concluded that the function of façade component will be as following:

Side light-upper: to provide diffused or redirected light with enhanced color tone. Glare should be controlled; however, it is not critical since it is located above eye level. Careful attention should be paid to back part of the class, where due to distance from façade, the reflected light through this window can reach eye level and cause glare.

Side light-View: To provide diffused normal color tone light with controlled glare. It is recommended to design View and light part of window separately so that they can be adjusted independently.

Side light-lower: to provide diffused enhanced color tone light with obstructed view. The light coming through this part, can help to reduce illuminance contrast.

Figure-5.6. Possible adjustments of sunshades and overhangs to provide optimal shading for different sun angles (from visual comfort viewpoint).

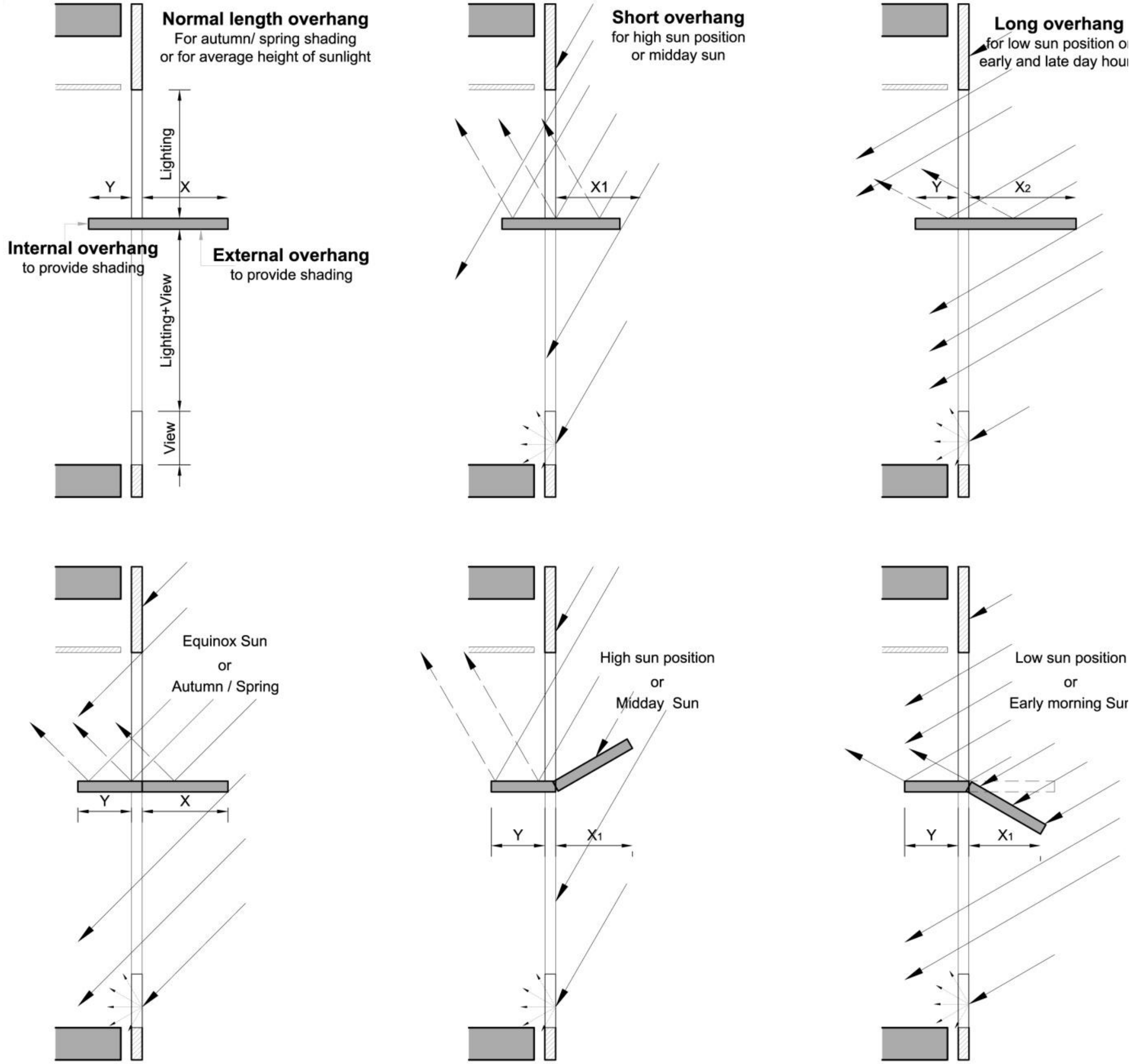
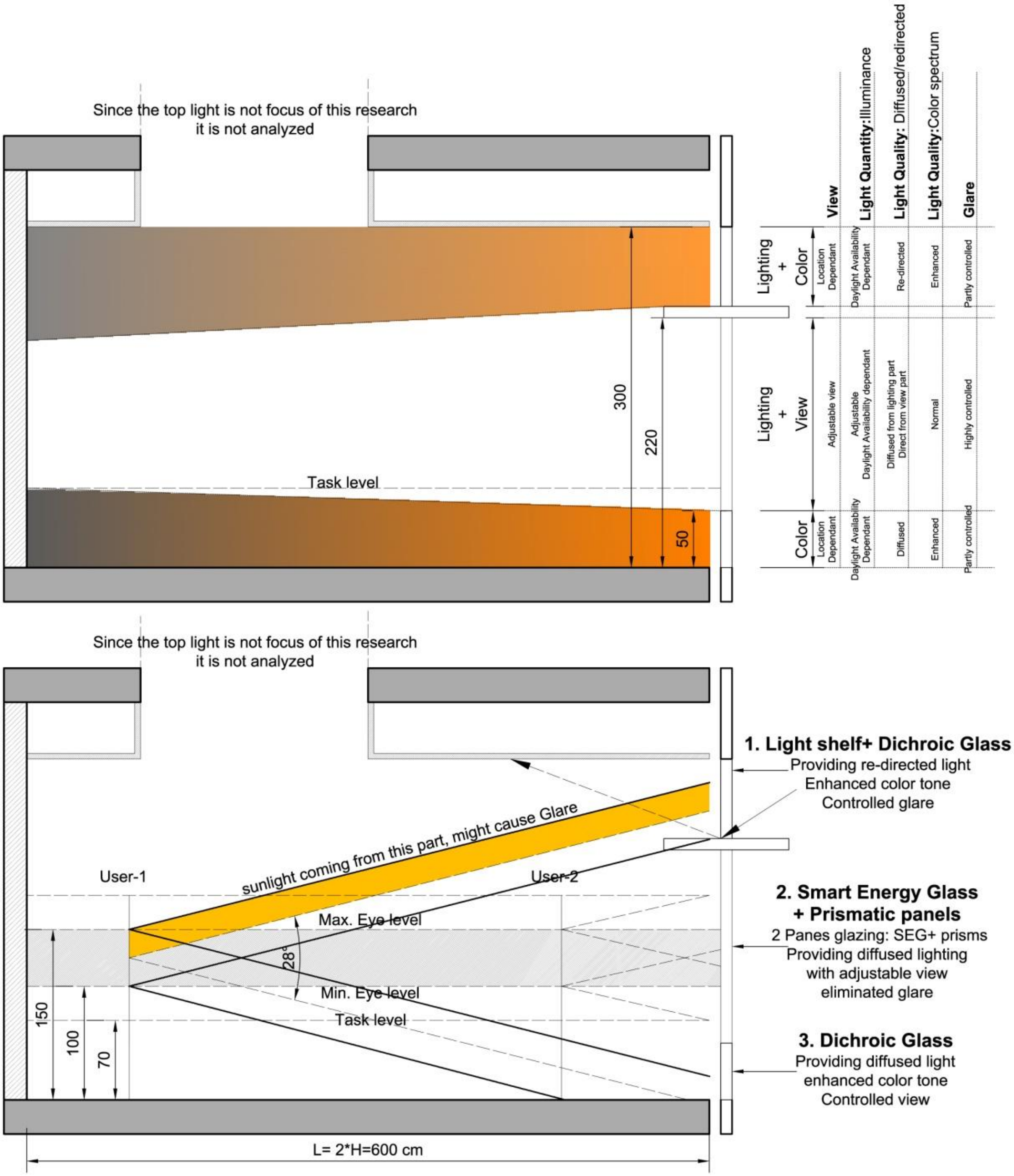


