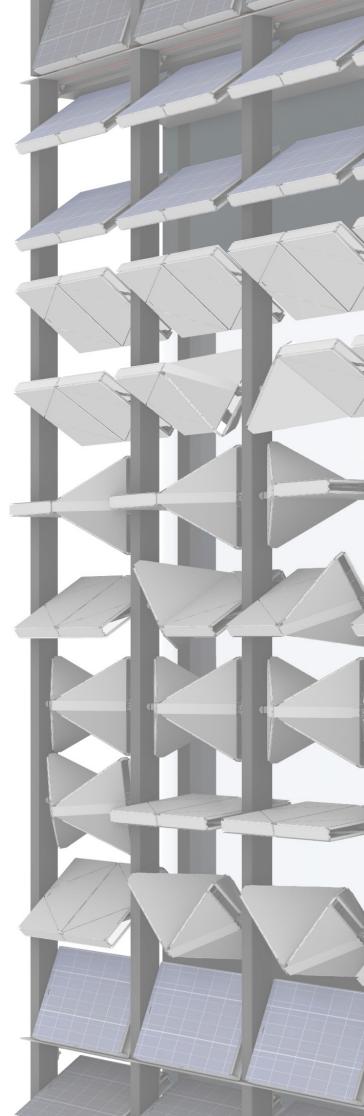# FACA-DE-LIT

**Facade optimisation for visual comfort
by controlled daylight distribution
in high rise office buildings**

Masters Graduation Report I 2019-2020

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Faca - de - lit

Facade optimisation for visual comfort by controlled daylight distribution in high rise office buildings

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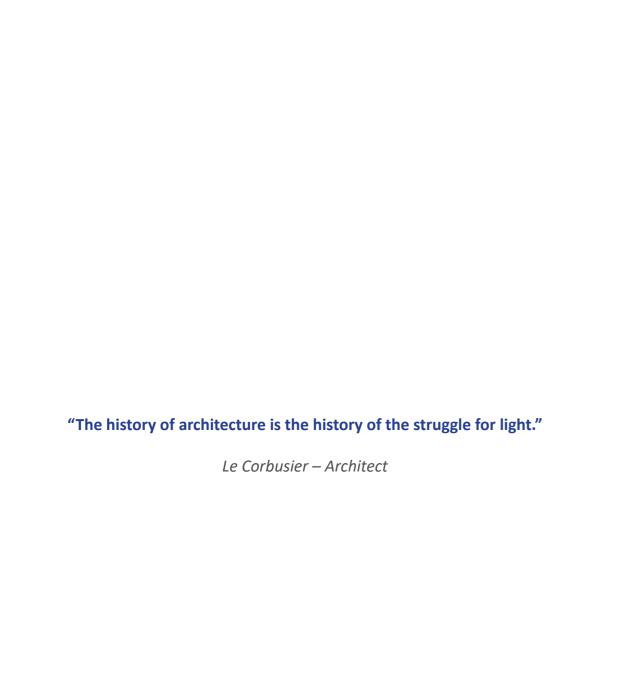
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F A C A D E + D A Y **L I T**

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F A C A - D E - **L I T**

Facade is part of building envelope that allows the penetration of light and influences the performance of daylight. (Rush, 1986)

Daylit is a term used for the amount of daylight that is visually comfortable for a humans eye. (Chauvel, 1982)

"The history of architecture is the history of the struggle for light."

Le Corbusier – Architect

Acknowledgement

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1.0
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1.1 Background

Architecture has always been influenced by historical, social, and political acts throughout history. A new concept that has evolved in shaping architecture is sustainable solutions to the built environment (Lechner, 2015). With technological advancement, it became necessary to develop the possibility for architecture to undertake a more scientific approach and perform well in response to the environment. Two major aspects offered within the building performance framework are energy consumption and human comfort - thermal, acoustical, indoor air quality, and visual.

Comfort and discomfort are major concerns of users in an indoor environment. From an architectural perspective, it is essential to study the surrounding environment and existing traditional design strategies that influence the building's configuration and performance.

On average, a person spends almost 80-90 % of his life living inside buildings (Klepeis, 2001). Therefore, the indoor environment of a building should be comfortable and healthy environment for its users. Construction accounts for nearly 19% of global greenhouse gas (GHG) emissions (Lucon, 2019) and about 31% of global energy demand (Urge, 2012). Minimizing energy demand and maximizing energy efficiency in the built environment is believed to be a solution to overcome climate change globally (Anderson, 2015). Furthermore, the energy demand of a building while dependent on the indoor environment, is also influenced equally by the behaviour of its users.

The European Union (EU) makes a high investment into resources to spread awareness about new energy-saving strategies and policies (EU, 2010). Amongst which electric lighting design has been identified as a critical issue that has been framed out in many architectural studies. It demands the need for better daylight designing. The European Union has introduced specific standards and methods in their addition EN 15193. The design assessment methods mentioned in the European Daylight of Building Standards focuses on building the comfortable environment. Thus, it has become essential to include daylighting standards into practice.

The evolution of multi-storey buildings has created a challenge when it comes to playing with the facade to obtain visual comfort.

Urbanisation

Population Rise

Growth of High-Rise

Indoor Comfort Demand

1.2 Problem Statement

According to a study by Raji, Tenpierik and Dobbelsteen, a high-rise building's orientation, shape, and envelope have major influence on the performance. However, the orientation and shape of the building are usually limited to site constraints and the urban condition. In this case, the building's envelope becomes a crucial element to be optimised for better energy performance. Building envelop is the layer considered between the inside of a building and the outside environment, which helps to improve human comfort. Also, with technological advancement in the evolution of the facade, an interest has been developed towards better energy performance of the building, that includes improving indoor comfort and visual performance. From the highly glazed facade system to a dynamic facade system, many approaches have been made that work best for providing daylight to the building.

Daylighting office buildings in high-rises is a challenging design problem. Side lighting is the only option that can be considered in high rise buildings (Figure.1.1). Daylight entering through a window creates an excessive lighting zone close to the window and follows with the gradient that goes light to dark towards the inner depth of space (Figure.1.2). It leads to a situation where illumination from the same facade exceeds the comfort requirement of the area closer to the window and make an over-lit situation and leads to excessive heat gain and glare. Wherein, on the other hand, the illumination from the same glazing facade is limited to profoundly deeper rooms, making the room situation under-lit which leads to the use of artificial lights. This unbalanced and uncontrolled distribution of light makes visual discomfort in the indoor environment (Figure.1.3). There are not enough facade solutions available that can help to bring a balance by a uniform distribution of daylight among these spaces with deeper depths. This thought creates a scope for research, to investigate a facade system that adapts to the room's depth simultaneously with external daylighting conditions and provide a uniform distribution of light along with its depth.

The daylighting condition is highly dynamic, which changes all throughout the day and over the year. Simultaneously, the parameters like depth of the room will affect the amount of daylight illuminance to pass through the facade, which adds complexity to the design. It is challenging to design with a conventional design method considering all these parameters; hence, the use of computational design can support to solve such complex challenges. Wherein, a specific method to solve this challenge is not available yet and therefore there is a possibility to explore design solutions and come up with the best performing method that has more efficiency in bringing visual comfort to the indoor environment.

Visual discomfort has a significant influence on health and productivity of occupants; and also has a significant impact on energy consumption. In such a situation, it becomes necessary to address this issue of daylight to gain controlled distribution and visual comfort throughout the space in an office building. It can result in an immense value of energy-saving on the scale of a high-rise.
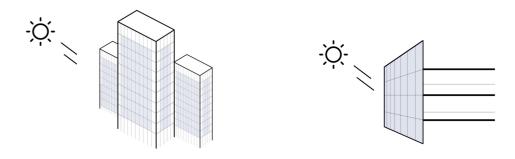

Figure.1.1 provision for daylighting in a highrise through side lighting.
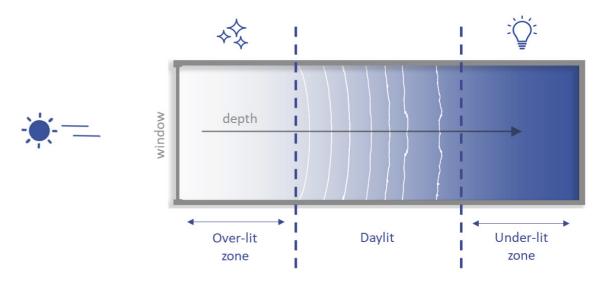

Figure.1.2 showing Gradient of intensity of light going dark towards greater depth making non uniform distribution of light
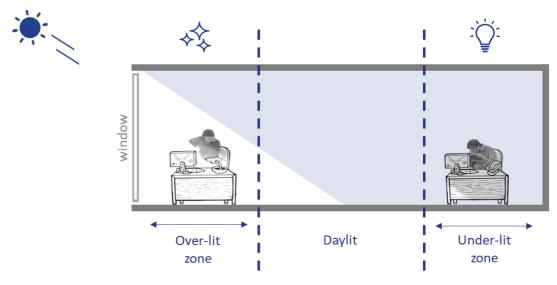

Figure.1.3 showing an illustration of Visual discomfort experienced by occupants in office workplaces

1.3 Research Objective

Main Objective:

Considering the aspect of the aforementioned statement, it becomes quite challenging for an architect to design a facade system to improve visual comfort with the focus on uniform distribution along with varying daylight conditions using conventional design methods. Thus, the main objective here for the research study is to increase performance efficiency for the visual comfort of an office space with help of computational methods and optimisation process by developing a facade system that distributes the daylight to indoor space more uniformly; bring a balance of light intensity between under-lit and over-lit areas of a space; adapts to various external factors that are responsible for dynamic daylight behaviour; and would results in a controlled distribution of daylight for occupant's comfort.

Sub objective:

- To develop an understanding of the fundamentals of daylight to determine the indoor factors responsible for the visual comfort of an occupant and the external factors responsible for the change in daylight levels.

- To propose an investigation on various facade strategies available for daylight performance to gain an in-depth knowledge of current trends of the facade in practice and as well as in research.

- To develop a façade design concept that is capable of controlling two different aspects simultaneously, which is to enhance daylight towards greater depth to overcome the under-lit situation and to reduce/diffuse daylight near to window to overcome the over-lit situation. Moreover, the designed façade should also be able to adapt to the dynamic nature of daylight which should respond to external factors responsible for uncertain daylight levels.

- To determine the evaluation criteria that can be useful for validating a façade for its visual comfort with uniform distribution.

- To determine the set of façade design parameters that are more crucial to lead the designed façade into a highly performative façade in controlling the distribution of daylight and can comply with all external daylight factors.

- To develop a computational workflow that will determine the process for gaining an optimal solution using parametric modelling, daylight simulation, and optimisation method.

- To determine the extent of the proposed facade for its effectiveness in performing for visual comfort in different seasons.

1.4 Research Question

Main Question:

" Based on computational design methods and techniques, how can a facade system allow for indoor visual comfort by daylight's controlled distribution throughout the depth of a room in a high rise office building? "

Sub-Question

1. What are the requirements and parameters that characterise the space and its occupants for visual comfort? *[Literature]*

2. What is the state of art in façades to control daylight distribution? *[Literature+Case Studies]*
   2a. What are the facade systems that deal with daylight enhancement in an indoor space?
   2b. What are the facade systems that deal with daylight reduce/diffuse in an indoor space?

3. What design approach could be best to avoid glare at the same time while gaining more daylight? Or a design approach to bring balance between over-lit and under-lit situation through a facade? *[Design Concept]*

4. How a facade system can be assessed for visual comfort that control daylight's distribution along the depth coping with the dynamic behaviour of daylight? *[Visual Comfort Criteria]*

5. What computational design approach could be best to achieve an optimal solution in this case? *[Computational Workflow]*

6. To what extent a balanced distribution of daylight within a space can be achieved throughout the depth for indoor visual comfort through the optimised facade? *[Performance Evaluation]*

1.5 Methodology

The result of the project is a dynamic façade solution to deal with visual comfort, achieved using a research methodology that consists of four different phases; Research Framework phase, Literature phase, Computational Design phase, and Result phase. All the phases play a role in achieving the final result.

Research Framework begins with a background study. The main issue to be improved is pointed out in the problem statement, followed by the research objective that helps overcome the issue. Based on this framework, a research question is formulated with various sub-question to define the research in steps.

Literature Review provides all necessary understanding of the topic and subtopics requires to proceed further in the research. The categories into which these topics were divided are - the present scenarios of high-rise Office buildings, understanding fundamentals of light and visual comfort, examining various facade strategies, consideration of guidelines for daylighting design, and use of computational design methods and simulation tools.

The analysed literature was used to determine the design requirements needed for facade design. A geometry was selected and modified, and the first design proposal of the facade was then made. This model was taken into Rhino and Grasshopper for parametric modelling, and the most crucial parameters of the façade were developed. This facade is formulated by fixing one location, weather type, and the room's dimension with appropriate depth. The model is further analysed for daylight simulation using plug-in Honeybee-Ladybug plus and was further sent into optimisation process using plug-in Wallacei. The optimisation method is applied to bring a near-optimal solution for the façade's performance on daylight's quality and its uniform distribution for indoor space by reducing over-lit and under-lit areas to gain maximum daylit area.

The solution obtained from the optimisation process was tested for the evaluation criteria to validate the façade for the visual comfort criteria of the space. The gathered knowledge from the optimisation process was used to formulate a full scope workflow that can help to optimise and evaluate a facade solution that deals with the dynamic behaviour of daylight to provide visual comfort indoors. Although, this research uses the limited scope of the same workflow. Furthermore, the final design of facade was detailed for its constructability and feasibility with its dynamic motion.

The following scheme of methodology (Figure.1.4) provides a general overview of the structure in which this research study is going to take place. The various steps that have been described are to carry out the solution for the main research question.
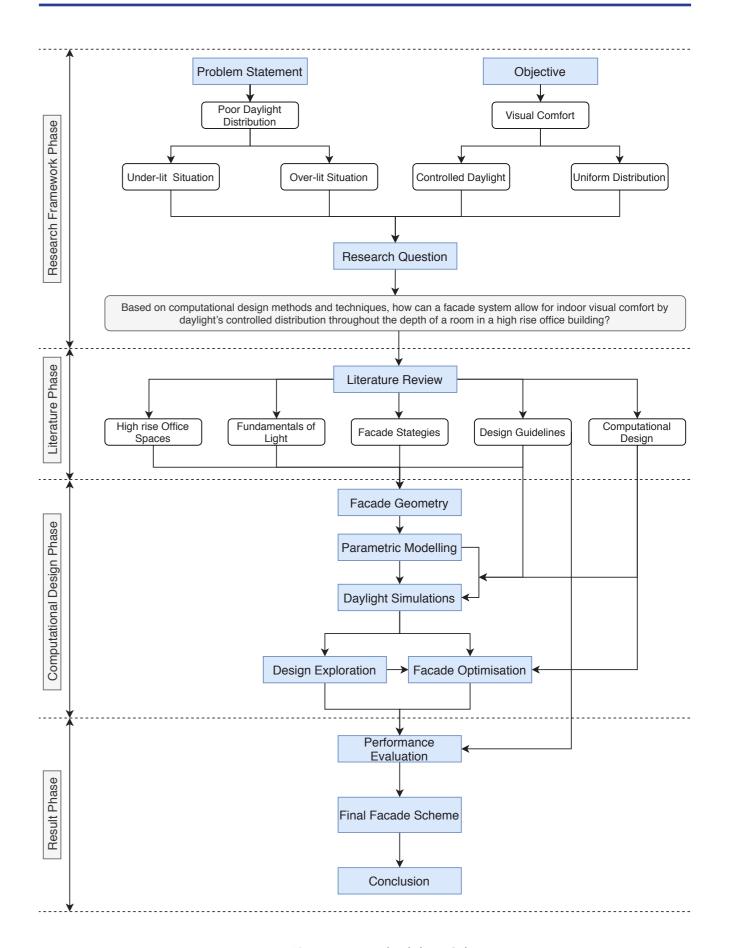

Figure.1.4 Methodology Scheme

1.6 Boundary Conditions

The boundary conditions are applied to define the intended scope of this research study:

- The research study focuses on high-rise buildings having an office as a typology with an open floor plan and deeper depths.

- The research is analysed for visual comfort and daylight performance for a hypothetical office space with a specific dimension and orientation. Consideration of the surrounding context and floor level is neglected for this study.

- • To reduce the complexity of the process and to achieve results within the determined time span, a set of only one parameter was considered for optimisation.

- The proposed final design of the facade is made based on the technology available in the market that can be integrated easily for its constructability.

1.7 Relevance

Scientific Relevance:

Many approaches have been made on controlling daylight with the help of a dynamic facade system responding to sunlight availability but what really matters is its performance. This research shares knowledge on the development of a facade system that behaves dynamically with respect to daylight to gain controlled distribution in spaces for visual comfort with high performance using computational design method and optimisation. Furthermore, this study provides a list of parameters that are crucial for improving the performance efficiency of the façade for uniform and balanced distribution of daylight. Moreover, the research study offers a list of evaluation criteria that are important for validating a façade for its visual comfort performance and uniform distribution of light intensity.

A full scope workflow for optimisation has been developed in this research study; however, the research uses limited scope from the same workflow to obtain the optimal solution of the façade due to the time constraint of the study. The developed full scope optimisation workflow is believed to have potential use for many designers and architects to follow this method to evaluate many different alternatives of a dynamic facade system with high effectiveness in daylight performance. The alternatives can vary according to their design language and aesthetic requirements with a vision to gain uniform distribution of daylight along with the depth of space. Furthermore, using developed workflow, a high performance efficiency of facade concerning visual comfort can be achieved. The developed workflow can also be further extended and modified to add other aspects like the view to outside.

Moreover, the proposed façade design has shown extraordinary results that align with all the required criteria for visual comfort; hence, the proposed façade design can be taken as base geometry for further research such as optimisation for thermal comfort or view to outside.

Social Relevance:

The final product of this research is a dynamic facade, capable of controlling daylight distribution for indoor spaces throughout the depth, and will likely have multiple impacts on the building and users. Accomplishing visual comfort in these spaces will broadly impact the user's functional efficiency, productivity, and healthy life. Also, the availability of an adequate amount of daylighting in indoor spaces will have a significant influence on the reduction in the building's overall energy-consumption level.

In recent years, many discussions are taking place mainly about topics like increasing energy demands in office buildings. Poor distribution of daylighting categorises energy consumption by:

- Over-lit room areas, due to excessive brightness and glare results in heat gain and demands high cooling loads. Moreover, High-rise buildings tend to be more energy-intensive due to direct solar gain from radiation (Godoy-Shimizu, 2018).

- • Under-lit room areas, due to low illumination demands the use of artificial lighting. Thus, as observed office buildings consumes a high level of energy owing to this use of artificial lights.

Heat gain and use of artificial light due to lack of daylight, increases the energy consumption of the high-rise which accounts for the energy consumption of about 40% in the building sector of Europe, 26% for an office building (Eurostat 2014), which further demands 44% of the energy only for lighting (Todd 2011). Therefore, using this facade system which will be developed using the computational design method will have high efficiency in performing controlled distribution of daylight that will result in a significant energy saving on a scale equivalent to a high rise building.

1.8 Planning and Organisation

	Activity	November			December				Janyuary				
		W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12
P1													
Research Framework	Idea Validation and Problem Statement												
	Background and Methodology Research												
Literature Study	Office space and Visual comfort												
	Facade strategies												
	Design guidelines and Design Stategies												
	Computation Design												
Façade Concept	Initial Design Concept												
P2													
Design Development	Investigating several geometries for façade design												
	Geometry Development and configuration for Facade												
	Parametric Modelling of façade geometry in GH												
Performance assesment	Set simulation workflow in GH												
	Study availability and behaviour of daylight and glare												
Design & Optimisation	Validate geometry with basic simulation												
	Define Parameters and Objectives for optimisation												
	Finalising workflow for optimisation process												
P3													
Design & Optimisation	Design exploration on Material Properties												
	Multi objective optimisation for all Instances												
	Result analysis and Selection of optimal solution												
Result Validation	Evaluation of daylight for Visual Comfort												
P4													
Final Output	Final set of façade design												
	Constructibility and Feasibility												
	Conclusion												
	Reflection												
P5													

February				March				April					May				June			
W13	W14	W15	W16	W17	W18	W19	W20	W21	W22	W23	W24	W25	W26	W27	W28	W29	W30	W31	W32	W33

2.0 Literature Review

2.1 High-Rise Office Spaces

Urbanisation and High-rise

United Nations forecast states that in 2018, population of the world residing in urbanised cities was about 55% and further will increase to 68% is expected by 2050. This will lead to many challenges for many countries to fulfil such needs of fast-growing urban populations (United Nations, 2018). This urbanisation is drawing attention towards building more high-rises as a sustainable key solution to population and need. There have been several definitions given for high-rise, amongst them the classification through building's height and the number of stories is more common. As per the Council of Tall Buildings and Urban Habitats (CTBUH, 2019), all the buildings having a height range between 50m-300m or more than 14 stories will be said as a tall building.

Daylighting in Office Spaces

By using a high glazing system as façades, it distributes the daylight to a certain extent into the office and controls brightness in nearby areas. At the same time, glare control due to direct sunlight penetration through the window is a severe issue of daylighting in office buildings. Occupants face glare in their working place on computer screens. The standard practice is to provide shading with coefficient and low transmission coefficient of glazing and manually operable mini blinds. Under the diffused sky, the blinds are open, and the glazing controls glare and heat gain providing insufficient light. However, during clear skies, due to excessive amounts of light, the blinds are kept closed. While on the contrary, the indoor spaces use artificial lighting to lit the room. And this demands a better solution.

Importance of Daylighting in Office Spaces

Daylight has a prominant impact on the work environment of occupants in a working office space. It increases the functional efficiency of a working person, increases human productivity and improves health (El-Dbaa, 2016). An adequate amount of daylighting in a working area allows for better functional activities like writing and reading. Also, it provides better visualisation towards colour, textures, and form and increases the functional efficiency of that space. A study shows that people working in artificial light or during the night have more negative mood swings compared to those who work in daylighting, as psychological well-being, brain activity, are somehow influenced through light quality in the built environment (Tomassoni, 2015). The reduced amount of lighting can affect the nervous system and leads to fatigue. Thus, controlling the amount of daylight in a working space improves user productivity and health (Tomassoni, 2016).

2.2 Fundamental of Light

2.2.1 Visual Comfort

For the activities related to Offices, the most important physical requirement is the availability of the adequate and ambient quality of light in the space (Raymond and Cunliffe, 1997). It makes the space visually comfortable for users to perform their work. Visual comfort in office spaces is the criteria that measure an individual's ability on how comfortably they do their tasks with the ability of perceiving the surrounding environment via photo-sensory perception (Vischer, 1986). Visual comfort is a dependent phenomenon on factors like the intensity of available daylight, light's incoming direction from the source, the contrast between surrounding, surfaces as secondary reflecting source the type of the activity to be made and also the photo-sensory reaction of an occupant's eye.

Daylighting for indoor visual comfort

Light plays a vital role in achieving visual comfort in indoor spaces by providing excellent visibility and visual indoor environment. A human eye is capable of observing the wavelength between the range of 360 to 830 nanometre (nm) (Baker and steemers, 2002)

As daylight is the source to create a pleasant environment in indoor spaces with visual comfort, with that, it is also a source of saving energy of the same building.
A daylighting system has to be sufficient enough to provide natural light to indoor space as required and simultaneously should create a visually comfortable environment (CIE, 1987). The penetration of daylight to indoor spaces is majorly through the facade system which comprises of the window opening or several other fenestration systems that are available in the market.
Some of the main factors that influence visual performance are:
• Good visibility which is obtained with a sufficient level of daylight and its uniform distribution,
• Visual comfort is when the space is free of glare or excessive brightness.
• Facade system, where window or fenestration system is determined by shape, position, the volume of opening or WWR, type of glazing (or percentage of visible light transmittance) and shading system (Baker, 2002)

By getting an idea of the available illuminance value in the space of the building can be used to create a visual comfort level while designing the facade system for the building.

The illuminance value given to spaces in designing a building will have a massive impact on energy efficiency on a daylit space of a building. The illuminance value assigning for space also depends on the location and its climate, as the amount of daylight varies for different climate conditions.

Considering an example of temperate climates where the facade has a glazing area with low thermal insulation results in high heat gain. In this case, the amount of glazing area recommended during design development is less on the facade, which is enough to allow an adequate amount of daylighting in indoor spaces. During winters, when daylight hours are short will demand to use artificial lighting during the working day due to an insufficient amount of daylight available. This transition makes the illuminance value sensitive to the light level required for indoor spaces. On the other hand, in tropical climates, the length of the day and illumination from the sky is remarkably higher, and daylight is uniform. It makes no penalty on energy level relating to the size of the glazing area on the facade; however, it does affect visual comfort due to glare that will be associated with a massive amount of diffused solar radiation.

Factors for visual comfort

Many studies on daylighting have mentioned several parameters that bring better visual comfort in a building. A good daylighting quality proves best for occupants when the lighting system (Veitch, 1995):
• Create an appropriate condition for seeing
• Support performing various tasks
• Provide a healthy environment and reduce illness
• Promotes comfortable interaction and communication
• Contributes to appreciating the aesthetical value of space
• Contribute inappropriate situational mood

The factors that contribute to lighting quality in a building to define visual comfort in a space (Miller in 1994):
(i) **Availability (or distribution) of Daylighting** - Task illuminance and its uniformity
(ii) **Glare** - from source luminance or comparative luminance of room surfaces
(iii) **Contrast** - Task contrast and contrast from surrounding surface
(iv) **Colour Temperature** - colour rendering of surrounding and spectrum
(v) **View** - Visual quality and visual interest

Above mentioned factors are essential to be achieved to provide comfort to occupants in a space. Following the main objective of this research, which is to gain controlled distribution, the first three-factor were considered for the scope of this research. Where distribution of daylight is taken as the main focus for the optimisation process of this research and the factors Glare and contrast are used in the evaluation to justify the achieving of visual comfort in a space. Colour temperature and View factor are not considered in the scope of this research.

2.2.2 Glare

The definition by the Illumination Engineering Society (IES) says that glare is when excessive and uncontrolled brightness causes the visual sensation to the human eye. In other words, when the sensation of luminance gets higher than the luminance accepted by eye, it causes annoyance, discomfort, and loss of visual performance. The two effects on the viewer due to glare are:

• Disability Glare
An intense light source causes a reduction in the visual appearance within the visible field.
• Discomfort Glare
The annoyance in the eyes experienced due to the overly bright source that causes sensational pain.

Glare is caused by direct light in the visual environment from the source of intense light that bounces back from any reflecting surface or material. To improve the lighting inside a building reduction of glare is an important phenomenon to be taken care of.

Factors Effecting Glare

• High illumination
• Reflection
• Direct sunlight

How do glare impact our comfort

Glare is directly linked to distribution and simultaneously quantity of light. Inside a building with a balanced level of light distribution, the addition of direct glare from outside sources will create visual discomfort. On the other side, glare not only impacts on visual comfort but thermal comfort. Radiation from excessive glare can naturally heat space. In the case of rooms with warm air temperatures, intense glare can cause overheating.

How to measure Glare

In practice, the measure of the glare phenomenon is to record the quantity of available light reaching to the human eye. The measure is possible by using a photographic technique called HDR photography, which combines multiple photograph exposure and creates a highly dynamic range. With using the captured photo, a luminance mapping is produced which can help to analyse daylight, glare and visual comfort.

2.2.3 Contrast

In daylighting phenomenon, the ability to see surrounding is determined by illumination level and its distribution in a space; where the quality of richness and complexity of the perceived composition is determined by luminance and contrast (Rockcastle, 2011). Thus, the distribution of lux level in a space within the ambient range of visual comfort will give an idea on how much area of the surrounding is appealing in the view of an occupant.

Contrast is a value of differentiating an object or an area based on luminance or brightness difference with other object or an area within the same field of view ("Contrat," n.d.). In other words, it can be said that the difference experienced between the brightness observed by an eye from highest white patches to that of the darkest black patches of an object or an area. Perceived contrast can be reduced significantly with maintaining ambient light level inside a space. A human eye is more catchy towards contrast than absolute luminance. For example, a human eye perceives the view in the same way, even if there are changes in illuminance for a whole day.

2.2.4 Daylight Metrics

Luminance - The amount of light that passes through which is emitted or reflected from a particular area and falls within a given solid angle.
Its unit in SI is Candela per square meter (cd/m2)

Illuminance - The measurement of the amount of light that is spread on a surface area. It is measured as the total luminous flux incident on a surface per unit area.
The SI unit for Illumination is lux.

Luminous Flux - The measurement of the brightness of a light source in terms of energy being emitted. In other words, it is the measurement of energy emitted from a light source in the form of visible light.
The SI unit of Luminous flux is the lumen.

Daylight Factor (DF) - Its the ratio of the availability of light level inside the building to that of the light level present outside the building. DF in architecture and the building design is used to access the natural light levels indoors as perceived on an imaginary working plane/working plane or surface.

Daylight Autonomy (DA) - It is the percentage of hours over period of a year where a given point on a working plane is above a given illumination level.

Useful Daylight Illuminance (UDI) - It is the percentage of hours on a period of a year where a given point on a working plane is above a specified range of illumination level.

Daylight Glare Probability (DGP) - The overall brightness level in the view, the position of sources vof glare and visual contrast.

2.3 Facade Strategies

2.3.1 Classification of Facade

A facade system is considered to be part of the building as an envelope, which plays the role of mediator between the inside space to the outside space. The facade is an element that functions to interface with the exterior, said by Knaack (2007), wherein Hyde (2001) said that the function of the facade is like a human skin which acts as an environmental filter and is capable of controlling climatic factors from the exterior. In short, the facade should be made with a goal to achieve the human comfort level (which can include thermal, acoustical and visual comfort) using some technical solutions.

Based on various technology use, Hyde (2001) define that facade as the skin of building can be classified into five different types shown in Figure 2.1, which are:
1. Thin Skin
2. Inclined Skin
3. Thick Skin
4. Buffering Skin
5. Valve Effect Skin

Here, five different types of facade which function as a climate controller has its strategies to control climatic condition. In the first type which is 'Thin Skin', the facade system has two different tasks to accomplish (i) window glass, to allow the required amount of daylight and (ii) interior shading, to eliminate the excessive brightness or glare issues. The optimal solution to the functionality of the facade is achieved when these two tasks perform coherently.

1. Thin Skin	2. Inclined Skin	3. Thick Skin	4. Buffering Skin	5. Valve Effect Skin
Strategies: Rely on materials for regulating climate such as insulation materials and optical properties of glass.	**Strategies:** Inclined wall and glass away from the sun.	**Strategies:** Using the depth and projections of the façade as well as the exterior shading and optimum orientation.	**Strategies:** Using the depth as well as the environment such as plantations, perforated walls and verandah	**Strategies:** Using open able dynamic windows as valves effects.

Figure 2.1. Classification of facade skin (Hyde, 2001)

2.3.2 Building Fenestration Systems

Rush (1986) takes more interest in lighting aspects in the facade and says the fenestration plays a crucial role as an element of building facade as it allows the penetration of light and influences the performance of daylight. Rush added saying that a fenestration system is a part of the facade system and is building's envelope system. The fenestration system is an opening or composition of openings which allows daylight to pass through and its purpose is to illuminate horizontal work plane and carries several other tasks to function, which are (Moore,1991):
- Increasing transmission of light for every unit of glazing area
- Sunlight's direct penetration and its control
- Minimise illuminance on a working plane
- Minimise surface glare from the working plane
- Excessive brightness and contrast level control, majorly between indoor space and fenestration.

Considering all the tasks and aspects of a fenestration system in a building; Knaack (2007) took this further into his research and divided the fenestration system into three different elements (Figure 2.2). He defines these elements as:
i. The exterior part of the fenestration (includes external shading)
ii. Glazing and framing
iii. Interior part of the fenestration (includes internal shading)

Moreover, considering these three elements based on their flexibility criteria on a facade, the system further categorises these elements into two distinctive typologies (Knaack, 2007):
i. Static component (includes glazing and static part of the exterior and interior shading)
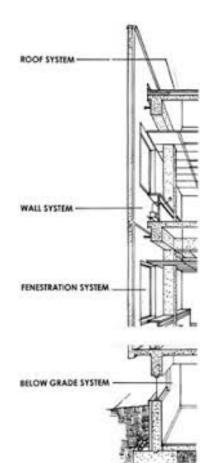ii. Dynamic/Adaptive Component (includes movable part of the exterior and interior shading)

Figure 2.2. Fenestration system. (Knaak, 2007)

2.3.3 Control of Daylight

Daylight is very dynamic in nature. The quality and quantity of illuminance from the sky are variable; this variation is experienced at a different time of the day, season, location, latitude and cloud condition. A specific application of the fenestration system hence becomes crucial to use it for controlled daylight in an effective way. Daylight can be made under control by mean of geometry sun shading devices, and materials.

i. Geometry

The amount of light inside a space can be controlled by altering the form and properties of geometry like its height and depth. Also, the level and depth of the window and the height of the ceiling has a significant influence.

ii. Sun-Shading devices

Shading systems are used to control a specific amount of light as per the requirement of an indoor space. The shading systems are installed to a position in accordance with orientation, geometry, activity, and occupancy of the building. These devices for shading can be installed inside of the window glazing panel or outside. External glazing acts first to redirect light, and it blocks solar radiation from passing it through glazing. Internal shading acts after the light has entered through glazing; here, the room behind gains some heat from solar radiation.

iii. Material

Properties of material like transmittance, reflectivity, absorptivity, has a massive effect on controlling daylighting.

Analysis and classification of Facade systems

To deliver daylight in indoor spaces, the glazing area, shading element, and indoor space must be considered as a single system. This will also determine the view, minimising heat gain in summers and maximising in winters.
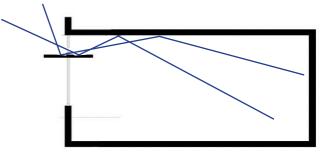
There are various facade component systems which are currently into practice. These systems are classified in two different types with a different purpose, one which is used to enhance daylighting to increase the amount of illumination into rooms with greater depth and an under-lit situation, and the other is for shading which is to block or reduce or diffuse the amount of illumination which generally is required for rooms with over-lit situations to protect it from high illumination and glare issues. The systems used in these two scenarios are:
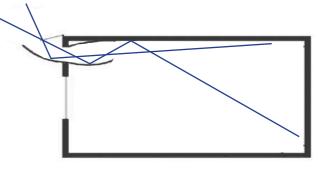
1. For Daylight Enhancement

The main purpose of such a facade system is to enhance the lighting to greater depth and distribute it through interior space. This system can be used to overcome the under-lit situation, where a room has a low illuminance level which is below visual performance comfort. The different types of such systems are (Figure 2.3):

- Light Shelves
    - Horizontal light shelves
    - Anidolic light shelves
- Anidolic collectors
- Reflectors
- Light ducts
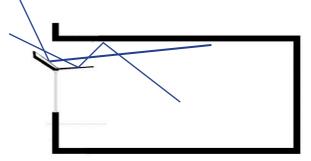
There are some methods and devices available to diverse and direct the penetration of light, 'light shelf' is one of the oldest and well-known examples. Light shelf help in controlling the direction of light by redirecting it from the ceiling. Here, the reflection from reflective material can gain a high amount of light but also the possibility is to create glare issues and replacing matt finish for the reflection will diffuse the light and lose directional control. Reflecting prismatic film could be one of the solutions (Littlefair, 1996).
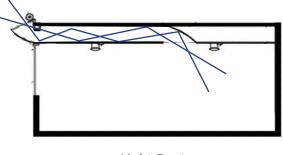
Light Shelves
2X depth of light

Anidolic Collectors
2X depth of light

Reflectors
2.5X depth of light

Light Ducts
3X depth of light

Figure 2.3. Light Redirecting systems

2. For Daylight Reduce/Diffuse

These systems generally help to reduce amount of daylight or diffuse the intensity of daylight or can blocks the penetration of daylight. Understanding of this system will help to overcome over-lit situations in case of this research study. Shading systems are considered in this category.

Shading systems are classified into numerous methods and techniques. The main function of a shading system is to filter the intensity of light passing through the facade. Also, it can function to block completely or part of the light or redirecting the light to indoor spaces. Some examples are:

Overhangs
Overhangs are the element that is placed over an opening like windows to have protection from direct sunlight and provide a better environment for occupants inside. Overhangs work best for south-facing windows, but for west and east orientation the sun is low and hence these overhangs do not perform effectively as they do not block lower sun rays and it results in higher solar gain. These overhangs can also work as light shelves, locating an overhang at the lower position can help to redirect light into greater depth of a deep room.

Louvres
Louvres are the fins element that can be arranged vertically or horizontally which can be placed fixed or at certain angles. Moving louvres has more advantages than a fixed one as it can be controlled according to external climate conditions to improve its performance. The maintenance here in the louvre system is very high as it is very difficult to clean such systems. These systems can be made from materials like aluminium, wood, glass, textile, etc.

Venetian Blinds
These system are the most common type used for shading systems, as it is easy to operate this system to control the penetration of sunlight needed inside the building. These systems are retractable that can be manually controlled or automatic through a switch as per requirement. These systems can be used inside, outside or between the panels.

Moving Shadings
These systems with the help of their motion provide a certain level of flexibility to control daylighting as per requirement and considering external climate conditions. These systems include elements that can do any motion like sliding, folding, rotating. Also, this motion can be in 2 dimensional or 3-dimensional space. These shading systems can be manual or automatic.

Kinetic Shading
These systems are dynamic that responds to external climatic conditions and try to maintain the indoor comfort for occupants. These systems are complex shading system that requires a need for using advanced technology and smart materials. With the help of dynamic simulations, these systems can be made more effective in terms of their performance.

Overhangs

Continuous
Source: Archi Expo

Individual
Source: Australian Louvre Industry

Louvres

Horizontal
Source: Google

Vertical
Source: LouvreClad

Venetian Blinds

Horizontal
Source: The Blind Shop

Vertical
Source: Finance Top Up

Moving Shadings

Sliding
Source: Hunter Douglas

Folding
Source: Fit3rs

Kinetic Shadings

Responsive
Source: Inhabitat

Responsive
Source: Modlar

Based on different performances, there are several categories in which this system has been classified according to its function. Such listing is useful to make it easy to select a system based on its performance, hence, overlapping of systems in various categories can be expected.

2.1. Classification in terms of performance

- Light reflecting
- Light filtering, absorbing.
- Light scattering

| Reflecting | Filtering | Scattering |
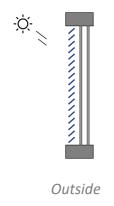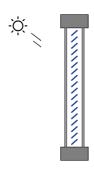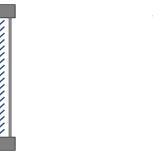
2.2 Classification on Position
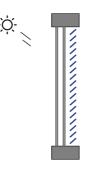
- **Behind the skin -** This system performs after the light has entered through the glazing layer of the facade. This system is used inside to operate and maintain it easily from inside. Also, it stays protected from outside weather, rain, dust, etc. Examples: Curtains, Venetian blinds, etc.

- **In-between the skin -** The elements in this system are fixed within the glazing. Examples: Venetian blinds, louvres, rolling textiles, etc.
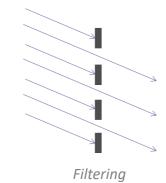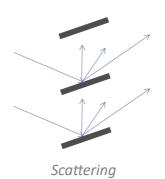
- **Outside the skin -** This system performs first in tackling light from incoming. These elements are exposed to the environment and can be affected by outside weather, rain, dust, etc. Examples: Brise soleil, canopies, rotating panels, etc.

| Outside | Midpane | Inside |

2.3 Classification on Geometry

- **Planar systems - 2D:** In this system, elements are arranged in a two-dimensional plane or can perform the move in the same 2D plane. Examples: Curtains, Sliders, Louvres, Venetian blinds, etc.

- **Spatial systems - 3D:** In this system, the element's movement due to rotation or folding-unfolding makes the use of the 3rd axis which makes them called spatial systems. Example: Venetian blinds, rotating panels, folding panels, opening shutters, etc.
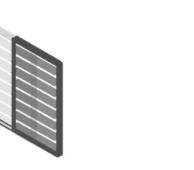
Static / Fix Facade System   Rotating   Sliding   Folding

Dynamic Systems

2.4 Classification on Adaptability

- **Static systems -** In this system, the element of shading system remains fixed throughout the year and do not change its position, orientation or dimension. As the sky condition is dynamic, the performance of this system remains unaltered and do not act differently when the intensity of light is changed. As they demand no movement, they are easy to construct and are a widely used system in practice.

- **Dynamic System -** In this system, all the elements which can change its position, rotation, dimension, or can slide, open-close, fold-unfold, stretch can be said as a dynamic system. Such movement happened in accordance with the change in light intensity to control the amount of daylight to enter the building. Examples: Curtains, Opening shutters, sliders, Venetian blinds, etc.

Planar system - sliding in 2D   Planar system - Rotation and Folding 3D

2.3.4 Adaptive Facades

An adaptive facade system is a dynamic facade that changes in response to surrounding environment to improve its overall performance in different conditions. This variations help to control indoor environment of the building and provide comfort to the users inside.
The ability of facade to respond to environment can be at two different scales (i)Macro Scale and (ii) Micro Scale.

(i)   Macro Scale - It involves changes in the configuration of facade by moving or folding the parts of facade. These includes adjustable and moving solar shadings which are used to optimise the amount of daylighting admitted into building and maximises natural daylighting.

(ii)   Micro Scale - It involves changes that relates to material's structure. These includes smart glazing and phase change materials where material changes its state.
Dynamic facade system can help to reduce building's reliance on artificial lighting and its energy requirements.

The motion and movement of components of adaptive facade system can be made controlled in two different ways:

(i) Manual Control - The motion of facade component is handled or adjusted by human as per their requirement.

(ii) Automated Control - In this, component of facade changes automatically with help of mechanism provided. The motion can be made pre set that automatically changes with time or it can be made responsive to sensor which indicates the change that is required for that particular time.

Figure. Adaptive desfinition in literature by Loonen, 2010.