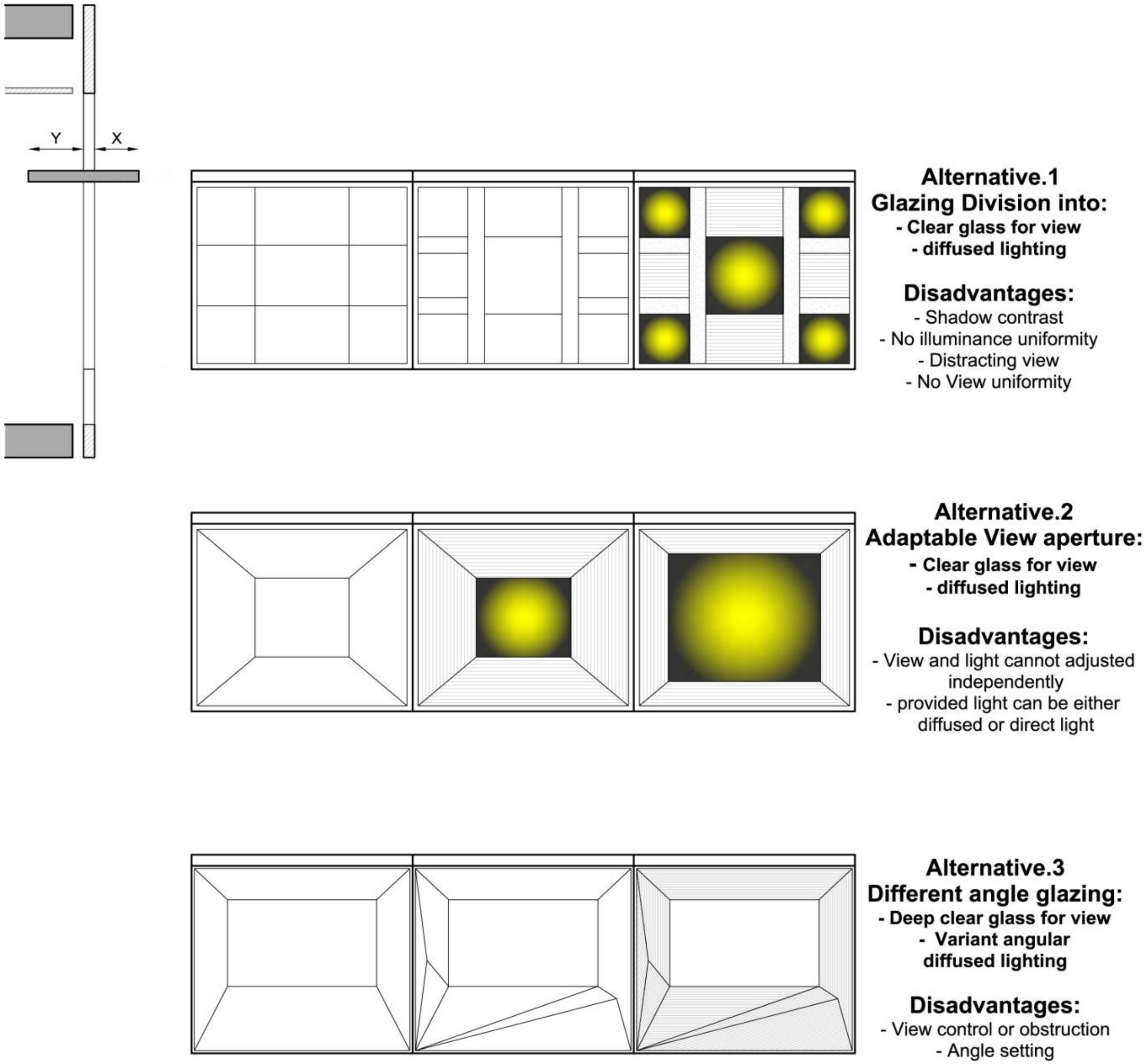
Figure-5.7. Daylighting functions of façade components in several layers.



5.5. Design alternatives

Based on daylighting requirements, here different design alternatives are analyzed:

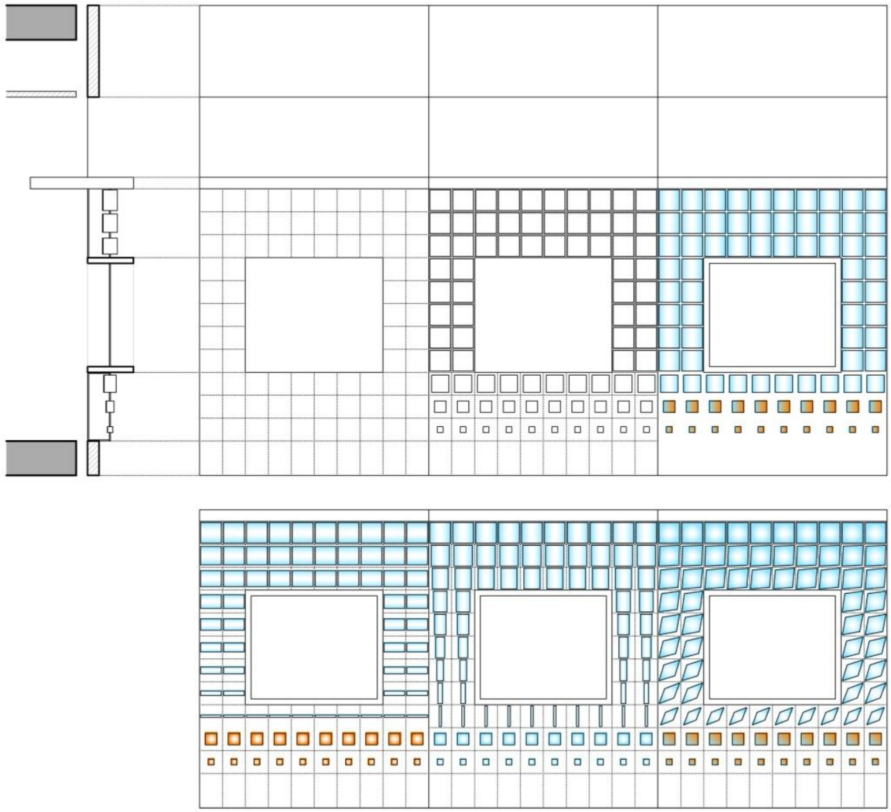
Figure-5.8. Different design concepts based on the lighting requirements of each façade components.