2.3.5 Case Studies

2.3.5.1 Existing Projects

Al Bahr Towers, Abu Dhabi

Al Bahr Towers, AEDAS in Abu Dhabi in 2012 by the architect Jean Nouvel . The building is covered with a membrane clad dynamic facade which has hexagonal pattern. The design was inspired from mashrabiya, a motif pattern. The facade includes 1049 hexagonal units of dynamic mashrabia on building's the east face and west face. The facade create folding and unfolding movement in response to the sun and changing surrounding environment condition. This dynamic facade system claims to be world's largest computer aided facade built for 150m high tower. (Nady, 2017)

source: 500px

source: eCycle

source: Arch20

source: Pinterest

Kiefer Technic Showroom, Austria

Kiefer Technic Showroom in Steiermark, Austria designed in 2007 by Giselbrecht + Partner. The dynamic facade was designed for an office building and exhibition space. The facade of this building was designed in a way that changes continuously every day and every hour and makes the elevation seems different at all time. The change of the facade is in accordance with external environmental condition to optimise indoor climate with a flexibility of allowing users to personalise their own comfort as per required with user controls. There are 56 different engines that has been used in this facade to achieve optimal condition for light and temperature for various activities (Uys, 2016).
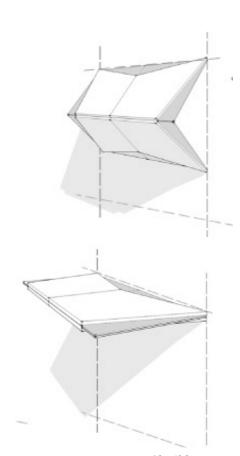
source: Mesetatsdesprit

source: Archdaily
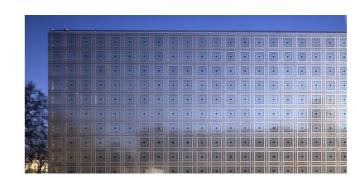
source: Archdaily
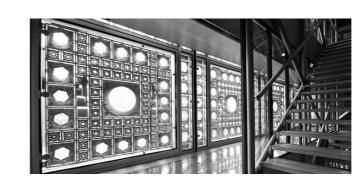
source: Sheikh

Arab Institute, Paris
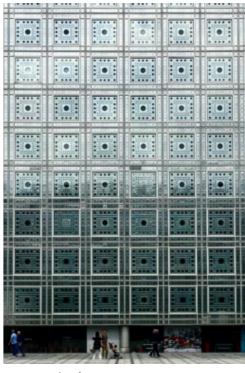
Arab Institute, Paris is designed in 1988 by the architect Jean Nouvel. The facade designed here was made to respond with changes in environmental conditions outside. The facade on south is composed of 20x10 square grids bays that consists of a circular shutter in the centre and surrounded by other small grid of shutters. There are total of 30,000 mechanical diaphragm of aluminium that is controlled by electro-pneumatic system depending on light coming from south orientation (Compagno, 1999). The design was inspired from geometry of traditional Arab screens. These screens of circular grids were made in a way that acts like a series of camera lenses in operation. The screen shrinks and widen to control the penetration of sunlight into the building with help of sensors.

source: Author

source: Arch Hello

source: Moreae Design

source: AMC

Furthermore, investigation is made on many existing examples of adaptive facade that works to improver daylight performance. The Table.2.1 shows comparison based on the type of Classification of the movement, Operational control system, Kind of daylight function done by the facade and the scale of element used on facade. Where,
Classification- FO(Folding), RO (Rotating), SL (Sliding), OC (Open-Close);
Operation Control- MN (Manual), AT (Automated);
Daylight Function- LR (Light Redirecting), LD (Light Diffusing, LB (Light Blocking;
Element Scale- EF (Entire Facade as one segment), PF (Part of Facade), LF (Large scale element in Facade), SF (Small scale element in Facade).
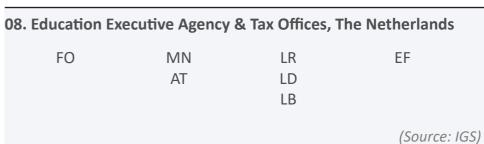
Classification	Operation Control	Daylight Function	Element Scale
01. Raiffeisen Regionalbank Hall, Austria			
FO	MN AT	LB	SF

(Source: Plexiglas)

02. Head office of SOKA-BAU, Germany			
RO	MN AT	LR LD LB	PF

(Source: filt3rs)

03. Helio Trace Centre of Architecture			
OC	AT	LR LD LB	EF

(Source: SOM)

04. A/S Group at ETH,Switzerland			
MO	AT	LB	SF

(Source: SCCER)

Table.2.1 Investigation on existing adaptive facades with daylight performance

Classification	Operation Control	Daylight Function	Element Scale
05. SDU Campus Kolding, Denmark			
OC	MN AT	LD	PF

(Source: Archdaily)

06. Lab building graz university of Technology, Austria			
FO SL	MN AT	LB	PF

(Source: e-architect)

07. One Ocean, South Korea			
OC	AT	LD LB	LF

(Source: Architectmagagine)

08. Education Executive Agency & Tax Offices, The Netherlands			
FO	MN AT	LR LD LB	EF

(Source: IGS)

09. Penumbra shading system			
OC	AT	LB	EF

(Source: Dazeen)

10. Fire and police station, The Netherlands			
RO	MN	LR LB	SF

(Source: ARUP)

Table.2.1 Investigation on existing adaptive facades with daylight performance

2.3.5.2 Research Studies

Case 01

In this research, the authors (Samadi et al., 2019) has shown an approach to gain balanced daylight in a building. The study proposes a kinetic shading system that can adjust with some independent shading parameters like 3d rotation of shading elements from the centre for each unit, 2d movement of shading elements along the surface of shading system and distance of shading from building's façade shown in figure.2.4 as a, b and c respectively; that will parametrically respond to sunlight to improve the quality of daylight inside a building.

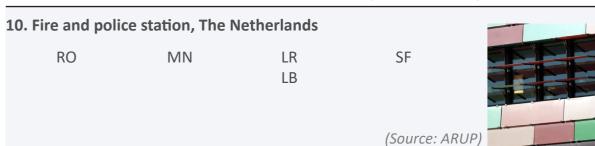The evaluation was made from simulation tests by studying changes in UDI metrics for annual calculations and obtain the optimal solution using Honeybee and Ladybug tool. The results observed from the study shows the improvement in overall daylight's performance throughout the year. Furthermore, the diffused light was distributed uniformly inside a space; with a reduction in glare and excessive illuminance near to the window and increased illuminance in-depth claimed by the author. Moreover, the author added saying a rise in results was observed when making each horizontal unit of the shading system separately with independent parameters of rotation and spacing that respond to sun position and target point.
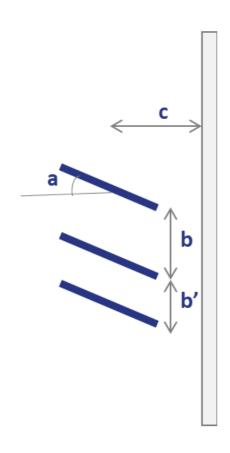

Figure.2.4 Parameters that influences Daylight performance

Consideration:

(i)   This research study helped to decide on a number of parameters like the rotation of elements, spacing between elements, and distance of shading elements from the window; it has a primly direct impact on the distribution of daylight where both glare reduction and redirecting of light phenomenon can be improved.

(ii)   Moreover, to further improve the efficiency of the shading system, all the elements should be treated separately with above mentioned parameters.

Case 02

In this research, the author (Sheikh, 2014) has studied the light deflection with a dynamic shading system with an approach for harvesting daylight in an office space. The author uses the elements of a proposed shading system with parameters from the same to separate and compared the set of configurational combinations to make the system that works best for improving daylight for two functions, gaining more daylight insight but keep blocking the direct sun from outside. The main objective of this research was to design an optimal solution for the static louvred system as a second skin that can harvest daylighting throughout the year.

The evaluation was made from simulation tests by studying three attributes, overall illuminance level, luminous distribution for contrast check, and depth of light reach in a space over a period of a year. The shading system has 5 horizontal louvre elements as shown in figure.2.5. The most optimal solution was obtained with a configuration where alternate elements were separated for different functions. This optimal configuration was when elements 1, 3, and 5 were tilted inward at 26° to block direct sunlight while tilting elements 2 and 4 outward at -17° to harvest more light. The combination was working in harmony that one shading element was helping to redirect a light reflected from the surface of another element around it.
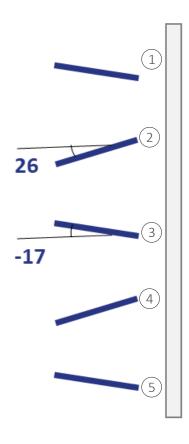
Figure.2.5 Configuration that impact Daylight performance

Consideration:

(i)   This research study provides an understanding about the importance of configuration of a dynamic facade system that works in harmony to attain two functions together (harvesting more light while blocking direct sunlight) that results in an overall improved daylight performance.

(ii)   Furthermore, the study included saying that the louvre should tilt inward to harvest more light by redirecting light-rays inside the space, and it should tilt outward to block direct sunlight.

Case 03

In this research, the author (Tabadkani et al., 2019) has investigated an adaptive façade for gaining visual comfort with help of parametric design approach. The author used an origami inspired form, Kaleidocycle, as a dynamic façade element. The Kaleidocycle module can change shape and control opening fraction which was considered as the parameters for daylight simulation in parametric modelling. For enhancing daylight's performance, the surfaces of Kaleidocycle were divided into two sets of texture with different reflectance and transmittance properties as shown in figure.2.6. The material applied to these set were a generic material for blocking light and a translucent material for enhancing light respectively. For its constructibility, set of rings were used for module's rotation and further, the module was made using five different sun shade fabrics as shown in figure.2.6, to make module fold easily while changing its shape and can maintain the material's property for its purpose.

The Use of Kaleidocycle has shown promising results on increase of illuminance with making bigger opening in module, but contrarily glare was experienced at some parts of the indoor space. This could be due to bigger opening in this shape is unable to get support of any adjacent shading element for blocking direct incoming light. The author proposed timing pattern over façade's response to sun which resulted in controlled glare metrics values together with increased daylight. The evaluation was made from simulation tests by studying changes in UDI metrics for annual calculations.

Consideration:

(i)   The research study gave the understanding of using different materials on a multi-surface geometry like Kaleidocycle helps to achieve different functions with same geometry over a period of time and improves the daylight performance efficiency.

(ii)   Without taking consideration of sun angle, opening and closing of the modules can help increase and decrease of daylight penetration.

(iii)   Motion were pre planned instead of façade's direct response to sun.

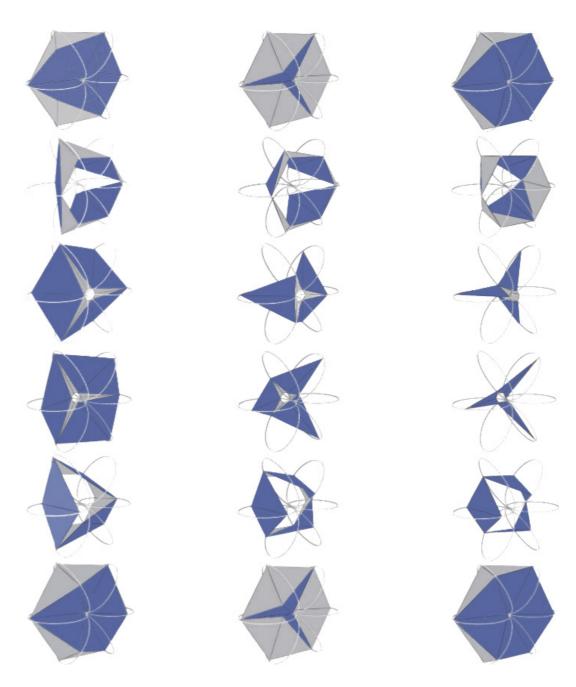(iv)   The constructibility and dynamic motion could be too complex with Kaleidocycle for a facade design.

Figure.2.6 Motion of Kaleidocycle facade by Tabadkani wt al. (2019).

2.3.6 Material

Material property of facade components plays big role in controlling daylighting to indoor environment. The properties like daylight reflectance value and daylight transmittance value of material determines a level of its performance.

Daylight Reflectance

It is said to be the ratio of the quantity of light-rays which gets reflected from any surface to the quantity of incoming light-rays which strike on the same surface. Daylight reflectance also correlates with material's surface property like (i) surface colour (includes exposed material colour or additional paint colour) and (ii) gloss level.

(i)   Material surface colour that are bright coloured reflects more light than any dark coloured surfaces. White coloured surface has the highest reflectance and black surface has the lowest reflectance.

(ii)   Gloss level is another characteristic of material surface that affects light reflectance. Material with higher gloss level tends to bounce more light off the surface and hence higher gloss will result in higher reflectance.

 For any material surface, the level of daylight reflectance is not a constant but daylight reflectance of a same material surface can vary with different conditions, which are:

•   Incident angle - Daylight reflectance is more when light incident at normal angle to surface than at oblique incident angles.

•   Observation angle of Reflectance - In terms of angle of reflection, a mirrored like surfaces has the highest reflectance.

•   Source of Light - Surfaces that are red coloured has high reflectance to the source of light having red colour and less reflectance to source of light having blue colour.

•   Observer's vision - The sensitivity or response of a human eye Human eyes for green colour is more than to that of blue colour. Hence, green colour will appear much brighter than blue coloured surface.

Daylight Transmittance

Transmittance property is said to be when a material allow to pass the light through the substance. Material with different transmittance property allow varied amount of light to penetrate. Transmittance is measure in percentage.

•   Completely Transparent material will allow to pass all the light.

•   Translucent material let limited amount of light to pass through, and it blocks the view to the other side.

•   Opaque materials blocks the passing through of light.

A material that is perfectly transparent will allow 100 percent of light to pass through the material while a complete opaque material will allow 0 percent of light to pass through. It is not necessary for a material to be colourless to transmit light through.

2.3.7 Design Strategies

Parameters and Objectives for Design

Parameters responsible for dynamic behaviour of daylight that impacts visual comfort:

(Controlled)
•   Location/Latitude
•   Orientation of Facade

(Uncontrolled)
•   Season (Sun's Altitude)
•   Hour of the Day (Sun's Azimuth)
•   Sky Condition (Luminous Distribution)

Some parameters of a building that influences the availability of light and its performance are :
•   Room's size - depth, height, volume
•   Room's functionality
•   Floor level of the room

T**he objective that asks for attention before applying the daylight system are:**
•   Redirecting daylight to greater depth for under-lit rooms
•   Diffusing daylighting for over-lit rooms
•   Uniform illumination for task performance
•   Glare control for visual comfort
•   Controlled contrast between surfaces

Strategies from previous researches

Yoo & Manz (2011) said that shading devices increases visual comfort and reduces glare. A study by Tagliabue (2019) says the maximum glare problems are experienced towards south orientation of the building, Fathy (2015) developed a shading system on exterior of facade and concluded that 1:1 depth ratio of louvre for shading with downward tilt angle improves the daylighting performance having material property of high surface reflectivity. Eltaweel and Su (2017) optimised a parametric blind with respect to sun by adjusting rotation of shading elements as well as number of elements to increase daylight performance and to reduce glare. According to a research by Yaseri (2017) Light shelf in office space were fulfilling the occupant's visual comfort and energy saving, but glare area was large.

2.4 Design Guidelines

2.4.1 Daylight Standards

The standards for lighting pertaining in various countries regarding office workplaces show similarity in their implementation. The prevailing ideology for daylighting adhered to these standards emphasizes on minimum criteria of task visibility.

Based on selected place-Rotterdam, The Netherlands; the standards followed is NEN-EN 17037 (2018) 'Daylighting in Building' norms. These standards are equivalent to European code of standards EN 17037 for daylighting translated in Dutch. These standards provide the required minimum value for daylight level to be achieved inside the building for a good visual performance. Provided standards by NEN-EN 17037 are:

Illuminance:
Illuminance: For vertical daylight opening, the target lux values provided are based on annual calculation. The value achieved for given percentage of area on working plane for half of total daylight hour annually, are in three categories:

	Target Value	Minimum Target Value
High	750 lux for 50% of area	500 lux for 95% of area
Average	500 lux for 50% of area	300 lux for 95% of area
Minimum	300 lux for 50% of area	100 lux for 95% of area

Glare:
The recommended value for protection against glare for 5% of the usage time of that relevant space are in three categories:

High	0.35
Average	0.40
Minimum	0.45

NEN-EN 17037 (2018) also recommends the surface reflectance values of interior surfaces are to be considered for daylight simulation. The reflectance values for ceiling, interior walls and floor should be 0.7, 0.5, 0.2, respectively.

NEN-EN 17037 has no mention about Uniformity Ratio (UR) whereas, BREEAM (2016) mentions of UR value for daylight enhanced spaces to be more than 0.3.

2.4.2 Daylight Guidelines

The recommendation for light levels for indoor office workplaces is 500 lux (CIBSE, 2015). The illuminance distribution across work plane gradually decreases from area close to the window to the end of the room, as discussed in problem statement. The consideration for the measurement of cases with varying illuminance should not limit to a specific value; rather, it should contribute within range of useful or ambient daylight levels (Nabil, 2020).

Chauvel in 1982 stated that UDI is a two-tailed metric where in the calculation of UDI follows a range within lower and upper illuminance threshold values. The range is categorised in three parts namely UDI over-lit, UDI daylit (or useful) and UDI under-lit. Debnath (2015) provided the values of all three ranges of UDI with a description; the range 0-100 lux is considered as UDI under-lit, as a space with daylight illuminance below 100 lux requires an additional supply of light. The range between 100 to 2000 lux can be said as UDI daylit, wherein the value of illuminance within this range is said to be sufficient for daily activities and is visually ambient. The range above 2000 lux is considered as UDI over-lit wherein the value of lux above 2000 indicates the presence of excessive daylight which can be caused due to direct sun exposure or bright reflection from the surrounding surfaces making occupants visually discomfort. Hafiz (2015) in his research also proposed a similar range for useful daylight by attempting a comprehensive study on occupant's behaviour. However, the range for useful daylight proposed by Mardaljevik (2009) from his research, based on occupant's daily activity, is given by 200-2000 lux; and a range for useful daylight proposed by Carlucci et al. (2015) from their research on occupant's behaviour with used operated shading device, is given by 300-3000 lux.

However, the limit values of the range are not standardized values, for various literature studies on different values for the useful range have been proposed by researchers based on their study's priority (Suk, 2016). Taking into consideration of all above-mentioned cases, a range of 300-2000 lux comes out to be a common value. Hence, the three range of UDI for proposed study can be considered as:

UDI under-lit =   0-300 lux
UDI daylit   =   300-2000 lux (useful or ambient light range)
UDI over-lit =   >2000 lux

The value of UDI is based on annual calculation of the hour percentage for a range of illuminance level in a timeframe of one year. This metric contradicts to the approach of this research where the cases studied here are for an instance with specific hour.

The Daylight Factor (DF) calculations are made with diffused sky settings. Due to which DF does not count for direct light and its redistribution after reflection from a surface, and fails to quantify diffused illuminance which is the main feature of a light redirecting facade systems. Furthermore, the building location and orientation are not considered for daylight simulation with DF (Table.2.4).

2.5 Computational Design

2.5.1 Computation Methods

Examining the objective of this study, the facade design must deal with dynamic daylight conditions from outside. Such situations add complexity in the design process and adds difficulty in finding a solution using conventional design methods.

The computational design methods offer diverse opportunity to deal with such complex situations by mean of parametric modeling, performance simulation and optimisation. In recent years, the use of computational design has led to a significant interest in the field of Architecture (Wortmann et al., 2017).

Parametric modeling is used to develop a geometric form with the set(s) of variables associated concerning the geometry; that allows iterating various design options during the parameterisation process (Turrin et al., 2016). All the possible design options generated using the provided variable(s) establishes a base for the solution of that parametric model.

Building Performance Simulation (BPS) has become typical to access the proposed design for its performance regarding energy or indoor comfort. The BPS eventually provides the calculated value as a result and has no part in decision making or finding an optimal solution. This eliminates the scope for designers in exploring design variables manually. However, the process becomes complicated when the design problem has a vast solution space, as the designer has to simulate each solution one by one. Hence, a solution to such challenges is solved by developing an integrated approach by adding the optimisation process with simulations, also known as Building Performance Optimisation (BPO).

Building Performance Optimisation (BPO) is a process that generates multiple possible solutions to distinguish an optimal solution that meets or is closest to the objective function.

Based on the complexity involved in the BPO process due to multiple objectives, large space population and discrete nature, it becomes difficult to obtain the most optimal or the global optimum solution for such design. Nonetheless, the obtained solution results is yet a well-performing design with a desirably higher value in front of a non-optimised solution.

Furthermore, addressing the potential applications of the computational method into performance solving design; this study emphasises the focus on daylight-oriented performance solution through algorithmically generated design alternatives. In such scope, the iterations to a solution are generated using a BPO tool, and the obtained solutions are evaluated based on provided performance criteria for a design using a daylight simulation tool.

2.5.2 Daylight Simulation

The new upcoming trends in the technology of façade design are diverting towards more adaptive and dynamic fenestration systems which are highly complex. This advancement demands more advanced modelling techniques that can bring more accuracy on daylight's performance with their controls over their operational use (Brembilla et al., 2019). Although the simplified model techniques are still being used for simulating daylight performance of such complex fenestrations. For a case like modelling a solar shading system arranged in uniform parallel layers, it calculate the quality of daylight considering all the surfaces as diffused material and fails to consider daylight redirection property of the component which result in reduced incoming light flux to interior environment (GhaggarianHoseini et al., 2013). This is because they omit to include the light transmission's angular dependency ;which influences daylight's spatial distribution inside a room significantly. Such limitations in simulations affect the accuracy in studying the performance of complex fenestration system (Brembilla et al., 2019). Many authors has reported several performance evaluation of complex fenestration systems including daylight redirecting system and most authors employed the use of Radiance lighting simulation technique (Ward et al., 2011; Molina et al. ,2015)

Basically, Radiance (Ward, 1994) is a backwards ray-tracing program and uses reverse ray-tracing. In Ray tracing, the simulation calculates rays of light that start from the sun and ends to sensor points or camera until some of the light has reached. Where in reverse ray-tracing it's the opposite, the simulation starts from sensor points or camera and calculates rays of light that can reach them. Radiance program also analyses and visualises the amount of lighting in design. The input data to be filled in are setting a view from geometry, luminaries, specific material, sky condition with time and date. As a result, the output gained will be demonstrated as an images with colour gradients, result values and plots of contour. Unlike other tools, this program has no geometry limitations nor the material limitation for the simulation process. Its uses are to speculate illumination and visualization of provided design spaces.

It started back in 2011 when Radiance gained its popularity and was widely used as a simulation tool in research topics that were related to daylighting and it was extensively validated by researches (Ochao et al., 2011). Yu & Su in 2015 also added in their research paper that Radiance is the highly admired simulation tool for daylight modelling. This technique became popular in application because of giving high accuracy in various validation tests it was subjected to with highly accurate renderings. Radiance has been considered as the most dependable technique for daylight performance simulation with complex fenestration system on a building for almost two decades for now.

Later in 2017, Jones and Reinhart stated that designers should use the 3-phase and 5-phase methods when working with complex models. They tested three simulation techniques, DAYSIM, 3- and 5-phase method. Here, DAYSIM uses rtrace where 3- and 5-phase method uses rcontrib. They also concluded saying that DAYSIM is not a reliable platform for analysing complex fenestration systems. Brembilla et al. in 2019 in their research, they compared

various façade with Complex fenestration Systems using Climate based Daylight Modelling with Radiance. He used five different CBDM techniques- the 2-, 3-, and 5-phase method, DAYSIM, 4-component method (4CM) for three different variation of shading system. The daylight analysis method of this research was with the focus on annual daylight metrics. He concluded that methods based on 'rtrace' like DAYSIM and 4-component method increases computation time and require higher value of render parameters. Where, methods followed by 'rcontrib' like 3PM and 5PM were more efficient. The efficiency of the results was due to the use of BSDF representation and it offers high potential in computation efficiency.

Daylight Simulation Tool

Several tools are available for daylight simulation. DIVA-for-Rhino, Ladybug (LB) with Honeybee (HB) are some of the example of software that works with Radiance Ray-tracing engine. DIVA-for-Rhino is a separate interface that works with Rhino, where DIVA for GH and HB/LB family (HB/LB Legacy and HB/LB Plus) works with Grasshopper interface used with Rhino. The comparison between these radiance based simulation tools was done based on their abilities to perform daylight simulation with accuracy and is shown in Table.2.3.

The comparison shows that the base of many tools for using most reliable engine, Radiance, is same except HB Legacy which uses DAYSIM instead (Roudsari, 2018). The simulation of CFS with its dynamic state can be made easy with tools that works with GH interface like DIVA for GH, HB Legacy and HB+. Furthermore, HB Legacy and HB+ are only two which count BSDF properties in their simulation and HB+ is the only tool acquaint with use of 3/5-phase method.

The new updated version HB+ shows the most promising tool to be used for CFS for high accuracy results with a reason of its possible capability of working with Radiance Simulation technique, using of BSDF property and simulating with 3/5 phase method, all in one single tool platform (Roudsari, 2018).

Although, the latest version HB+ is still under development state, it has a limitation where the simulation for Glare assessment like DGP is not yet been developed, but it is believed to be out soon in near future. Moreover, for the calculation of DGP, HB Legacy is used beside HB+ which is to keep the definition easy to work in same canvas of GH interface and to keep various properties aligned together in same HB family and keep the definition more simpler. Above all, HB Legacy is the second tool that is capable to deal with BSDF property and CFS together.

		DIVA for Rhino	DIVA for GH	HB,LB Legacy	HB,LB Plus
Simulation Engine	**DAYSIM** (rtrace)	✓		✓	
	Radiance (rtrace)	✓	✓		✓
	Radiance (rcontrib - for Phase Method)				✓
Complexity	**CFS**		✓	✓	✓
	BSDF			✓	✓
Metrics	**Illuminance**	✓	✓	✓	✓
	DGP	✓	✓	✓	
	Contrast	✓	✓	✓	✓

Table 2.3 Comparison between four simulation tool available for daylight simulation

Simulation Tool - Honeybee+Ladybug

Honeybee(HB) and Ladybug(LB) are the larger part of environmental tools and is an open source plugin (Roudsari, n.d) for Grasshopper. The visual programming environment of this plugin connects to 4 different simulation engines - Daysim, Radiance, EnergyPlus, and OpenStudio. Ladybug uses the EnergyPlus Weather (EPW) file of the location to generate graphical outputs. Wherein, Honeybee runs the simulation engine to perform various analyses like energy, daylight, and comfort.

Honeybee allows users to input specific geometry, sky property as well as material property, and radiance parameters. Changing these parameters can impact the duration of the simulation and the quality of the simulation outputs.

The HB runs daylight simulations using Radiance engine with reverse ray tracing where the simulation begins first by defining surrounding geometry with its material. This process calculates the amount of bounces that light ray will go through around the geometry and/or building and the amount of light that will get reflected or absorbed on each bounce. Then those rays will cover the source of light which could be the sun with different sky models that generate light. Later, HB allows you to control some settings that has effect on the quality of reverse ray-tracing process and it leaves with a result in a format relating to the type of simulation.
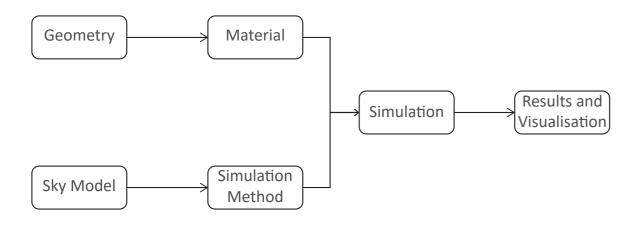

Figure. Workflow used within Honeybee and Ladybug

Sky Model

I. Climate Based Daylight Modelling (CBDM)
This sky model utilizes standard meteorological dataset available from weather file to predict the values for luminance distribution like luminance, illuminance, or values for radiant like radiance, irradiance by using sky and sun condition available in dataset (Mardaljevic, 2006). CBDM produces much accurate resultant values of illumination etc. as it uses the realistic description of sky and sun condition for simulation.

In HB, Climate Based component works only with point in time simulation method. It takes weather data as input from weather file in '.epw' format. Here, the sky type is as per data set of the location as per selected time. One can set analysis period in format of Months, days and/or hour of day. The main three evaluation modes for CBDM (Mardaljevic, 2006) are:

(i)   Cumulative Annual – The averaged Illuminance etc. of all individual hourly sky and sun condition per entire year.
(ii)   Cumulative Monthly – The averaged Illuminance etc. of each month, for one year.
(iii)   Time Series – The averaged Illuminance etc. of hourly or a period of hours in a year.

II. Discrete Sky (Sky Metrix)
Discrete sky model is a series of sky vectors that combines various time steps available from weather data. A light vector from sky utilizes the mean sky luminance value in a form of discretized sky patch for a specific sky luminance (McNeil, 2014). A Discrete model of sky utilize Perez model where the sky is divided in several patches. The first division was introduced by Tregenza which has 145 sky subdivisions. Later, Reinhart divided sky into 5185 sky subdivisions to improve the accuracy of the result (Mehlika, 2016).

In HB, this sky model is used with annual simulation method. This component also utilises the standard meteorological dataset available from weather file. Here, the sky type is as per data set of the location as per selected time. Analysis period here is annually, so its not possible to simulate for a period of time with this sky model. But a resultant value can be extracted for a specific hour of year.

III. CIE Sky

The Commission International I'Eclairage (CIE) is a sky model category that allows to bring real context to model by generating a sky dome for simulation. This concept of CIE sky model has capability of modelling various skies that ranges widely from cloudless sky to overcast sky, with or without sunlight availability which are based on sky luminance distribution. Perez et. Al in 1990 introduced a framework on various such sky models that allows to characterize sky with building based on the level of brightness and clearness and surrounding luminance distribution. Here, luminance distribution a depended variable on the weather and climate.

The GH plugin HB+ provide the possibility of having daylight simulation using CIE sky model with help of its 'CIE Standard sky component'. This sky component allows user to choose sky luminance distribution for a location from six different settings of skies (as shown in figure.2.7) using its weather file. These six settings are, sunny with sun, sunny without sun, Intermediate with sun, Intermediate without sun, cloudy sky and uniform sky. All these different kinds of sky type have separate, well defined sky luminance pattern that helps in calculating daylight illuminance for a defined sky patch on a surface. Some examples of available sky types are Clear Sky, Intermediate sky, Overcast sky (Commission International I'Eclairage, 2003). All these different kinds of sky type have separate, well defined sky luminance pattern that helps in calculating daylight illuminance for a defined sky patch on a surface. The most commonly available sky models can be defined as:
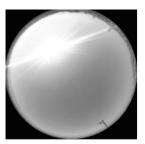
(i)   Clear Sky:
The clear sky (CIE, 2013) is basically considered as a sky with absence of clouds. This sky type represents highest luminance distribution possible in environment. The intensity of such sky type varies with change in position. The luminance distribution is highest when is close to sun, and it reduces subsequently while moving away from sun.
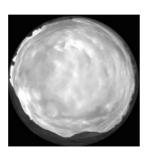
(ii)   Overcast:
This sky type (Hopkinson et al., 1997) is when the visibility to sun becomes negligible due to heavy cloud cover over entire sky. This sky type represents least luminance distribution in environment. In such sky condition, the difference between the quantity of diffuse illuminance with global illuminance are negligible due to extremely low or no direct lighting available.

(iii)   Intermediate sky:
This sky type (Igawa et al., 1997) lies between clear sky and overcast and has few to some amount of clouds. The luminance distribution here is more complex as it varies drastically depending on the visibility of the sun, amount of clouds and their shape and size.

| *Clear Sky* | *Intermediate* | *Overcast* |

Figure.2.7 Type of CIE sky in Chile. (Piderit at el., 2014)

Simulation Methods

I.   Grid Based/Point in time
Point in time method utilises reverse ray tracing technique from radiance. This method can simulate with any sky model. This method is used when simulation is needs to be done for a particular hour of the day or a year; or for particular period of time (the period here can be period of hours, period of days, period of months). Here, simulation with the complex fenestration system are done in two ways-
(i)   By treating glazed window as a glass and transparent material and modelling shading system (like Venetian blinds) or additional external façade geometry as an explicit geometry.
(ii)   By making glazing behave as a secondary source of light with using BSDF. The BSDF will determine the property of light scattering for the glazing and shading system and will add on to final results (Greg et al., 2011).
This method divides the analysis surface in grids and consider all segments of grids as test points. This method distributes the results of illuminance values on chosen grids.

II.   Image Based
Simulation with Image based method utilizes captured HDR images as light source during the process of rendering (Debevec, 2002). For a particular location and time, the actual sky condition is captured with the HDR photography technique. From the capture, the stored information on a scale of pixel regarding luminance distribution is used to simulate light in environment. This method generates a real time rendering with light effect in a space using fisheye view.

III.   Annual Simulation
This simulation method allows to calculate daylighting throughout the year to get annual performance results instead of simulating it for few selected hour/date/months of the year. The approximation on available daylight hour annually can be considered as 3500 to 4000 (Mehlika, 2016), where this amount changes for different locations. Simulation of all this instance of hours individually becomes complex and a long process, thus, annual simulation method utilises the concept of multi-step simulation. This process starts with simulating limited number of instances to determine the reach of light to the interior from uniform sky. This step determines the resultant amount of light availability in that particular point. Furthermore, this ends with calculation of multiplying metrics which gets the outcome of actual sky instances from uniform sky patches for each hour over a period of year. This process makes it much easier to predict overall result instead of repeating all simulations.
In HB, this simulation method works with Sky Matrix and not with CIE sky model. Thus, the simulation with different sky type option as available in CIE sky model is not possible in annual simulation method. This method evaluates the value for luminance distribution based on the data available in weather file of a location. But it is possible to extract the simulation result for a particular hour of the year from sky matrix component in annual simulation method.

IV.   Phase Methods

The phase method are based on annual simulations and all these method uses metrix based sky model for daylight simulation and annual metrics calculations.

2-phase Method (or Daylight Coefficient Method)

This method is widely known as Daylight Coefficient Method (DC). This method facilitates a user to calculate illuminance for different sky conditions by utilising matrix-based calculation (Tregenza, 1983). This method is primly suitable for simple shading or glazing with simple radiance based material. More complex geometry can be modelled in simulation with using BSDF primitive (Sarith, 2017).

In DC method, the daylight that strikes a surface directly or indirectly in an indoor environment, can be calculated using two separate phenomenon – sky and object geometry's luminance intensity, and surrounding surface's geometry and optical properties.

Daylight Coefficient Equation,
$$E_{DC} = C_{dc}S_{sun}$$
Where,
C_{dc} = Daylight Coefficient, S_{sun} = Sun Matrix

3-phase Method

This method is capable in calculating diffused daylight with more accuracy by implementing bidirectional scattering distribution function (BSDF) material. Annual simulation of a CFS or dynamic fenestration system are meant to perform with this method. This method was made to perform simulation at beginning stages like concept design, and for some parametric analysis. As the simulation technique of Metrix layer calculation by Klems,1994 was unsuitable for representing of light peaks transmission with accuracy, where it used to average all the incident light over solid angles.

Beyond the Daylight coefficient approach, this method breaks the light flux transmission from outdoor to indoor environment into three different phases with independent simulation (McNeil, 2014):
(i)   Outdoor Transport - Light flux transmission from sky to exterior of fenestration.
(ii)   Fenestration Transmission – Light flux transmission through/within fenestration through BSDF dataset.
(iii)   Indoor Transport – Light flux transmission from interior of fenestration to the simulated space.

The 3-phase method measures the coefficients related to light flux for input to output at each phase of transmission separately instead of simulating for a specific daylight condition as shown in figure.2,8. In a perticular daylight condition, the result measured will be the multiplication of the obtained coefficient values with sky luminance values (which will be input values). In this way, it becomes very quick for users to simulate matrix calculations with several sky condition and CFS's transmission properties (McNeil, 2014).

3-Phase Equation   :
$$E_{3ph} = VTDS$$
Where,
View Matrix (indoors), V
Transmission Matrix (BSDF), T
Daylight Matrix (outdoors), D
Sky Matrix, D

5-phase Method

This method is an extension of 3-phase method. In 5-phase method, the direct sunlight is simulated separately from both, the light from sky and the reflected sunlight or diffused light of interior. This results in gaining high accuracy of direct sunlight and its distribution together with diffused daylighting in a space with CFS. The figure.2.9 shows difference in rendering with 5-phase method.

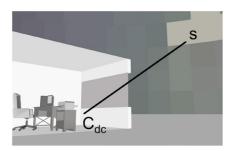The 5-phase method follows the three step approach for simulation:
(i)   It will perform 3-phase simulation to gain the accuracy of diffused flux in results.
(ii)   It will remove the direct solar contribution from 3-phase simulation which is considered to not be giving so accurate direct solar contribution result but more diffused results. But here it will leave the internal reflection of solar component.
(iii)   It will perform daylight coefficient method on top of second step to add direct solar contribution which will be more accurately simulated.
Thus, the equation of 5-phase is formulated using equation from 3-phase and daylight coefficient.
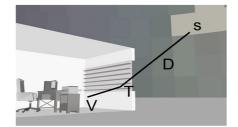
Five-Phase Equation:
$$E_{5ph} = E_{3ph} - E_{DC-3ph} + E_{DC}$$
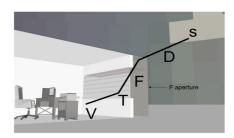$$= VTDS - V_dTD_dS_d + C_{ds}S_{sun}$$
Where,
Direct View Matrix (indoor), Vd
Transmission Matrix (BSDF), T
Direct Daylight Matrix (outdoors), Dd
Direct Sky Matrix, Sd

2-phase Method

3-phase Method

5-phase Method
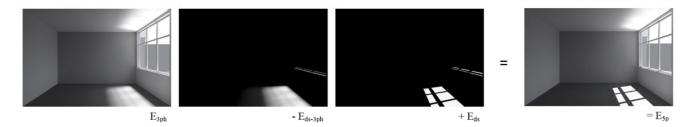
Figure.2.8 The process of phase method

E_{3ph} $- E_{ds-3ph}$ $+ E_{ds}$ $= E_{5p}$

Figure.2.9 The result of 5-phase method in a render for a space with clear glazing (McNeil, 2013)

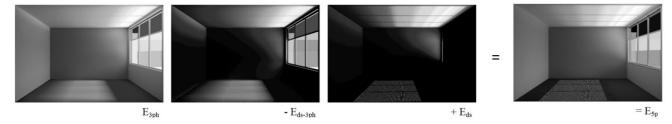E_{3ph} $- E_{ds-3ph}$ $+ E_{ds}$ $= E_{5p}$

Figure.2.9 The result of 5-phase method in a render for a room with redirecting facade elements in top part of windows and bottom part of window with Venetian blinds. (McNeil, 2013)

Daylight Metrics	Simulation Type	Analysis Type	Analysis Method	Sky Component	Location or Weather Data
Illuminance (lux)	Point in Time	Illuminance	Illuminance Grid Based(GB)	CIE, CBDM	Location, Weather
	Annual		Annual Daylight, 3/5-phase method	Sky Matrix	Weather
DGP (%)	Point in time	Luminance	Image Based (IB), Glare Analysis	CIE, CBDM	Location, Weather
Contrast	Point in time	Luminance	Grid Based (GB)	CIE, CBDM	Location, Weather
UDI (%)	Annual	Illuminance	Annual Daylight, 3/5-phase method	Sky Matrix	Weather
DF (%)	Annual	-	DF Analysis	-	-

Table.2.4 Showing comparison between Daylight metrics and required component for simulation in LB/HB+

From the literature study of daylight simulation, it is found that phase method with BSDF material in simulation are most accurate. From the comparison made in Table.2.4 amongst different simulation methods with different metrics, it is found that the recommended phase method works only for annual calculation and not for particular hour of time, furthermore, it does not work with CIE sky model. This contradicts with the requirement for this study, where the analysis made will be for a particular hour using CIE sky. Furthermore, as per needed requirement of simulation, it is found that three Analysis type needs to be used in this study; Illuminance GB for average Illuminance, Luminance IB for DGP and Luminance GB for contrast. The comparison of UDI and DF is to show that UDI also works for annual calculation and no CIE sky; and DF considered no sky type nor location, which makes it useless for this case.

Radiance Parameters

In daylight simulations, the accuracy of daylight modelling results have its major dependency on the input values for Radiance simulation parameters. Some of those parameters are Direct Parameters (-dc, -dt, -dj), Ambient Parameters (-ab, -ad, -aa, -as, -ar), Specular Parameters (-st, -ss), Rays Parameters (-lw, -lr) and View Parameters (-vp, -vd, -vt). Higher the input value settings for these parameters, more accurate the simulation result will be. The simulation is fast when the value input for these parameters are low.

From list of all the above-mentioned Radiance simulation parameters, the use of direct, specular rays and View parameters is not much amongst users. This is due to the assumption of using diffused surfaces in design and considering sun as the only direct light source in the environment (Sarith, 2019). Ambient Parameters are more often used for the accuracy, more specifically, -ab and -ad are highly impactful.

Ambient Parameters

(i)   Ambient Bounces (-ab) : The value determine the number of bounces of diffuse light to be consider for simulation. The accuracy of results is high when -ab values are higher than 4.

(ii)   Ambient Divisions (-ad) : This indicates the quantity of sampling rays that are projected from test points towards sky to measure indirect illuminance. Using a higher number leaves less errors in prediction of indirect light and gives more accuracy to results.

(iii)   Ambient Accuracy (-aa) : This indicates the percentage of ambient interpolation error. Taking 0.1 as a value of -aa represents an error not more than 10% is allowed. Here, lower the number is more accurate for the results.

(iv)   Ambient Super-samples (-as) : This indicates the percentage of extra rays generated in between two samples close to each other. Accuracy is high with higher values like 1024 and above.

(v)   Ambient Resolution (-ar) : This parameters controls the density of light in renderings. Accuracy is high with higher values like 128 and above.

Material Properties

I. Radiance Based

Reflectance:
In HB, reflectance value controls the quantity or amount of light that will get reflected and absorbed by a surface. The reflectance value will define the effectiveness of a surface in reflecting light. The input value is between 0.0-1.0, higher value defines more quantity of light that will get reflected. A value of 0.8 shows that 80% of light striking the surface will reflect back and 20% of light will get absorbed by material.

Specularity:
In HB, the specular value controls the specular reflections from the surface in simulation. The specular value defines how shiny or reflective a surface is. The input value is between 0.0-1.0, higher value defines high specular reflection from a surface.

Roughness:
In HB, roughness value controls the diffuse reflection, which is produced from the rough surface that helps to reflect light in all direction. The roughness value defines how smooth or rough texture of the surface is. The input value is between 0.0-1.0, higher value defines the surface is more rough with highly diffused reflection.

The chart shown in figure.XX provides an insight on how these radiance material properties like Reflectance, Specularity and Roughness affects the bouncing and scattering of light on an opaque and metal objects.

Moult. 2018 gave example of some reference values to be considered for the type of material based on above mentioned properties:
•   Most of the opaque or non-metallic surface's specularity value lies between 0.0 to 0.1.
•   Specularity of Metal surfaces are generally kept between 0.8 to 0.99 but usually 0.9 or more is preferred.
•   The roughness value of both opaque and metal surfaces were 0.2 or less.
Moult D. (2018).