5.6. Final design

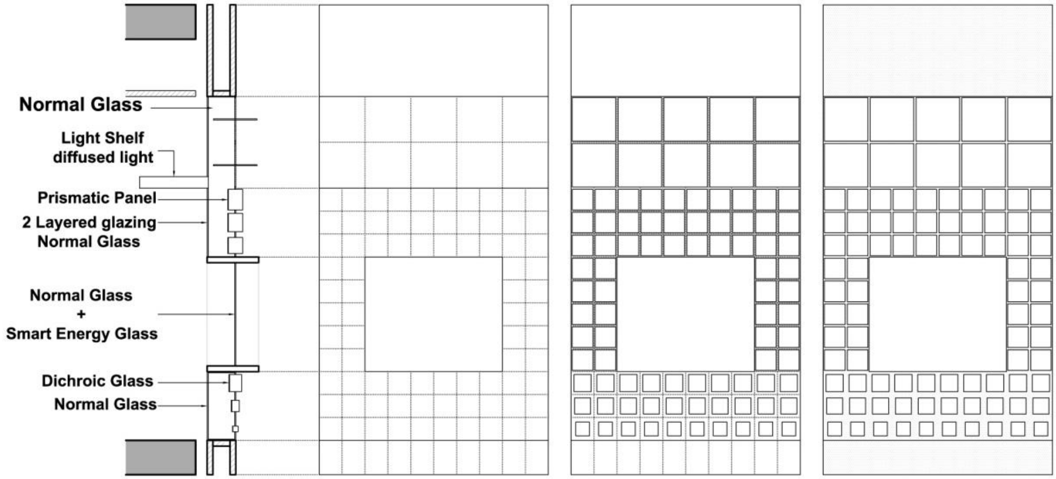
Since all the previous mentioned design alternatives have got some disadvantages, another proposed design concept can be seen in figure-5.9. In this concept the view and light part of side light-view part are separated. So, the central part is reserved for view, which is supposed to use the Smart Energy Glass, which makes it possible to adjust the view through the glass in three options; Dark, Privacy, Bright (for detailed information see [29]). The rest of window is composed of modular perforated surface, which inside each opening an adjustable prismatic panel is mounted. These panels are supposed to rotate in 3 directions (vertical, horizontal, diagonal). This can be achieved by a system of central hinge (which is the only fixed point of the panels) to adjust them. The whole system is like a curtain wall system hanged in front of two-layered glazing behind it which is made of normal glass.

Figure-5.9. Design Final Concept, rotating prismatic panels which provides movement in 3 directions.



The light shelf is divided into two inner and outer parts. The inner part which is fixed made of matt surface to provide diffused light. The exterior part in fact is part of curtain wall system, which can adjust its angle horizontally to provide appropriate redirection of sunlight. Its surface is coated with warm color tone color, which can enhance the reflected light color tone.

Figure-5.10. Combination of Light shelf with rotating prismatic panels.



The modular design of façade component makes it possible to customize it based on different application needs. For example, the size of view opening can vary based on view requirements (Figure-5.11).

Figure-5.11. Examples of Modular design of façade system which makes it possible to provide different options and variation.