II. BSDF

BSDF is Bidirectional Scattering Distribution Function, it was introduced by Bartell et al. in 1980. It is used as a mathematical function to describe the behaviour of light's scattering from a surface and describes the appearance of the material. The BSDF ia addition of two different phenomenon, Bidirectional Transmittance Distribution Function (BTDF) with Bidirectional Reflectance Distribution Function (BRDF),

BSDF = BRDF + BTDF

The ability of using BSDF in daylight simulation program for CFS was made to characterize the angular reflection and/or transmission of the light from the surface of CFS. In simulations, use of BSDF in material inputs gives a possibility of estimating the light scattering effect from any complex geometry with more accuracy and results in increased and much accurate overall illuminance and luminance values. This is due to Radiance treats BSDFs to get more accurate specular distribution. Use of BSDF also increases the simulation time and much effort with additional work. The difference of resultant value and run time may also vary depending on the complexity of geometry as well as rendering parameters used for simulation.

BSDFs can be made either using LBNL Windiw or genBSDF. LBNL Window generates BSDF data for CFS like multi-layered fenestration measured or calculated independently for angularly resolved data of any single layer by utilising the Klems'matrix algorithm (Klems, 1993). In Radiance BSDFs can be made using the tool genBSDF, this will generate data for light flux transfer from the macroscopic system of geometry and surface property of the applied material (Ward, 2011).

BSDF files are made in XML format. These XML are made with static state of the fenestration geometry, which will calculate the specular distribution from the surface of the geometry in that particular position. Hence, simulation of BSDF with dynamic façades that keeps changing its state is a complex process.

2.53 Building Performance Optimisation

Building Performance Optimisation (BPO) in combination with performance simulation helps to obtain the optimal solution using a schematic process shown in figure.2.10. Entitled in a loop with simulation process, the optimisation process demands inputs like Design Variables and Objective functions. Both design variable and objective function having specific criteria concerning design solution need to be defined at the start of the optimisation process.

Design Variables- The input for design variables are considered in the optimisation process to generate different design alternatives to evaluate for its performance using simulation. The design variables are classified into three categories as discrete - which allows integer values, continuous- which allows a range of real numbers; and hybrid - which allows combination from both. In some cases, a variable can be a result from other variable which creates variable dependency and creates constraints in solution space (Si, 2018).

Objective Functions - The input as objective functions are considered criteria to obtain suitable result after comparing the results of multiple solutions. The design problem is said to be a single objective, having an objective function with only one criterion to perform. Similarly, a design problem is said to be a multi-objective, when an objective function has two or more criteria to be performed simultaneously. The Objective function can be further defined as qualitative or quantitative. All building performance-related problems lie in the quantitative category, which is calculated by mean of mathematical and statistical methods.

For running the optimisation process, several optimisation algorithms are developed, which uses different techniques to obtain the near-optimal result in the performance of the design.
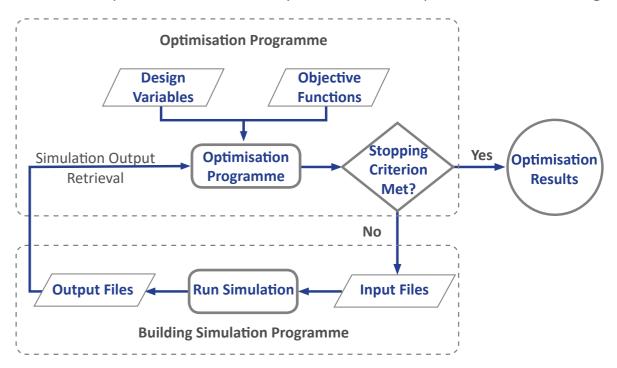

Figure.2.10 Classification of optimisation algorithms. Recreated from Özkaraca (2018), Fazlelahi et al. (2015) and Evins (2013).

Optimisation Algorithms

Selection of the epitome optimisation algorithm (OA) is significantly very crucial thing. According to the optimisation problem, the OA helps to find the correct solution. Few considered aspect of OA are its robustness in finding a global optimum rather than a local optimum; its accuracy to achieve result closest to the criteria provided and its convergence rate to find an optimal solution with minimum iterations.

The approach towards selecting an OA dealing with Building Performance Optimisation (BPO) with key aspects to be considered are (Nguyen et al., 2014):
I. The kind of Optimisation problem (static or dynamic)
II. The form of the objective function (Linear/non-linear, etc.)
III. The type of design Variables (continuous, discrete or hybrid)
IV. Applied constraint(s) to the list of provided objectives
V. The potential to derive multiple objectives separately in order

The algorithms used for optimisation can be classified into three main categories: enumerative, deterministic and stochastic. The enumerative techniques evaluate all the solution and select the solution that fulfils all the criteria of objectives; this way, they conclude to a solution which is local optimum at a much early stage. The deterministic technique demands for objective criteria having continuity and derivability conditions. This technique fails for a non-linear problem with multi-objective criteria. The Stochastic techniques deploy random search in the process and allow to deal with meta-heuristic approach to work with non-linear problems with multi-objective criteria (Yang, 2011).

Wetter et al. (2004) said that simulation-based optimisation problems are ordinarily non-linear and multi-objective, which makes the use of stochastic algorithm more feasible for BPO; and Genetic Algorithms (GA) are the most common choice for BPO related studies with a diverse range of application. GA is a sub-category of Evolutionary algorithm, which uses the Darwinian principle by eliminating least favourable solution from parent population and keeping a population of survived solutions fittest to the criteria. This children population with the fittest solution acts as a parent to produce another children population using crossover and mutation. This process continues until getting a near-optimal solution (Evins, 2013). One of the most common algorithm techniques implemented for multi-objective optimisation is NSGA-II, which stands for Non-sorting Genetic Algorithm. Brownlee et al. (2012) made a comparative analysis for 5-different algorithms (PAES, SPEA2, NSGA II, MOCell and IBEA) with a case of optimising best location for a window with multi-objectives; from the result, he concluded saying NSGA II performed best. This method is also found to be faster and accurate with diverse set of solutions. The figure.2.11 shows the classification of NSGA II in the chain of OA.
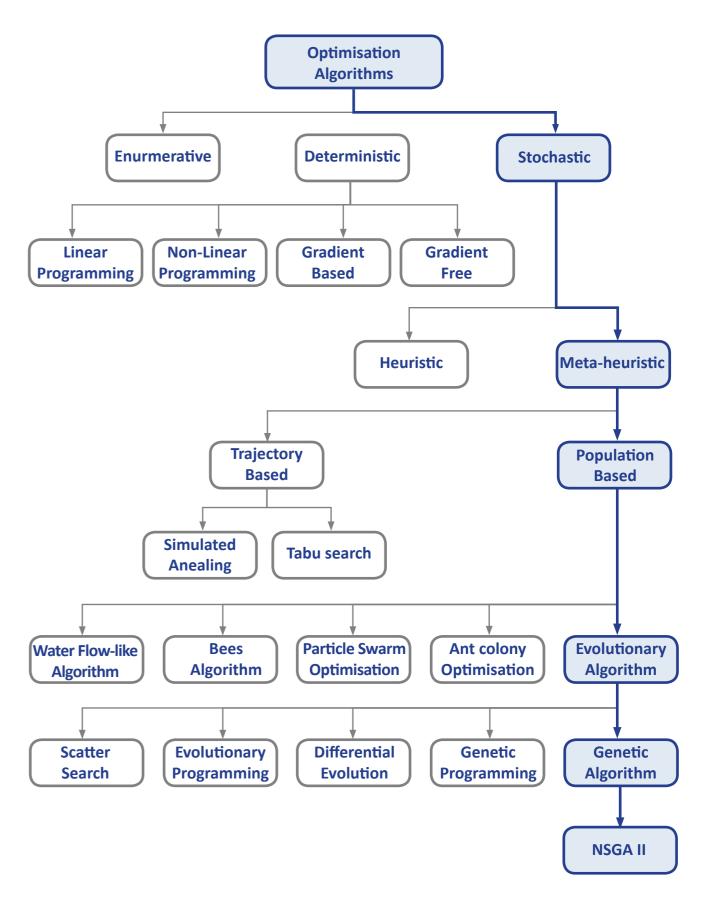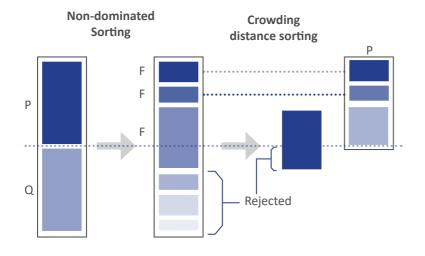

Figure.2.11 Classification of optimisation algorithms. Recreated from Özkaraca (2018), Fazlelahi et al. (2015) and Evins (2013).

Genetic Algorithm - NSGA II

NSGA II (Non dominated Sorting Genetic Algorithm) is one of the most used multi-objective optimisation algorithms due to its three primary abilities; rapid approach towards non-dominated sorting, rapid procedure on crowded distance estimation and simple operation with crowded comparison as shown in figure.2.12 (Deb et al., 2002). In the process of optimisation, this technique optimises each objective simultaneously without getting dominated through any other solution (Yusoff et al., 2011).
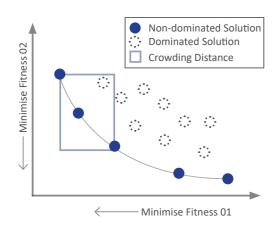
Figure.2.12 NSGA II working principle (Deb et al., 2002)

Furthermore, figure.2.13 shows the flow chart of detailed process by steps that is held by using a NSGA II algorithm for reaching to an optimal solution stage. Several tools are available that works with different algorithm techniques for optimisation process. Wallacei is one of the optimisation tool that works with the algorithm of NSGA II

Figure.2.13 Flow chart showing detailed process of NSGA II. Recreated from Mahadevan et al. (2012)

Optimisation Tool - Wallacei

Wallacei is a free plugin (Makki et. al, n.d) for multi-objective optimisation that works with Grasshopper3D. Wallacei is combination of evolutionary engine plus analytic engine in one single platform.
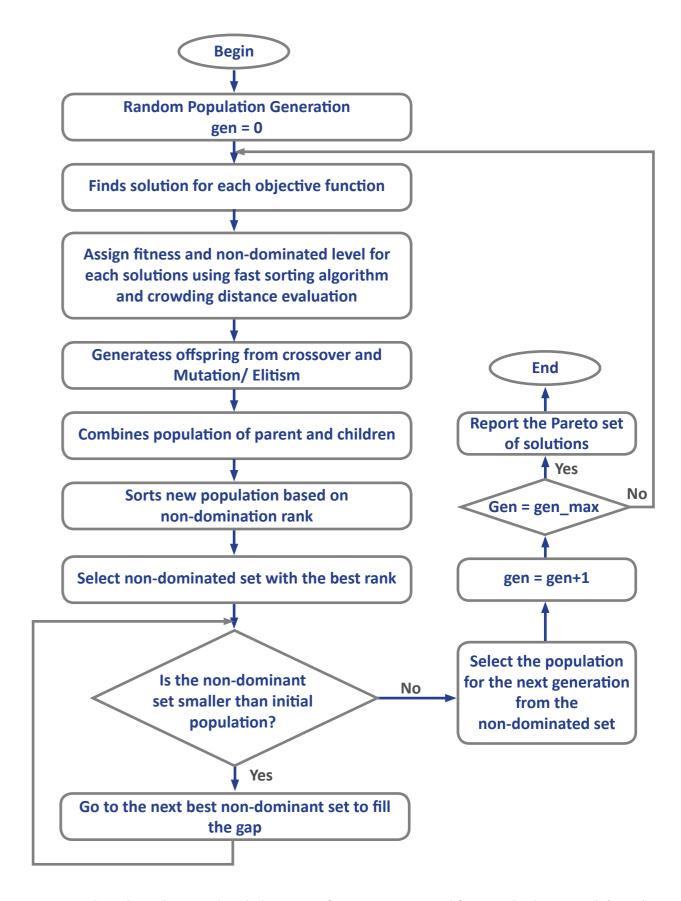
Its evolutionary engine allows users to run evolutionary simulations. As an evolutionary algorithm, Wallacei make use of NSGA-II algorithm (Deb et. Al., 2000). This optimiser helps user to understand their evolutionary run simulation through various comprehensive selection methods and detailed analytic. This allows a user to have control on making elucidate decisions in all different stages of evolutionary simulation process which include setting up design problem, analysing results and selection of final solution (Makki et. al., 2019).

Some Advantages of Wallacei

- It can take upto 10-objectives for optimisation.
- Various options for selection of solutions. The selection can be made via:
  - Pareto Front solutions
  - Parallel Coordinate Plot
  - Picking solution from any Generation
  - Based on Ranking of all different objectives
  - K-means clustering and Agglomerative Hierarchical clustering
- Various graphical visualization options to select and compare best solution
  - Fitness Value Chart
  - Mean Fitness Trendline Chart
  - Standard Deviation Chart
  - Standard Deviation Trendline Chart
  - Objective Space and Pareto Front
  - Diamond Fitness Chart
  - Parallel Coordinate Plot
- Easy to export multiple solution geometry/mesh/data in Rhino. It exports all at once and makes it easy to study and compare.
- After completion of simulation, Wallacei provides flexibility in selecting and outputting any phenotype from the population, and reconstructing of any phenotype from definition.
- It has feature of Null point/value. This optimizer indicates if there is an issue with geometry and will stop taking simulation result which helps to avoid getting a wrong result on faulty geometry.
- It is capable of storing optimisation data even after closing GH file.

Answer to Sub-Question

01. What are the requirements and parameters that characterise the space and its occupants for visual comfort?

The requirements needed to define visual comfort for an occupant are:
- Amount of Daylight (or Distribution of Daylight)
- Glare
- Contrast
- Colour Temperature and
- View to Outside

However, colour temperature and view to the outside is not taken further in the scope of this study. The first three factors are taken further as evaluation criteria for validating any space for visual comfort

All the external factors that are responsible for the change in available daylight are the parameters for an indoor space that impact on the visual comfort. Such factors are:
- Location
- Orientation
- Seasons
- Hour of the day
- Sky Condition

These factors are taken further to formulate Instances to use it in daylight analysis.

Moreover, some factors of the building like floor level, room's volume and room's functional requirements for daylight are another parameters for a space that can impact on visual comfort; however, these factors are fixed for further analysis of this study.

02. What is the state of art in façades to control daylight distribution? [Case Studies]
2a. What are the facade systems that deal with daylight enhancement in an indoor space?
2b. What are the facade systems that deal with daylight reduce/diffuse in an indoor space?

Several systems of the facade with their classification were studied based on state of the art in controlling daylight with the focus on two aspects, daylight enhancement and daylight diffuse/reduce inside the building. The system like light shelves shows promising potential in daylight enhancement to a greater depth by redirecting light; while shading systems like lovers and blinds showed potential towards diffusing or blocking the daylight. However, the external daylight factors add the most significant challenge for performance along the year and use of above-mentioned systems in their static form limits to the requirement of this study. Henceforth, the use of an adaptive facade system was found to be more feasible showing potential to tackle the external daylight factor as well as to perform different functions like daylight enhancement and daylight reduction using the same system.

Furthermore, from selected research case studies, it was found that a multi-surfaced geometry can help to attain different functions on the facade at the same time and providing flexibility on configuration by treating each element independently can improve the performance regarding daylighting. These considerations are taken further for developing a geometry and facade for this study.

3.0
Design
Consideration

3.1 Site

3.1.1 Location

Rotterdam

Located in the most populous province of Netherlands, the city of Rotterdam is famous for its modern architecture and is considered the architectural capital of the Netherlands. Rotterdam has the highest number of high-rise in all of Netherlands, with 38 skyscrapers and 352 high-rises till date ("Rotterdam," n.d.), The city has an impressive skyline and has been named 'Manhattan at the Meuse'.

Figure.3.1 Map of NL showing Rotterdam (Aalst, 2012)

3.1.2 Climate

The climate experienced in Rotterdam is temperate Oceanic as per Köppen Climate Classification (cfb). A climate study of Rotterdam is carried out to understand the local environmental aspects that contribute towards the daylight performance of the building. The factors like cloud, sun for annual pattern are analysed.

Sun

Over the period of a year, the Rotterdam experiences extreme change in length of the day with a difference of around 12 hours between the longest and the shortest day (figure.3.2).

According to Average Weather in Rotterdam 2020 ("Average Weather in Rotterdam," 2020), the longest day is 20th June having daylight availability for 16 hours and 43 minutes, wherein the shortest day is 21st December having daylight availability for only 7 hours and 45 minutes. The earliest and the latest sunrise timing experienced are, 5:21 AM on 17th June and 8:49 AM on 30th December. The earliest and the latest sunset timing experienced are, 4:30 PM on 12th December and 10:05 PM on 24th June. The difference between the earliest and the latest sunrise stays with a gap of 3 hours and 28 minutes' wherein for sunset is 5 hours and 35 minutes over course of a year.

The Daylight-Saving Time (DST) in Rotterdam will last for 6.9 months where it will begin in spring on 29th March until the Fall on 25th October.
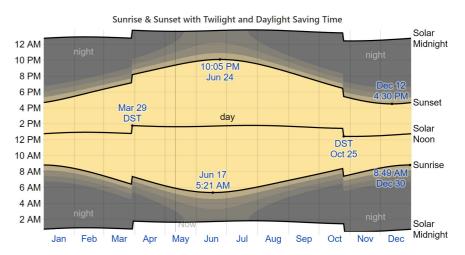

Figure.3.2 Solar days for a period of year 2020. ("Average Weather in Rotterdam," 2020)

Clouds

Over the period of a year, Rotterdam experiences a significant amount of seasonal variation (figure.3.3) and the average percentage of sky remains covered with clouds ("Average Weather in Rotterdam," 2020).

Clear skies are experience upto 6.5 months where it begins around the 26th March and ends around 9th October. In Rotterdam, 21st June is said to be the clearest/cloudless day of the whole annum; 58% of the time the sky is clear, partly cloudy or mostly clear, and 42% its mostly cloudy or overcast.

Cloudy skies lasts upto 5.5 months of a year, beginning at the time when clearer sky period ends, which is around 9th October and ending around 26th March, which is again the start period for clearer sky. In Rotterdam, 26st December is said to be the cloudiest day of the whole annum; 68% of the time the sky is overcast or mostly cloudy, and 32% its mostly clear, clear or partly cloudy. Hence, the probability of getting clear sky is not more than 10%.
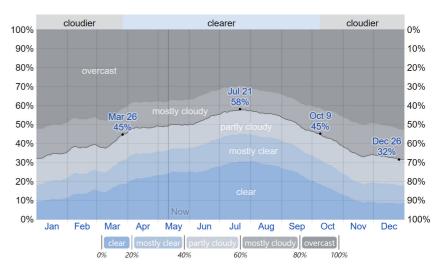

Figure.3.3 Cloud cover for a period of year 2020. ("Average Weather in Rotterdam," 2020)

3.2 Building Description

Building Typology and Activity
The subject space to study in this research is an office space in a high-rise office building. The activity for the office space selected for this research is a workplace with a task that requires the use of computer screens.

Office Space
An office space can be as small as one cabin for a single occupant to an open office plan where whole floor space is open without any partition. To restrict the limit, and to study the nature of the distribution of light levels in a space with respect to its depth, a tube-shaped modular room is proposed as a fraction of a typical floor plate. The room is proposed with a dimension of 3m of width, 9m of depth (figure.3.4) and has 3m clear height from floor to ceiling. The dimension of the window with respect to the amount of space it is supposed to lit inside is one of the important aspects to be considered. The desirable glazing ratio (the ratio of floor area to the glazing area) should be typically in the range of 5%-30% (Fontoynont, 2014). Due to the consideration of longer depth in the proposed scenario, the glazing ratio of the proposed room comes out to be 3%, which is almost 40% less than the least desired value of 5% as previously mentioned. The idea behind proposing a room with less width but longer depth was to bring out a study to examine the effectiveness of the designed façade in distributing daylight to check the extent of its performance for maintaining uniform distribution along the length of the proposed room; also, this is in accordance with the main objective of this research.

Interior Furniture layout and occupant's sitting position
The furniture in an office space can be arranged in many possible ways as long as it allows its user to fulfil their tasks and activities. In a workspace environment, work areas and equipment have designated positions. Hence, the furniture placement in the proposed case is considered as a fixed arrangement. The furniture layout inside the room has been filled by adding a set of three workstation/desk at a distance of 3m centre to centre having a size of 1.50m width and 1.20m depth each as shown in figure.3.4. The alignment of the workstations on the floor is along the centre of the longest side of the proposed room. Each workstation accommodates two occupants in a sitting position, facing each other; hence, a total of six occupants inside the proposed room. The occupants are facing in a perpendicular direction with respect to the view to the window, and have a computer screen in front of each occupant on top of their workstation. The workstation height is considered at a standard height of 0.70m. Furthermore, the proposed room is an open plan without any partitions in-between.

Facade Segment
The whole face in front of the glazing window has been considered as the facade segment, which is 3mx3m in dimension.

Facade Orientation
In accordance with the objective of this research to examine the nature of light distribution within the building using a facade, the orientation of the façade was selected keeping in mind the sunlit orientation. Hence, the proposed room is aligned to north-south axis and a south facing opening is considered for facade and is taken further for daylight analysis. of this research study.

Window Glazing Type
Visible Light Transmittance (VLT) is a measure to determine the quantity of visible light from outdoors to penetrate inside the building by passing through a glazed window. In other words, the transmission of a portion of light in the visible spectrum that passes through the window glazing. This implies the big value of VLT represents high amount of light will pass through the glass, which means more light gain inside the building. Thus, a high value of VLT leads to improve daylight level and reduces the lighting loads (Syed, 2012). On the contrary, a high value of VLT can also lead to high solar gain; hence, the Visible transmitted (VT) value for the window glazing taken is 0.65, which means only 65% of the light will be transmitted inside the building. This value will further be taken into simulation for daylight performance as a fixed input.
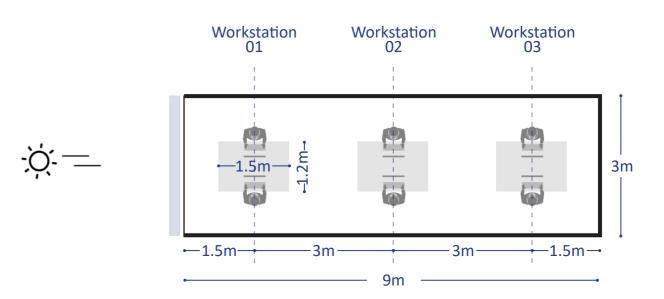

Figure.3.4 Proposed Room for this study and analysis.

3.3 Instances

The quality, as well as the quantity of daylight in a building annually or diurnally, is highly dependent on its geographical location and climate. The position of the sun for any specific location is a variable, which depends on the earth's revolution around the sun annually, and the earth's rotation around its own axis daily. Moreover, the prevailing climatic condition affects the luminous intensity and visibility of the sun and the luminous distribution of the sky. Thus, after fixing the location and orientation, there are three main important external factors that influence the behaviour of light that reaches the building and affects daylight performance; sun's altitude, sun's azimuth and luminous distribution in sky.

A part of the objective is also to develop the façade that can perform effectively by adapting to change in external factors that influences the change of daylight levels. Hence, the designed facade was supposed to be analysed for its performance for all factors mentioned above. To keep the scope of the research feasible to finish on time available; the selection of different cases within these factors was made by considering the extremities possible in all factors of an outdoor environment. The selection of cases are categorised as follows:

Based on Sun's Altitude (Days)

The selection of the day was based on the extreme condition of Sun's position along the whole year. Here, two day of solstice was taken into consideration. First, summer solstice, when the altitude of the sun is in highest position. Second, winter solstice, when the altitude of the sun is on the lowest position. According to Rijkswaterstaat, 21st June and 22nd December are considered as Summer and Winter solstice respectively in The Netherlands, hence, the same in Rotterdam.

Based on Sun's Azimuth (Hour of the Day)

The hours of the day were selected considering the orientation/azimuth of the sun that changes by time along the day but within the workday hours of office. Most of the office in Netherlands works between 9:00 to 17:00 in daytime. Three different time were selected at an interval of 3 hours between them; 10:00, 13:00, 16:00 and the orientation of the sun w.r.t subject window is towards south-east, south and south-west respectively.

Luminance Distribution (Sky Conditions)

Again, the sky condition considered for research were two extremes based on CIE sky type. First is Clear sky, when the luminance distribution in sky from the sun is the highest possible. The second is an overcast sky, when the sky is completely covered with clouds and the luminance distribution in sky from sun is one of the lowest for that particular hour.
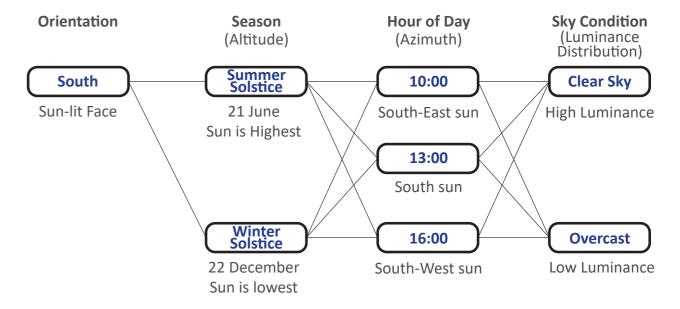

Figure.3.5 Showing combination of all the instances to be analysed.

By keeping the location as Rotterdam and orientation towards South as a fixed parameter, the final instances were formulated by combining permutation of 7 cases of external factors, which includes two days of two different seasons, three different hours and two different CIE based sky condition. Hence, the facade will be analysed for two CIE based sky type for all three different hours for both days of two seasons, which makes 12 different instances as shown in figure.3.5

The instances used are coded in the format of XX-YY-ZZ, where XX will be first two initials from season (SU for Summer solstice or 21st June and WI for Winter solstice or 22 December); YY will be the hour of day (10 or 13 or 16) and ZZ will be sky condition (CS for Clear Sky and OC for Overcast). For example,

SU-13-CS

WI-10-OC

3.4 Visual Comfort Criteria

The evaluation process of this research is based on the criteria that will help to achieve visual comfort inside the building, along with uniform distribution of daylight intensity. The factors that determine visual comfort, as discussed in section.2.2.1 were taken further as the base for evaluation. The analysis will focus on these three factors - the distribution of daylight, glare availability and Contrast. The metrics correspond to these three factors is considered as the foremost focus for the visual comfort criteria to validate proposed facade for visual comfort in this research. None of the annual metrics is considered for the daylight analysis study.

From the discussion made in section 2.4.1 for daylight standards, the standards for daylight provided by NEN-EN 17037 (2018) is based on annual calculation; wherein the analysis to perform in this study is for a specific hour. Also, NEN-EN does not mention uniformity ratio and contrast ratio, whereas BREEAM (2016) has guidelines on these metrics. Furthermore, CIBSE (2015) recommends the specific illuminance value of 500 lux for an office workplace; while on the contrary Chauvel (1982) recommends to use the range (Section 2.4.1) for validating a room for daylight as the spread of daylight's intensity keeps varying with the depth.

Hence, all the values for the visual comfort criteria mentioned below in Table.3.1 are based on Design standards- NEN-EN 17037, BREEAM (2016) and Design guidelines. The required values for evaluation criteria are formulated as below:

Factors	Daylight Metrics	Target Values
Distribution of Daylight	Average Illuminance	300 - 750 lux
	Daylit Area	300-2000 lux for >95% Minimum lux >100
	Uniformity Ratio	> 0.3
Glare	Daylight Glare Probability (DGP)	0.45 - 0.35 (Perceptible Glare) <0.35 (Imperceptible glare)
Contrast	Contrast Ratio	< 3.0

Table.3.1 List of evaluation criteria requirements, to validate the proposed facade's daylight performance for visual comfort

I.   Distribution of Daylight

The evaluation criteria for the factor - distribution of daylight inside a room, is separated into three different metrics. The first metric is Average Illuminance (E), to get an idea about the average intensity of daylight available inside the whole room. The second metric is the Daylit Area (DLA), to see how much area on a working plane receives the ambient or the useful daylight (300-2000 lux). Moreover, the third metric is Uniformity ratio (UR), which is to know the extent of uniformity achieved in the distribution of light intensity along with depth of the room. All the metrics mentioned above have specific criteria to be fulfilled for a good daylight performance. The recommended criteria values for these three metrics are mentioned below:

a.   Average Illuminance
Average illuminance (E) is the average of all the illuminance values obtained on each grid of a working plane. The target value recommended by NEN-EN 17037 is a minimum of 300 lux, a medium of 500 lux and a maximum of 750 lux. As a criterion for evaluation, the range of minimum to maximum is considered, i.e. 300 lux to 750 lux. The resultant value of the average illuminance of all the instances should fall within this range to validate the criteria.

b.   Daylit Area
The area is said to be daylit if it falls under the ambient range of illuminance. The ambient range considered for this research is between 300 lux to 2000 lux. Combining the ambient range with the provided percentage of the area by NEN-EN (section-2.4.1), two criteria for Daylit Area (DLA) are formulated. First, more than 95% of the area on working plane should fall within the range of 300-2000 lux. Second, the minimum illuminance inside the room should be more than 100 lux. The resultant value should fulfil the first DLA criteria or at least second DLA criteria in case it fails to fulfil the first criteria.

c.   Uniformity Ratio
The ratio between minimum available illuminance inside a room on a working plane, to that of the average illuminance value of entire room on the same working plane, is considered as Uniformity Ratio (BREEAM, 2016). The recommended value of Uniformity Ratio (UR) provided by BREEAM (2016) should be at least 0.3 or more for spaces illuminated by daylight. The evaluation for UR will be checked considering the full depth of 9m (as per proposed room).

$$\text{Uniformity Ratio, } UR = \frac{Minimum\ value\ of\ Illuminance}{Average\ Illuminance}$$

II. Glare Check – DGP

Glare is experienced when there is an excessive brightness or availability of direct sun. The most notable possibility of experiencing such a situation is in a region close to the window, and the most affected person would be the one sitting next to it. With that consideration, the two occupants sitting on Workstation 01, which is located closest to the window, are prone to experience major glare issues. Hence, the evaluation of glare analysis will be made for these two occupants in their sitting position looking towards their computer screen, represented as O11 and O22, as shown in figure.3.6. The metric used for glare check is Daylight Glare Probability (DGP). The accepted DGP value recommended by NEN-EN 17037 is 0.45-0.35 for perceptible glare or <0.35 for imperceptible glare.

III. Contrast Check - Contrast Ratio

The contrast occurs due to the difference in brightness of the light between two surrounding surfaces. As the main objective of this study is to have uniform daylight distribution along the depth of a room, the evaluation of contrast check for the proposed design is executed by considering three divisions of floor depth. The number of divisions are equivalent to the number of workstation provided in the room. The three divisions are denoted as Area 01, Area 02, and Area 03, as shown in figure.XX. Each area corresponds to one workstation, respectively. Contrast Ratio (CR) is the ratio of average luminance between two surrounding surfaces, and the recommended minimum contrast ratio between luminance on two surrounding surfaces should be less than 3:1. Hence, the evaluation is made between Area 01, 02 and 03 where contrast ratio between Area 01 to Area 02 will be C1, and the contrast ratio between Area 02 over Area 03 will be C2.
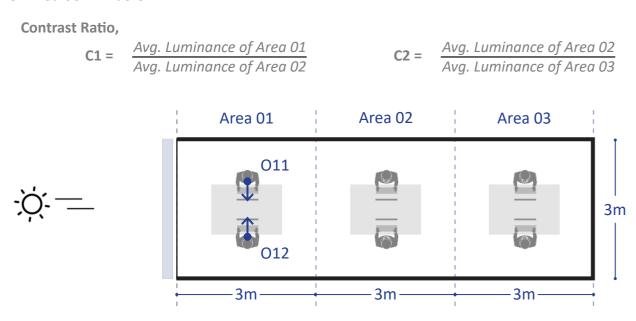
Contrast Ratio,

$$C1 = \frac{Avg.\ Luminance\ of\ Area\ 01}{Avg.\ Luminance\ of\ Area\ 02} \qquad C2 = \frac{Avg.\ Luminance\ of\ Area\ 02}{Avg.\ Luminance\ of\ Area\ 03}$$

Figure.3.6 View of occupants for Glare check and Division of depth for contrast check

04. How a facade system can be assessed for visual comfort that control daylight's distribution along the depth coping with the dynamic behaviour of daylight?

As mentioned in answer of sub-question 01, the requirements that defines visual comfort were taken further to formulate as visual comfort criteria includes following metrics:
I. Average Illuminance - It shows the average amount of intensity of light spread within a space.
II. Daylit Area - It shows the amount of light within the spread light in useful or comfort range.
III. Uniformity Ratio - It shows how uniformly the intensity of light within spread light is distibuted in provided length of space.
IV. Glare - This shows the level of brightness available in the visual field.
V. Contrast Ratio - This shows the difference in brightness between two adjacent surfaces

Further, all the criteria with required values that defines visual comfort range were formulated referring available daylight standards NEN-EN 17037 (2018) and BREEAM (2016); and some design guidelines provided by researchers.

The performance of the facade for each instances developed based on dynamic conditions of daylight should fall within the provided range of visual comfort criteria for each metric to get validated for visual comfort.

4.0 Geometry

4.1 Concept Formulation

After investigating various facade systems available in practice (Section 2.3.5) that performs under and adapts to daylight, a design concept for the facade in this study can be proposed. The concept is formulated by taking the main aspects gathered from research case studies 01, 02 and 03 further. The origami- inspired and multi-surfaced geometry of a Kaleidocycle is taken as a reference from research case study 03 as the initial geometry, with the intention to use separate materials on different surfaces to make the facade multi-functional thereby fulfilling the objective of this study. The main architectural idea for designing an adaptive façade for this study is developed by apprehending the concept of Kaleidocycle geometry and its repeating tetragonal disphenoids. The geometry is further modified to make it more flexible to integrate the most influential parameters like rotation and configuration for daylight performance, taking reference from research case studies 02 and 03.

A basic Kaleidocycle is a 6-tetrahedrons or 6-tetragonal disphenoid with isosceles triangles, connected together on opposite edges, and forming a cycle using origami technique ("Kaleidocycle,"n.d.). Furthermore, Kaleidocycles are a flexible polyhedron that can be twisted along a circular axis by making transitions at coinciding edges of tetrahedron's degenerated pair.

As shown in figure.4.1, a Kaleidocycle can have connections higher than 6, in even numbers like 8, 10, 12, etc. with a gap left in the centre which increases with the number of connection. The amount of gap can be altered by changing the proportion of the triangular faces or tetragonal disphenoids. Moreover, with 6-connections it leaves almost no gap in-between. It is assumed that this uncontrolled phenomenon of openness or closeness can lead to direct sun or not enough penetration of light respectively.
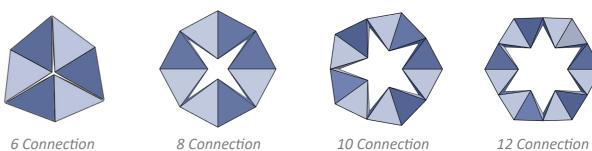

6 Connection   *8 Connection*   *10 Connection*   *12 Connection*

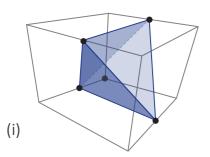*Figure.4.1 Variations of Kaleidocycle. ("Math GIFs,"n.d.)*

As said by Samadi (2019), every element should be treated independently with separate rotation to improve the daylight performance; which in the case of Kaleidocycle, the repeating modules inside one cycle are not independent. All the modules move together to make the motion of a Kaleidocycle geometry work, and hence, the control over such geometry might become limited. Also, Sheikh (2014) said that the rotation of each individual elements should be configured in a way that they correspond to each other to improve daylight performance. Again, in the case of Kaleidocycle, all the tetrahedron in one cycle has different angles and are aligned on different axes, this may limit in terms of flexibility required for forming configurations.

4.2 Geometry Selection

The approach towards developing the final geometry began with understanding an 8-connection Kaleidocycle, as shown in the figure.4.3-(i), made with paper-folding technique. Keeping in mind the difficulties that could compromise the performance while fully using a Kaleidocycle geometry as discussed in the preceding paragraph, the cycle of Kaleidocycle was broken and stretched linearly by keeping corresponding connections together as shown in figure.4.3-(ii). Now, each disphenoid remains within the same axis after making it linear. This linear connection was further divided into a pair of disphenoid to gain adequate control, and the outcome was 4-independent modules of a pair of disphenoid, as shown in the figure.4.3 (iii). Now, all the modules can be treated independently. Henceforth, a pair of mirrored disphenoid as one module, as shown in the figure.4.3-(iv) which is still a multi-surfaced geometry, is selected as the base geometry for a facade of this study. As the sole purpose behind the choice of Kaleidocycle was to use a multi-surfaced geometry to treat different surfaces with different material property, the purpose is still being fulfilled by finalised repeating geometries of disphenoid but with a more flexible approach.

Selected Geometry – A pair of Tetragonal Disphenoid
A tetrahedron disphenoid has four congruent acute-angled triangular faces, the two opposite edges of which are equal in length. The tetragonal disphenoid geometry can be made in two ways, by positioning it inside a cuboidal space where the midpoint on its two opposite faces bisects or where the diagonal points on two opposite faces bisect as shown in figure.4.2 ("Disphenoid," n.d.). For simplicity, a pair of tetragonal disphenoid with all equal edges is selected for further analysis. The shape is equivalent to a tetrahedron or a triangular pyramid.
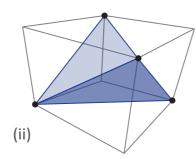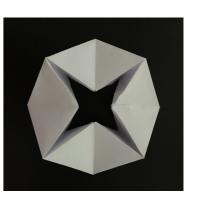

(i)   (ii)

Figure.4.2 Making of tetragonal disphenoid by selecting (i) Midpoints, (ii) diagonal points

After finalising the geometry, a dynamic motion within the selected geometry needed to be created to make it more efficient for daylight performance and gain control over daylight distribution. Some modifications are made over selected geometry keeping in mind that while integrating the geometry in a façade, it should be capable of:
- Using each element separately and independently.
- Perform well with all the instances of dynamic daylight along the year.
- Possibility in closing the whole façade, which can be required to protect against extreme weather from outside.
- Possibility in providing a maximum opening that can work during very cloudy days to gain maximum light, and to provide a full view when needed on a specific occasion.
- The geometry should be simple with the minimum required motion and should integrate with the mechanism available in the market.
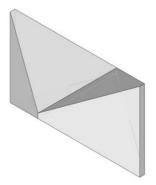

(i) Kaleidocycle Module-8 connection

(ii) Opening up the Kaleidocycle

(iii) Selecting one repetative module from the series
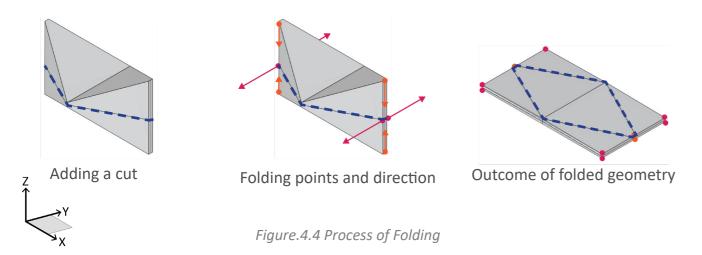

(iv) A pair of Tetragonal Disphenoid

Figure.4.3 Showing steps of geometry selection

4.3 Geometry Modification

Taking the base geometry - a pair of disphenoid, where the module is motionless and has a static shape; the module is modified in three steps to make it dynamic in order to adapt with dynamic daylighting. The idea behind the modification process was to make the module as flexible as possible to achieve the optimal result in performance.
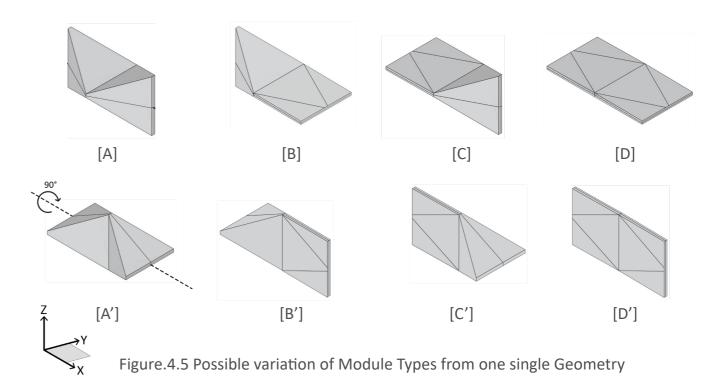
I. Adding Fold

The first modification over geometry is made by adding a half-cut at the centre of the geometry along the XY-plane, with a folding feature (figure.4.4). The module is now capable of folding and unfolding dynamically to gain several variations. Furthermore, the fold/unfold is separated for both tetragonal disphenoid, resulting in four different variations obtained from one single module, as shown in figure.4.4. These four module types are categories with different names as A, B, C and D. Module A is equivalent to the original geometry; here the geometry is said to be in an unfolded state or can be perceived as an open module. On the other hand, Module D is said to be in a completely folded state or can be perceived as a close module. Furthermore, the module B and C can be perceived as half fold/unfold or half-open/close. The abbreviation can also be used as; to increase the openings in a façade, more modules need to be folded or need to be closed.

Adding a cut   Folding points and direction   Outcome of folded geometry

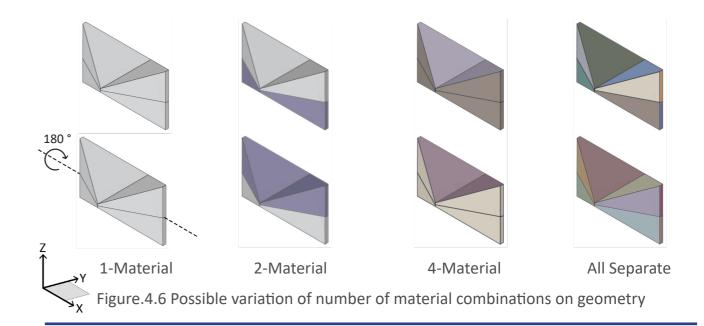*Figure.4.4 Process of Folding*

II. Adding Rotation

Rotation is a major parameters which can influence the performance of daylight largely, as said by Samadi (2019). The rotational motion can be executed in various ways; along the x, y, or z-axis or along a non-axial direction. In order to to keep the dynamism of the proposed facade as simple as possible while thinking of its practical application and automation; the module is provided with the rotation along the axis that is formed on its longest length from the centroid point (or X-axis), as shown in figure.4.5. Folding/Unfolding of the module together with the rotation of about 90° is providing four more variations - A', B', C', and D' as shown in figure.4.5.

[A]   [B]   [C]   [D]

[A']   [B']   [C']   [D']

Figure.4.5 Possible variation of Module Types from one single Geometry

III. Adding Material

After understanding the possible outcomes of dynamic variations achieved using the finalised multi-surface geometry, in this last step of modification, the module is provided with different material properties on different surfaces, which was the foremost reason behind selecting this geometry. The number of material variation needs to apply on a module can vary from having the same material on each surface to all surface with different material, or different material on a group of few surfaces. The figure.4.6 shows a few examples on different possibilities in applying material on a module; where a module is having one, two, four material or each surface with separate material. The amount and selection of material on the module eventually depends on the daylight performance requirements of the optimised facade.