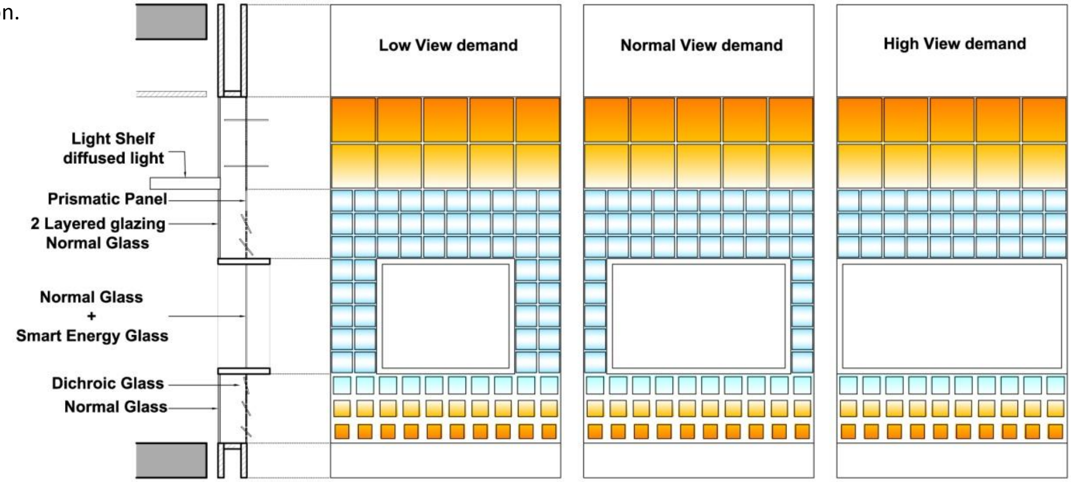
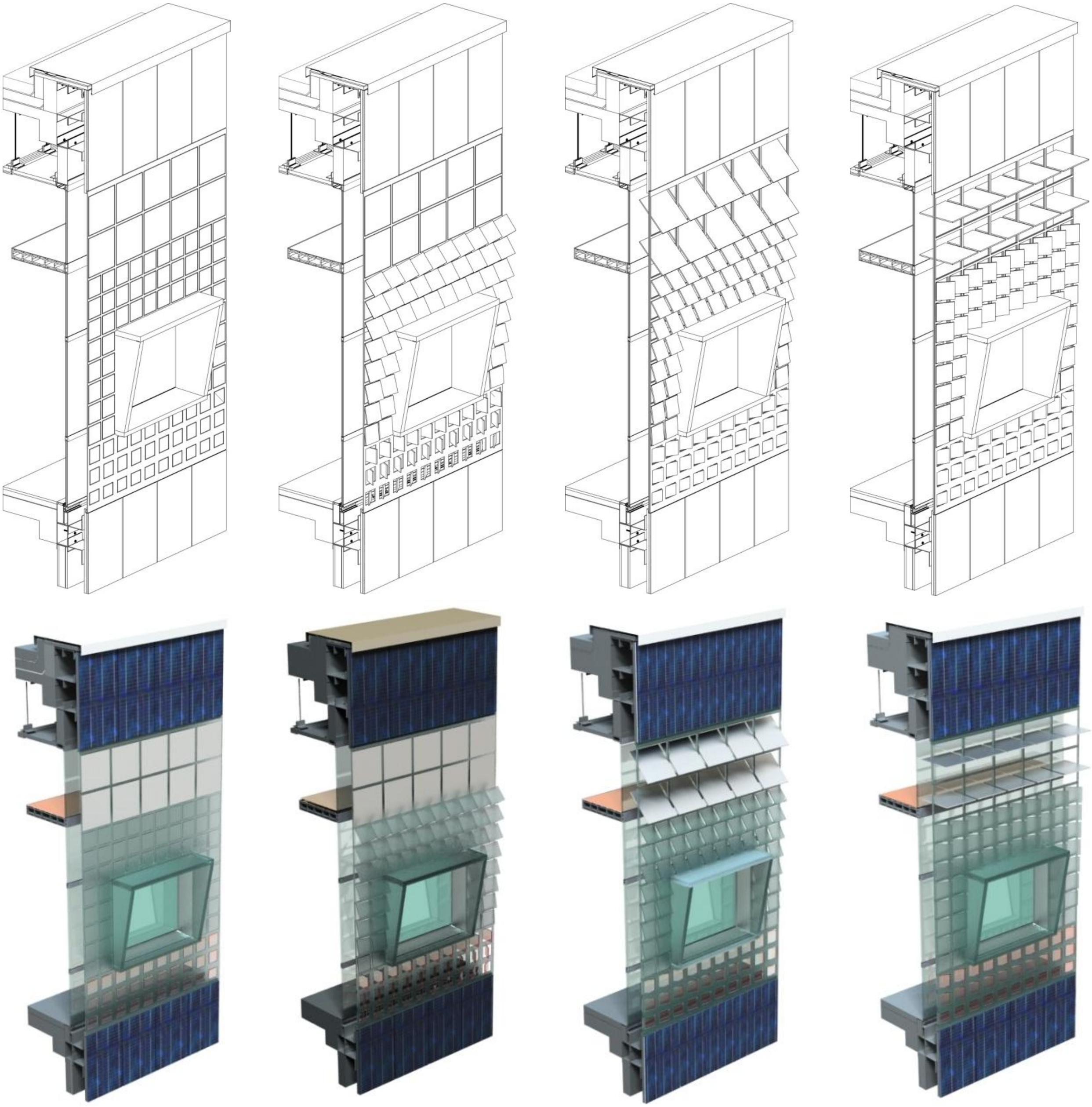


Figure-5.12. Examples of different façade situation resulted from adjustment of panels based on sun angle.



5.7. Sizing overhang

A well designed overhang on south facing windows is the one which can provide shading from high summer sun, while still allowing the low winter sun to shine in and provide welcome solar heating. The length of overhang or sun shading depends on the angle of sun and also the height of shading element. The aim is to minimize summer ray penetration inside the building. So according to façade design and height of overhangs the required length of overhang can be calculated. This can be calculated by using the following equation [6]: $\tan\theta = \frac{Y}{X}$

$\theta =$ Sunray angle

$Y =$ Height of overhang above ground

$X =$ Horizontal penetration in feet behind the edge of the overhang

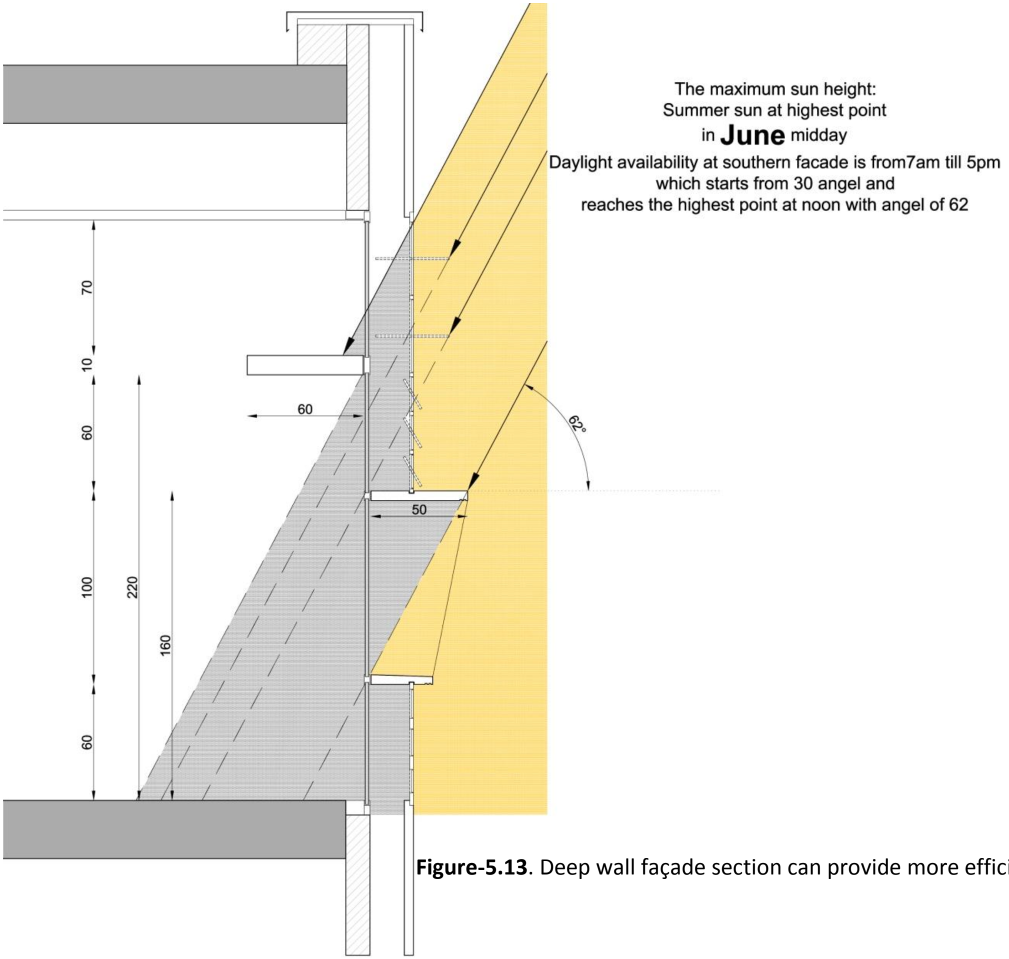
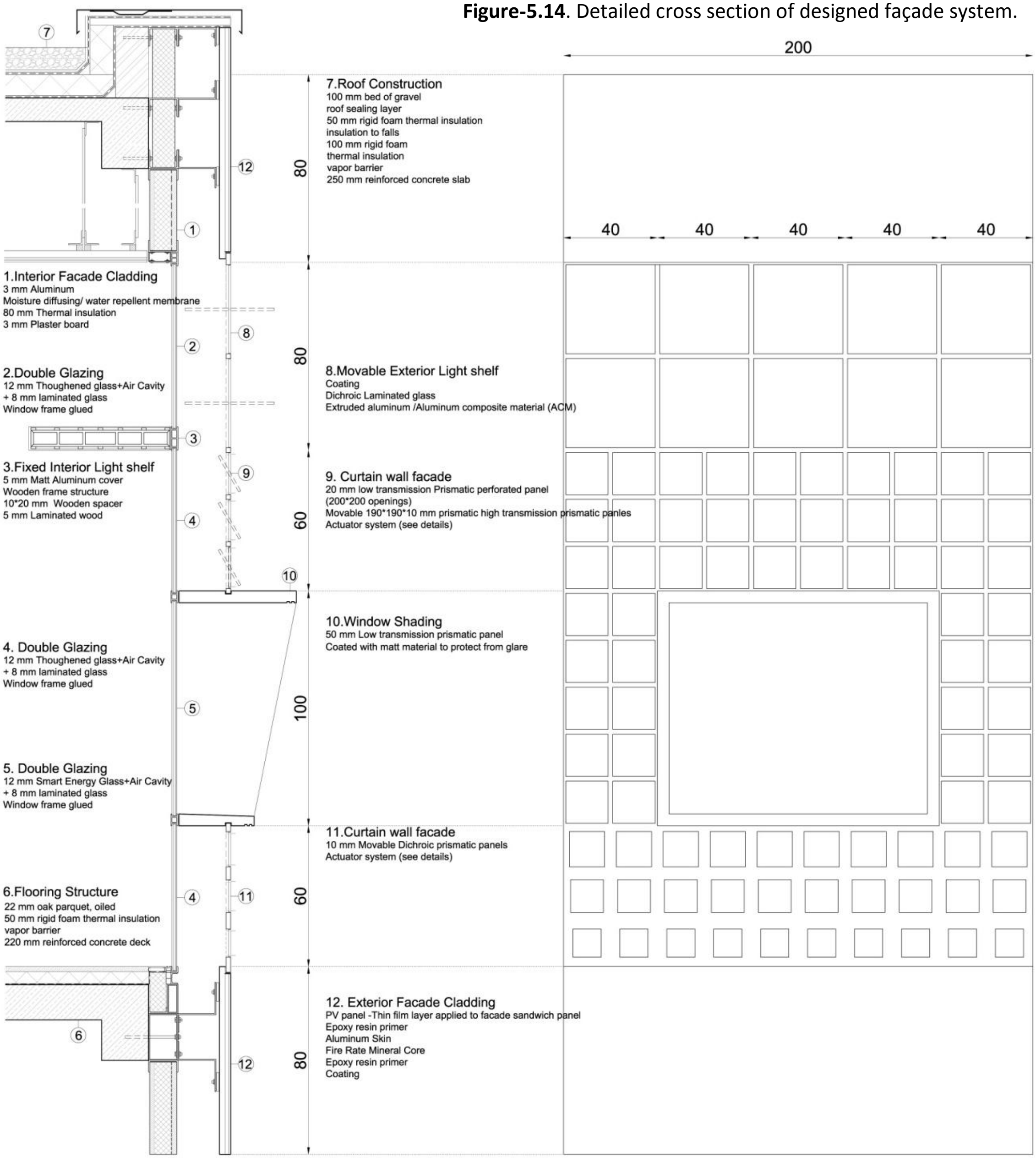