1-Material   2-Material   4-Material   All Separate

Figure.4.6 Possible variation of number of material combinations on geometry

4.4 Advantages of Geometry

Openness / Closeness

One of the advantages of using the modified module from selected geometry is the potential to control the amount of openness and closeness when configured in a facade. As shown in figure.4.7, a wide range in percentage of openness is obtained utilising different variations of the modified module by looking at their elevation. This wide variation of the range is believed to help in controlling two factors, the amount of light penetrating the room, and the amount of visual connectivity with the outside. The penetration of light can be increased by folding more modules, which increases the openness of the façade. Similarly, to increase the visual connection to outdoors, more modules need to be folded and visa versa.
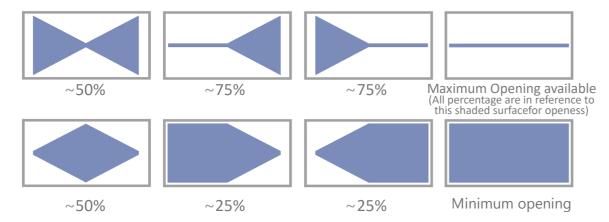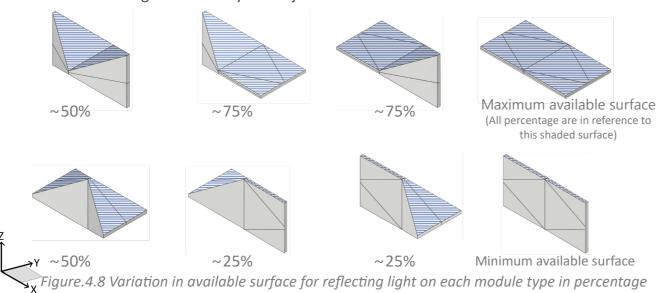

~50%　　　~75%　　　~75%　　Maximum Opening available
(All percentage are in reference to this shaded surfacefor openess)

~50%　　　~25%　　　~25%　　Minimum opening

Figure.4.7 Variation of closeness of facade for all module type in percentage

Surface available for reflecting and blocking of incoming light

Another advantage of using a modified module is the potential to control the amount of direct light to be redirected or to be blocked for inside using the surface available on the module. As shown in figure4.8, a wide range in percentage of the available surface is obtained utilising different variations of the modified module by looking on the top. Again, this wide variation of the range is believed to help in controlling two factors, the amount of light redirected inside, and the amount of light blocked by the adjacent surface.

~50%　　　~75%　　　~75%　　Maximum available surface
(All percentage are in reference to this shaded surface)

~50%　　　~25%　　　~25%　　Minimum available surface

Figure.4.8 Variation in available surface for reflecting light on each module type in percentage

Light redirecting Benefit

The law of reflection of light states that a striking light ray on a surface bounces back on the opposite side of the normal line with the angle similar to the angle of incidence ("Reflection", n.d). With consideration of this concept, it is believed that from the available set of variations of a module, their geometry is made useful to reflect light in different directions to cover dark spaces. For example, the incoming light from south-east direction inside a south-facing room creates a dark corner towards the east of the room, in this situation, the use of module B can help in reflecting south-east light back to the east corner of the room (Figure.4.9). This is because the shape of module B, with one disphenoid is unfolded, has a slant surface which is tilted towards the east. Similarly, the use of module C having slant surface tilted towards the opposite direction to module C can help to reflect the incoming south-west light to the dark west corner. Whereas, module A can reflect the light to both directions due to the presence of two opposite slant and module D which help to reflect in a straight direction due to flat surface. Henceforth, the variations of a module are assumed to provide enhanced daylight with controlled distribution in all directions of the room. Similarly, module B will redirect light from south west coming light.
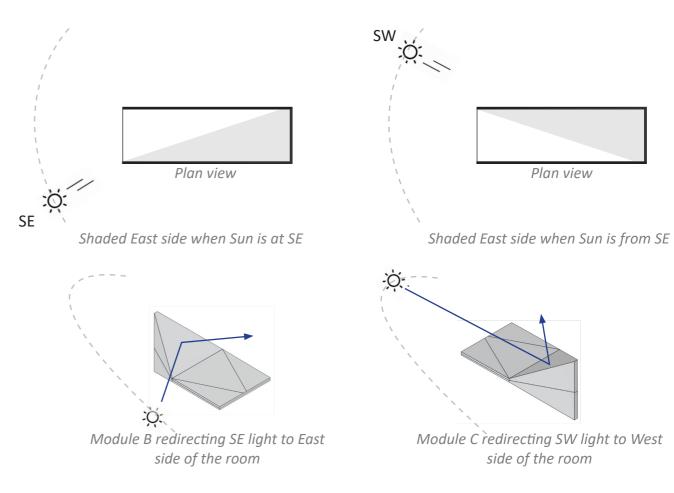

Plan view　　　　　*Plan view*

Shaded East side when Sun is at SE　　*Shaded East side when Sun is from SE*

Module B redirecting SE light to East side of the room　　*Module C redirecting SW light to West side of the room*

Figure.4.9 Showing redirecting benefit of module's variation for SE and SW incoming light

4.5 Facade Configuration

The selected facade segment, as discussed in Section.3.2, measures 3mX3m. The facade is configured within the available dimension as a modular facade system using the modified geometry. The application of the modified module on a façade is made by arranging a series of four modules in 7-rows. For simplicity, the number of rows and columns are kept fixed for further analysis study and optimisation process. The proportion of the module is made to fit along the width of the façade in multiples of an integer number along the width.

The figure.4.10 shows a few examples of facade configurations using different module types and their corresponding percentage of closeness. It can be seen that with the proposed facade configuration, nearly a full range of control in openness/closeness can be achieved. With the right combination of different module types, the configuration which can be played randomly or in harmony with a logical pattern. The configuration of the facade can vary as per the required daylight performance within the room, which will be the results from the optimisation process.
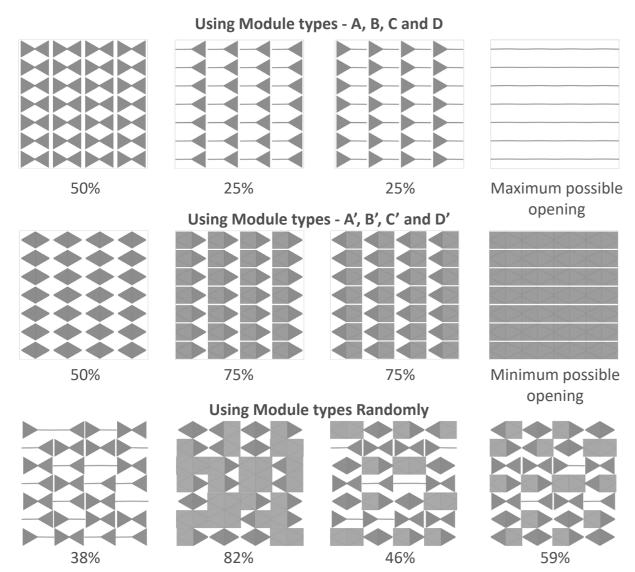
Using Module types - A, B, C and D

| 50% | 25% | 25% | Maximum possible opening |

Using Module types - A', B', C' and D'

| 50% | 75% | 75% | Minimum possible opening |

Using Module types Randomly

| 38% | 82% | 46% | 59% |

Figure.4.10 Possible variation of configuration of facade using different module type and its closeness in %

Façade's division in two parts

The configured facade is further modified by dividing it into two parts, upper and lower at the height of 2.1m, which is considered as the standard lintel height. The division is made to make the facade serve two different purposes - redirection and diffusion of light, whilst separating the module groups into rows. Sheikh's research (2014) mentioned in Section.2.3.5, states that for the light to be redirected inside the space, panels should be tilted towards the inside, and for blocking the light the panels must be tilted towards the outside. By applying the same consideration, the first two rows of modules, above 2.1m, in the configured facade, are rotated towards the inside (Figure.4.11) in order to make them work as redirecting panels and gain more daylighting at greater depth and improve the performance of under-lit areas. All the remaining panels below 2.1m, are rotated towards the outside (figure.4.10) to make them work as diffusing panels that serve to block or diffuse the light near the window, thereby reducing excessive light in over-lit area.
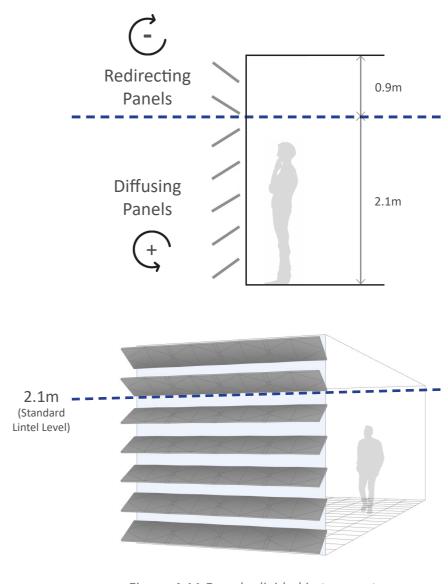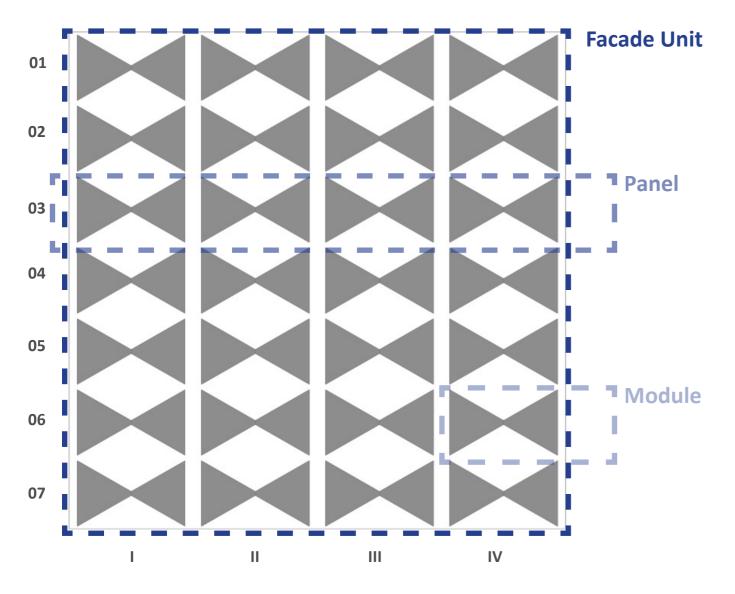
Redirecting Panels

0.9m

Diffusing Panels

2.1m

2.1m
(Standard Lintel Level)

Figure.4.11 Facade divided in two parts

Defining Terms

Facade unit
A facade unit is a selected facade segment in front of the room's opening. A facade Unit comprises of 7 Panels and 28 Modules.

Panel (Row)
A panel is a horizontal row in a facade unit. A facade Unit comprises of 7 panels and each panel comprises of 4 modules.

Module
The proposed geometry is considered as a module. It is dynamic and can fold/unfold and rotate. Each panel comprises of 4 modules and there are 28 modules in a facade unit.

Answer to Sub-Question

04. **What design approach could be best to avoid glare at the same time while gaining more daylight? Or the design approach to bring balance between over-lit and under-lit situation through a facade?**

The considerations taken from research case studies and as discussed in the answer of sub-research question 02, a multi-surfaced geometry with applying different optical properties on different surfaces shows good potential to perform different functions of redirecting and diffusing light simultaneously. To allow these functional aspects on geometry to perform with different daylight factors, a parameters of rotation was given to the geometry. Furthermore, the facade was divided in two parts to provide different rotation.

The proposed facade was divided in two parts to serve two functions,

Furthermore, the development process of geometry in the proposed study shows some important aspects that should be considered on a geometry.

- A geometry should be able to control openness/closeness of the facade to contribute in controlling the amount of light to pass through window.

- A geometry must have certain depth to provide a surface for redirecting or blocking of light. Moreover, a geometry that can transform to provide different surface areas is more likely to be preferred to contribute in controlling the amount of light to redirect or block at different spaces within the room.

- For a south-facing facade, an incoming light from SW or SE creates dark areas at the West and East side of the room respectively. Hence, a geometry should be developed in a way that can redirect light to such dark areas.

5.0
Computation
Design

The developed geometry of façade from previous chapter is taken further to find an optimal solution of façade design that performs to gain visual comfort indoors with high efficiency dealing with all selected instances which are based on different external daylight conditions. As discussed earlier (Section-2.5), the computational design method allows to deal with complex challenges; however, a computational workflow is developed as shown in figure. XX, which is applied for this study to find a façade design solution having high performance efficiency in achieving visual comfort. The workflow is divided in several steps that includes parameterisation of façade geometry through parametric modelling using Grasshopper (GH) and Rhino; then performing daylight simulation using Honeybee and Ladybug plugins used within GH; then attempting optimisation process for getting optimal solution regarding performance using Wallacei plugin used within GH; and ending with finalising design solutions by going through an evaluation process to fulfil visual comfort criteria developed in this study. The solutions that do not fulfil all required criteria will be sent back for few changes on façade and continue the process until all the required criteria relating visual comfort are met.
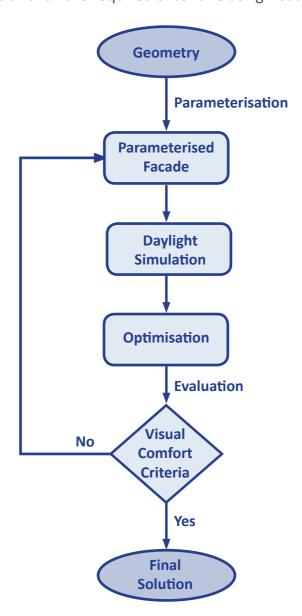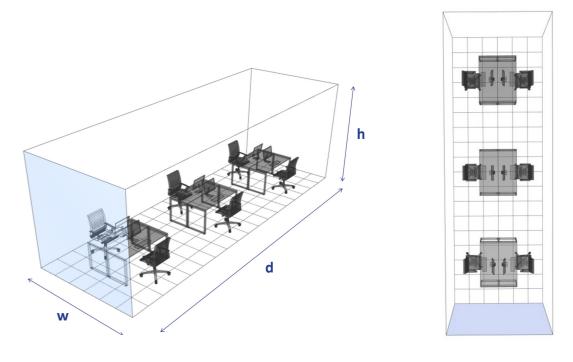

Figure.5.1 Applied Computational Workflow

5.1 Parametric Modelling

I. Room Setup

A setup is made for the room in grasshopper, as shown in figure.5.1, to study daylight performance. The dimensions are kept fixed as mentioned in section-3.2. The dimensions of the room is kept fixed. The room created is made to integrate facade geometry.

Room Dimension:
Depth (d)   : 9m
Height (h)   : 3m clear
Width (w)   : 3m

Figure.5.1 Room setup in Rhino + GH

II. Facade Setup

The selected geometry, a pair of tetrahedron disphenoid, with the implemented modifications of folding and unfolding, is taken into Grasshopper software. The geometry is then configured for the facade in front of the window glazing of the proposed room within the decided size of facade segment. The facade is made capable of controlling each module parametrically with sets of few essential parameters for daylight performance that can be taken further for the optimisation process.

Facade Parameters

Taking considerations from the three selected research cases concerning their essential aspects - rotation, configuration and material; three parameters for this study are developed - Rotation of modules, Folding/unfolding of Modules (perceived as configuration) and Material on module(Figure.5.2).

I. Rotation of Modules: The rotation parameter of modules is separated by rows; each panel is kept independent, and all modules within the same panel will have the same rotation.

II. Folding/Unfolding of Module: The folding/unfolding parameter for each module is kept independent; each module within the panel can change independently too.

III. Material on Module: The material parameter is based on the number of applied materials on each module. The change of material is basically linked to the first parameter- rotation. A module, having two material on opposite faces, will be rotated 180°, to flip the other material on the effective side for daylight performance by facing towards incoming light.

Rotation of modules-
Separated by Rows

Fold/Unfold of Modules-
Change Individually

Material change-
Whole facade unit

Figure.5.2 The proposed parameters of facade

5.2 Daylight Simulation

The simulations are made assuming that the proposed office space is located in Rotterdam. For climate data, a weather file of Rotterdam is used ("Climate.OneBuilding.Org", n.d) in EnergyPlus Weather Format (EPW). The used EPW file contains typical meteorological data obtained from hourly weather data of Rotterdam for the most recent 15-years (2004-2018).

The simulations are performed using Ladybug Tools (Roudsari, n.d). For illuminance simulations, LB legacy (Version 0.0.68- 01 Jan, 2020) and HB+ (Version 0.0.04- 06 Oct, 2018) is used and for simulation of glare analysis, LB Legacy (Version 0.0.68- 01 Jan, 2020) and HB Legacy (Version 0.0.65- 01 Jan, 2020) is used.

A workflow within the scope of used tools is applied as shown in figure.5.3, for performing daylight simulation and gaining the resultant value and visualised data for analysis. The developed Grasshopper script for daylight simulation process can be referred from Appendix. A4.
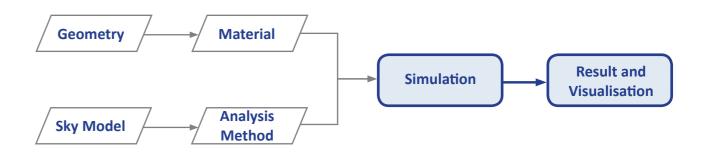
Figure.5.3 The applied workflow for daylight simulation used within LB and HB Family

5.2.1 Simulation Setup

Geometry Input

The developed facade geometry in GH with proposed geometry of an office room, as mentioned in the previous section, is now taken as an input geometry for performing daylight simulation. The geometry is attached to HB+ components first by converting into HB surfaces that can be computed for simulation and can be recognised as geometry by the simulation engine of HB+. While converting the geometry into HB surfaces, the surfaces are given the material properties. The care is taken in separating the surfaces of geometry in GH to apply different material properties.

Material Input

The material properties used in the proposed study are radiance material, and the definition of material is purely based on its transmittance, reflectance, specular and roughness values. The consideration of colour on material or a specific name/typology of material is not considered in this study. The material property is applied to both inputted geometry; proposed facade and proposed room.

For the proposed facade, all the surfaces used are taken as an opaque surfaces with no transmittance value. The geometry of the module is divided into two parts from the line of the fold to implement two different material property on one single module so that each module can obtain two separate material properties. As the configuration of the proposed facade is divided in two set of group of modules for two different purpose- redirecting and diffusing (Section-4.3); the redirecting modules are given two diffusive specular properties, and diffusing modules are given two diffusive properties as shown in figure.5.4. In total, four different materials are used; henceforth, 4-variant of composition - M11, M22, M12, M21 on the facade are possible as shown in figure.5.5 and figure.5.6. To maintain the simplicity of this study, and the feasibility of facade; only material sets M11 and M22 are considered for the analysis study. The selection of these two materials is based on the extreme values of the property in combination.
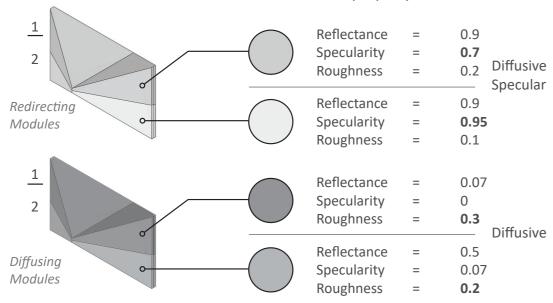

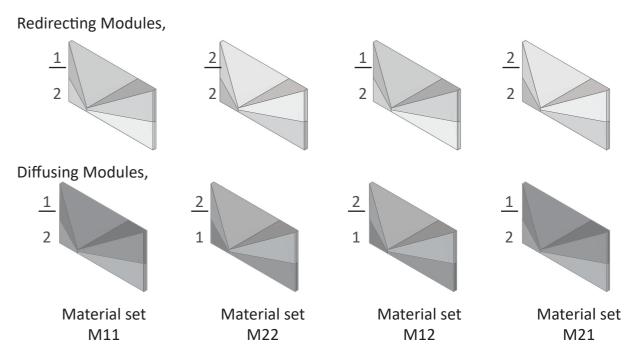*Figure.5.4 Different Material applied on module for different functions*

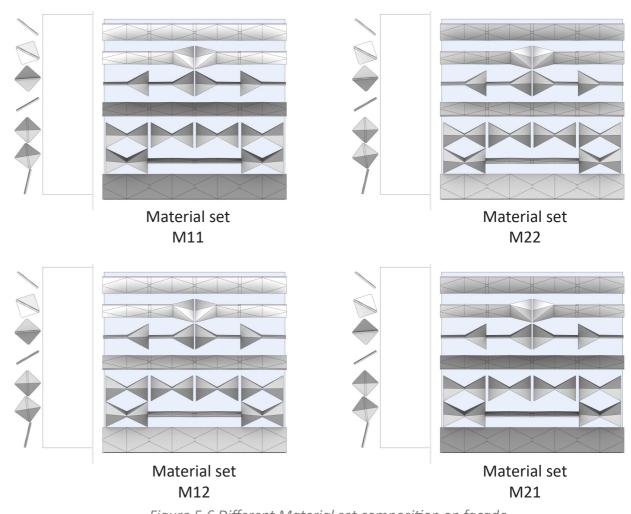*Figure.5.5 Different Material set composition*

Figure.5.6 Different Material set composition on facade

For the proposed room, the consideration of the values for internal surfaces are taken as per the recommendation of NEN-EN 17037. The reflectance value of 0.7 and 0.2 is applied for ceiling and floor respectively. The reflectance value for wall is not considered for any simulation in this study due to the proposed narrow size of the room. A comparative analysis of using reflectance property of internal surface is explained in Section-5.2.3(III). Also, a transmittance value of 0.65 is given to glazing window of the proposed room.

Sky Type Inputs

For sky settings, CIE sky component of HB+ is used. Amongst all available sky type options (discussed in Section-2.5.2), only two sky type -clear sky and overcast is taken; and input for days and the hour of the day is as per the selected cases of instances for the analysis study(Section-3.3).

Analysis Method

Three different analysis methods are being used to calculate different metrics from the evaluation criteria,

(i) Grid-based Illuminance for Average Illuminance, Daylit Area and Uniformity Ratio. This method provides the values of lux on each grid cell on a working plane. All the values of lux are averaged to gain resultant value for Average Illuminance in lux. A threshold upper and lower limit of 300-2000 lux is inputted, and the percentage is calculated for the number of grids with their lux values that fall within inputted range to gain the result for Daylit Area in %. Furthermore, a division is applied between the lowest lux value on the reference grid to the previously calculated average illuminance value; the resultant value is Uniformity Ratio.

(ii) Image-based Luminance for DGP. This method quantifies the spread of brightness, within the field of view selected. The value of DGR is calculated using an inbuilt component 'Glare Analysis' in HB+.

(iii) Grid-based Luminance for Contrast Ratio. This method calculates the value of luminance on each grid cells of the working plane. The working plane is divided into three equal parts as per the requirement of evaluation criteria for contrast ratio, and the obtained values of luminance for each division is averaged separately. The value for Contrast ratio is obtained by dividing the average luminance of one division to the adjacent division.
The working plane is considered at the height 0.70m, a standard height for a workstation. The same working plane is divided into a number of grid cells of size 0.5x0.5 for GB simulations.

Simulation Run

The simulation process has a big impact from the values of radiance parameters used. It defines the accuracy of the simulation. More defined reasoning with a comparative investigation is made between different simulation accuracy with changing radiance parameter values is discussed in Section-5.2.3(IV).

Result and Visualisation

The resultant values of all the criteria from the evaluation is obtained at the end of the simulation. The results obtained from HB+ is visualised differently for different analysis method. The representation of GB-Illuminance is a gradient of colour on a grid mesh. Two different grid mesh is used, as shown in figure.5.7. One represents the gradient of light intensity in lux used for Average Illuminance, and other represents useful (300-2000 lux) and non-useful (<300 + >2000 lux) used for Daylit Area. The representation of IB-Luminance is a fisheye view image in HDR and false-colour format for DGP, as shown in figure.5.8. The representation for GB-Luminance is not taken as the requirement is to get the ratio of average values for the evaluation.
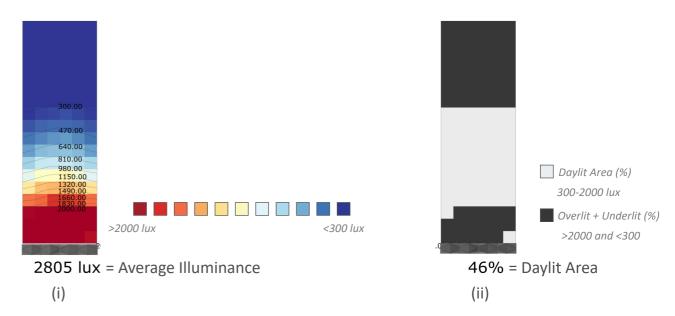

2805 lux = Average Illuminance
(i)

46% = Daylit Area
(ii)

Figure.5.7 Grid Mesh representation for (i) Average Illuminance (Lux) and (ii) Daylit Area (%)
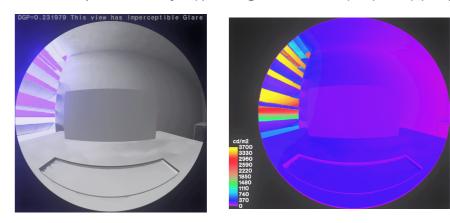

Figure.5.8 Fisheye image representation for IB-Luminance or DGP

5.2.2 Daylight Behaviour

I. Behaviour of light without Facade (Daylight Availability)

After setting up the simulation workflow and before commencing the simulation with facade geometry, a study is made for the availability of daylight in lux inside the room on a working plane but using only glazing. Also, the value of outdoor illuminance is noted. The availability of light is checked for all 12 proposed instances, and the resultant values and grids are sorted according to change in altitude, azimuth and luminance distribution and compared in figure.5.9. The sole purpose of this study is to understand the behaviour of daylighting for different instances prior to using the proposed facade. The obtained values are considered as available threshold values.
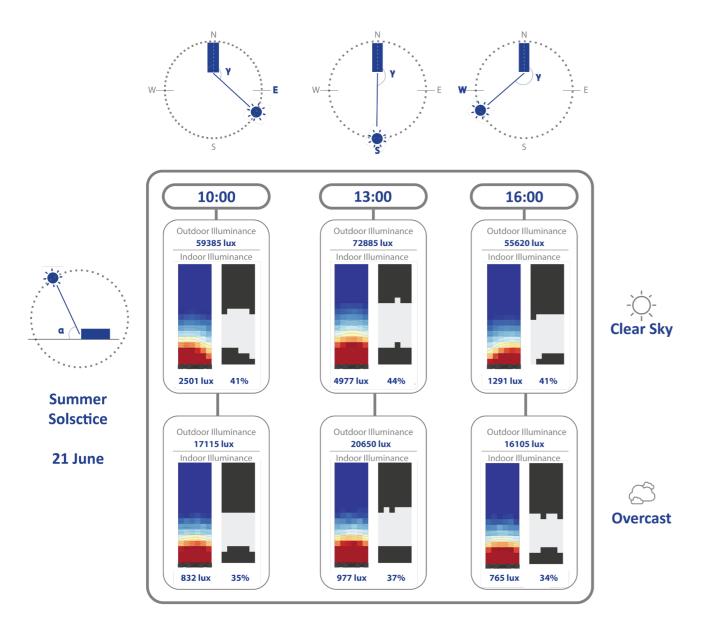
From the analysis, it can be seen that the value of average indoor illuminance varies from 70 to 7000 lux, where the criteria for visual comfort demands a value within 300-750 lux. The values of the daylit area remain below 44%, where the criteria for visual comfort demands more than 95%. A notable difference in available illuminance value is observed in winters between clear sky and overcast sky situation. In the case of Winter solstice at 13:00 Hr and clear sky, almost whole working plane is observed to experience the over-lit area, this is due to lower inclination of the sun that makes direct penetration of incoming sunlight to depth.
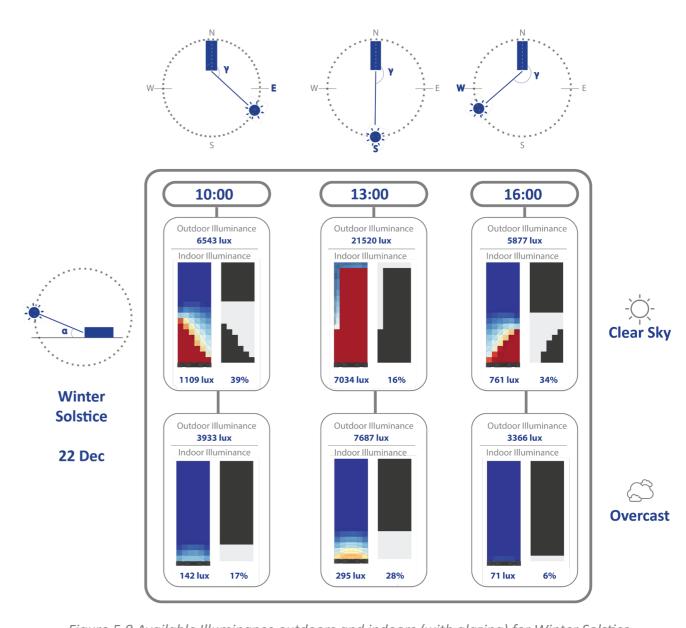

Figure.5.9 Available Illuminance outdoors and indoors (with glazing) for Summer Solstice

Figure.5.9 Available Illuminance outdoors and indoors (with glazing) for Winter Solstice

II. Behaviour of light with proposed Facade

An understanding was developed on the effectiveness of delivering the outcome from two separate functional elements (redirecting and diffusing) of proposed facade. The simulations were done for same instance SU-13-CS but with three variation in facade; only redirecting panels, only diffusing panels and combine facade and one with only glazing. The results were gathered for illuminance distribution on working plane and available daylit area (Table.5.1) and lux values per every meter in depth (Figure.5.10). The results of three variations in facade were compared with the result from only glazing. It was found that redirecting panels was able to lift the lux value at the end of the room, the diffusive panels showed some improvements but glare was observed because upper facade was open. But the combination of whole facade showed an impressive balance in distribution of lux values throughout the depth. It can be concluded here that both element of facade fulfils their role when used in combination.
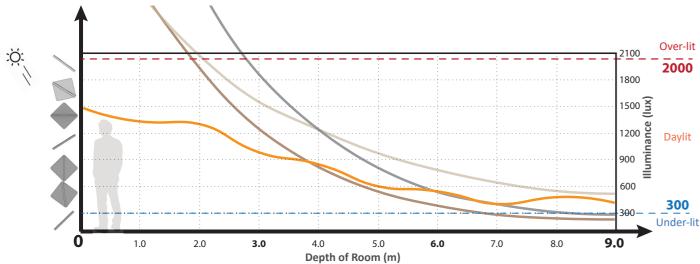

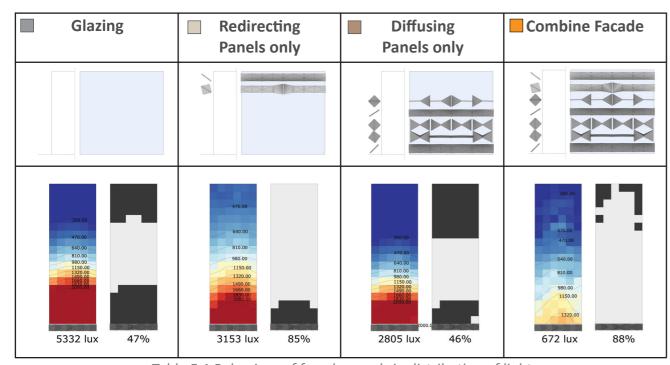*Figure.5.10 Distribution of Illuminance values on refrence plane along the depth of room.*

Glazing	Redirecting Panels only	Diffusing Panels only	Combine Facade
5332 lux　47%	3153 lux　85%	2805 lux　46%	672 lux　88%

Table.5.1 Behaviour of facade panels in distribution of light

5.2.3 Considerations for Simulation

I. Redirecting East and West light

Based on the assumptions made pertaining to the use of modified geometry in redirecting east and west light (see section-4.3), a few simulations were made using ray-tracing diagrams and illuminance grid. The simulations were made considering the SE and SW position of sun while using module type C and B, respectively. The first simulation is done with SE incoming light at WI-10-CS using module type C with three variations of facade configuration (Figure.5.11). The obtained results are compared with the no facade situation; it is observed that using module type C for East light, the over-lit area is reduced while maintaining lux distribution on the opposite corner at East. Similarly, the second simulation was done for SW incoming light at WI-16-CS using module type B with few variations in facade configuration (Figure.5.11) and compared the result with no facade situation. Here again, the result showed reduction in the over-lit area while maintaining lux levels on the opposite West corner. This understanding can be used for prioterising concerning module based on orientation of Sun to improve daylight performance.
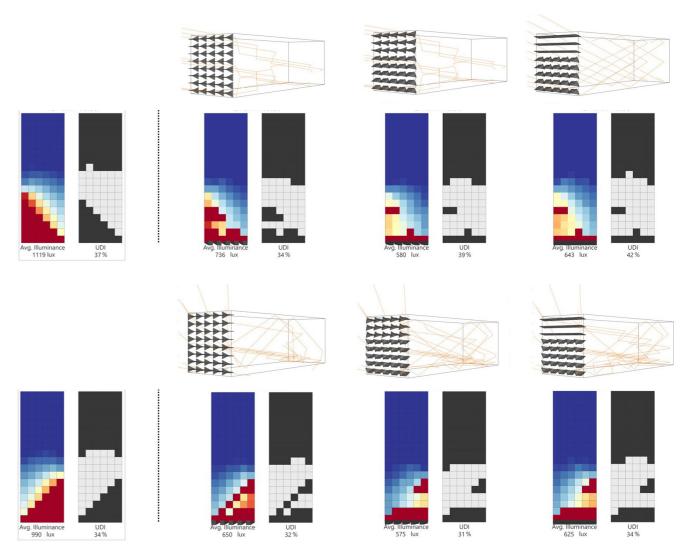

Table.5.11 Behaviour of facade panels in distribution of light

Daylit Area (%)　Overlit + Underlit (%)

>2000 lux　　<300 lux

300-2000 lux　>2000 and <300

II. Addition of Supporting Panels for Simulations

After attempting several simulations for illuminance and while analysing visualised data on a grid, dark red spots (>2000lux or over-lit spots) as shown in Table.5.2 was observed near to the window. The occurrence of this phenomenon is due to the penetration of direct light from the gap at the peripheral side of the window and proposed facade, as shown in figure.5.12. The modules arranged on facade segments are kept limited within the boundary of the window surface; this leaves a gap at the peripheral edges for the incoming of light that strikes from the direction like West, East or south during summers when the sun is at the higher position.

This issue is neglected by proposing a solution with the consideration of a more practical approach in simulation. In reality, the facade stays continuous and is not only limited to a segment in front of the room. Hence, a layer of additional modules is proposed along the periphery of existing proposed facade panels, as shown in figure.5.13. The set of additional modules are proposed in a way to correspond it with the modules on the opposite end of the existing facade, as shown in figure.5.14. The correspondence of the modules is in terms of parameters; the sequence of module type and the rotation of each module. Table.5.2 shows that a simulation done by adding supporting panels neglected the possibility of occurrence of red spots and improved the overall performance that looks more real. These supporting panels are used as a secondary context for further simulation and not as a part of the proposed facade.

Figure.5.12 Direct light entering from sides that are open
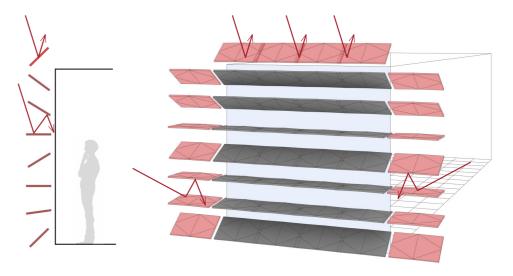
Figure.5.13 Adding supporting panels around the periphery

Red Spots spotted with proposed panels		Realistic results with adding supporting panels
1425Lux 79%	893Lux 88%	824 lux 84%

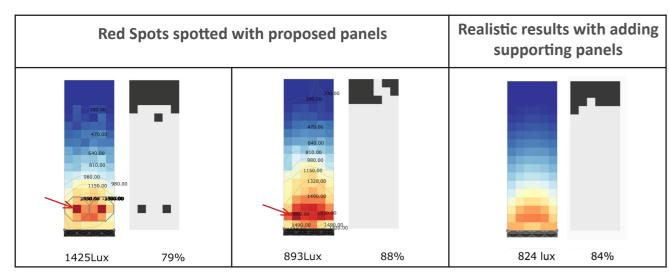Table.5.2 Showing an improvement by adding supporting panels surrounding proposed panel on facade for simulation process.

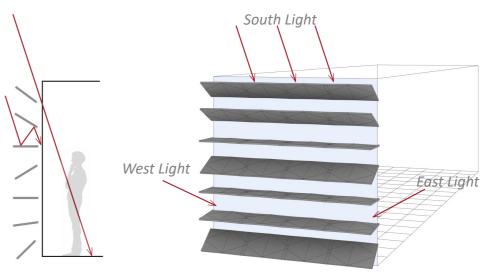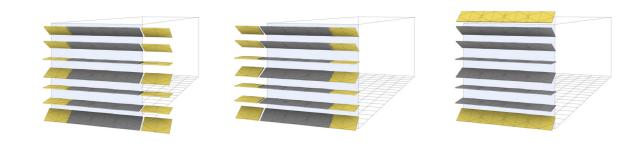Figure.5.14 Showing the correspondence of additional modules with modules on the existing facade w.r.t its rotation and module type

☐ Daylit Area (%)   ■ Overlit + Underlit (%)
300-2000 lux   >2000 and <300   >2000 lux   <300 lux

III. Adding reflectance to interior surfaces

The norms from NEN-EN 17037 recommends the use of surface reflectance properties for interior surfaces while performing a daylight simulation for any space. The addition of reflectance properties can have minor to more significant effect in performance which depends on the value taken. As discussed earlier, NEN-EN 17037 recommends using reflectance value of 0.7, 0.2 and 0.5 for the ceiling, floor and walls respectively while performing daylight simulations.

A comparative investigation is made to understand the effectiveness in performance by adding reflectance values of each surface individually and when it is used in combination (Table.5.3). From the comparison of ceiling+floor with ceiling+floor+walls, it is seen that the addition of reflectance property of walls has a more significant influence on final result values which enhances the daylight's levels further. This is due to the narrow width of the proposed room and the extended surface of the walls. Here, the walls become the secondary source by reflecting 50% of the light (as per 0.5 reflectance value) from the sides. Therefore, the use of reflectance property on the wall is neglected for simulations of this study to avoid the addition of lighting levels from surrounding walls with an intention to study light distribution caused by a facade and the depth elements.
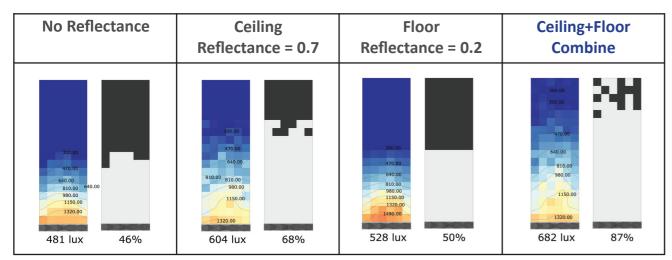
No Reflectance	Ceiling Reflectance = 0.7	Floor Reflectance = 0.2	Ceiling+Floor Combine
481 lux 46%	604 lux 68%	528 lux 50%	682 lux 87%

Table.XX Behaviour on result by using reflectance of Ceiling and floor separately and combine

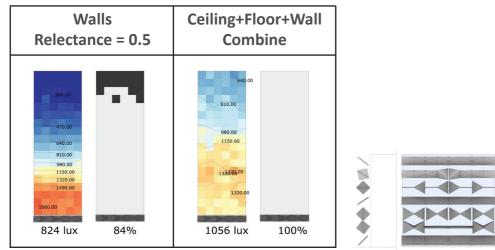| Walls Relectance = 0.5	Ceiling+Floor+Wall Combine	
824 lux 84%	1056 lux 100%	

Table.5.3 Showing effect on adding Wall reflectance (will not be considered for simulation)

IV. Increasing simulation accuracy by changing Radiance Parameters

The radiance parameters plays an essential role by changing the results drastically in simulation. The hike in results is because of the high value of radiance parameters increases the accuracy of the result in simulation by increasing the efficiency of calculating more bounces of light's reflection from any surface and several other parameters (Section-2.5.2).

A comparative investigation is made among simulation result with different radiance parameter settings for one particular instance of the facade. The sole intent of this investigation is to decide the set of radiance parameters values to be used in the further simulations of the proposed study. The values of Radiance parameters utilised are with the settings provided in HB+ as Low, Mid and High accuracy. Additionally, a simulation with very high accuracy is made by taking higher values of -ab and -ad (Table.5.4). An increase of about 30% is observed in the values of the Daylit area by increasing simulation accuracy. While increasing the accuracy of simulation, the run time for simulation is observed to be taking longer. The time taken by simulation with different accuracy setting is mentioned in Table.5.4. Furthermore, the difference in result between low accuracy to high accuracy was significant. Though a minor change is observed between high and very high accuracy setting and the run time consumed is way higher. Hence, the decision is made to run all simulation within the optimisation process at low accuracy to save time and evaluate obtained final optimised solution with 'High' accuracy setting and not with 'Very High'.

Moreover, it is observed that the intensity of light is getting higher with higher accuracy. Henceforth, while going through the process of selecting a solution obtained from optimisation at low accuracy, the recommendation is to pick a solution with low intensity of lux, but the more daylit area.

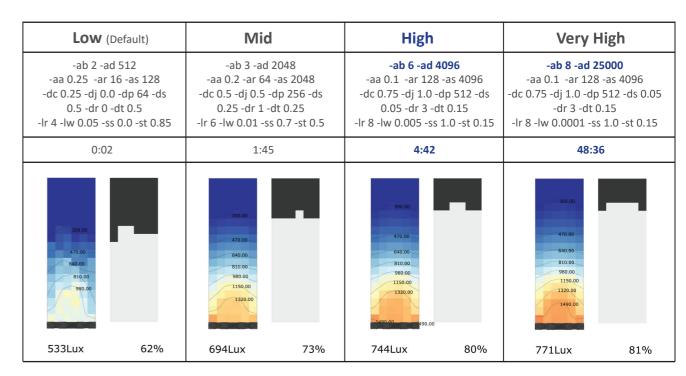| **Low** (Default)	**Mid**	**High**	**Very High**
-ab 2 -ad 512 -aa 0.25 -ar 16 -as 128 -dc 0.25 -dj 0.0 -dp 64 -ds 0.5 -dr 0 -dt 0.5 -lr 4 -lw 0.05 -ss 0.0 -st 0.85	-ab 3 -ad 2048 -aa 0.2 -ar 64 -as 2048 -dc 0.5 -dj 0.5 -dp 256 -ds 0.25 -dr 1 -dt 0.25 -lr 6 -lw 0.01 -ss 0.7 -st 0.5	**-ab 6 -ad 4096** -aa 0.1 -ar 128 -as 4096 -dc 0.75 -dj 1.0 -dp 512 -ds 0.05 -dr 3 -dt 0.15 -lr 8 -lw 0.005 -ss 1.0 -st 0.15	**-ab 8 -ad 25000** -aa 0.1 -ar 128 -as 4096 -dc 0.75 -dj 1.0 -dp 512 -ds 0.05 -dr 3 -dt 0.15 -lr 8 -lw 0.0001 -ss 1.0 -st 0.15
0:02	1:45	**4:42**	**48:36**
533Lux 62%	694Lux 73%	744Lux 80%	771Lux 81%

Table.5.4 shows Simulation accuracy, its correspond Radiance parameter values, the amount of time taken by simulation in minutes, and the result obtained using same instance.

Daylit Area (%) 300-2000 lux   Overlit + Underlit (%) >2000 and <300   >2000 lux   <300 lux

5.3 Optimisation

All the attempts of optimisation made in this study are using Wallacei (Version V2.55- 29 March, 2020), (Makki,n.d).

A workflow within the scope of Wallacei is applied as shown in Figure.5.15, for performing optimisation and to gain an optimal solution of the proposed facade for visual comfort.
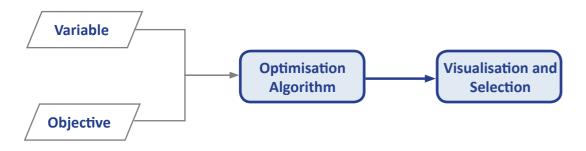

Figure.5.15 The applied workflow for optimisation used within Wallacei

5.3.1 Optimisation Setup

5.3.1.1 Design Variables (Parameters)

The three-developed parameters on façade geometry through parameterisation process are taken further as design variables to attempt the process of optimisation as:
I.   Rotation- The rotation provided is separated by row, each modules on same row is given similar rotation; however, each rows are treated independently having individual variables. The considered rotation angle for optimisation process is limiting to 0-90°, where the diffusing modules are given rotation outside(0 to 90°) and the diffusing modules are given rotation towards inside (-0 to -90°).
II. Module – Four module type as A, B, C and D is considered for the optimisation process as folding/unfolding variation of module. The variables foe changing module type is provided to each module individually.
III. Material – Two sets of material as M11 and M22 with are provided as variables that applies same for each module on façade segment.

5.3.1.3 Objective Functions

As per the objective of this study, which is to achieve visual comfort with controlled daylight distribution by mean of a facade that reduces under-lit and over-lit area to provide maximum daylit area along the depth for all instances (Figure.XX); only one metric 'Daylit Area' is considered as the main objective function for the optimisation process, which is to bring maximum area on working palne between 300-2000 lux. This choice is made with the idea that increasing daylit area by reducing over-lit and under-lit area will solve major issues related to glare and light reaching to depth. However, this idea is taken further, and two objective functions are proposed to support the main objective function- (i) to maximise lux values of under-lit area illuminance is below 300; and (ii) to minimise lux value of over-lit areas where illuminance is above 2000 lux. This addition is made to reduce the complexity within optimisation process and to achieve good results in a comparatively short time.

Consideration

Three objective functions are developed for the optimisation:
I.   Maximise % of Daylit Area
II. Minimise Illuminance (lux) where lux values are >2000 lux on working plane (Over-lit area)
III. Maximise Illuminance (lux) where lux values are <300 lux on working plane (Under-lit area)

Here, (i) is the main objective to be optimised where (ii) and (iii) are proposed objectives to support main objective.
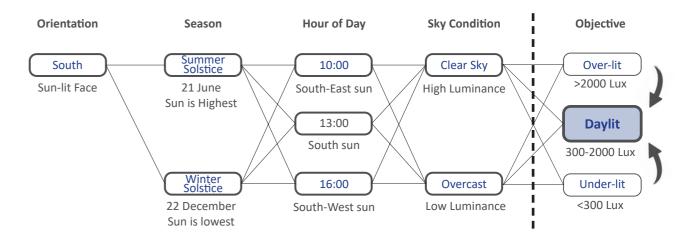

Figure.5.16 Showing combination of all the instances to be optimised to bring it in Daylit range

5.3.1.2 Optimisation Algorithm

The optimisation algorithm settings considered are:
Crossover probability value at 0.9 and mutation rate equivalent to 1/n (where, n=Number of Design Variables applied).
The population size considered is 2500, having 100 generations with 25 solution length each.

5.3.2 Considerations for Optimisation

While performing an optimisation using selected sets of variables and objectives, the process was found to be complicated by taking a very long run time in the process of simulating each iteration and was resulting in low-value results. Furthermore, the optimisation process is needed to be performed for each 12-selected instances individually. This showed the complexity of the design problem and demanded a solution for gaining a good result in a short time. A researcher in his study on louvres for daylight performance dealing with various parameters recommends using few parameters at a time in the optimisation process while fixing the others to improve the performance (Wegdy, 2016). This recommendation was taken further, and three attempts of optimisation were made by fixing one parameter each time, and the results are compared concerning the time taken by the optimisation process and the obtained result for Daylit Area in % as shown in Table.5.5. All the attempts are made for the same instance SU-13-CS for a fair comparison. It was observed that by reducing the number of parameters each time the run time has reduced, and the result obtained is increased. Furthermore, the result obtained by fixing material parameter by taking first set M11 in the second attempt did increase the performance value, but in a third attempt, a remarkable rise was seen by fixing second parameter- module in its unfolded state as Type D (which is

a neutral state for a module). Overall, from using all three parameters together to using one parameter as Rotation, reduced run time from 3+ days to 1+ days and result of Daylit area from 57% to 72%.

From this finding, a decision was taken to divide the optimisation process into two steps; where the first step of optimisation needs to performed using Rotation as a parameter and for the second step of optimisation needs to perform using other two parameters improving daylight performance. The developed computational workflow with two step optimisation is shown in figure.5.17.

Attempt	Facade Segment	Optimisation Parameters		Population	Optimisation Run Time	Daylit % Achieved
01	Redirecting	Rotation Module Material	Separated by Row Individual M11/M22	2500	3+ Days	57%
	Diffusing	Rotation Module Material	Separated by Row Individual M11/M22			
02	Redirecting	Rotation Module Material	Separated by Row Separated by Row (Fixed M11)	2500	2+ Days	61%
	Diffusing	Rotation Module Material	Separated by Row Separated by Row (Fixed M11)			
03	Redirecting	Rotation Module Material	Separated by Row (Fixed Type D) (Fixed M11)	2500	1+ Days	72%
	Diffusing	Rotation Module Material	Separated by Row (Fixed Type D) (Fixed M11)			

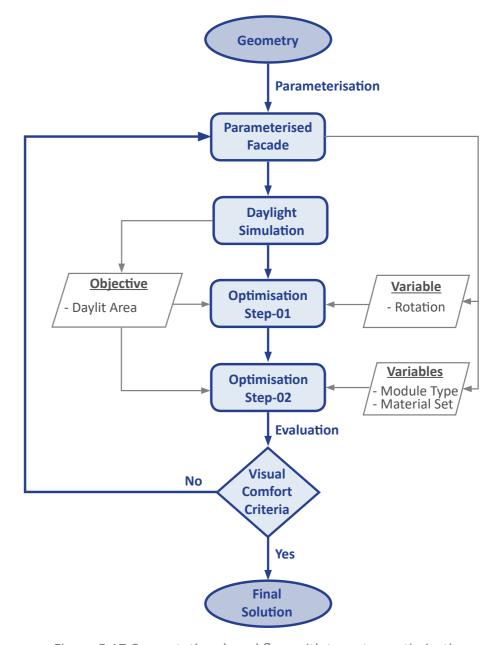*Table.5.5 Result comparison of Optimisation attempts made by fixing parameters*
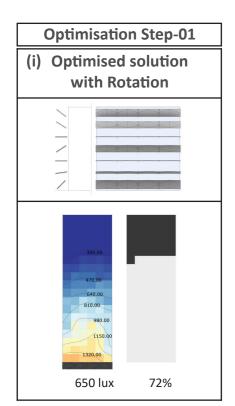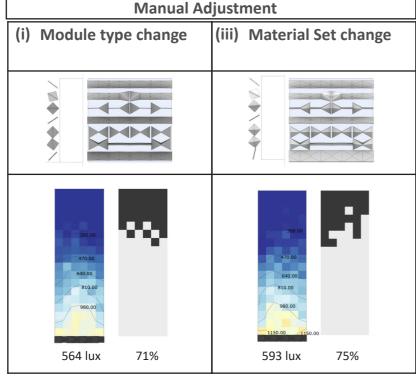

Figure.5.17 Computational workflow with two-step optimisation

Furthermore, dividing the optimisation into two steps shows potential for getting a high-value result, but on the other hand, it increased the timeframe of the whole process, where now each 12-selected instances has to go through the optimisation process twice, which makes 24 optimisations in total. Allowing the fact that available time for this research study limits to perform each optimisation on time; a decision was made to attempt the first step of optimisation, and replacing the second step of optimisation with Manual Adjustments where the module types and material set are changed manually on the obtained solutions from the first step of optimisation. Hence, a computational workflow is developed limiting to this research study as shown in figure.5.18.

However, an attempt of manual adjustment is made on the obtained solution from the third attempt of Table.5.6 where the optimisation is made with Rotation parameter as the condition of the first step of optimisation. The first adjustment is made by changing few module types in; in continuation to above adjustment, the second adjustment is made by changing material set to M22; and the result obtained is compared with the result of solution from optimisation (Table.5.6). This attempt is made to see the contribution of the other two parameters towards improving the result for daylight performance. From the Table.5.6, variations are observed in the resultant values. By changing module types, a difference in the distribution of intensity of light is observed; comparing the grid mesh of optimised solution (i) with the adjusted module type (ii), it was seen that the average illuminance has reduced from 650 lux to 564 lux. Furthermore, looking at the gradient on the grid cells of (i) having dark orange colour in front of the window which indicates high lux values is changed to light orange or white in (ii) which indicates lower lux values. However, this difference is achieved by losing just 1% of the Daylit Area. This comparison showed that module types contribute towards bringing the spread of light intensity towards a more uniform state on working plane.

Further, as shown in Table.XX, the result obtained by changing the material set to M22 on the geometry at (iii) with previously changed module types in (ii) shows the enhancement in light intensity along the depth. Comparing the grid mesh of (ii) and (iii) from Table.XX, the Daylit Area, has increased to 75% and average illuminance has slight increase to 593 lux with a minor increase in lux value on working plane at grid cells seen with light orange colour near to the window. This comparison showed that the change of material set contributes towards enhancing the light intensity on the working plane. Overall, the result is found to be increased by 3% of the daylit area, and average illuminance decreased to 593 lux with more uniform gradient on the working plane.

The above comparison showed the importance of the other two parameters and showed their contribution is essential in improving daylight performance. The coherent approach is to apply these parameters by performing the second step of optimisation. However, limiting to this research study, the manual adjustment on these two parameters shows an essential part in improving daylight performance.
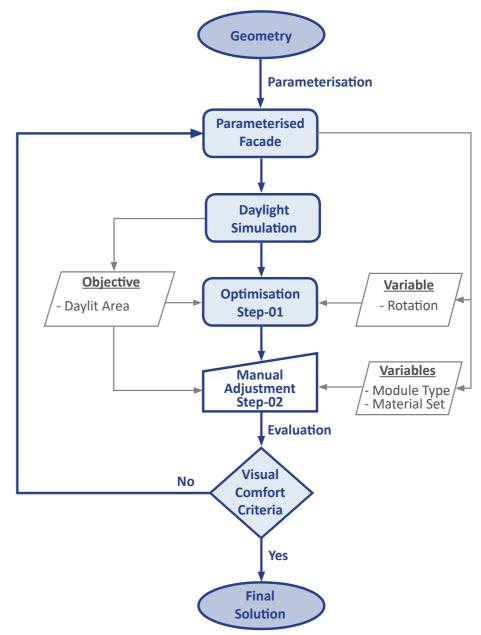
Optimisation Step-01	Manual Adjustment	
(i) Optimised solution with Rotation	(i) Module type change	(iii) Material Set change
650 lux 72%	564 lux 71%	593 lux 75%

Table.5.6 Comparison of results with results from optimisation and Manual Adjustments

Figure.5.18 Computational workflow with Manual Adjustment (limited to this study)

	Daylit Area (%)	Overlit + Underlit (%)		
	300-2000 lux	>2000 and <300	>2000 lux	<300 lux

5.3.3 Optimisation Step-01

The first step of optimisations are perfomed using a workflow provided within Wallacei plugin (Figure.5.19). As discussed earlier, the variable taken is Rotation and the objective taken is Daylit Area. The optimisation is performed for 12-selected instances each individually.
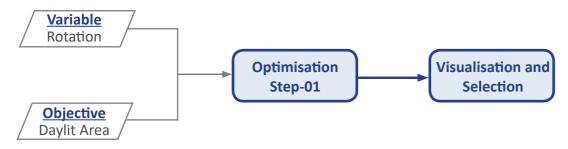
Variable — Rotation
Objective — Daylit Area
→ **Optimisation Step-01** → **Visualisation and Selection**

Figure.5.19 The applied workflow for optimisation used within Wallacei

After whole population of solutions is simulated in optimisation process, a total of 53 best solutions are analysed for each instance which includes top ranking of considered three objectives, 25-Pareto solutions and 25-solutions from last generation (Gen99). The final solutions are selected with the priority of maximum daylit area (%) with no over-lit area and further less under-lit areas. In most cases, the selected solution is the top ranking of the main objective having maximum Daylit Area. These obtained solution is said to have an optimal set for the rotational angles concerning each panel in a facade. The obtained angles are mentioned in Table.5.7 for each of 12-instances. Furthermore, the obtained facade solution is shown in figure.5.20.

Panel No.	SU 10 CS	SU 10 OC	SU 13 CS	SU 13 OC	SU 16 CS	SU 16 OC
1	-56	-18	-37	-36	-38	-15
2	-26	-27	-32	-22	-27	-13
3	2	3	0	83	4	2
4	19	20	33	68	30	1
5	21	4	0	8	2	17
6	20	35	8	32	9	33
7	1	18	45	74	77	7

Panel No.	WI 10 CS	WI 10 OC	WI 13 CS	WI 13 OC	WI 16 CS	WI 16 OC
1	-8	-36	-60	-30	-22	-32
2	-5	-25	-85	-12	-10	-18
3	1	0	27	12	42	7
4	13	3	34	23	69	8
5	66	2	56	10	59	20
6	81	2	0	20	39	4
7	6	83	14	10	32	15

Table.5.7 Obtained angles from first step optimisation for 12-instances

SU-10-CS   WI-10-CS
SU-10-OC   WI-10-OC
SU-13-CS   WI-13-CS
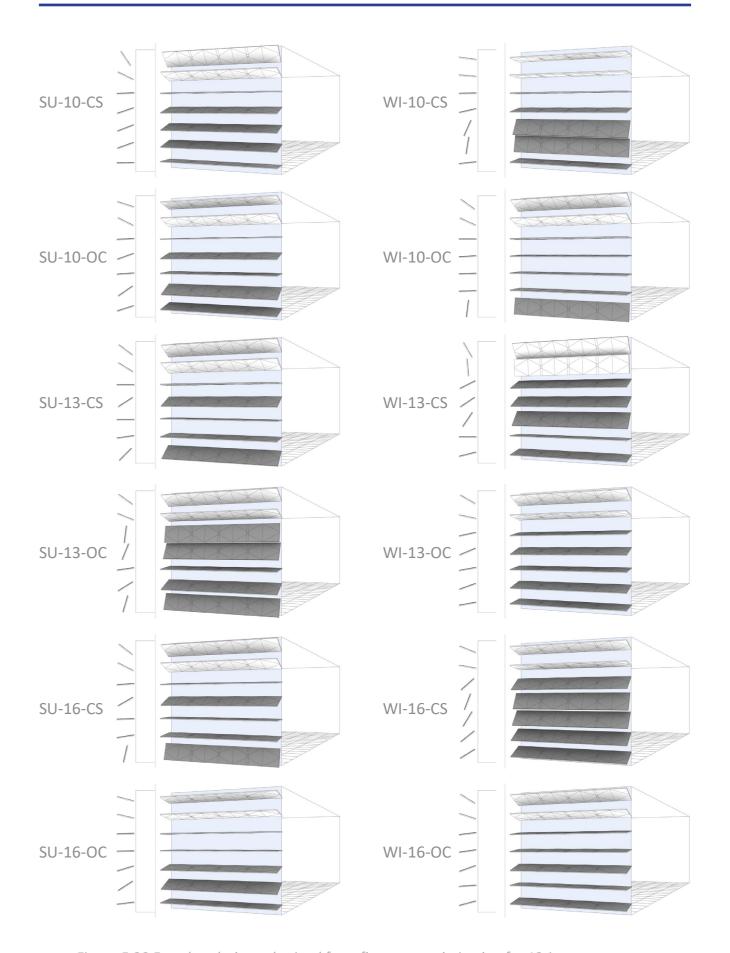SU-13-OC   WI-13-OC
SU-16-CS   WI-16-CS
SU-16-OC   WI-16-OC

Figure.5.20 Facade solutions obtained from first step optimisation for 12-instances

5.3.4 Manual Adjustment Step-02

The scope of this study limits to first step of optimisation, and the second step is to be made with manual adjustments. Hence, a workflow (Figure.5.21) is prepared for getting final solutions for each instance. The adjustments mainly includes changing module types and change of material set as per requirement attempted on obtained best solution from first-step of optimisation.
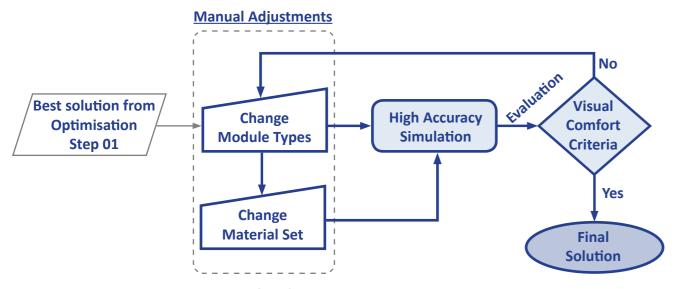

Figure.5.21 The applied workflow for manual adjustment process limited to this study

The obtained best solutions from optimisation set 01 for each instances are taken for manual adjustments by changing few module types keeping the same rotational angles obtained from optimisation. The adjustments are attempted based on the gained knowledge through various investigation and attempts made along the simulation process of this study and discussed advantages of the geometry. Noticeable improvements are observed in the resultant values of the average illuminance and uniformity ratio for all selected solutions.

The optimised solutions obtained are with material set M11, which has a medium specular and medium diffusive material property. The material set is changed to M22 for few instances where the need of more enhanced light was required like when the luminous distribution of sky outside is low, and it was required to intensify more light inside. Furthermore, the results for overcast sky condition of Winter is found to be a little exceptional amongst all instances due to very less daylight availability from outside.

For the final resultant values of all selected solutions, the simulations are made at high accuracy with corresponding radiance parameters (Section-5.2.3 (IV)). Furthermore, the solution with unsatisfied results that failed to fulfil any evaluation criteria was taken back for some more adjustments, and solutions for each instances are finalised. The values are taken further for performance evaluation in next chapter.

Considering the practical scenario of developed facade having different solutions for each instances, it results in a dynamic facade that changes its configuration for each instances where each instances have different sets of rotational angles resulting in 12-sets. However, a stretagy is applied to reduce the sets of angles to reduce the complexity for the motion of Facade. This stretagy is applied on finalised solutions obtained after going through adjustment process of changing module types and material set, by making a similarity check amongst solutions at different instances and using rotational angles from other instances. The 12-sets of rotational angles are reduced to 7-sets as shown in Table.XX where set of angles are common between two instances.

For all instances at Summer, good results were obtained using same rotational angles for different sky condition for a particular instance of hour but with different module type configuration (Figure.5.22). However, for the instances at Winter, it was different than summer condition. Good results were observed with using same set of angles for two different time instances but within same sky condition (Figure.5.23), this is due to the available intensity of light for different sky condition varies a lot.

Panel No.	SU						Panel No.	WI					
	10		13		16			10		13		16	
	CS	OC	CS	OC	CS	OC		CS	OC	CS	OC	CS	OC
1	-56	-18	-37	-36	-38	-15	1	-8	-36	-60	-30	-22	-32
2	-26	-27	-32	-22	-27	-13	2	-5	-25	-85	-12	-10	-18
3	2	3	0	83	4	2	3	1	0	27	12	42	7
4	19	20	33	68	30	1	4	13	3	34	23	69	8
5	21	4	0	8	2	17	5	66	2	56	10	59	20
6	20	35	8	32	9	33	6	81	2	0	20	39	4
7	1	18	45	74	77	7	7	6	83	14	10	32	15

Table.5.13 Obtained sets of rotational angle for each instance

Panel No.	SU						Panel No.	WI					
	10		13		16			10		13		16	
	CS	OC	CS	OC	CS	OC		CS	OC	CS	OC	CS	OC
1		-18	-37		-38		1	-8	-36	-60	-30		
2		-27	-32		-27		2	-5	-25	-85	-12		
3		3	90		4		3	1	0	27	12		
4		20	33		30		4	13	3	34	23		
5		4	90		2		5	66	2	56	10		
6		35	98		9		6	81	2	0	20		
7		18	45		77		7	6	83	14	10		

Table.5.8 Finalised reduced sets of rotational angle for each instance after similarity check

SU-10-CS

SU-10-OC

SU-13-CS

SU-13-OC

SU-16-CS

SU-16-OC
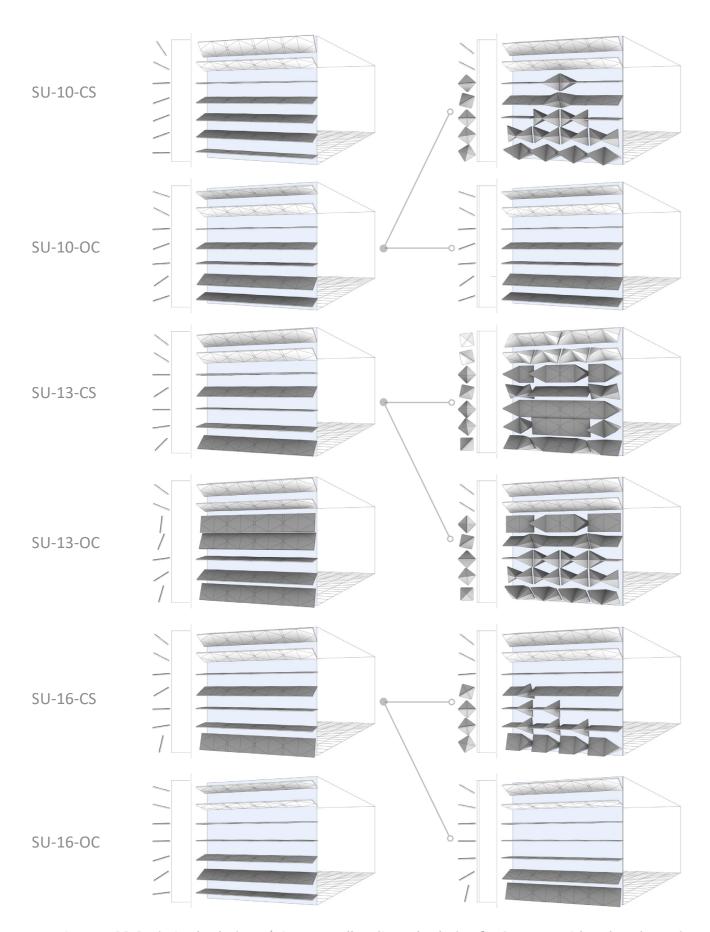
Figure.5.22 Optimised solution v/s its manually adjusted solution for Summer with reduced rotation set

WI-10-CS

WI-10-OC

WI-13-CS
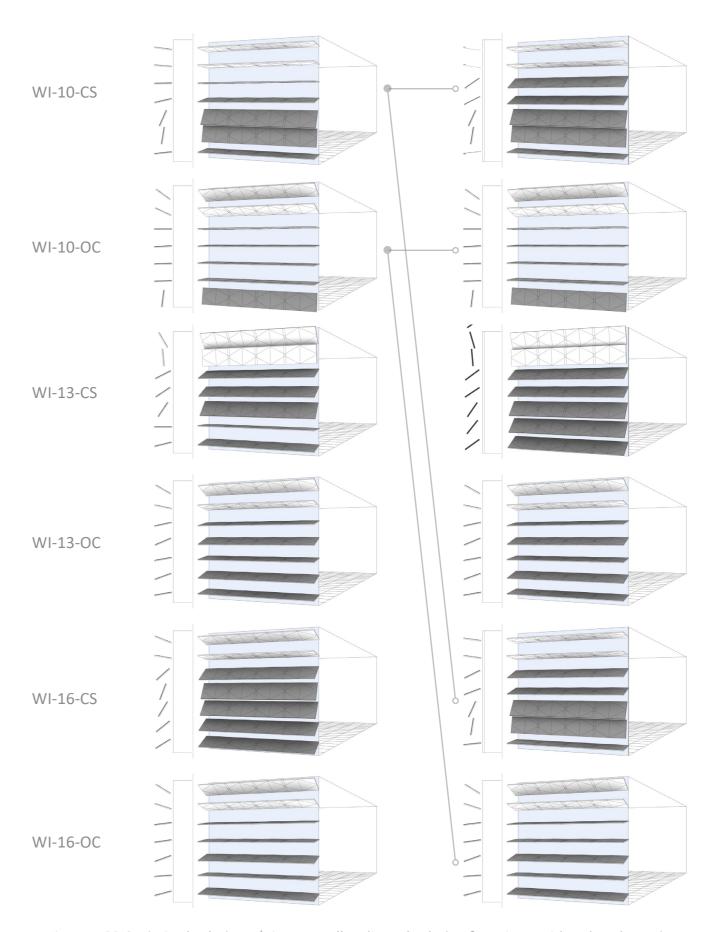
WI-13-OC

WI-16-CS

WI-16-OC

Figure.5.23 Optimised solution v/s its manually adjusted solution for Winter with reduced rotation set

Distribution of Illuminance along the Depth - Summer

After getting results for each solution for Summer, the distribution of light in ambient range along the depth showed impressive results. To understand the distribution, a graph showing the behaviour of flow of intensity along the depth is made (Figure.5.24, 5.25); and is compared with the curve obtained when no facade but glazing with 0.65 transmittance value is used.
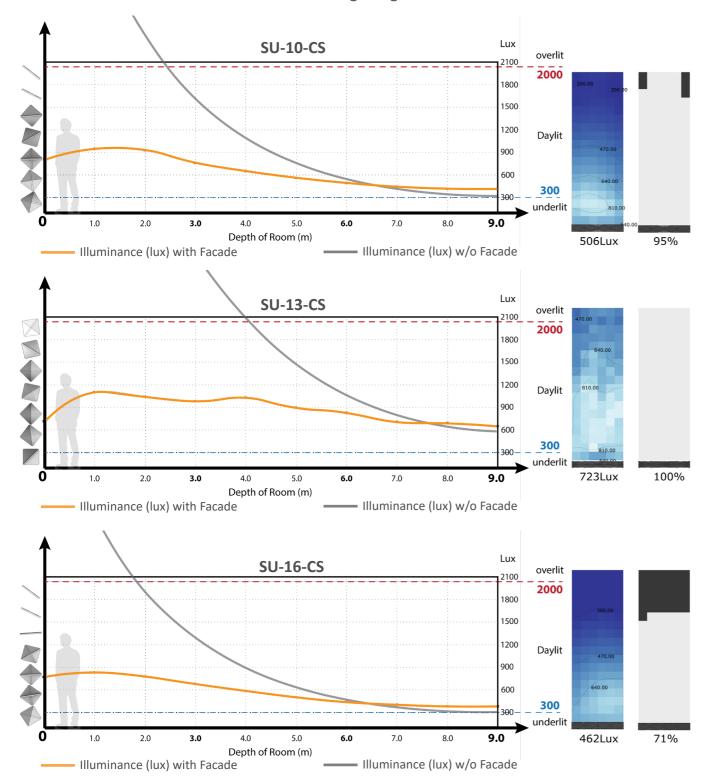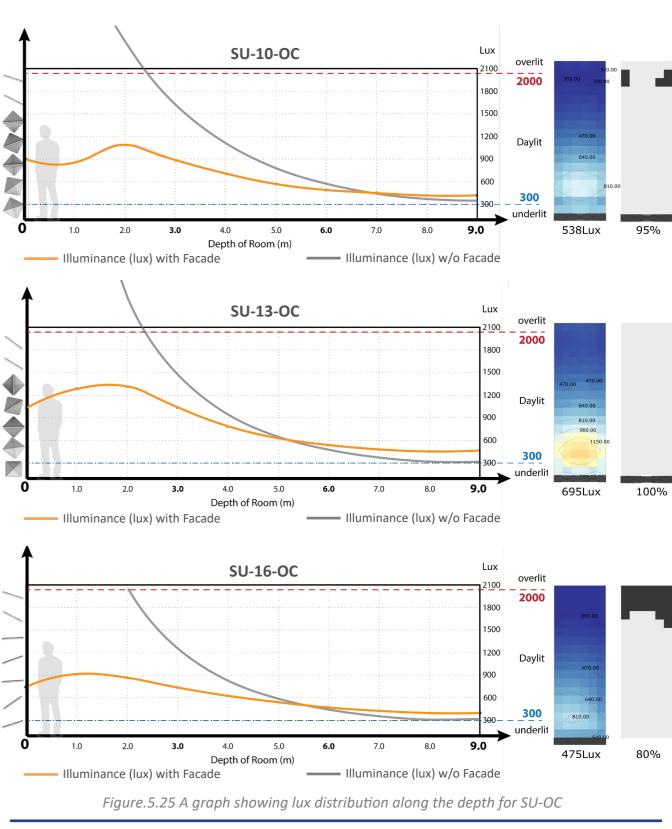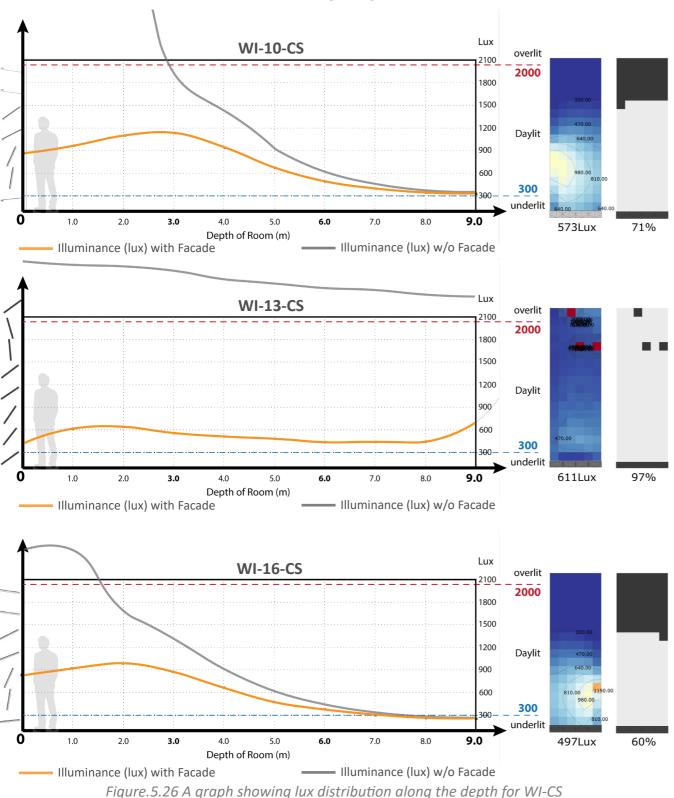
From the graphs it can be seen that a hike is observed between 1m to 2m for all the instances. hence, occupant at workstation 01 are prone to experience the highest intensity of light compared to others.

Figure.5.24 A graph showing lux distribution along the depth for SU-CS

Figure.5.25 A graph showing lux distribution along the depth for SU-OC

Daylit Area (%)
300-2000 lux

Overlit + Underlit (%)
>2000 and <300

>2000 lux

<300 lux

>2000 lux

<300 lux

Daylit Area (%)
300-2000 lux

Overlit + Underlit (%)
>2000 and <300

Distribution of Illuminance along the Depth - Winter

After getting results for each solution for Winter, the distribution of light in ambient range along the depth showed impressive results. To understand the distribution, a graph showing the behaviour of flow of intensity along the depth is made (Figure.5.26, 5.27); and is compared with the curve obtained when no facade but glazing with 0.65 transmittance value is used.
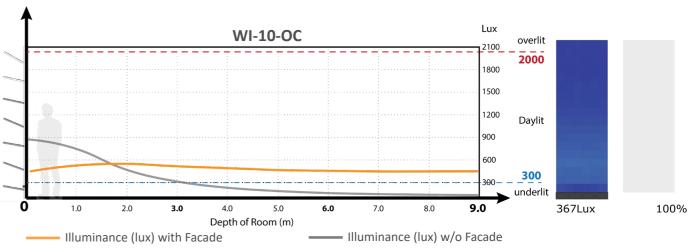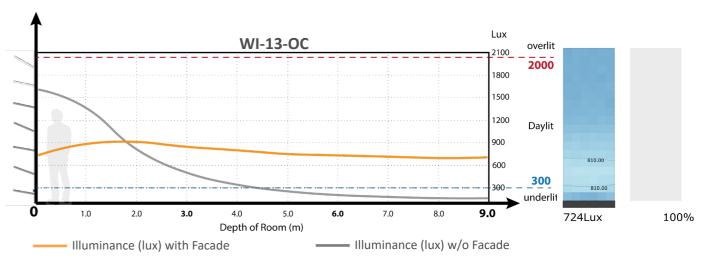
The results of all three winter overcast instances is made using higher reflective properties on diffusing panesl (Section-6.2(I)). The material property is changed to examine the effectiveness on the designed facade of 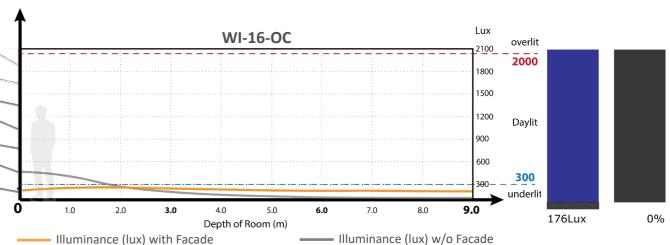using the proposed facade. Furthermore, over-lit areas in WI-13-CS are observed on side walls due to low altitude Sun (Section-6.2(III)).

Figure.5.26 A graph showing lux distribution along the depth for WI-CS

Figure.5.27 A graph showing lux distribution along the depth for WI-OC

Discussion

Summer	Winter
• Foe SU, the focus for getting an optimal solution remained towards redirecting light towards depth to reduce under-lit area. Due to sun's higher altitude, direct sun remains in front and creates under-lit zone at depth. Some improvement was observed in redirecting light but high improvement was seen in reduction of high intensity lux.	• For WI-CS, the focus remained towards reducing direct light that was causing over-lit areas, this was mainly due to low sun's altitude which makes direct light to penetrate throughout the depth of the room (can be seen from figure.XX showing daylight availability). Yet some glare points were experienced in WI-13-CS.
• For Summer, different instances have varied configuration of facade. All type of module variation are used as well. The use of different modules in combination showed an impressive result in distributing light with ambient intensity.	• For all instances in WI, flat panels (module type D) have shown the best results. Using any other module showed rise of over-lit areas on working plane. This was because the module type D was able to deliver some kind of staggered configuration through which direct light from one panel will be blocked and redirected through panels on surrounding but will avoid getting direct sun in. Wherein, use of other module type leaves the opening for light penetration (refer figure.XX) and leads to experience of over-lit areas. This two things led to adjust angles for some panels manually to improve the performance.
• For Summer during 13:00, for both sky condition, the configuration used module types A', B', C' and D' to improve the performance. This was made by rotating corresponding panels by 90 degrees.	
• In summers, the percentage of daylit area for a specific hour of time showed that without changing rotational angle of panels, the facade can serve for different sky conditions with only operating module types by folding and unfolding.	• For WI-CS, daylit area over 60% were observed. But during WI-OC, no distribution in light was seen with selected set of material properties.
• The selected set of materials based on optical properties showed good results at each instance of summer	• Application of highly reflective material for redirecting panel and diffusive specular for diffusing panels showed some distribution of daylight.

Answer to Sub-Question

04. **What computational design approach could be best to achieve the most optimal solution in this case?**

Along the process of computational design, it was found that fixing a few parameters reduces the complexity of the optimisation process; hence, the computational workflow used includes two-step optimisation divided by different variables. However, this study limits to first step optimisation and the second step is replaced with manual adjustment of concerning variables. Moreover, as per the requirement of this study, only the Daylit Area metric is used as an objective.

The more intuitive computational design approach for getting the most optimal solution would be to use the developed workflow by performing both steps of optimisation and considering all the metrics within visual comfort criteria as objectives; also each criteria can be used individually or in a group of few as per the requirement of the design problem. Concerning the above-mentioned approach, a full scope computational workflow is proposed for finding the most optimal solution for facade dealing with visual comfort, as shown in figure.5.28.
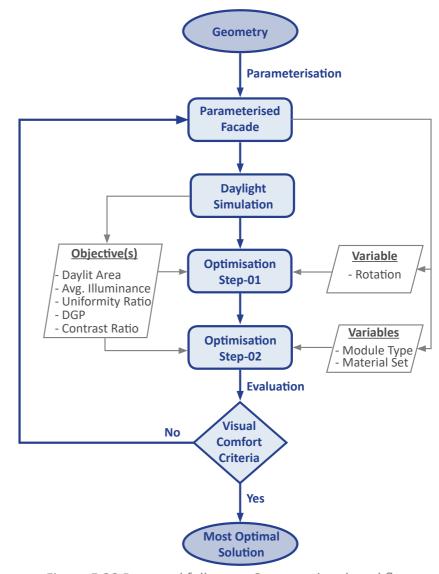

Figure.5.28 Proposed full-scope Computational workflow

6.0 Performance Evaluation

6.1 Evaluation

Evaluation is an essential phase for any design solution to validate the design for its performance as per the needed criteria; the design that fails to met the criteria should be investigated further for improved performance. The performance evaluation is run using daylight simulation tool HB+ And HB Legacy and developed script for simulation(Appendix. A4). Performance evaluation is made based on the set visual comfort criteria as discussed in Section.3.4.

I. Average Illuminance (300-750 lux)

After finalising on final sets of the façade's configuration from all the instances, the values for average illuminance values each instances were compared with each other and with the illuminance values obtained from simulation made with using only glazing. The result showed much higher improvement for summers and winters both. The results showed an effective improvement in bringing Average illuminance (E) values within the desired range. The maximum lux value is experienced during SU-13-OC having 695 lux and minimum at WI-16-OC having 176 lux due to low light availability from outside. However, each instance fulfils the requirement for having lux values between 300-750 except WI-13-OC.

Summer	Glazing	Shading
SU-10-CS	2968	506
SU-13-CS	6737	723
SU-16-CS	1788	462
SU-10-OC	1056	538
SU-13-OC	1249	695
SU-16-OC	1036	475

Winter	Glazing	Shading
WI-10-CS	1425	573
WI-13-CS	8672	611
WI-16-CS	1000	497
WI-10-OC	188	367
WI-13-OC	359	724
WI-16-OC	90	176

Table.6.1 Values for average Illuminance in lux with glazing and with shading for both Summer and Winter.
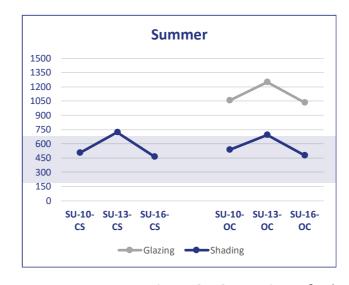

Figure.6.1 Comparison of values of shading with glazing in lux

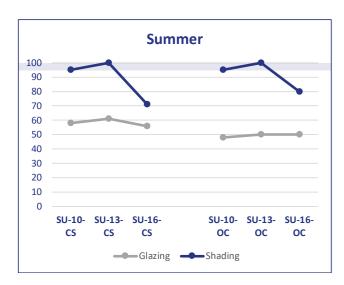## II. Daylit Area (300-2000 lux for >95% or Minimum lux >100)

The Daylit area in percentage for all the instances from Summers and Winters are noted in Table.6.2 and compare with threshold values when no facade is used. The comparison is made to understand the behaviour of daylight indoors with different availability of daylight outside and to see the impact of using designed facade.

The result showed an impressive improvement over gaining more daylit areas for each instance except WI-16-OC. For WI-13-CS, a drastic change is observed in increasing daylit percentage. Furthermore, there are seven instances with more than 95% of the area within 300-2000 lux range; hence, these instances fulfils the first criteria of the Daylit Area of having lux values within 300-2000 lux for more than 95%. However, there are five instances having Daylit Area below 95%. But, looking at the lowest lux values, the obtained values for these five instances on the same working plane are above 100 lux. Thus the other five instances fulfil the second criteria considered for this evaluation, where the minimum value of lux required was more than 100 lux. Henceforth, all the instances are meeting the requirements validate the performance of facade regarding criteria of Daylit Area.

Summer			
	Glazing	Shading	lowest lux
SU-10-CS	58	95	284
SU-13-CS	61	100	447
SU-16-CS	56	71	252
SU-10-OC	48	95	286
SU-13-OC	50	100	353
SU-16-OC	50	80	258

Winter			
	Glazing	Shading	lowest lux
WI-10-CS	57	71	200
WI-13-CS	5	97	305
WI-16-CS	47	60	147
WI-10-OC	22	100	326
WI-13-OC	25	100	640
WI-16-OC	9	0	156

Table.6.2 Values for Daylit Area in % with glazing and with shading for both Summer and Winter.
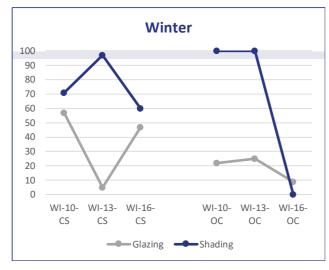

Figure.6.2 Comparison of values of shading with glazing in %

III. Uniformity Ratio (>0.3)

The Uniformity Ratio (UR) for all the instances from Summers and Winters are noted in Table.6.3 and compare with threshold values when no facade is used. The comparison is made to understand the uniformity distribution of daylight indoors with different availability of daylight outside and to see the improved impact of using designed facade.
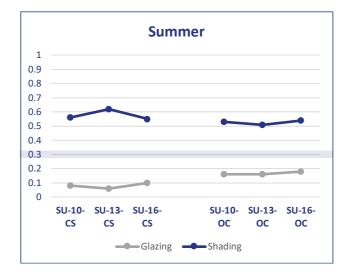
The results of the final solutions of facade showed an extraordinary result in achieving improved uniformity in the distribution of light intensity along with the depth of the room. The most impressive result was found with SU-13-CS, where the light is getting distributed with UR of 0.62. However, the least uniformity in distribution was found with WI-16-CS.