Figure-5.13. Deep wall façade section can provide more efficient shading inside.

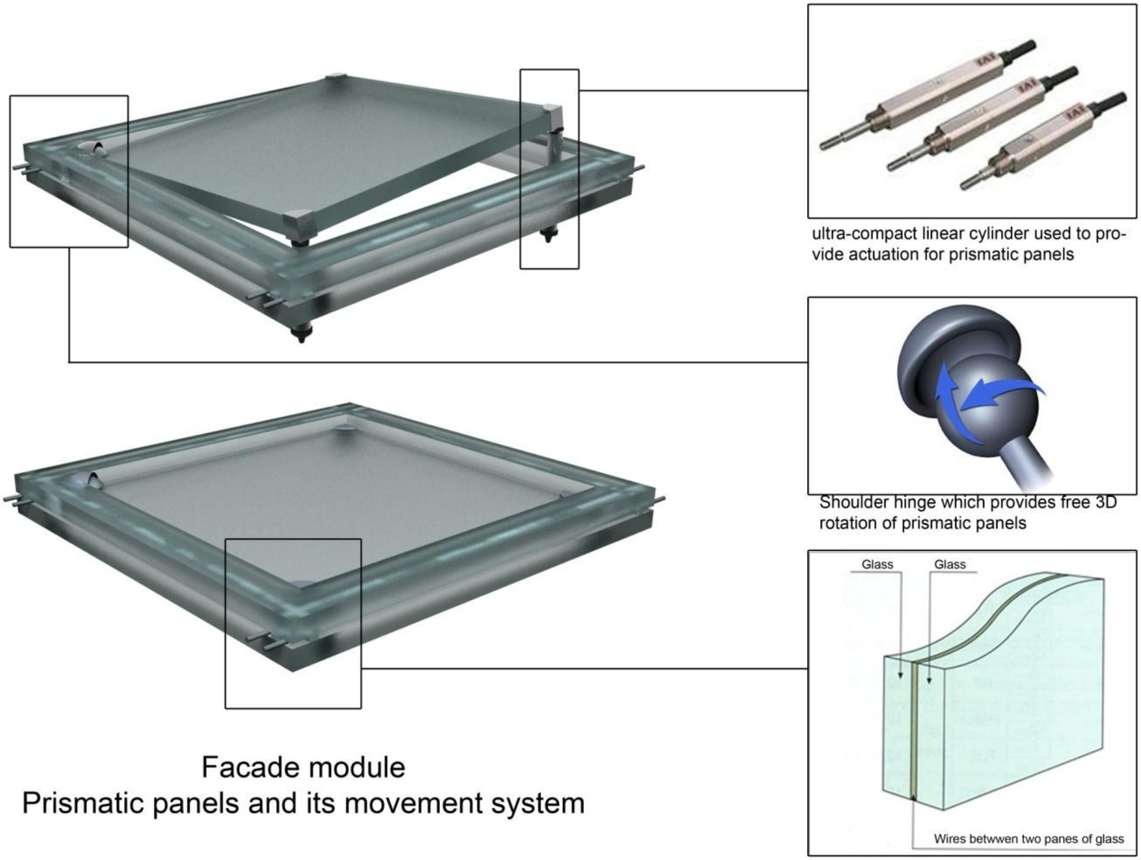
5.8. Technical analysis

Figure-5.14. Detailed cross section of designed façade system.