Overall, all the instances in the Summers show highly impressive results by distributing daylight with UR values above 0.5; Whereas the Winter has two instances which that are found to be below 0.5. However, all the instance are meeting the requirement for having UR values >3.0 to validate the facade for its performance regarding UR criteria. Furthermore, the chart shows that the UR values has been improved 2-5 times in comparison to the threshold values with glazing.

Summer		
	Glazing	Shading
SU-10-CS	0.08	0.56
SU-13-CS	0.06	0.62
SU-16-CS	0.1	0.55
SU-10-OC	0.16	0.53
SU-13-OC	0.16	0.51
SU-16-OC	0.18	0.54

Winter		
	Glazing	Shading
WI-10-CS	0.16	0.35
WI-13-CS	0.19	0.55
WI-16-CS	0.16	0.3
WI-10-OC	0.16	0.89
WI-13-OC	0.15	0.88
WI-16-OC	0.16	0.89

Table.6.3 Values for uniformity ratio with glazing and with shading for both Summer and Winter.
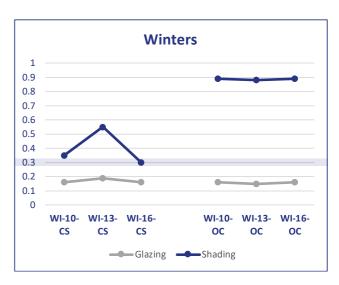

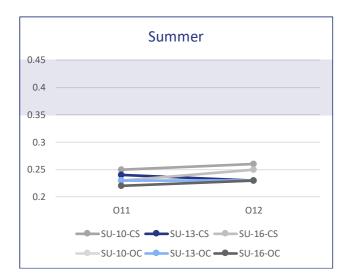*Figure.6.3 Comparison of values of shading with glazing*

IV. DGP (0.45-0.35 or <0.35)

The DGP values for all the instances from Summers and Winters are noted in Table.6.4. The Glare analysis is made for two occupants in their sitting position looking towards their computer screen; the results are noted for both occupants as O11 and O12 (Table.XX). The results show the remarkable performance of final facade solutions for protection against glare for both occupants. Moreover, it is observed that the difference in DGP values obtained for both occupants is almost negligible for all instances. All the values obtained are below 0.35 as per the required criteria. These results represent that both occupants observe imperceptible glare. Hence, the performance of facade meets the necessary criteria for DGP. However, few challenges were faced while studying glare results, and some considerations are made which can be seen in section-6.2. Furthermore, refer Appendix.A5 to see the obtained visualisation results from the simulation of Glare analysis in HDR image and False-colour Image.

V. Contrast Ratio (<3.0)

The Contrast Ratio (CR) values for all the instances from Summers and Winters are noted in Table.6.5. The (CR) is made by dividing the depth of the room into three parts as Area 01,02 and 03; and then taking ration of average Luminance between Area 01 and 02 as C1, and between Area 02 and 03 as C2. All the obtained results show a reliable performance of facade regarding the difference in brightness level on the working plane along the depth of the room. The values of CR goes from 0.85 as least to 2.96 as the highest in terms of the difference in brightness between the two areas. The instance Su-13-CS shows a peak drop in CR between C1 and C2. Furthermore, SU-10-OC shows a neutral situation by having the same values for C1 and C2. With many instances, the CR value is observed to go down from C1 to C2; however, there are few instances where CR values go high from C1 to C2. Above all, each value obtained is <3.0 and meets the requirement of CR; hence, it validates the performance of facade regarding CR criteria.

Summer	O11	O12
SU-10-CS	0.25	0.26
SU-13-CS	0.24	0.23
SU-16-CS	0.23	0.25
SU-10-OC	0.23	0.23
SU-13-OC	0.23	0.23
SU-16-OC	0.22	0.23

Winter	O11	O12
WI-10-CS	0.2	0.22
WI-13-CS	0.2	0.21
WI-16-CS	0.21	0.2
WI-10-OC	0.12	0.12
WI-13-OC	0.19	0.19
WI-16-OC	0.03	0.03

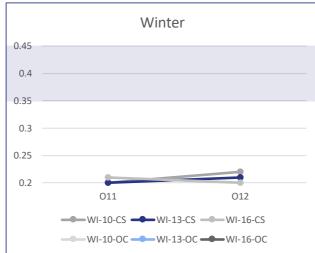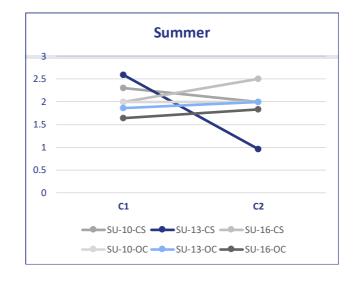*Table.6.4 Values for DGP at two different view points for both Summer and Winter.*

Summer	C1	C2
SU-10-CS	2.3	2
SU-13-CS	2.59	0.96
SU-16-CS	2	2.5
SU-10-OC	2	2
SU-13-OC	1.86	2
SU-16-OC	1.64	1.83

Winter	C1	C2
WI-10-CS	1.98	2.24
WI-13-CS	0.85	0.37
WI-16-CS	2.98	1.97
WI-10-OC	1.89	1.56
WI-13-OC	2.12	2.1
WI-16-OC	1.4	1.21

Table.6.5 Values for Contrast ratio along the depth as C1 and C2

Figure.6.4 Plotted values of DGP for two view points
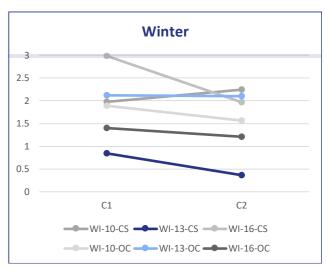

Figure.6.5 Plotted values of two Contrast Ratios C1 and C2

6.2 Considerations within Evaluation

Along the process of evaluation, several challenges are faced. To overcome such challenges, some considerations are made for improving the performance of the facade and some considerations are based on real world scenario. Furthermore, all the solutions are validated after including the following considerations.

I. Due to low luminance outside in case of Winter-Overcast (Section-5.2.2(I)), the availability of daylight inside the room without using facade is extremely low (Figure.6.6). However, performing simulation on the finalised solution of facade for WI-CS using selected sets of material (M11, M22), the uplifting of illuminance level was observed to be very minimum. But an imposing result was obtained by increasing the reflectivity of diffusing panels into the simulation. Uniform distribution with high uniformity ratio and 100% daylit area was found (Figure.6.6). Hence, the final results for WI-OC are considered with a set of material shown in the figure.6.6, having higher reflectivity on diffusing panel. Here, the property of material considered is based on assumption. However, irrespective of comparing material, the obtained result shows the effectiveness and potential of the proposed facade in enhancing daylight.

II. Moreover, even after applying a higher reflective material set, WI-16-OC is yet a problematic instance to bring illuminance >300 lux to achie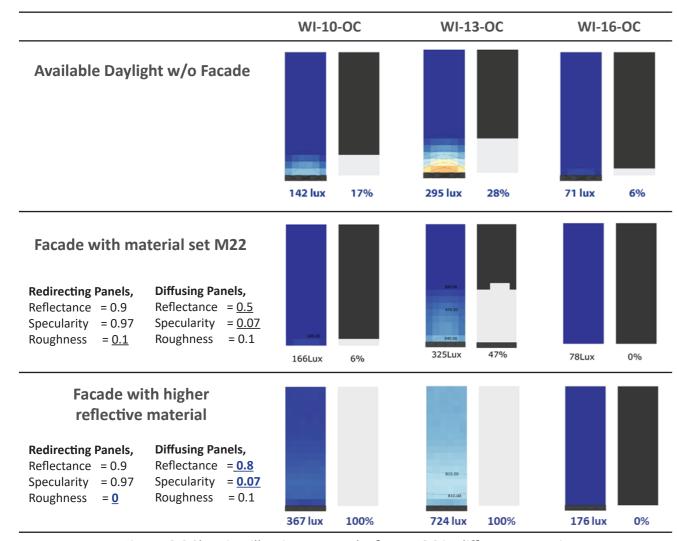ve the desired daylit range. Because, for the selected location Rotterdam, the sun is almost set around this time (Section- 3.1.2). Hence, the instance WI-16-OC is considered as an exceptional case and is not considered for validating the performance of facade and in average calculations. Yet, uplifting some value of lux in compared to available daylight (Figure.6.6) shows excellent achievement, but with using higher reflective material.

III. Simulation for glare analysis was made and studied from generated HDR and False-colour Image (Appendix.A5). All the solution at WI-CS, the visual comfort criteria is achieved, but glare analysis has shown over-lit areas on sidewalls (Figure.6.7). However, it was found that to attain a specific range of illuminance required for comfort criteria, the facade needed to be in a certain open configuration to let the light in and enhance it along the depth. But with even smaller openings on facade, the direct light was observed to penetrate inside due to very low altitudes of Sun (Figure.6.6). The software used shows very lower values for DGP by indicating no glare situation. However, the impact shown in the image is exaggerated by the used software to spot the difference, but the intensity of light is low. Furthermore, at the location Rotterdam, the Clear sky condition during Winters is a rare possibility with the probability of 10% (Section-3.1.2). Hence, such a situation will rarely occur in real-world, and henceforth, the situation is not investigated further.
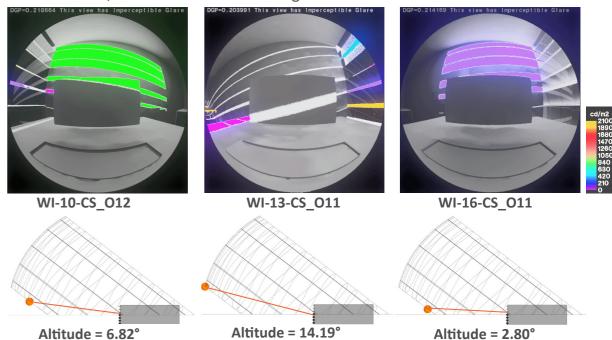

| | WI-10-CS_O12 | WI-13-CS_O11 | WI-16-CS_O11 |

| Altitude = 6.82° | Altitude = 14.19° | Altitude = 2.80° |

Figure.6.7 HDR image from Glare analysis (above) and respective Sun Altitudes (below)

IV. For the case SU-13-CS, a glare analysis was made by increasing the visual field of the lens, the result showed over-lit patches on the floor (figure.6.8). It was found that the light penetrates through few gaps forming during configuration and is not getting a shading support from surrounding modules. However, this situation was not affecting the comfort for an occupant; hence, further investigation is not made.

SU-13-CS_O11
Figure.6.8 HDR image from Glare Analysis

	WI-10-OC		WI-13-OC		WI-16-OC	
Available Daylight w/o Facade	142 lux	17%	295 lux	28%	71 lux	6%
Facade with material set M22						
Redirecting Panels, Reflectance = 0.9, Specularity = 0.97, Roughness = 0.1 Diffusing Panels, Reflectance = 0.5, Specularity = 0.07, Roughness = 0.1	166Lux	6%	325Lux	47%	78Lux	0%
Facade with higher reflective material						
Redirecting Panels, Reflectance = 0.9, Specularity = 0.97, Roughness = 0 Diffusing Panels, Reflectance = 0.8, Specularity = 0.07, Roughness = 0.1	367 lux	100%	724 lux	100%	176 lux	0%

Figure.6.6 Showing illuminance results for WI-OC in different scenario

☐ Daylit Area (%)	■ Overlit + Underlit (%)		
300-2000 lux	>2000 and <300	>2000 lux	<300 lux

6.3 Comparative Analysis

All the obtained values are noted in Table.6.6 to gain an understanding of the overall performance of the designed facade. There are four instances for which 100% daylit area is achieved and three instances that are above 95%. The least daylit area is experienced in WI-16-CS. It was again due to a similar reason where at location Rotterdam, the sun is almost set around 16 Hr.; hence, such low value is expected even for Clear Sky conditions. The uniformity ratio for more than half of instances are found to be above 0.5, where SU-13-CS shows the best distribution of 0.62; moreover, the same instance SU-13-CS has a considerable drop in contrast values from C1 to C2 and has high average illuminance value. However, it was found that the highest illuminance inside the room was 1336 lux for Summers and 1483 lux for winters.

Moreover, it can be seen from Table.6.6 that for each instance, the absence of over-lit areas is found except for WI-13-CS where a minor 3% of the over-lit area was seen due to lower altitude sun. Furthermore, material set M22 is used for three instances; it was mainly during the overcast of summer and two instances in winter when the daylight availability outside is low. Thus with material M22, it helps to enhance more light.

6.4 Conclusion (and answer to Research Sub Question-06)

The obtained average values from all instances show that 88% of the working plane remains within the range of 300-2000 lux values. The average of all 'average Illuminance' value attain is 561 lux on the same working plane and is very close to 500 lux, which is the recommended lux value for a workplace in office buildings. Furthermore, the light in the room is spread with a uniformity ratio (UR) of 0.57 along with the depth; and this value fulfils the requirement of UR with artificial lighting, which is 0.5-0.7 as per BREAAM (2016). Hence, it can be said that the room is lit equivalent to artificial lighting through daylight, using designed facade. Furthermore, the average value of glare, 0.21 and 0.22, shows the absence of glare for occupant's eyes. The average values of Contrast Ratio, 2.04 and 0.22, shows that the difference in brightness along the depth is minimum.

It is found that all the design solutions meets the performance criteria required for visual comfort. However, the solutions from Winter does show some limitations but with minor impact on comfort. Furthermore the average values of each metric shows excellent performance achievement by designed facade. Hence, it can be said that the facade validates with visual comfort criteria.

Henceforth, after validating the design based on its performance, which showed the promising potetial of designed facade by meeting all the required criteria for visual comfort indoors, next step is to realise the same facade in practical world. Henceforth, the facade is explored and is detailed with an approach to integrate within available material and technology in the market for construction in next chapter.

Instances	Distribution of Daylight			DGP		Contrast							
	Avg Lux	Daylit%	Uniformity Ratio	O11	O12	C1	C2	Highest lux	lowest lux	Avg lux/mt.	Overlit	Underlit	Material Set
SU-10-CS	506	95	0.56	0.25	0.26	2.3	2	915	284	59	0	5	M11
SU-13-CS	723	100	0.62	0.24	0.23	2.59	0.96	1002	447	50	0	0	M11
SU-16-CS	462	71	0.55	0.23	0.25	2	2.5	807	252	52	0	29	M11
SU-10-OC	538	95	0.53	0.23	0.23	2	2	979	286	75	0	5	M11
SU-13-OC	695	100	0.51	0.23	0.23	1.86	2	1336	353	98	0	0	M22
SU-16-OC	475	80	0.54	0.22	0.23	1.9	2	846	258	57	0	20	M11
WI-10-CS	573	71	0.35	0.2	0.22	1.98	2.24	1137	200	62	0	29	M22
WI-13-CS	611	97	0.5	0.2	0.21	0.85	0.37	607	305	4	3	0	M11
WI-16-CS	497	60	0.3	0.21	0.2	2.98	1.97	1483	147	40	0	60	M22
WI-10-OC	367	100	0.89	0.12	0.12	1.89	1.56	441	326	12	0	0	Higher reflectivity
WI-13-OC	724	100	0.88	0.19	0.19	2.12	2.1	863	640	24	0	0	Higher reflectivity
WI-16-OC*	176	0	0.89	0.03	0.03	1.4	1.21	211	156	6	0	100	Higher reflectivity
Average**	561	88	0.57	0.21	0.22	2.04	1.79	946	318	48	0	13	-

Table.6.6 Showing all obtained values for each selected instances

* WI-16-OC is considered as an exceptional case and is not considered for validation or in any comparison.
** All the average values calculated are excluding WI-16-OC, as the instance is considered as an exceptional case.

7.0
Facade Scheme

7.1 Constructibility

7.1.1 Facade

The proposed façade is a second layer to building envelop as a dynamic facade that comes in front of curtain walls. The detailing is made to integrate construction process of proposed façade with unitised system. The support system is provided using Galvanised Mild Steel (GMS) sections by making connection to slab of the building. The provided offset between two skin layer is 0.7m.

Furthermore, the process of detailing the facade is done by proposing a one floor (bottom of slab to bottom of slab) segment a high-rise building (Figure.7.1). It was found that the part of a building segment which includes the thicknesses of the floor, slab and service ceiling leaves an unconditional surface on building envelope. The modules in front of these dead surfaces require no role to perform toward daylighting. A more intuitive approach is made to gain maximum potential from these modules by integrating the modules with PV sheets by replacing material sheet cover. The integration of PV sheets on non-performing modules is intending to contribute a part towards energy generation for the building and keeping the versatility in design.

Three rows of modules are integrated with PV sheets by considering an overall depth from clear ceiling to clear flooring. Hence, the provision of PV sheets contributes about 30% area of the building envelope segment per floor, that can be useful to generate electricity. However, the energy generation or the use of PV is not in the scope of this study; hence, much focus further is not given to PV modules in detailing part.

Hence, the final segment of façade is now a composition of three different kind w.e.t their functions and are divided as; 5-rows for diffusing modules, 2-rows for redirecting modules and 3-rows of PV modules (Figure.7.2).
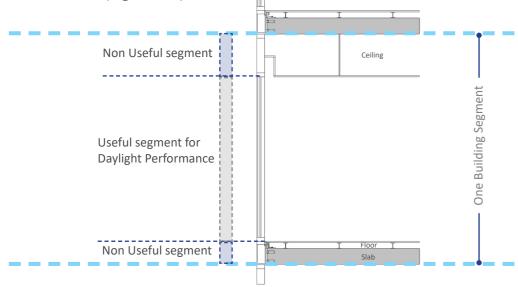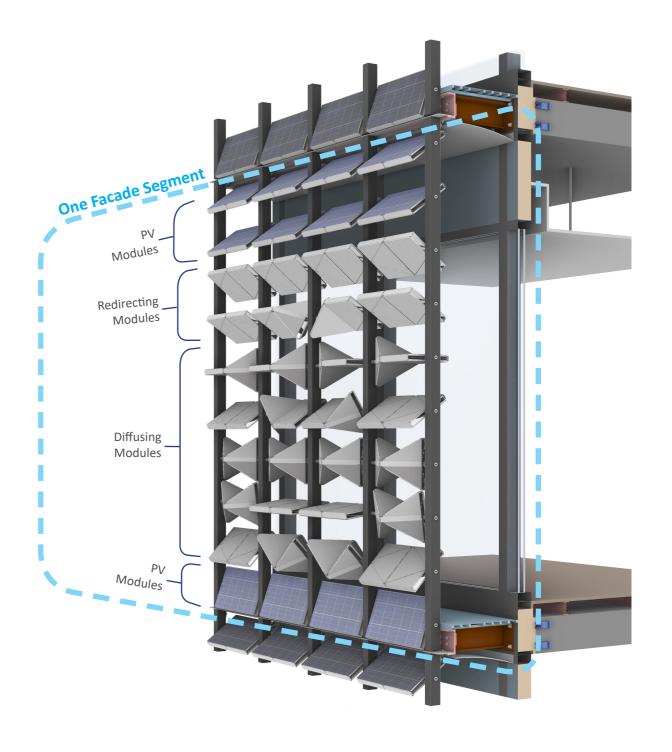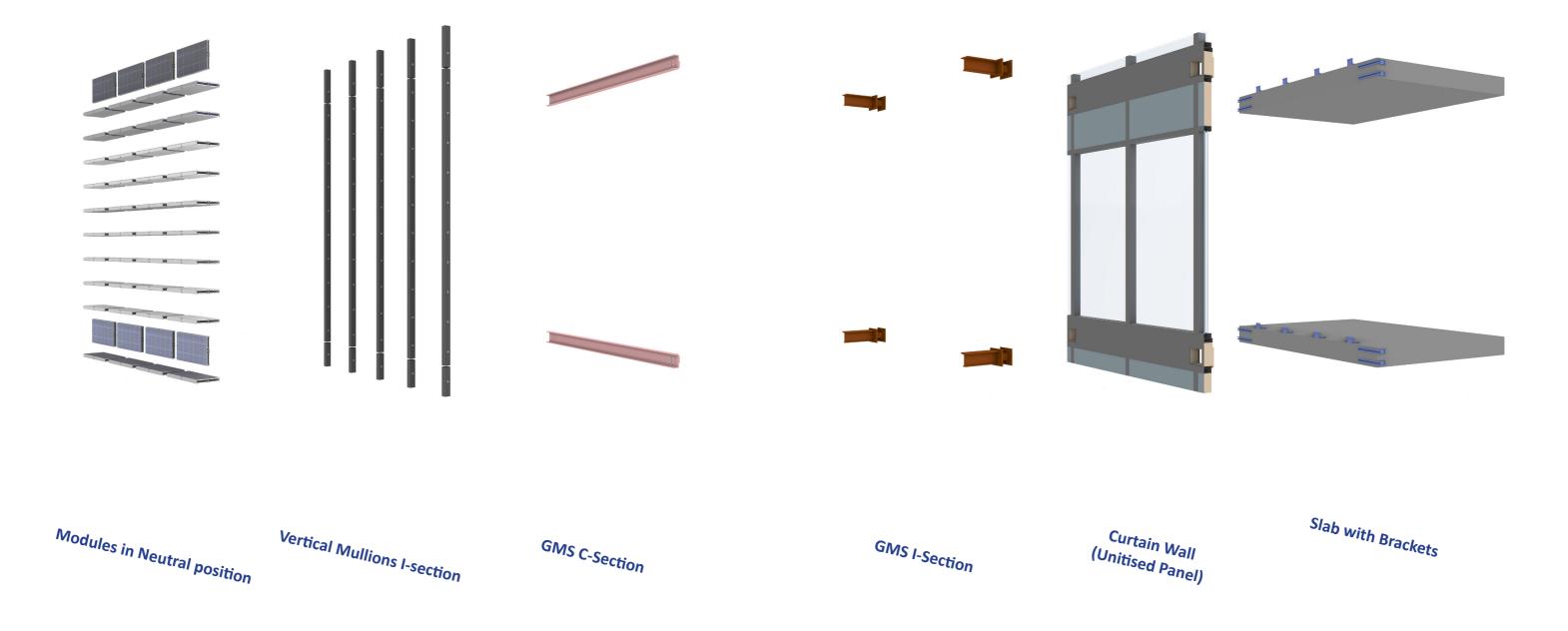

Figure.7.1 Section of a Building Segment

Figure.7.2 Final Facade Scheme
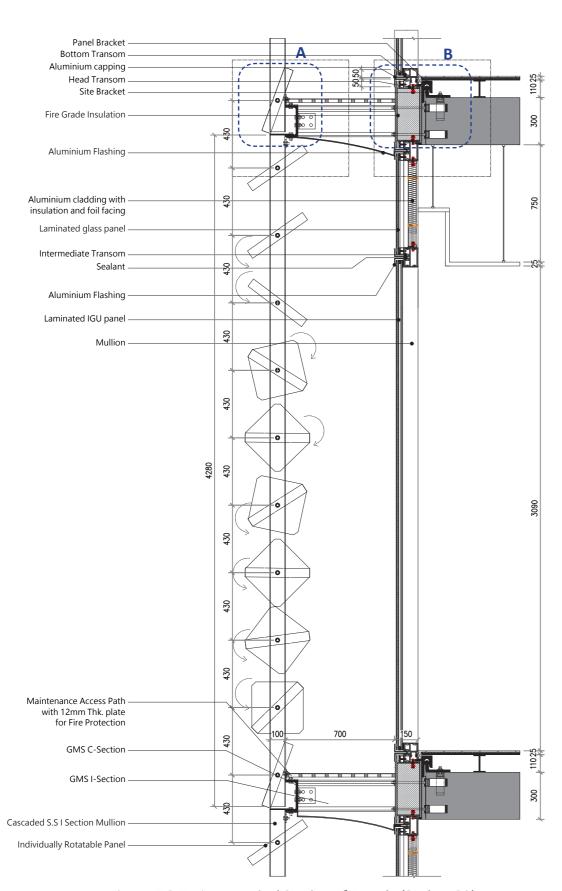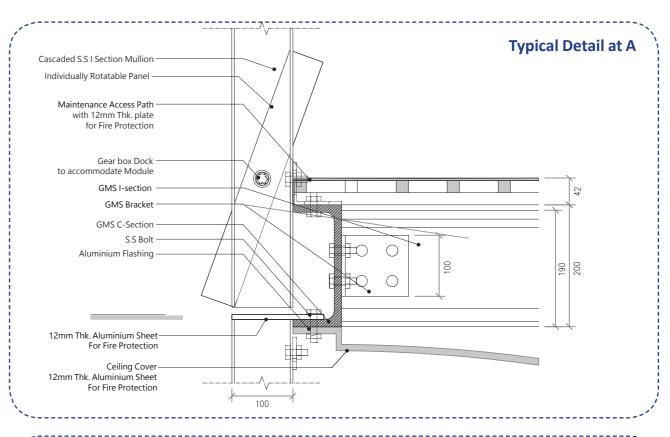
Facade Elements (Exploded View)

Modules in Neutral position

Vertical Mullions I-section

GMS C-Section

GMS I-Section

Curtain Wall
(Unitised Panel)

Slab with Brackets

Facade Details

Figure.7.3 Typican Vertical Section of Facade (Scale 1:20)
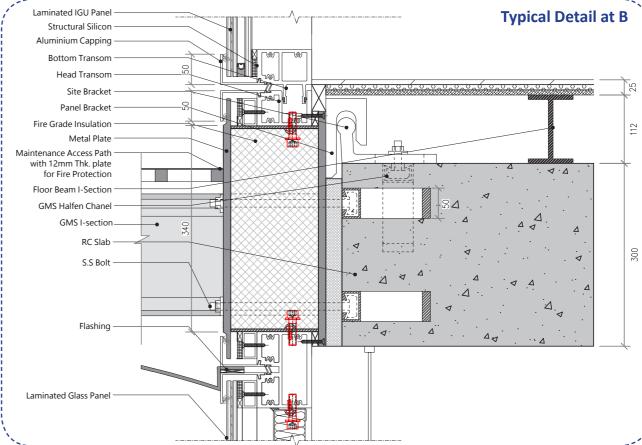
Typical Detail at A

Typical Detail at B

Figure.7.4 Typican Details of Facade (Scale 1:5)

Tolerances and Movement

Provision of tolerances is essential in facade installation in order to react to internal forces like foundation settling or thermal expansion; as well as to external forces like wind loads. However, the tolerances are provided to both layers of the building envelope to have safe movements.

The system used between the curtain wall and slab is a combination of three elements- a cast in the channel, a bracket and a hook allowing the movements in X, Y and Z directions respectively. Such a system is given by Halfen and has wide application in high-rise buildings (Figure.7.6).

Similarly, to support the second layer, tolerances are provided to I section in connection to slab using Halfen channel to withstand internal loads. Furthermore, the tolerances are provided between the connection of horizontal C section and vertical mullions in X, Y and Z directions within the elements using brackets to deal with external loads like Wind majorly (Figure.7.7).

Tolerance detail at A

Figure.7.6 Tolerances in connection to slab

Figure.7.5 Facade scheme showing connection to slab structure
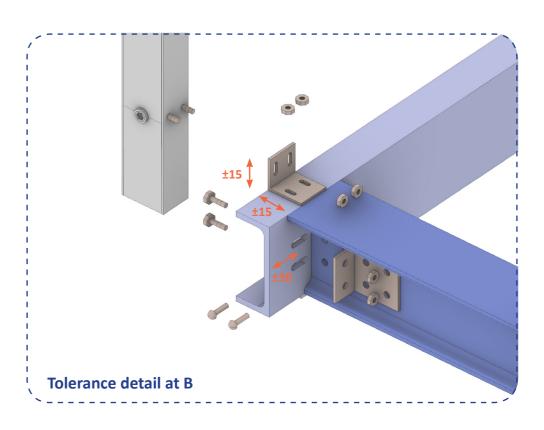
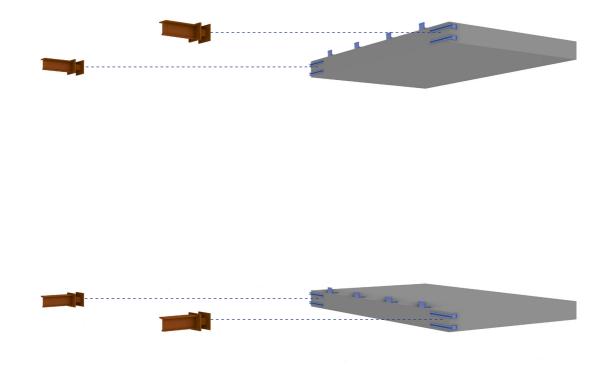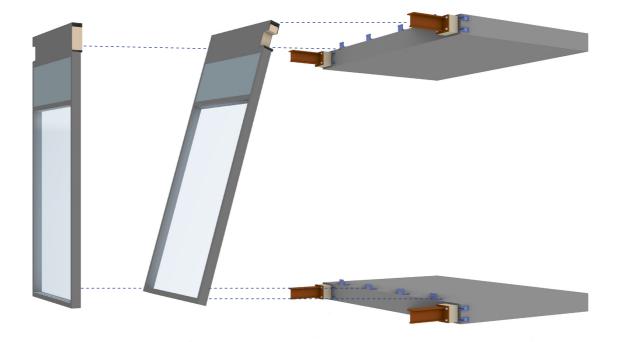

Tolerance detail at B

Figure.7.7 Tolerances for external layer of proposed scheme
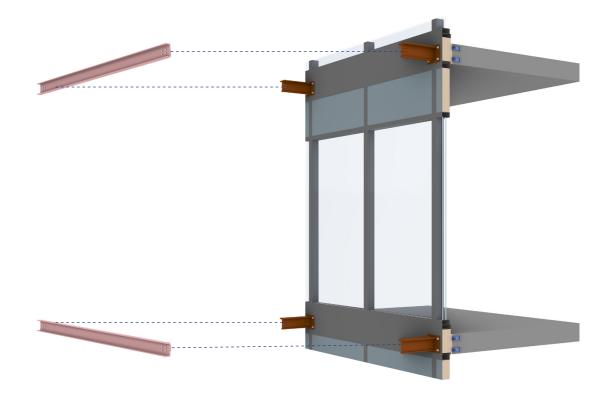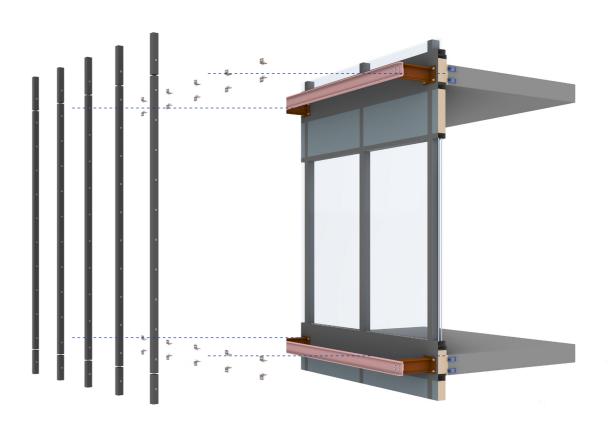
Assembly Sequence

(i)

A slab with fixed Site Bracket and GMS Halfen Chanel at the time of construction.
Fixing of GMS I-section at the position of GMS Halfen Chanel using S.S Bolt

(ii)

Installation of Curtain Walls, having a gap on one side of Insulation segment to accommodate I-section
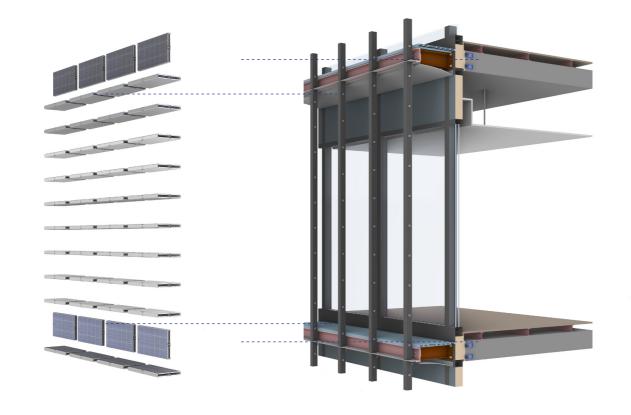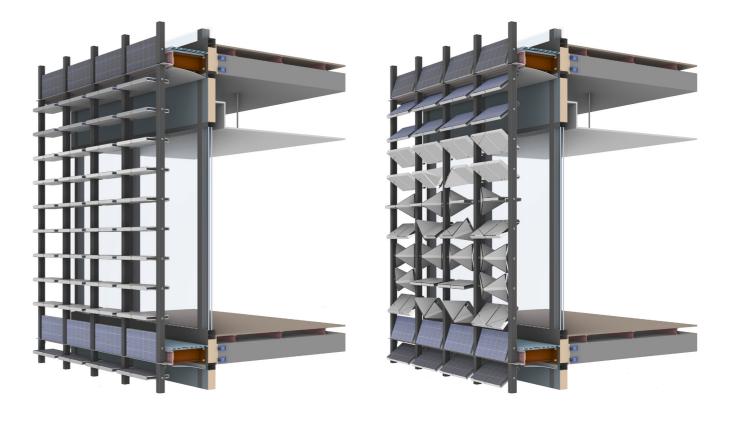
(iii)

Installation of GMS C-section horizontally in connection with two I-sections

(iv)

Installation of vertical mullions along the length of C-section using L-section GMS brackets

(vii)

Installlation of modules in unfolded state in connection with vertical mullions

(viii)

Installed Modules on Facade in neutral position

(ix)

Modules in Motion

7.1.2 Module

The final module developed is shown in Figure.7.8 having size 0.70x0.42x0.06m as width, depth and thickness respectively. The whole structure of the module is divided into five layers; however, the middle layer is common, and two layers on both sides are equal but in the opposite direction, as shown in Figure.7.9 as an exploded view of a module in layers. Basically, there are three categories of layers:

I.   Structural Frame
This layer is the core part of the module that holds its overall weight and responsible for providing rotation of the module when connected to a rotary actuator on side mullions. This layer also includes the integration of a folding mechanism that includes a linear actuator connected with 3-link sliding and bar mechanism.

II.   Folding Frame
It is a combination of three triangular frames with two triangles on sides having common dimensions. The folding frame is connected to a 3-link bar mechanism component. Folding frames provide the shape to the module in the process of folding/unfolding. Also, the same frame has a function to hold the material sheets.

III.   Material Sheet
These sheets are cover to the module and should be the material with optical properties that are required for the performance of the facade. Hence, two different sets of material sheets are used for two sides of a module as Type A and Type B.
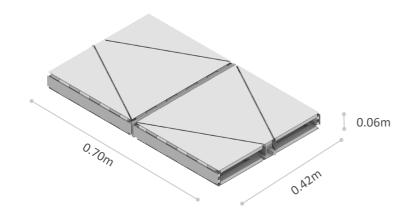
Figure.7.8 Final product of a Module in neutral position

Material Sheet Cover - Type A

Folding Frame

Structural Frame

Folding Mechanism components

Folding Mechanism Elements

Structural Frame
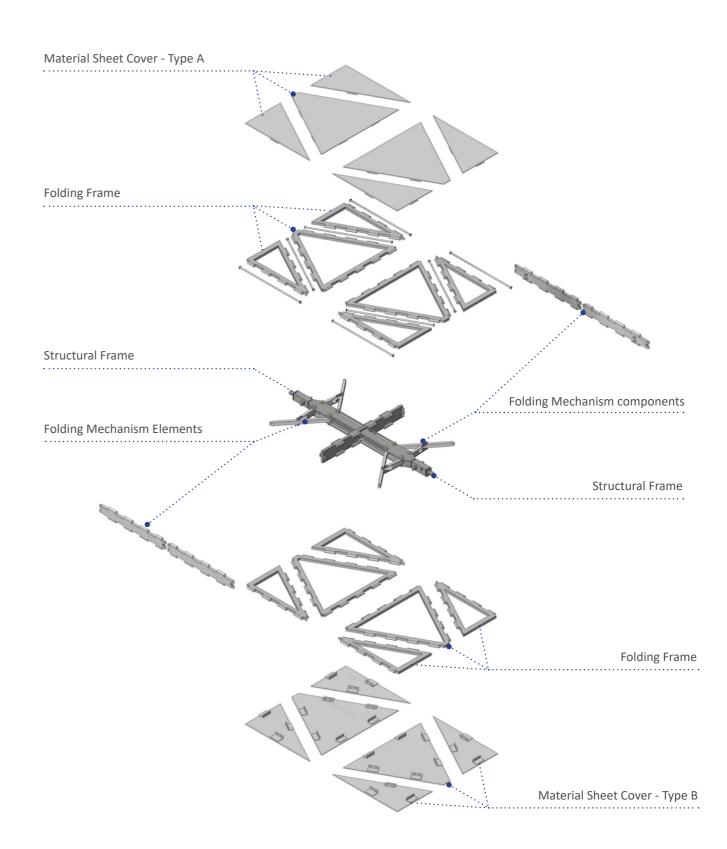
Folding Frame

Material Sheet Cover - Type B

Figure.7.9 Exploded view of a module

As a necessity of the design to provide a folding/unfolding feature on the module, the connections on the module are developed with the concept of a hinge. Inspired from the piano hinge, the hinge provided on components is extended all over the edge along the periphery where the connection to another component is demanded. The same theme of connection is followed for the whole module to provide a smooth transition during motion. However, the Material sheets are fixed on the folding frame with a screw connection from behind to hide joineries and contribute the exposed surface for daylight performance

Considering the fact that many modules have to integrate on one segment of façade, the choice of material for each component of the module made is Aluminium to make the structure lightweight. However, Aluminium is also corrosion resistant and can withstand external weather. Moreover, to reduce the complexity within the module and the manufacturing of components; major components (excluding structural frame) are designed using only two sizes of the cross-section and in multiple to each other; 30x10mm for vertical components that provide thickness to the module; and 15x10mm for all horizontal component which includes folding frames. All the component with these two cross-sections are utilising a hollow Aluminium box section.

However, the module is designed to assemble and disassemble its major components. All the needed components to build one module are shown in Figure.7.10 and Table.7.1.

Element	Code	Components	Quantity
Material Sheets	m1	Trepezoid	4
	m2	Triangles	4 (x2)
Folding Frame	f1	Trepezoid	4
	f2	Triangles	8
	f3	Hinge Rods	20
Folding Mechanism Component	e1	Actuator	2
	e2	Sliding Connector	2
	e3	Sliding Bar	4
	e4	Inner bar	4
	e5	Outer Bar	4
	e6	Hinge Rods	20
Structural Frame	s1	Primary Element	1
	s2	Sliding Track Cover	4
	s3	Actuator Cover Plates	2
	s4	Bolt Box	2
	s5	Bolt	2

Table.7.1 Components of Module and quantity

Figure.7.10 All components needed to built one module
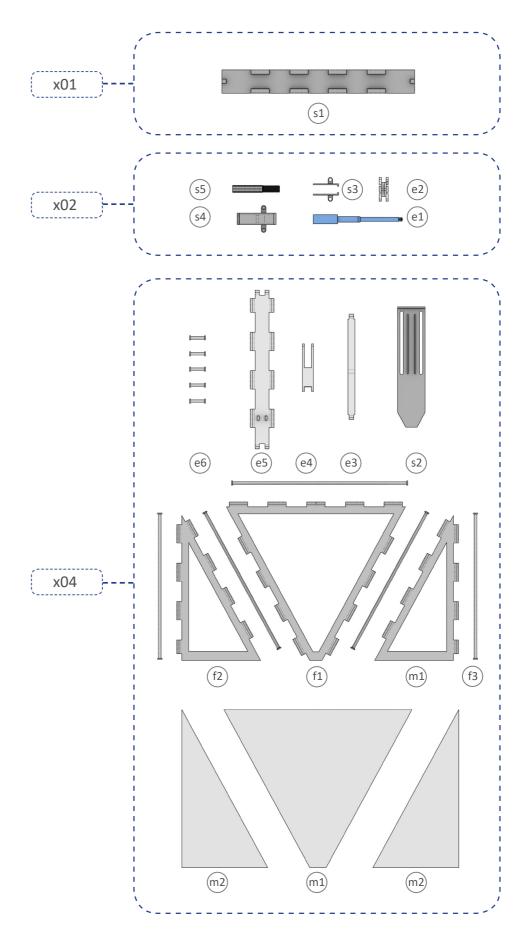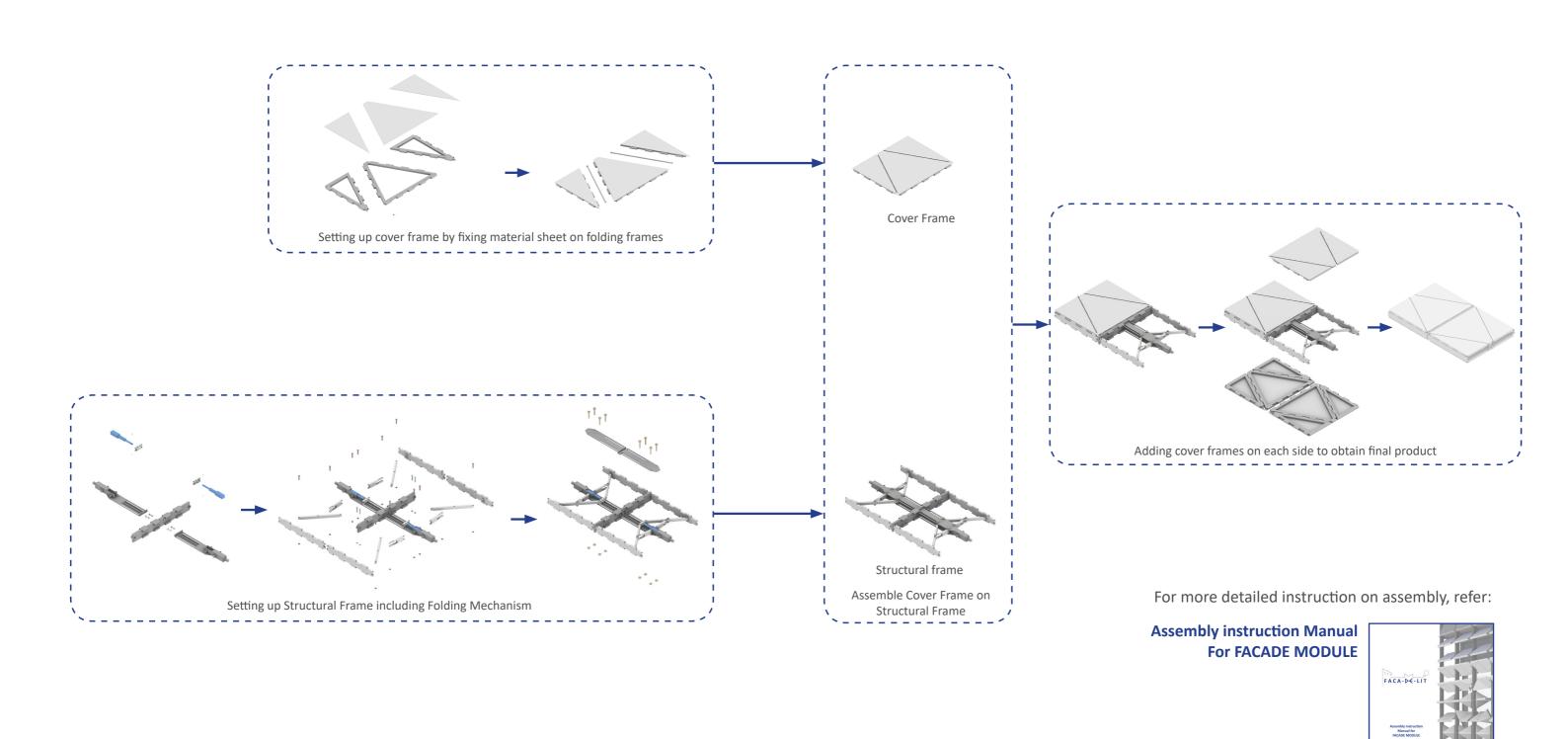
Assembly Sequence - Module

Setting up cover frame by fixing material sheet on folding frames

Cover Frame

Setting up Structural Frame including Folding Mechanism

Structural frame

Assemble Cover Frame on Structural Frame

Adding cover frames on each side to obtain final product

For more detailed instruction on assembly, refer:

Assembly instruction Manual
For FACADE MODULE

Folding Mechanism

The folding mechanism is provided using an linear actuator having a linear motion in connection with a 3-link sliding and bar mechanism having two bar fixed from one point and one bar in sliding motion to provide specific angle needed to fold the folding frames on module (Figure.7.11). The linear actuator provides the mechanical pull and push within provided stretch length in connection to sliding bar to achieve desired motion as per the requirement.

Two tracks are provided within the structural frame, that is expanded along the stretch of the linear actuator. Both tracks hold different functions; a hollow track on both side of structural frame to hold the sliding bar which is in connection to the actuator and a niched track to provide smooth motion along the length coping with actuator's push and pull. Furthermore, a ball catch element is provided within structural frame on both side to hold the folding position of the module (Figure.7.11). Furthermore, the folding/unfolding sequence of a module is represented in Figure.7.12.
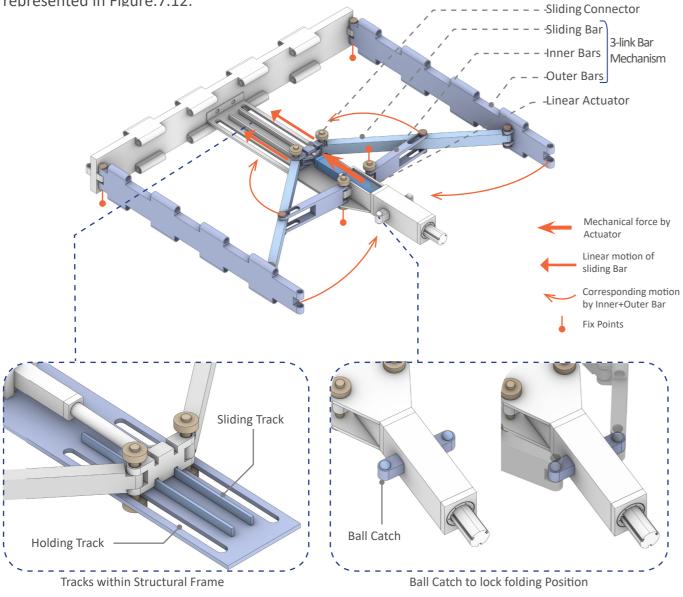
Sliding Connector
Sliding Bar
Inner Bars — 3-link Bar Mechanism
Outer Bars
Linear Actuator

Mechanical force by Actuator

Linear motion of sliding Bar

Corresponding motion by Inner+Outer Bar

Fix Points

Sliding Track

Holding Track

Ball Catch

Tracks within Structural Frame

Ball Catch to lock folding Position

Figure.7.11 Folding Mechanism components and connection

Module   **Folding Mechanism**

Folding Sequence

Full Unfold State

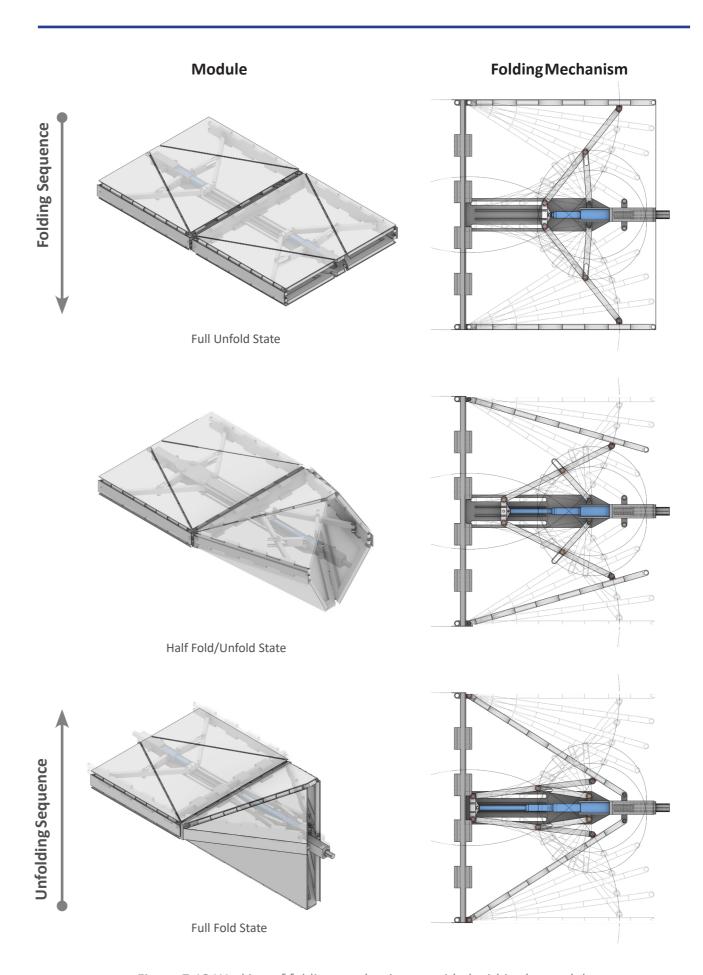Half Fold/Unfold State

Unfolding Sequence

Full Fold State

Figure.7.12 Working of folding mechanism provided within the module

Rotation Mechanism

The rotation mechanism is provided using simple rotary actuator with a hollow shaft servo motor. This actuator is installed within the vertical mullion I-section of the facade inside a gear box made of steel. The modules with rods on sides are connected to mullions by accommodating into hollow shaft (Figure.7.13). The hollow shaft with servo motor provides necessary rotation to module (Figure.7.14)

The gear box is provided on both sides of I section in order to fix the module from both sides. To rotate a module, one rotary actuator is enough; hence gear box at one side will have rotary actuator with motor and the side will have no motor but a hollow shaft to accommodate module allowing circular motion (Figure.7.15)
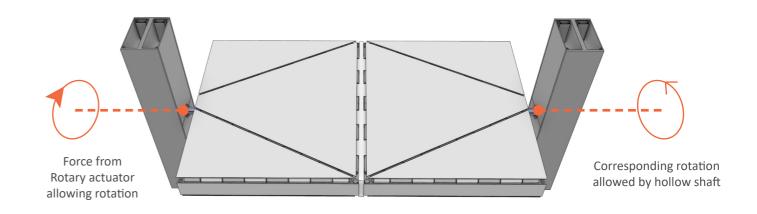

Rod Extends out by rotating it

The section is provided with niches to hold the position of module

Figure.7.13 Process of installing a module into hollow Shaft on Vertical Mullion Or Module's connection to Facade

Force from Rotary actuator allowing rotation

Corresponding rotation allowed by hollow shaft

Figure.7.14 Installed module between two vertical mullions

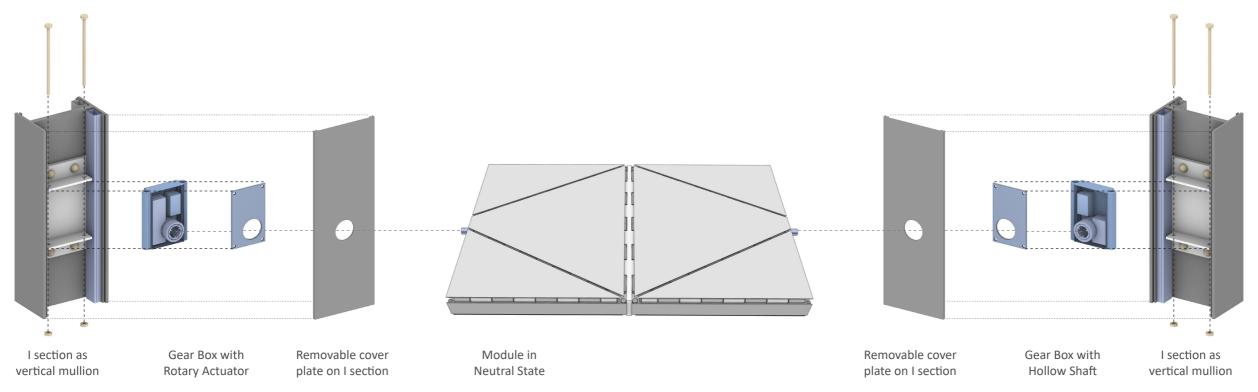| I section as vertical mullion | Gear Box with Rotary Actuator | Removable cover plate on I section | Module in Neutral State | Removable cover plate on I section | Gear Box with Hollow Shaft | I section as vertical mullion |

Figure.7.15 Exploded view of Module's connection   with Rotary Actuator and vertical mullion

7.2 Feasibility

7.2.1 Automation

For the automation process of proposed façade, two motion - rotation and folding/unfolding are required. Folding/unfolding can be attainable by linear motion. Several mechanisms in the form of devices are available in the market that suffices the requirement. The most suitable choice to make is by selecting the most feasible system acknowledging factors like durability, smoothness, accuracy and potential to integrate with the proposed system. The components selected for listed below:

Rotary Actuator for Rotation

To provide rotational motion to module, a rotary actuator also known as worm reducer with a hollow shaft servo motor is used shown in the figure.7.16. The shaft is made of aluminium. Such motor provides smooth and controlled motion. These actuators are capable of rotating 360°. They are available in a varied diameter and rotational gear speed. The required diameter for the proposed module is 15 mm and considered speed of rotation is 10°/s, which indicates the module will take 9 seconds to rotate 90° (from horizontal to vertical) and 18 seconds to rotate 180° (to change material surface).

Linear Actuator for Folding/Unfolding

For the folding/unfolding mechanism within the module, the use of mini stepper linear actuator shown in the figure.7.16 is considered. They are made with anodised aluminium shafts. It allows the movement in a linear path with straight movement along its longitudinal axis. The actuator functions both for pushing and pulling movement. They provide clean and precise motion with full control. In the market, they are available with various stroke lengths, various force capacity and different speed required for operation. Some actuators provide three set speeds ranging from 8mm/s to 32mm/s. The length required for the proposed module is 130mm to cover for folding and the speed considered is 20mm/s, which means the module will take 6.5 seconds to fold and 6.5 seconds to unfold.

Gear box

A gear box is prepared with a metal box casing that contains a rotary actuator with its motor , and a power supply unit to linear actuator, as shown in figure.7.17. A PVC conduit is added to take wire connection from gear box to the building (Figure.7.18). The module is acquainted with the rotational motion;hence, the connection of power supply line from gear box to linear actuator inside the module becomes a challenging task. The solution is fixed using a pogo pin provided within gear box at the end of the hollow shaft. The pogo pin is spring-loaded element, that transfer electricity by being in touch to conducting surface. The power line of linear actuator to pogo pin is provided within the centre of the fixing rod of the module, that gets in connection with pogo pin when is connected to hollow shaft of rotary actuator (Figure.7.19). This connection works even the module is rotating. The used linear actuator requires 6V of power supply; hence, a pogo pin capable of transferring such power is considered.

(i)   (ii)

Figure.7.16 An example of used (i) Rotary actuator ("HZPT",n.d.) and a (ii) Linear actuator ("Actuonix", n.d.)

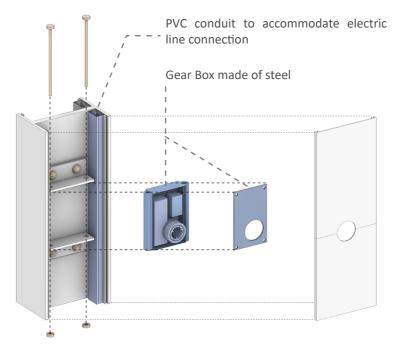PVC conduit to accommodate electric line connection

Gear Box made of steel

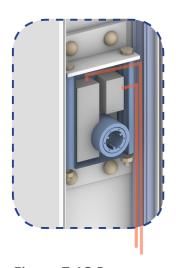Figure.7.17 Assembling of Gear box inside I-section mullion

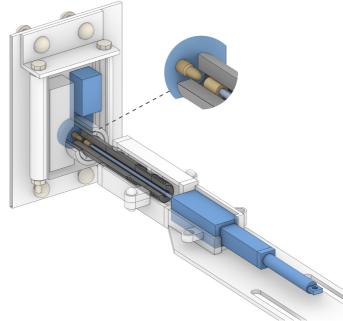Figure.7.18 Power connection from building to actuators

Figure.7.19 Power connection to Linear Actuator with pogo pin

Motion Logic

To allow the motion, the mechanism developed for automation consists of four main components for motion adaptation, as shown in the Figure.7.20 :

I. Sun Sensors- It reads the external condition for sun position and sky condition and sends the signal to the Processing unit.

II. Processing Unit – Or centralised control. It collects the data and generates a response by calculating the required rotation and number of modules needed to fold/unfold as per optimised solution to provide visual comfort. Further, this data is sent to the data transfer unit.

III. Data Transfer unit – or decentralised control. They receives the calculated data and sends the signal to operate actuators.

IV. Actuators – They provide mechanical motion – rotation and folding, after getting signal. The first motion will be in the rotation. After acquiring the final rotational position, only modules necessary to adapt will be folded/unfolded.
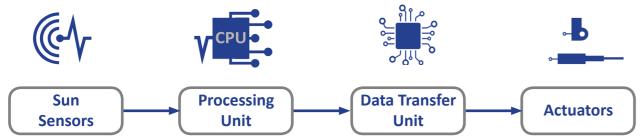
Sun Sensors → Processing Unit → Data Transfer Unit → Actuators

Figure.7.20 Automation Process

The provided motion to the facade elements are rotation and folding/unfolding. The logic for adaptation to different daylighting is provided with a hybrid system which includes combination of predefined data as well as responsive to real time condition in following way:

I. Rotation - The parameter has major impact from Sun's altitude and azimuth, which is easy to be predicted for any location. Hence, the angles for each panels will be predefined in the system that will change three times a day.

II. Folding/Unfolding - This parameter has major impact from Sun's azimuth but also from changing sky condition. Here, sky condition is least predictable phenomenon and sometime shows drastic change; hence, this motion is responsive to exterior condition that will receiving generated data using processing unit and sun sensors for different instance.

Furthermore, each modules are made to control individually (Figure.7.21) to provide separate information to each module regarding folding. And manual control is possible during emergencies.

The time required for motion

As discussed earlier, with the considered speed of actuators, where the time taken by rotation is 9s for 90° and folding takes is 6.5s. Adding 4.5 sec of a gap to carry out both mentioned motion one after the other; the façade takes a maximum of 20s for change from one configuration to another. Motion to all individual modules are separated, the movement of each module will work simultaneously; hence, no extra time is needed to reach the desired configuration. The choice of speed of motion for each actuator is with an idea of having a smooth and noiseless movement of the whole façade segment together. As per the proposed study, the façade will acquire configuration change minimum of three times per day.
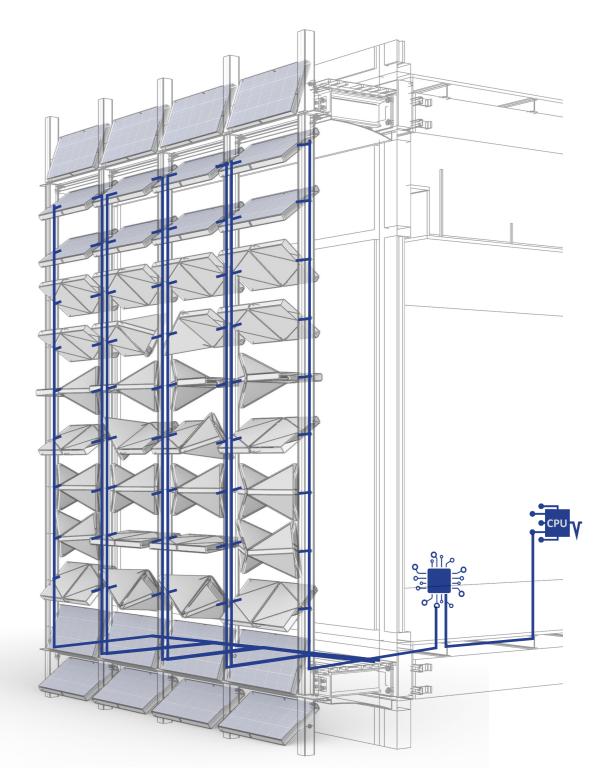
Figure.7.21 Connection of each module system with Processing Unit

7.2.2 Fire Safety

The Dutch government provides several requirements necessary during the construction of building and facade to prevent the risk to users against the occurrence of fire in 'The Building Decree 2012' (Bouwbesluit). Besides, several other norms within Dutch regulation are established under NEN-6068, NEN-6071, NEN-EN 13501-1, NEN-EN 13501-2, NEN 6068 and NEN 6071 which contribute information regarding fire resistance of façade, façade's fire behaviour and others. Furthermore, the façade is a non-substantial way towards the fire expansion. Hence, the façade should at least comply fire rating classification of B and above for 95% of used construction material (this counts for a case where fire expansion within the cavity is not possible)

Façade Fire Performance

In the concept of double skin façade, the risk is higher for fire expansion vertically from one floor to another due to the formation of a cavity between two skins. The cavity demands to be treated carefully with peculiar fire-resistive barrier to either block or slow down the spread of fire vertically. With such consideration, the proposed scheme is provided with the extended platform, as maintenance tray, filling the gap between two facade skins on each floor. Furthermore, the platform is covered with a fire-resistive material plate on top and bottom, which acts as a fire-resistive barrier by blocking the flow of fire. The thickness provided for both covering plate is 12 mm aluminium to hold fire for at least 120 minutes.

I. Fire next to façade or on the Facade

At the time of occurrence of fire; with fire alarm, the fire detectors will send the signal to the automation system as well, which will have a pre-installed setting to convert all the modules that fall on the same floor level of fire to its fully open state (horizontally stacked). Moreover, the modules on floors above and below the floor with fire will be brought to its fully close state (vertically stacked). Such configuration will protect the fire from spreading to other floors (Figure.7.22). The fixed module at the level of the extended platform within the cavity is positioned at a specific angle with a reason of PV, but the same slight tilted edge prolonging outside will help keep the flow of fire away from the modules above. Furthermore, the close façade above will block fire from getting inside and will protect internal glazing and structure. The provision of a water mist fire protection system with high and low pressure is implemented within the ceiling of cavity using a pipeline that can be taken from the roof. This system is to help extinguish less intense fire and help buy more time during highly intense fire.

Fire protection in Cavity

Fire Grade Insulation between slab and curtain wall

Water mist system

Ceiling with 12mm thk. Aluminium

Figure.7.22 Showing the protection from spreading the fire to upper floors during occurance of fire next to window

II. Fire inside the Building

During the fire caused inside of a building, where the access to circulation space is blocked, or there is nowhere to go around except evacuating from the front face of the building; in such cases, a provision within the proposed scheme is provided with a door like opening as shown in figure.7.24. The door-like opening on the proposed scheme is made by separating one of the columns of modules using two C-section on both sides of the module instead of usually used I-section, as shown in figure.7.23. One C-section on both sides of the module is kept loose in connection from the horizontal structural member, and these two C-sections is connected with a metal plate at top and bottom to make it work as an openable frame. One side of the frame is connected with hinge support to adjacent fixed C-section and the other side, the openable frame is connected with a lock system to adjacent fixed C-section. The modules within this openable frame are still working for motion.

The provision of such openable frame will be in front of glazing that is openable to provide straight access to outside. The occupants can be evacuated through this door with the help of cranes from the outside. Furthermore, with detection of fire, the automation settings will convert all modules of the same floor in a fully open state (horizontal stacked); and the modules within the openable frame will be converted in the full close state (vertically stack) to provide more width of opening (figure.7.24).
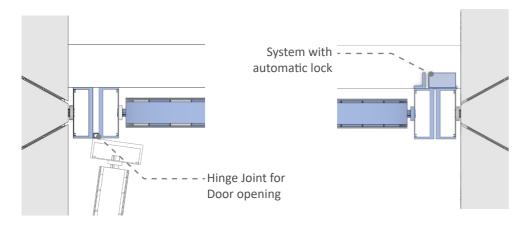

Figure.7.23 Plan view showing provision of Door opening using C-section for vertical mullion

Overview of Material

The major usage of material in the whole proposed scheme is with steel (support system)and aluminium (module), which has fire ratings of A and above. The used PVC has a fire rating of B. The TiO2 coating used on modules has good resistivity against fire. In general, all the material used are classified under A and B fire ratings, and hence it complies with the fire requirement as per Dutch regulation.

Overall, considering the thickness and fire ratings of each material; the support system and proposed facade are able to withstand fire for 120 minutes including the cavity due to provided 12mm thick aluminium for as ceiling that blocks the cavity.
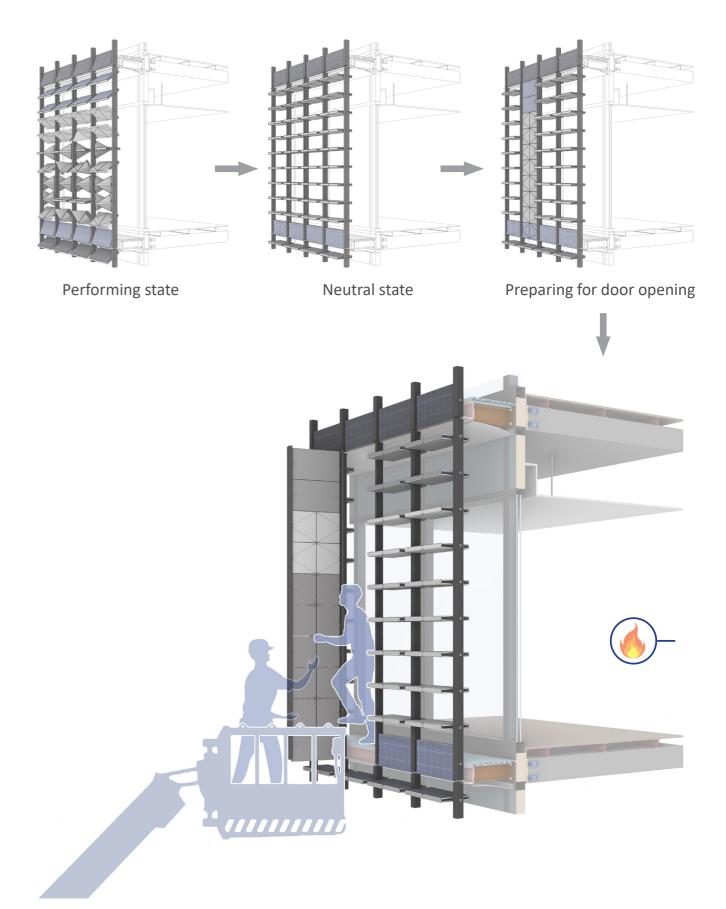

Performing state   Neutral state   Preparing for door opening

Figure.7.24 Fire escaping from outside from a door like opening within facade when fire occurs inside of the building

7.2.3 Maintenance

The elements within the proposed scheme of the façade have the rotating and folding mechanism that allows adapting to diverse external daylight conditions to hold the balance of visual comfort criteria inside. The provided mechanism requires scheduled maintenance within some course of duration to keep the façade in its pristine condition. The maintenance required includes cleaning and fixing or replacing some parts within façade.

The typical way to deal with the maintenance of building envelope on a high-rise is with a provision of Building Maintenance Units (BMU). BMU is the system to provide maintenance from the outside of exterior façade and provide simple and safe access to façade using a lifting platform hung from the top of the high-rise. Although BMU is a standardise way, the maintenance required to clean few modules or fix few random single modules every time in an extended field of numerous modules on the entire building envelope makes the process complex, expensive and less feasible. Hence, a provision from the inside of the building to access the façade is also provided. However, the proposed façade acts as a double-skin façade and is equipped with a cavity between glazing and proposed layer. The passage is made accessible for maintenance purpose with sufficient gap by providing a maintenance tray of 0.70m in width. It works as a platform on each floor in front of the slab to perform cleaning and repairing/fixing activity. The gap provided is for the ease to reach all façade elements by cleaning personnel.

Cleaning

A material with specular surface demands to retain its reflecting property to perform for light redirecting. Dust can account for 8-12% of reduction in reflecting property of a material (Atkinson, 2015). Numerous coatings are developed and made available in the market that keeps the potential of maintaining the optical performance of a material. To prevent the situation here, the application of a photocatalytic coating - TiO_2 is applied as a self-cleaning layer on every material sheet on each module. TiO_2 is an anti-soiling layer which helps to prevent dust accumulation and dirt deposits on a surface. It reduces the frequency required for cleaning. Furthermore, the application of TiO_2 coating has the ability of self-washing under the rain with effect from water driving over the surfaces. Moreover, the self-cleaning property of material sheet due to TiO_2 coatings and certain angled orientation of modules works well for rainwater runoff. In addition, TiO_2 has high protection from UV radiation, which makes this coating a good choice to use on shading elements with daylighting purpose.

When whole envelope demands cleaning, use of BMU should be considered; and when a part of facade requires cleaning process from inside should be considered using maintenance walkway. The manual cleaning can be made smooth and quick by switching the part of façade that needs cleaning in a closed configuration; where all modules are stacked vertically and provide a plain vertical surface to clean as shown in figure.7.25. Rotating each module 180° helps to clean the other face of the modules. While keeping closed configuration, it creates more room within the cavity to perform the needed activity and a smooth movement on outside with BMU, as shown in figure.7.25. As all the modules needs cleaning on both sides,

(i)   (ii)

Figure.7.25 (i) Cleaning from outside using BMU, when whole envelope needs cleaning
(ii) Cleaning from inside, when part of facade needs cleaning

the cleaning process of whole envelope needs to go through twice; once by keeping one side of the modules and the second by rotating each modules within whole envelope to the outer side.

The frequency required for manual cleaning depends on various factors. To sustain the efficiency in the performance of the facade, the specular material sheets on reflecting modules are the most crucial component to consider due to the accumulation of dust on surfaces. Assuming the self-cleaning property of TiO_2 coating applied and self-washing due to rainwater runoff, the modules needs manual cleaning once in a year.

Fixing/Repair

Module Components:

Composition of three parts (or three layers)
I. Main frame for structural (includes rod, actuator and folding mechanism/track) plus folding component
II. Frames for material
III. Material sheet cover

Modules are susceptible to get damaged. All the three elements can be fixed, repaired or replaced at the site itself: first by detaching module from side column with mechanism and then disassembling the damaged part. The damaged part can be reused or recycled.

When Material sheet cover is damaged
The damage caused on material sheet includes losing of optical properties, scratches and dents due to external factors or tearing out of the material sheet due to lose connection. The specific module with damaged material sheet needs to detach from the side column. The material sheet with the material frame needs to disassemble by removing the hinge rod, as the connection to frame provided is from the inside. The new material sheet bought from the supplier is then replaced at site itself. Other option could be to replace the new material sheet with a new frame. With minor damage, the material sheet can be sent for new polishing, and with major damage it can be sent for recycling.

When frames of the material sheet are damaged
The damage can cause due to faulty piece or deformation due to stress developed from much folding and unfolding movement. The module requires to disassemble from the column, and the frame needs to detach by removing hinge rod. The frame needs to be changed keeping the same material, or a set of new frames with a new material sheet on it can be replaced at site itself. Minor damage on the frame can be repaired, and a component can be reused else with major damage the frame can be sent for recycling.

When the structural frame is damaged
The damage can cause due to faulty piece or deformation due to the mass weight of the

entire module after some span of time. After dismantling module from the column, all the components of the module need to be dismantled. The damaged structural frame needs to be replaced with a new one, and the rest components should be assembled again. The whole process can be performed at the site. The damaged piece can be sent for repair or recycling.

When the entire module or many components within the module is damaged
The damaged module will be replaced with the new one simply by detaching it from the side column. Similarly, various damaged modules can be replaced in a similar manner.

Automation components:

When Linear Actuator stops working
The linear actuator is made detachable from the module with a provision of a sliding component on the structural frame. The whole module needs to disassemble to replace the linear actuator within the same module.

When one of the gear boxes stops working- the column has a removable PVC covering in front of each gear box. Also, the gear box is fixed with bolts from two sides. The gear box can be removed and replaced with the new one. With minor damage, the gear box can be sent to the manufacturing plant for repair, and with major damage, the useful parts like casing can be reused or recycled.
Similarly, many individual damaged gear boxes can be replaced in a similar way.

When connection line to gear box in column stops working- The power supply wires to gear boxes are kept together in a PVC box covering. The provision for power supply to gear box is by mean of a pin to connect with output line from PVC. These connection pins from all gear box should be disconnected, and the PVC box with damaged connection lines can be replaced with the new working one bought from the manufacturing plant. The minor damage can be repaired; and for major damage, the PVC box can be reused for a similar application but cannot be recycled

When the column with all gears shows major issues- The modules on both side of the columns needs to be detached, and the whole column needs to be replaced with a new column having a working connection with gear boxes. The working gear box from the damaged column can be reused.

It can be seen that the repair and fixing process is easily and quickly manageable and no expert labour is require, the maintenance team of the building can take care of such fixing. Also, the process of fixing doesn't require longer time which assure the facade to continue staying in its performance state.

Causes of Failure

- **Module** - Poor construction, improper installation and fixing of modules, poor manufacturing of a module

- **Automation** – Use of low-quality products; damage of equipment (linear/rotary actuators, gear box and sun sensors); damage of any specific connection for power supply; high voltage supply to the equipment.

- **Other Failures**- Damage due to extreme weather and heavy wind load; surface damage by birds sitting; an occurrence of fire.

During very extreme weather condition like a storm or heavy snowfall, the façade can be transformed into closed configuration to reduce the risk of damage of façade elements. Furthermore, the close configuration will provide protection to inner layers of the building like glazing by preventing it from any damage.

Reduction in Performance efficiency

- **Module**
  Material sheet cover -
    - Change of optical properties of each material sheet
    - Dust accumulation on surfaces of reflecting panels
    - Decaying of TiO2 coating
  PV Sheet cover – Dust accounts for 30% of efficiency reduction by shadowing the PV cells. Visual discolouration of the cell and module's orientation.

- **Automation** – Malfunctioning of the module due to software issues; signal receiving issues from sun sensors; not providing accurate schedule timing for the motion of façade for its configurational change where the modules are not positioned as per their optimized configuration.

Recommended life expectancy

- **Modules** - Aluminium used in the framework is about 30 years considering the motion of modules. The cover material plates need replacement every 10-years on top of redirecting panels due to its expected change in reflecting properties with time, which accounts for daylight performance. Later, a minimum of 95% can be recovered through recycling process for aluminium. The PV sheets applied on module and inverter used is expected up to 30 years; although 10% of parts of the inverter requires replacement in every 10-years.

- **Automation** – 10 years for the linear and rotary actuator if properly maintained and 30 years for all cables and wiring is expected.

7.2.4 Glare to Outside

While designing a facade, the glare causing outside due to facade elements is one of the aspects to be taken care of. As per the proposed scheme, the facade is divided into three segments - PV Panels, Redirecting Panels and Diffusing Panels having separate material sheet cover on their modules with different optical properties. The most critical segment here is redirecting panels which uses reflective sheets; but considering its functional aspect which is to redirect light inside, the redirecting panels or concerning reflecting sheets are positioned in a way to reflect light inside. The diffusing panels are somehow oriented facing the sun, but they have a diffusive material property which has the least risk of causing glare. On the other side, the risk of glare from PV panels is negligible. Moreover, the materials on the thickness part of the modules provided are dark, and matt finished.

Henceforth, it is assumed that the proposed facade scheme will not cause a major issue in terms of glare to outside. Yet, an attempt on detailed analysis is needed to quantify this situation.

7.2.5 Energy Performance (PV Modules)

I. Lighting Energy Consumption (LEC):

As per SEA (2007), an office building accounts for 40% of the energy consumption behind lighting and the annual consumption on lighting electricity per meter square of an office building goes from 20 to 50 kWh/m². The total LEC for proposed room including automation use is shown below:

(i) Proposed Office Room:

Area (9mX3m)	=27m2
Annual LEC/m2 (Highest value)	= 50 kWh/m2
Total annual LEC by proposed Room	= 1350 kWh

(ii) Automation Components:

One time use LEC for one actuator	= 0.0014 kWh
Total number of actuator used	= 96 (3 actuators for each 32-performing modules)
Required motion	= 3 times a day
Total annual LEC by automation component	= 148 kWh
Total Lighting Energy Consumption	**= 1498 kWh/annum**

II. Energy Potential by PV :

Although the efficiency of PV cells is directly influenced by the altitudes of the sun, weather conditions and; orientation and the tilt angle of PV modules. The PV potential is calculated by performing Radiation analysis in Grasshopper using Ladybug Tools and the result in visual is shown in figure.7.26. The followed result is based on the annual global irradiation value for Rotterdam.

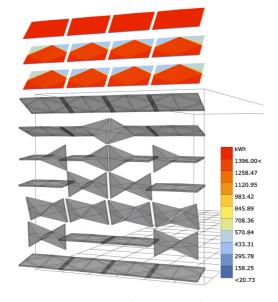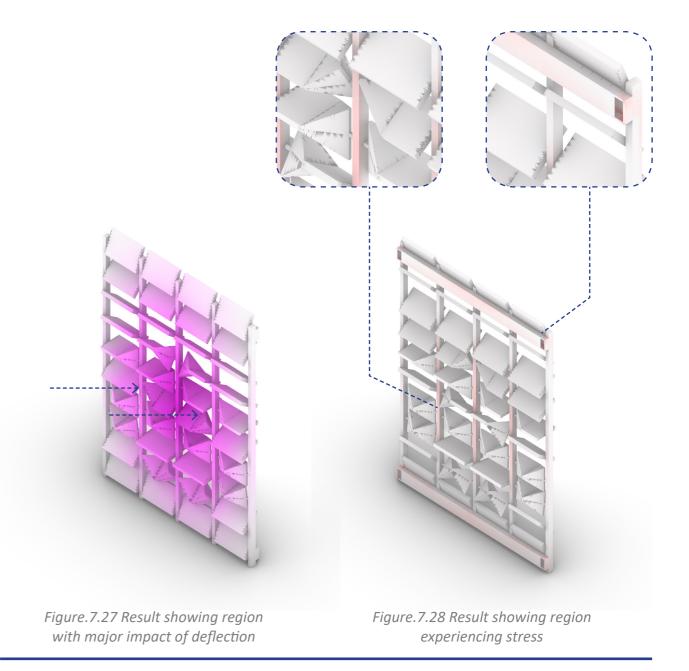|	
Area of one PV module (0.7mX0.42)	= 0.294 m2
Total area of PV (12 nos.)	= 3.53 m2
PV Efficiency (Monocrystalline)	= 22%
Rotational Angle of PV Modules	= 38°
Annual Energy Potential	**= 1083 kWh/annum**

Figure.7.26 Radiation analysis on PV Modules

The results obtained shows the potential of provided PV for generating electricity equivalent to 72% in comparison to total lighting energy consumption by proposed room and automation included.

7.2.6 Structure Performance

The structure analysis is made for the facade skin using Karamba plugin with Grasshopper. The analysis is made for rotterdam location, and considered wind load is 0.46KN/m2 ("WIND LOAD-NEN-EN 1991-1-4, n.d.). The result showed a deflection of 15.2mm with maximum tensile stress of 328MPa and maximum compressive stress of 243 MPa.

Figure.7.27 Result showing region with major impact of deflection

Figure.7.28 Result showing region experiencing stress

7.2.7 Weight Calculation

Module

Element	Code	Components	Quantity	Volume per Piece (mm3)	NET Volume mm3	Density gm/mm3	Weight Gram	Demountable	Recyclable	Directly Reusable
Material Sheets	m1	Trepezoid	4	115880	463520		1256	Yes	Yes	Yes
	m2	Triangles	8	48687	389496		1056	Yes	Yes	Yes
Folding Frame	f1	Trepezoid	4	102363	409452		1110	Yes	Yes	Yes
	f2	Triangles	8	81565	652520		1768	Yes	Yes	Yes
	f3	Hinge Rods	20	8638	172760		468	Yes	Yes	Yes
Folding Elements	e1	Actuator	2	-	-		160	Yes	No	No
	e2	Sliding Connector	2	6400	12800		35	Yes	Yes	Yes
	e3	Sliding Bar	4	13729	54916	0.00271	149	Yes	Yes	Yes
	e4	Inner bar	4	6675	26700		72	Yes	Yes	Yes
	e5	Outer Bar	4	44547	178188		483	Yes	Yes	Yes
	e6	Hinge Rods	20	11904	238080		645	Yes	Yes	Yes
Structural Frame	s1	Primary Element	1	215545	215545		584	Yes	Yes	Yes
	s2	Sliding Track Cover	4	44470	177880		482	Yes	Yes	Yes
	s3	Actuator Cover Plates	2	8720	17440		47	No	Yes	Yes
	s4	Bolt Box	2	30094	60188		163	No	Yes	Yes
	s5	Bolt	2	16655	33310		90	No	Yes	Yes
Total Weight of one Module (Gms)							8569			
Total Weight of one Module (Kgs)							8.57	93.70%	98.13%	98.13%
Total Performing Modules (Kgs)						35	299.90	(% of Mass weight of Module)		

				Area (m2)	Weight/m2		Weight (Kgs)			
PV Module			1	0.294	15		4.41			
Total PV module						12	52.92			
Total Modules (Kgs)							352.82			

Supporting Structure

| Elements	Components	Quantity	Volume per Piece Cubic/	NET Volume	Density gm/mm3	Weight Gram	Demountable	Recyclable	Directly Reusable
GMS I-section	Tolerance Brackets	4	526850	2107400		16543	Yes	Yes	Yes
	I-section	2	6400660	12801320		100490	Yes	Yes	Yes
	Bolts	8	58508	468064		3674	Yes	Yes	Yes
GMS C-section	C-Section	1	14638200	14638200	0.00785	114910	Yes	Yes	Yes
	Bracket	4	502450	2009800		15777	Yes	Yes	Yes
	I-section	4	5546880	22187520		174172	Yes	Yes	Yes
	L-Brackets (C-section)	20	79931	1598620		12549	Yes	Yes	Yes
Vertical Mullion	Gear Boxes	80	46150	3692000		28982	Yes	Yes	No
	L-Brackets (Gear Box)	160	30240	4838400		37981	Yes	Yes	Yes
	Cover Plate	88	59275	5216200		40947	Yes	Yes	Yes
	PVC Conduit	8	-	300100	0.001	300	Yes	Yes	Yes
Ceiling Plate		1	-	17530468		47508	Yes	No	Yes
Maintenace Tray		1	-	49244800	0.00271	133453	Yes	Yes	Yes
Total Weight of Façade (Gms)						727288			
Total Weight of supporting Structure (Kgs)						727.29	100.00%	99.95%	96.01%
							% of Mass weight of supporting structure		
Total weight of Façade scheme (Kgs)						1080.11	97.70%	99.50%	96.90%
Weight/m2 (Kgs) - 4.3m x 3.5m						71.77	of Mass weight of whole Façade scheme		

7.2.8 Sustainability and Circularity
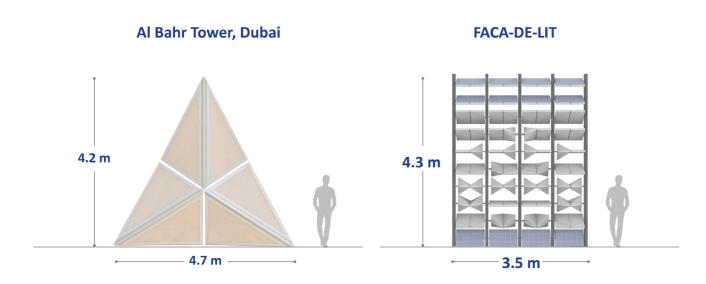
Calculating the volume for each component used in one module and multiplying it with the density of aluminium, which is 2710 kg/m2; provides the mass weight of each component. Adding all mass weight of all component, it has found that one module has mass weight of 8.6 kgs. Further, the total weight of whole facade scheme is 1080 kgs.

From the components and material used in whole façade scheme, 97.70% by mass weight is demountable or remountable; 99.50% by mass weight of the material and product used is recyclable and 96.90% by w of all elements is directly reusable. The calculated percentage shows achieving of a sustainable approach which ask for 75%, 90% and 25% by mass weight respectively for demountability, recycling and reusability

Moreover, each material that has been used except PVC casing used inside the column with mechanism and motors used for the operation of rotary and linear actuator is non-recyclable.