Prismatic panels are supposed to move in 3 directions: vertical, horizontal and diagonal to be adjusted for different sun ray direction. To provide this movement, one possibility is to rotate these panels around one of their edge corners, and three other corners should be free to provide movement. The mechanism to provide the movement, is ultra-compact linear Cylinders, which makes it possible to adjust the length of corner levers.

Figure-5.16. Mechanism used to provide moving system of prismatic panels.



The energy needed for actuation of Electro cylinders, can partly be provided by PV panels installed in parts of façade which does not provide glazing inside the building:

A: Surface area of PV panels in each façade module: 200*80cm (number of PV modules=30)
N: number of required min pneumatic cylinders per each façade module: 50*2
(2 mini pneumatic cylinder for each movable prismatic panel)
Mono-crystalline Sunpower PV, power per each module : 3.33 w (module size=155*155mm)

PVGIS estimates of solar electricity generation for Eindhoven [30]:

Location: 51°26'29" North, 5°28'11" East, Elevation: 19 m a.s.l.,

Solar radiation database used: PVGIS-classic
Nominal power of the PV system: 0.1 kW (3.33 *30=100w)
Estimated losses due to temperature: 10.3% (using local ambient temperature)
Estimated loss due to angular reflectance effects: 4.3%
Other losses (cables, inverter etc.): 14.0%
Combined PV system losses: 26.1%

Ed: Average daily electricity production from the given system (Wh)= 152

Calculating the required energy for ultra-compact linear cylinder [31]**:**

Each The ultra-compact linear cylinder needs 2.5 W
2.5 *2* 50 (number of panels)= 250 W

P= 250 (w)* 2 (hour: average duration of time being in use)=500 (Wh per day)

152*100/500= 30 % of required power can be provided from generated power by PV panels.

5.9. Simulation of façade daylighting performance

To simulate daylighting performance of designed façade product, rotating panels were simulated in grasshopper, and the result was run in Ecotect. The aim is to put into practice different selected daylighting availability and examine the façade performance in different positions inside the classroom. It is needed to mention that, due to many various characteristics aspects of daylighting, the focus of the simulation is only the study of illuminance. So, view, glare, and color tone are not studied in simulation phase. So, here are the selected situations:

- **Extreme Daylight availability:** around noon in June, and early in the morning or late afternoon in December

- **Skylight or Sunlight:** diffused or direct sunlight

- **Distance from the façade inside the classroom:** 2 points are selected inside the classroom, close and far from the window.

The daylighting performance of the façade is analyzed in Ecotect. Also to simulate, the façade sun-tracking performance according to sun position, the rotation of panels in two days are simulated:

- 1 June for high sun ray angle.
- 1 December for low sun ray angle.

The results are shown as video files in the CD, attached to this report.

6. Discussion and Conclusion

6.1. Conclusion

Daylighting has a major impact on providing visual comfort and health of users. This requires the façade design to rely on using maximum available daylighting. However, both contextual requirements (quality and quantity) and users' lighting requirements are variable. On one hand, the desired daylighting quality, quantity, and needed amount of view depend on users' comfort situation and their type of activity. And on the other hand, the contextual situation which is the daylight availability is variant. This requires the envelope of building to be designed in a way that can be adapted regarding to those variations. There are so many different daylighting systems which provide different enhanced daylighting characteristics. A heterogeneous fenestration, makes it possible to apply appropriate daylighting systems to different parts of façade, which makes it possible to get desired daylighting inside. By combining appropriate and consistent daylighting systems including light shelf, smart energy glass, dichroic glass, and prismatic panels with different light transmission in such a heterogeneous fenestration, the transmitted daylighting has got both diffused and redirected characteristics, with the ability to adjust the amount of view without effecting the illuminance, and also enhancement of its color tone.

6.2. Recommendations

Due to research scope, this research had to narrow its focus in several phases. So, it is focused on visual comfort, and the design approach was focused on side light (top light is not studied) and later in lighting quality and quantity measurements it was focused on illuminance, view, glare and color tone. Moreover, the lighting quality and quantity inside the classroom must be studied with presence of top lighting also. For example, the illuminance and its uniformity on horizontal surface is highly influenced by top light which is not studied in this research.

According to lighting simulation result, it can be concluded that the designed façade product could provide illuminance variation (with controlled glare, adjustable view and enhanced color tone). However, since there are other lighting quantitative and qualitative factors which might influence visual comfort, this research requires completed studies in these fields also.

Furthermore, this research has studied visual comfort, and other comfort indicators (specially thermal comfort which is highly influenced by daylighting) must be studied also to achieve the desired comfort level. Designed rotating prismatic panels with combination of light shelf, has shown good performance in sun shading and illuminance variation; however, overheating and thermal discomfort situation must carefully be studied to avoid unwanted discomfort in other areas.

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