7.2.9 Comparison
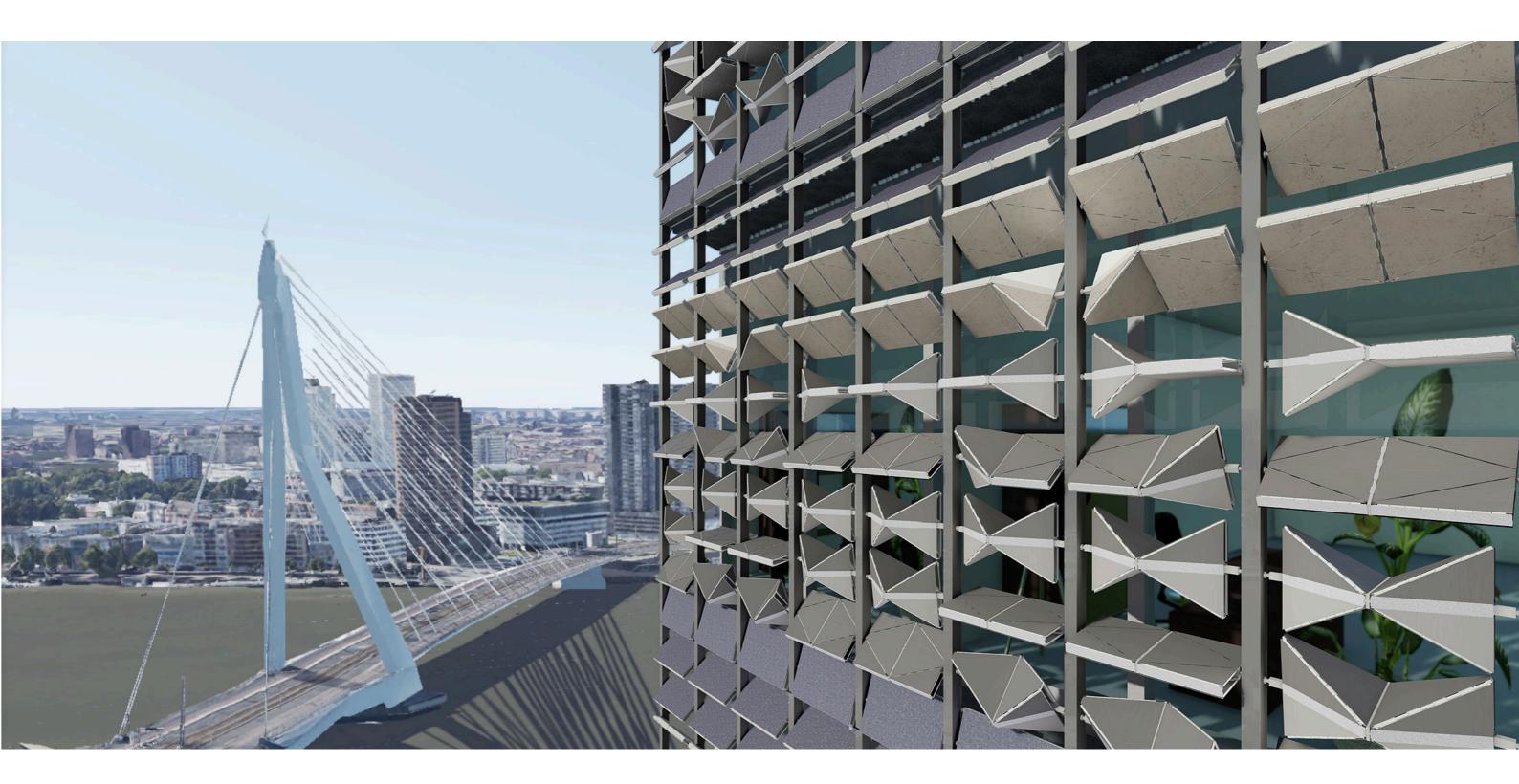
A comparison of proposed facade scheme is attempted with Al Bahr Tower, Dubai; one of the considered case study for this research; in several aspects as shown below:

Al Bahr Tower, Dubai
4.2 m
4.7 m

FACA-DE-LIT
4.3 m
3.5 m
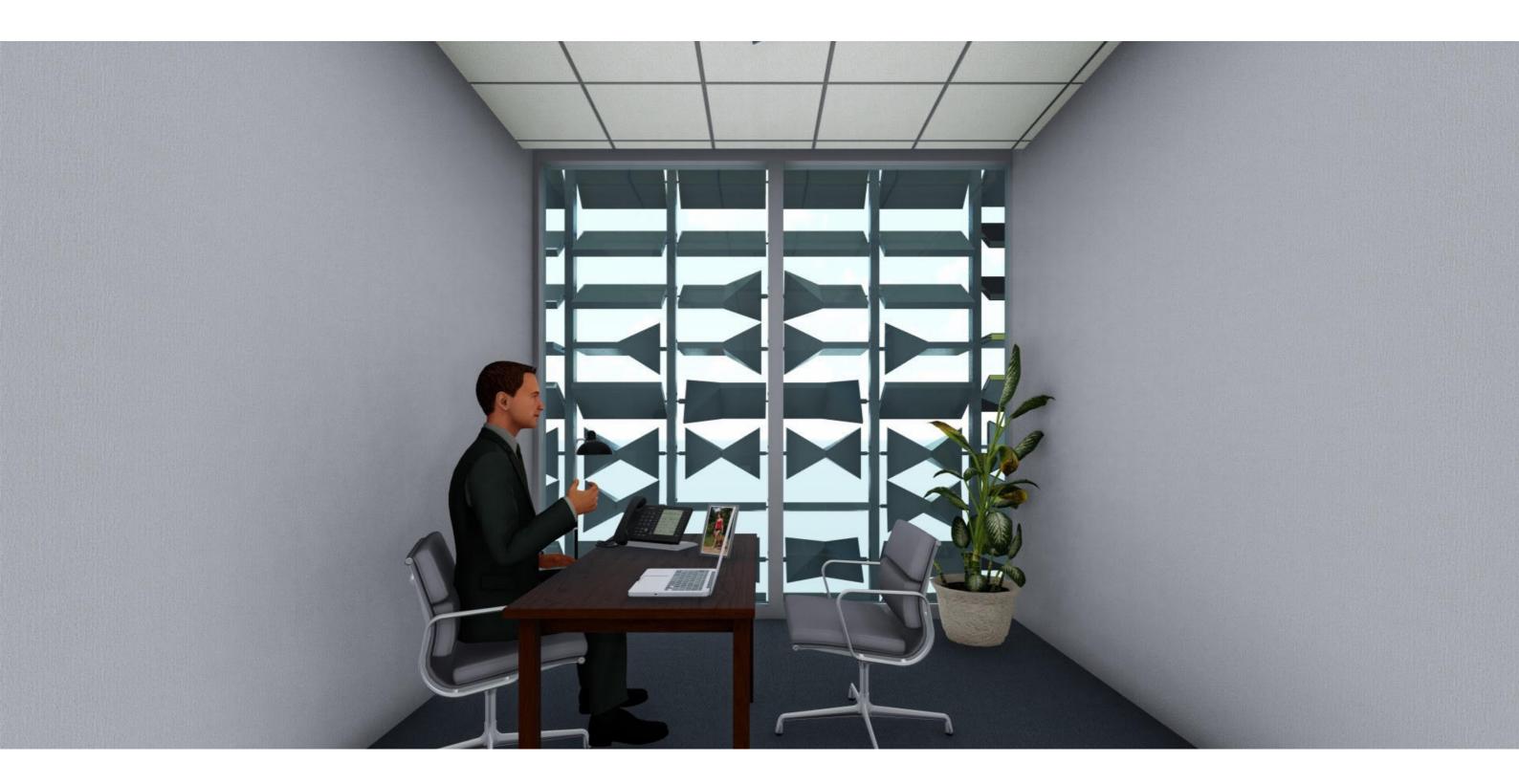
	Al Bahr Tower	Faca-de-lit
Facade Element	Large scale Panels	Small scale Modules
Element Variations	22 different shapes	All shapes similar (includes PV, redirecting, diffusing modules)
Material	Stainless Steel (Structure) Aluminium (Panel Frames) Fiberglass Mesh (Panel Cover)	GMS (Structure) Aluminium (Panel Frame and Cover)
Classification	Folding	Rotating + Folding
Facade Segment	One Mashrabiya Panel Triangle: 4.2m (Height) 4.7m (Base)	Proposed Facade Segment Rectangle: 4.3m (Height) 3.5m (Width)
Weight (Including Supporting Structure)	1500 Kg/Segment 152 Kg/m²	1080 Kg/Segment 72 Kg/m²
Maintenance	BMU Basket (Cavity)	BMU (exterior) + Maintenance walkway (Cavity)
Automation Control	Centralised + Manual	Centralised + Manual (Emergencies)
Fire Safty Measures	Sprey Applied System	Blocked Cavity, An opening within Facade, Water mist System
Fire Protection	120 Minutes	120 Minutes
Life Expectancy	20 Years (Panel) 15 Years (Actuators)	30 Years (Panel) 10 Years (Actuators)
Visual Comfort	40% (as per Occupant's experience)	88% (as per the results obtained)

The source of information for Al Bahr Tower is from- Boake (2014) for Fire Safety; Karanouh (2015) for Fire Protection; and Attiya (2017) for the rest.

8.0
Closure

8.1 Conclusion

Conclusion on Research Question

"Based on computational design methods and techniques, how can a façade system allow for indoor visual comfort, by daylight's controlled distribution throughout the depth of a room, in a high rise office building?"

The outcome of this study is a dynamic façade for an office space, that adheres to visual comfort criterias of a high-rise building; allowing for controlled distribution of daylight throughout the depth of the space by adapting to diverse external daylight conditions. The applied computational design method is found to be a reliable medium to explore a design solution for a façade that has increased performance efficiency while achieving visual comfort. This is explored specifically through parametric modelling, daylight simulation and optimisation.

The façade scheme allows visual comfort with controlled distribution based on three features provided for each module– Rotation, Folding/Unfolding and different Material Sets. However, with the help of computational methods, the final sets of configurations in combination with previously mentioned features were achieved for each instance using a developed digital workflow. By optimising the process with daylight simulations, a near-optimal solution was found.

The selected features and external factors each play an important role aiding to control the indoor environment. More elaboratively, the individual roles are:

I. **Rotation –** This feature was found to have a major impact from changing Sun's altitude and minor with Sun's azimuth and sky condition as an external factor; and was found to be responsible for controlling daylight reach to depth for the indoor environment.
II. **Folding –** (Or change of Module types) This feature had a major impact from changing Sun's azimuth and minor with Sun's altitude and sky condition as an external factor; and was found to be responsible for controlling uniformity of light intensity along the depth for the indoor environment.
III. **Material set –** This feature had a major impact from changing sky condition and minor with Sun's altitude and azimuth as an external factor; and was found to be responsible for controlling enhancement of light intensity for the indoor environment.

These features are correlated and together influence the external factors; hence, the process of this study showed that each feature contributes to deliver the final result. Furthermore, the combination of three features showed the potential to deal with diverse external daylight factors, and bring control over daylight distribution indoors.

A detailed study was conducted prior to the design stage to identify specific aspects related to the study. The design of the facade is developed with a coherent approach in which a balance is maintained between visual comfort performance and real-life feasibility aspects. The final façade scheme is developed considering the available technology and material in the market to establish the design sustainably and avoid unnecessary complexities.

Conclusion on Computational Design

While attempting an optimisation process using all the parameters (design variables) and objectives together, a never-ending process was noted within optimisation tool, and this shows an example about the complexity level of the project when taking into account every aspect of visual comfort.

Within a few attempts at optimisation, it was found that it was found that use of one parameter at a time by fixing other parameters showed higher value achievement within less time compared to optimisation using two or more parameters. Hence, the developed computational workflow was divided into a two-step optimisation. Moreover, the scope of this study is limited to the first step of optimisation having parameter as rotation; and the second step of optimisation was replaced with manual adjustments for parameters module types and material set. However, the recommendation is to go through both steps to gain an optimal solution.

Due to less availability of light outside for instances at Winters-Overcast, a different set of materials within the simulation process was used than the rest instances. It was found that by increasing reflective properties on diffusing modules, the light can be enhanced inside with uniform distribution along the depth even though the available light outside is very low. This showed the effectiveness of the proposed façade in light distribution. Hence, this study concluded that two different sets of material on geometry are recommended that can deal with both- different sky condition as well as different seasons. Thus, the right choice in a combination of optical properties for material is highly recommended.

Conclusion on Performance Evaluation

All the obtained solutions for the 12-instances analysed resulted in a solution that fulfils all the criteria needed for visual comfort. However, the case during Winter-Overcast sky at 16:00 Hr is considered as an exception for evaluation as the available light outside was found to be not enough. Hence, the average for all criteria was made for 11-instances excluding the above-mentioned case.

From final results, an average daylit area on the working plane was found to be 88% amongst all cases having an average light intensity of 561 lux distributed with an average uniformity ratio of 0.57. The obtained average light intensity is almost near to 500 lux, which is the minimum need for an office workplace. Furthermore, the average of DGP and contrast validates the absence of glare and low contrast difference in the same working plane. This shows that the room has achieved a visual comfort environment for occupants dealing with diverse external

daylight conditions.

Furthermore, the uniformity ratio of 0.5-0.7 is the requirement for artificial lighting as per BREEAM (2016). Here, it can be seen that the obtained value of uniformity ratio of daylighting for proposed façade as 0.57 fulfils the criteria equivalent to artificial lighting; hence, it is assumed that the use of artificial lighting can be completely neglected for those areas. This further concludes that for 88% of work plane area, the use of artificial light can be neglected furthermore saving 88% of energy consumption concerning artificial lighting.

However, the visual comfort criteria was achieved for all cases at Winter-Clear sky condition but on account of direct sunlight due to low altitudes of Sun. The situation here was found to be contrary; because to maintain specific illuminance inside the room, the façade elements need to open at a certain angle, but with opening up the façade, incoming light from low altitude sun penetrates inside. This was observed from the glare analysis, which showed over-lit areas on sidewalls for WI-CS cases, although the DGP values are low and conclude imperceptible glare situation from simulations pertaining occupant's eye; this was due to comparatively low intensity of direct light. However, the Clear sky condition during the winter solstice is a rare phenomenon at the considered location Rotterdam; this phenomenon was not investigated further in the scope of this study.

Conclusion on Facade Scheme

The last step made was to examine the final façade scheme by conducting a feasibility analysis in different aspects that covers automation, fire safety, maintenance and cost.

For automation, several modules are combined in a segment to cover the room face. The segment is connected to the processing unit, which gets signal from the sun sensors. It was found from the study of used actuator component that the façade takes a maximum of 20s to transform from one configuration to another. The automation component is seen to be the weak link of the structure in terms of life expectancy. While the whole structure has a life span of at least 30 years, the automation component requires replacement every 10 years. Furthermore, the actuators account for the highest fraction within cost of the segment as 3-actuators are required for each module. Hence, the automation part is still comparatively an expensive process.

In the purpose of fixing/repairing, an advantage was found for not keeping the façade in the non-performing state for a long period due to the assembling/disassembling characteristic of the components of façade, including modules and automation components; and requires no expert labour. On the contrary, the cleaning of the building envelope was found to be an expensive process and time consuming due to the two cleaning processes required in a year to clean each module surface on both sides, even though the façade is cleaned keeping closed state to make the process easy. The material used for each component has a good fire rating which can withstand fire for a minimum of 120 minutes, and the provision for an opening within the façade provides a safe escape plan for the occupants.

Overall conclusion

A feasibility test done regarding weight of the entire façade segment showed 53% less weight in comarison to the facade of an existing project Al Bahr Towers, Dubai and can said to have feasible weight for adaptation as facade. Hence, it can be said that the proposed scheme is feasible for new construction projects, and also to few renovation projects that can withstand such equivalent load. The reduced weight is mainly due to the use of Aluminium as a material for modules. However, the proposed façade scheme is highly suitable for buildings with deep floor plans and high consumption of artificial lighting for visual comfort. Furthermore, the study also shows that the final product of design has high potential to be integrated with circular strategy by reusing and recycling of each component except electric part within actuators; and sustainability approach where more than 90% of parts of the façade product by mass can be disassembled and recycled.

An energy saving of 88% owing to the avoided use of artificial lighting is also achieved. It was found that the integrated PV modules on façade which covers 30% of the face within a façade segment was able to generate energy equivalent to 72% in comparison to lighting energy consumption by proposed office room and automation combine. Hence, the overall calculation shows +60% of gain in energy (in comparison to energy consumption by artificial lighting).

The applied methodology shows compatibility for developing several alternatives of façade design that fulfils visual comfort criteria with daylight's controlled distribution. However, the developed digital workflow can be made useful on a facade system for evaluating and increasing daylight performance efficiency concerning the same objective. Moreover, the proposed façade has shown promising results in both sky condition, with the availability of direct sunlight (Clear Sky) and with diffused light (Overcast). This indicates that the proposed façade works for a wide range of outside available luminance. Hence, it is assumed that the proposed façade can also work within any surrounding context unless the façade receives enough Luminance from outside. Yet, there is a need for research to prove this. Thereby, the developed digital workflow can be made useful for any input as location and context. The study summarised that a façade can control daylight's distribution to bring visual comfort indoors with the help of computational methods.

8.2 Reflection

The final result of this study as a dynamic façade scheme that deals with controlled daylight's distribution in indoor space to provide visual comfort has been developed through several steps that include literature, computation design, evaluation and façade's constructability and feasibility. Along the process, many challenges were faced where some considerations were made on a few challenges, and other few challenges require further investigation.

Literature

Starting from the literature study, where different aspects related to the topic of this research were studied. After understanding the aspects of visual comfort and while going through finding required standards, it was found that the available norms in NEN-EN 17037 (2018), which applies to Rotterdam, are based on an annual calculation for illuminance and for a constant/diffused daylight condition. Furthermore, no standards are provided to measure daylight in its uniform state or to evaluate contrast. Hence, the evaluation criteria was developed for this study by combining daylight standards from NEN-EN 13073 (2018) and BREEAM (2016); and few design guidelines provided by researchers. The developed visual comfort criteria for evaluation can be made useful in any further research or design to evaluate the performance of a façade system that deals with visual comfort and uniform distribution.

Going further, a comparison was made for a few simulation tools that support daylight simulation. Even though Honeybee plus was found to be the most suitable tool for this study, the tool is still under development phase for improvements; and hence, few restrictions were faced during the simulation workflow setup. For the simulation of DGP matric, use of Honeybee Legacy components was placed. A thorough investigation through the literature on daylight simulation methods showed that 3- and 5-phase method are more accurate for daylight calculations. However, this method was not taken further for this research due to many limitations of phase method like- it works only for annual calculation, it does not work with CIE sky (as in clear sky and overcast) separately, highly time-consuming. Furthermore, integrating the use of BSDF (Bidirectional Scattering Distribution Function) properties of the material for simulation can change the result and provide more accurate daylight results by taking account of scattered light into the calculation. On the contrary, BSDF can be used only on static geometry and shows limitation for simulating with dynamic geometry; in addition, it is time-consuming for running simulation for a number of solutions. Henceforth, the integration of BSDF for each static geometry and aptly applying the use of phase method can provide more realistic results by taking into account scattered and diffused light more accurately.

Computation Design

While performing daylight simulation, it was found that over-lit areas were observed on the working plane due to direct penetration of light through the periphery of the window opening because no shading was provided. In reality, the façades are continuous on a building envelope; considering the fact, an additional layer of shading elements corresponding to existing elements was added on the outer side of the periphery of the façade segment. This addition showed a much more realistic result. Furthermore, a deep floor plan is used with a narrow width for the simulation study. This decision was made the intention to study the effectiveness of façade in performance along with the depth. With this consideration, the wall reflectance values for side walls were not considered in simulation, but a generic material was used. However, a room with sidewalls can show much-enhanced results by adding reflectance property to walls while attempting simulation; and for an open plan, it might show lower results. Moreover, for the hours when incoming light is from SE and SW, a shadow is cast towards East and West side of the room respectively, and this phenomenon needs to be considered as criteria while selecting a geometry or parameters. The selection should be based on the idea to distribute light at such a dark side as well and bring a balance of light intensity. Although, the proposed geometry of this study claimed to be useful in above-mentioned situations using different variation of the module; the geometry did contribute to distributing light to the darker side; however, some minor difference during summers, and a noticeable difference during winters were observed based on intensity of light between east and west side of the room for the hour 10 and 16 respectively.

There is a vast difference in the results obtained from the simulation at low and high accuracy setting. All the optimisation were made with low accuracy setting, and obtained solution was simulated again with high accuracy to gather final results. It can be a possibility that a different design solution is obtained while attempting the optimisation with high accuracy setting; however, this can account for a very long simulation run-time.

Furthermore, for all three case during Winter-Overcast, the study uses separate materials in simulation setup with high reflective property on diffusing modules for daylight performance due to lower availability of light from outside, this change of property was made to validate the effectiveness of the proposed facade. However, in reality, the material sets should remain same on façade along the year; hence, a set of material with the right choice of optical properties that can withstand the performance for all different season along the year must be considered. Above all, each set of materials on modules with different optical properties that have been used in this study were considered based on assumption. This opens-up a scope for exploring material options based on their optical property through optimisation.

The computational workflow applied in this study was divided into a two-step optimisation process where the first step includes optimisation using one parameter as rotation, and the second step would be to use module type and material set as parameters. However, this study could cover only one step of optimisation using the parameter as rotation; and one evaluation criteria as an objective-based on priority, the remaining four criteria were used for performance evaluation process from obtained final results. This helped in reducing the complexity into the optimisation process and allowed to finish all simulation within the timeframe. The second step of optimisation where the change of Module type is parameter was replaced with manual adjustments; hence, all the variation of modules seen on final configuration were manually changed keeping rotational angles obtained from the first optimisation. The adjustments were based on the in-depth knowledge gained from literature, geometry exploration and

made simulation on daylight behaviour. Although the results obtained fulfils all the criteria, all the configuration can be said to have an optimal rotation, but the schedule of modules are not optimal. Hence, it is believed that there is a big scope of improving the result further by attempting a second step optimisation process for each instance considering module type as a parameter. Nevertheless, the coherent approach would be to go through an optimisation process by using parameters in two-step optimisation and taking all five or few criteria as per the requirement as an objective function.

Façade Scheme

Going through the process of detailing the façade, a few changes were made to integrate the facade with the building's structure. Few factors which are believed to affect the overall performance in comparison to obtained results are:

I. All daylight analysis were made with a proposed room, without taking consideration of the surrounding context or floor level. The addition of context and change in floor level can affect daylight levels.

II. All the analysis was made without considering the structural elements, which were added during the detailing period.

III. All the analysis of façade was made keeping the modules very next to the window opening with a minimum gap. Whereas in the final detailed scheme, the modules are shifted with an offset of 0.70m. A rough performance analysis check was made on few finalised solutions by shifting façade to 0.70m away from the window; the performance reduction was found to be in-between 1-3% in the daylit area.

IV. The considered size of the module for the optimisation process used was 0.80x0.42X0.03m as width, depth and thickness respectively; during detailing process, this module was reduced by 5cms from both sides and has changed to 0.70x0.42x0.06m.

V. Furthermore, the addition of PV modules on the row above reflecting modules are prone to cast a shadow by blocking a portion of direct light needed to be reflected inside from redirecting modules below PV modules. For such case, priority needs to be considered for reflecting modules for performing towards providing visual comfort, and the rotational angle of PV modules needs to be set differently to avoid casting a shadow.

The material sheets used on modules in the proposed scheme are anodised aluminium; however, any material that can fulfil the optical properties needed for performance can be used. Use of colour sheet or any other metal sheet with similar optical properties can be used concerning aesthetic feature of the building. Furthermore, the scope of this study solely focusses on visual comfort criteria and daylighting; the in-depth investigation of PV modules is not included. The study has minor calculation on energy to check the feasibility. However, a closer look at energy-related approach can be taken further for analysis.

The automation provided is using available technology in the market, yet, few components like gear box needs customisation regarding the fitting of a rotary actuator with pogo pin and its power supply unit. Furthermore, for the noise that will be generated during the transformation process of façade modules and due to wind; it is assumed that the short time taken by façade in the transformation (which is 20sec.) and use of glazing window with good acoustic properties

on the building; the noise will not be a major issue. Yet, an analysis on acoustics is required to quantify this aspect. Moreover, the module is developed with folding mechanism and to check its feasibility with the weight of connected elements, an approach of making a physical prototype of one module using an actuator, and similar detail is recommended.

It was concluded that the automation part is an expensive process. But considering the performance aspects, the façade accounts for 88% of cost-saving by neglecting the use of artificial lighting. It can be said that 88% of cost spending behind artificial lighting is being saved. Furthermore, the installation of the automation component is a one-time cost (for 10-years as per its life expectancy), whereas the cost-saving from artificial lighting is every year. Looking at the comparison, it can be assumed that the use of automation is yet a cheaper option in front of total cost spending on artificial lighting.

Furthermore, the complexity within automation can be reduced in the following way:

I. From the obtained finalised solutions, it was found that the redirecting modules doesn't require any folding/unfolding configuration except one case at SU-13-CS. Hence, a first step towards reducing complexity would be by removing the folding feature from redirecting modules and just keeping rotational motion; performance is not compromised here. Moreover, this will also reduce the complexity into construction process that is required to make folding mechanism within the module, and the use of linear actuator can be neglected, this can result in some cost-saving, and reduced weight of the system. However, the folding feature on the diffusing panel is critical to be removed, which can cause a high reduction in uniformity ratio of light intensity along with the depth.

II. Moreover, the rotation given in this project for modules within the same row is similar. Hence, some modules within the same row can be merged together with a common mechanism to provide rotation. This can reduce the use of few rotary actuators within the whole scheme.

It was also found that for a scale of a high-rise, the small scale of the designed module can increase some complexity in terms of maintenance and construction cost. With light weight material like aluminium, the width of the module can be taken up to 1.5m, which is almost double to the width of designed module 0.70m. Although, the proportion of the depth is the critical factor to be considered. The increase of module size can be in proportion to designed module in terms of width vs its depth; or the depth and the height can be altered by choosing different sizes of triangles within a module. The size alteration can be developed from the understanding of the geometry- tetragonal disphenoid and its forming principle. The configuration with selected bigger size of module can be optimised for visual comfort using proposed workflow of this research. A module with bigger scale that matches with the requirement of visual comfort criteria and construction can be used for the façade with similar construction details.

8.3 Limitation and Future Scope

Along the process of this study, several limitations were found at different steps which requires further investigation:

I. As the study was able to perform only one step of optimisation. The immediate scope behind this study will be to perform second step of optimisation.

II. While achieving specific criteria for visual comfort, the over-lit areas were found on side walls for instances at Winter-Clear sky. This was mainly due to low altitudes (2-14°). A scope arises here to find a solution on proposed façade to make it work with low altitude sun.

III. While folding and unfolding of geometry, it leaves a vertical gap when module type A and A are side by side. This can cause glare spots inside the room unless it gets shading from surrounding modules. Hence, there is a scope to further investigate this issue for finding a solution on facade that can avoid such gaps.

IV. The integration of PV modules on façade segment showed a feasible and profitable approach. However, the part of PV modules was out of the scope of this study; hence, much exploration was not made. There lies a scope to study the integration of PV modules with optimised rotation to gain maximum energy without disturbing the performance of other modules in delivering visual comfort.

V. From final configurations of façade, some configurations were found to block the view to outside. However, the criteria of view to outside was not considered in this study, a scope of optimising façade for visual comfort coping with view to outside can be made.

VI. This study uses CIE sky (clear sky and overcast sky), however, a more realistic approach using climate-based sky should be made. Furthermore, the instances cover extremely diversed cases and the optimisation has been made only for two days- summer solstice and winter solstice. Hence, an optimisation run for other instances like spring and fall need to be made to understand behaviour of façade for intermediate daylight conditions.

VII. The scope also lies to develop same façade for East and West orientation of building and for curved buildings.

Further Research Possibilities
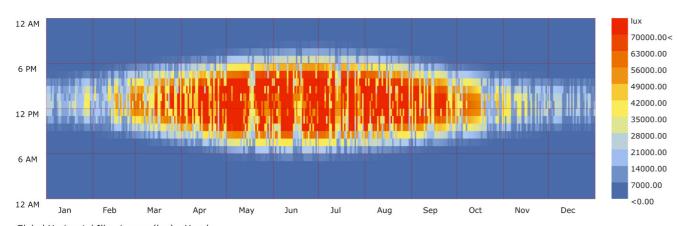
All the below points provide a scope for research using same facade and/or with a scope of expanding the digital workflow. All points can be attempted as an individual topic or in combination of some.

I. **Rooms at different level** of a high rise. As the amount of daylight illuminance could be different for different level.

II. **Rooms facing in different orientation.** Comparative analysis between S/W/E/N and/or SE, SW, NE, NW.

III. **Different Location/ Different climate.** Comparative assessment for high rise buildings in different locations and/or different climate zones.

IV. **With surrounding Context.** Comparative assessment between high, mid and low dense context around a high rise.

V. **Different Program/function** with varied illuminance requirement.

VI. **Different typology.** Other than high rises like residential, commercial etc.

VII. **Thermal Insulation for indoor comfort.** With the most optimized façade solution.

VIII. **Material Variations** for the façade elements.

IX. **Optimizing Interior Ceiling.** Shape/slope/material

X. **Module/Panel size variation.**

XI. **Different design/geometry/Patterns.** Coping with same concept, method and work-flow.

XII. **For curved faced façades.**

XIII. **For outdoor glare check** caused by Façade and its improvement.

XIV. **Optimisation for Better view to outside** using same facade system.

XV. **Make a Tool.** Make computational method smart enough,
- Code it in python for generative solutions.
- Reduce runtime for optimisation.
- Artificial Intelligence (AI), Machine learning (ML), Deep Learning (DL). Can adapt to various parameters like regulations, climate etc.
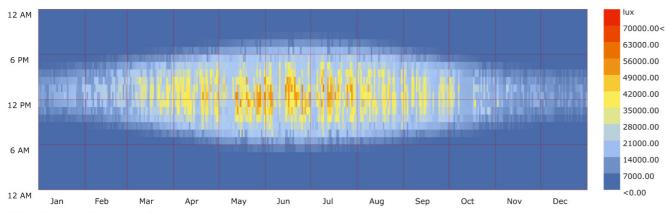
9.0
Appendix

A1.Annual Illuminance in Rotterdam

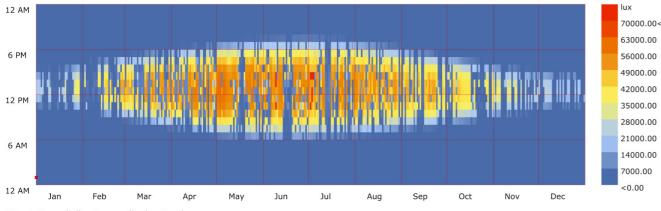## Global Horizontal Illuminance

Global Horizontal Illuminance (lux) - Hourly
Rotterdam The Hague AP_ZH_NLD
1 JAN 1:00 - 31 DEC 24:00

Diffuse Horizontal Illuminance

Diffuse Horizontal Illuminance (lux) - Hourly
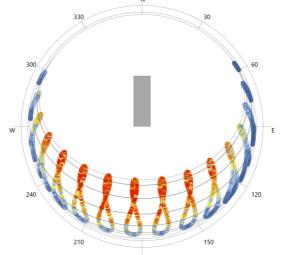Rotterdam The Hague AP_ZH_NLD
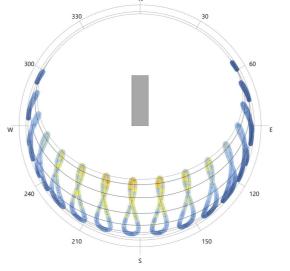1 JAN 1:00 - 31 DEC 24:00

Direct Horizontal Illuminance

Direct Normal Illuminance (lux) - Hourly
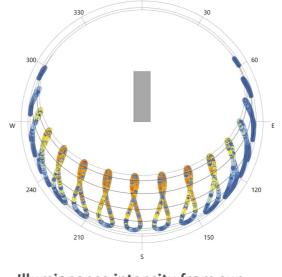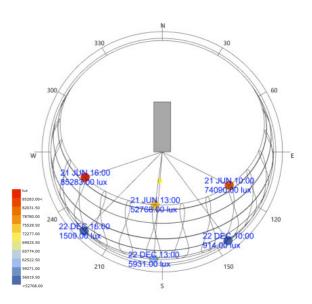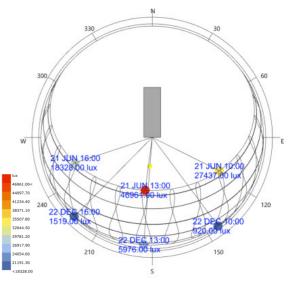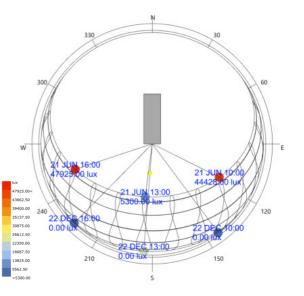Rotterdam The Hague AP_ZH_NLD
1 JAN 1:00 - 31 DEC 24:00

Annual Illuminance Chart

Global Horizontal Illuminance

Diffuse Horizontal Illuminance

Direct Horizontal Illuminance

Illumianance intensity from sun   **Illumianance for selected Instances**
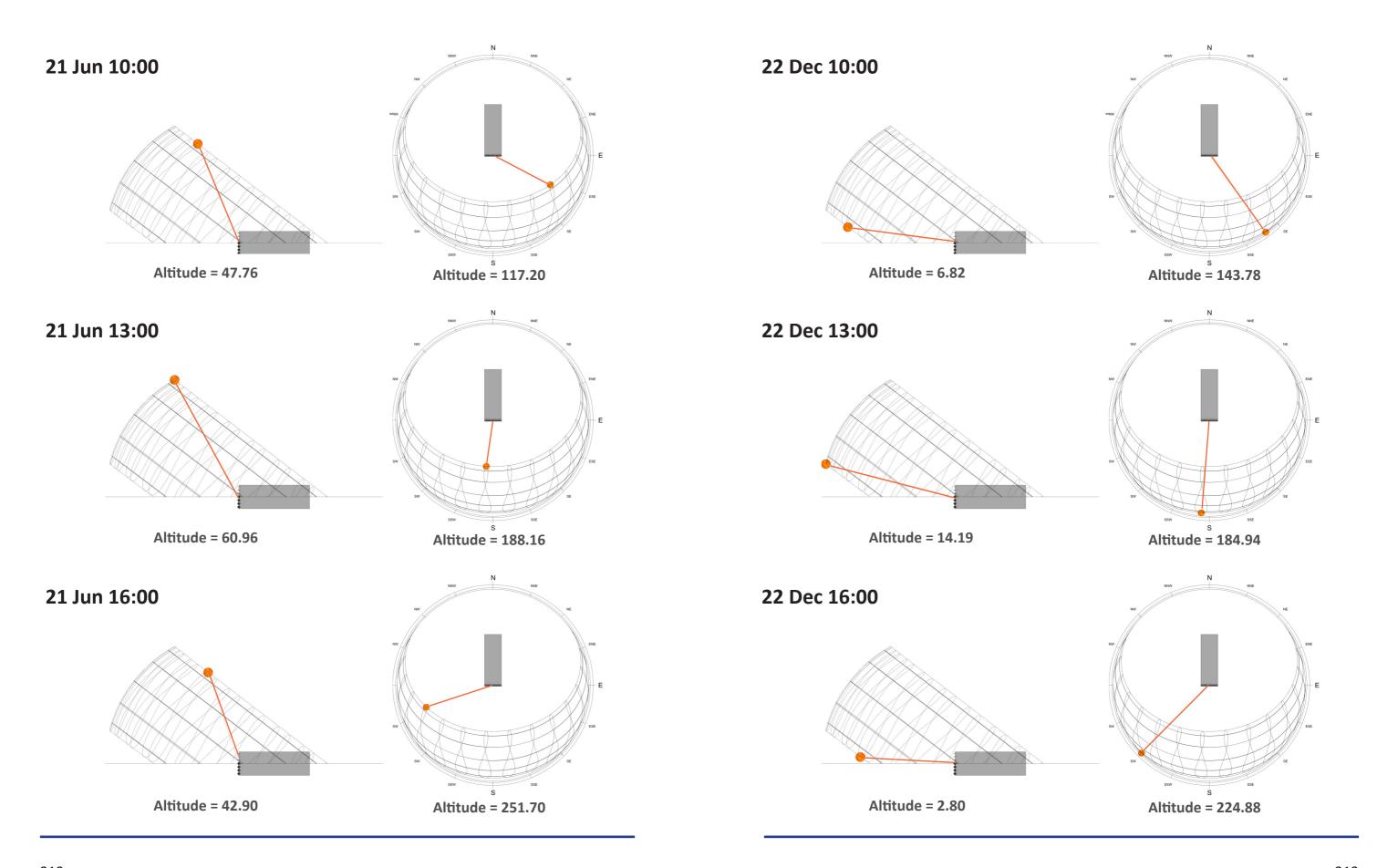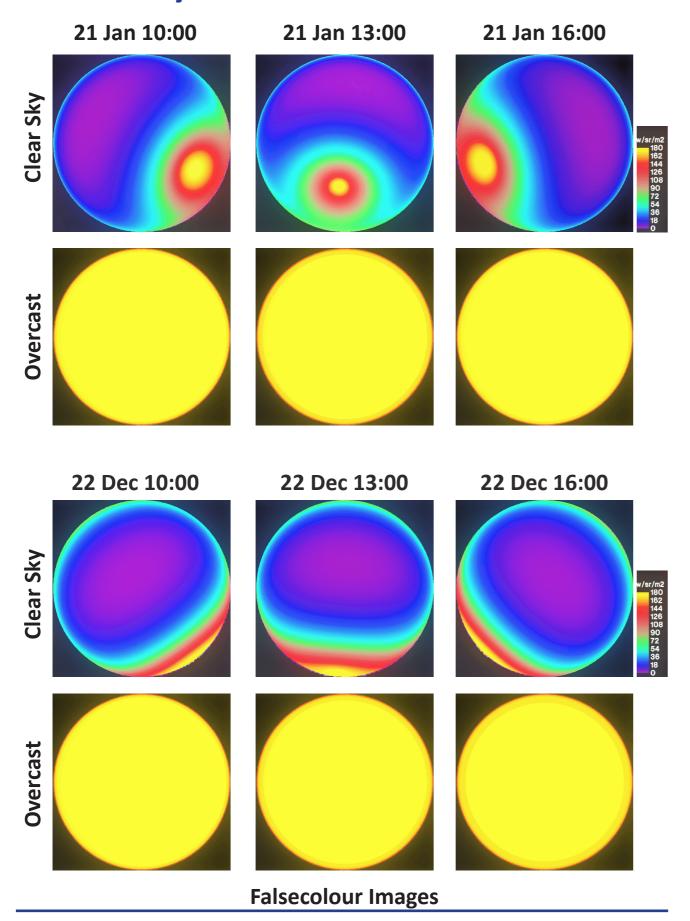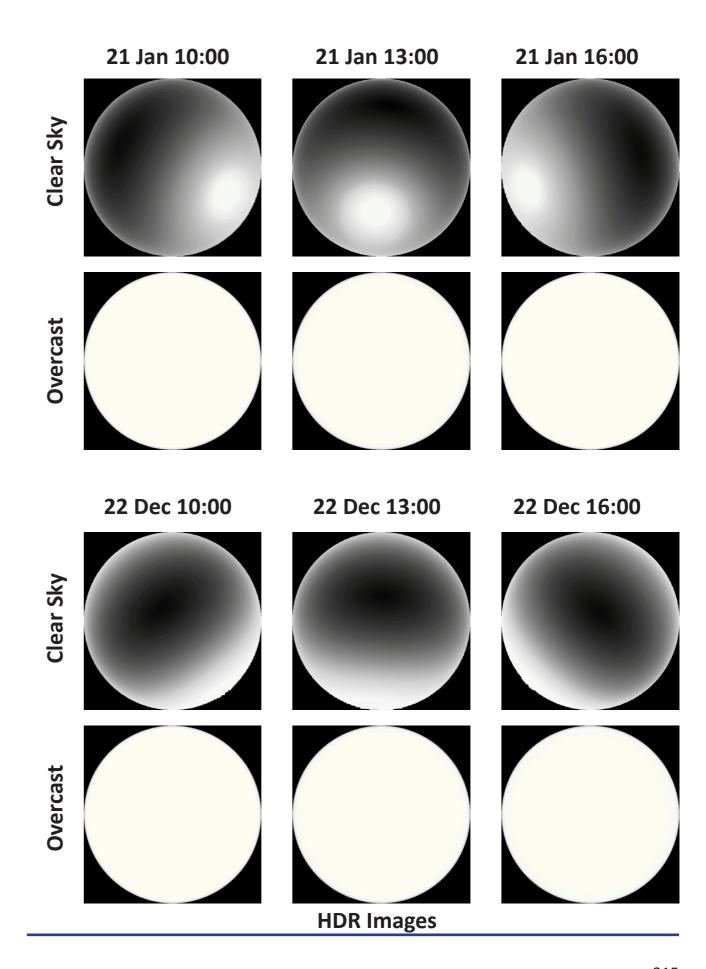
A2. Altitudes and Azimuths of Selected Instances

21 Jun 10:00

Altitude = 47.76

Altitude = 117.20

21 Jun 13:00

Altitude = 60.96

Altitude = 188.16

21 Jun 16:00

Altitude = 42.90

Altitude = 251.70

22 Dec 10:00

Altitude = 6.82

Altitude = 143.78

22 Dec 13:00

Altitude = 14.19

Altitude = 184.94

22 Dec 16:00

Altitude = 2.80

Altitude = 224.88

A3.CIE Sky models

21 Jan 10:00 **21 Jan 13:00** **21 Jan 16:00**

Clear Sky

Overcast

22 Dec 10:00 **22 Dec 13:00** **22 Dec 16:00**

Clear Sky

Overcast

Falsecolour Images

21 Jan 10:00 **21 Jan 13:00** **21 Jan 16:00**

Clear Sky

Overcast

22 Dec 10:00 **22 Dec 13:00** **22 Dec 16:00**

Clear Sky

Overcast

HDR Images

A4.Developed Script in Grasshopper
Geometry

01. Module Setup_Fold/Unfold

Fold/Unfold Control
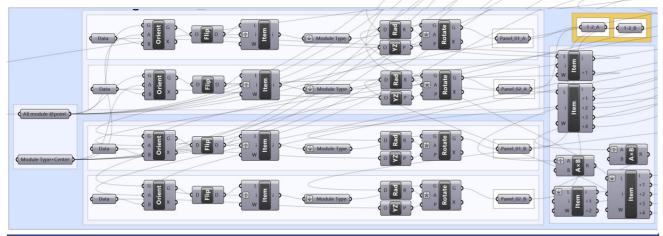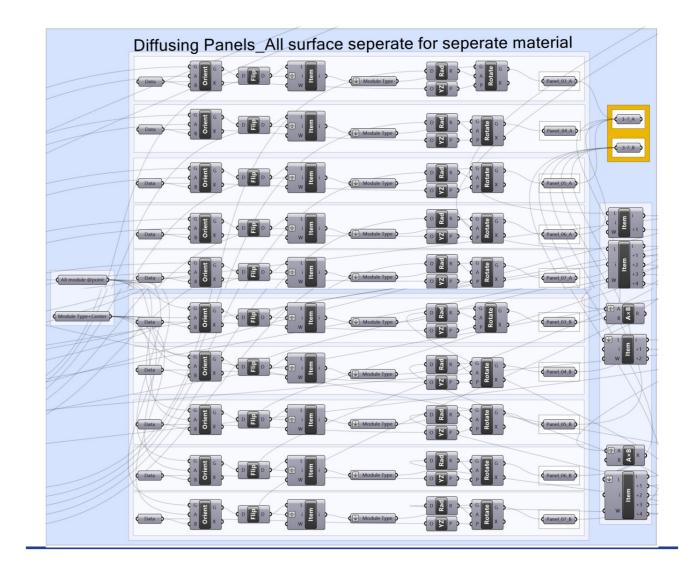
02. Facade Configuration Setup

Rows/Column & Scale/Align
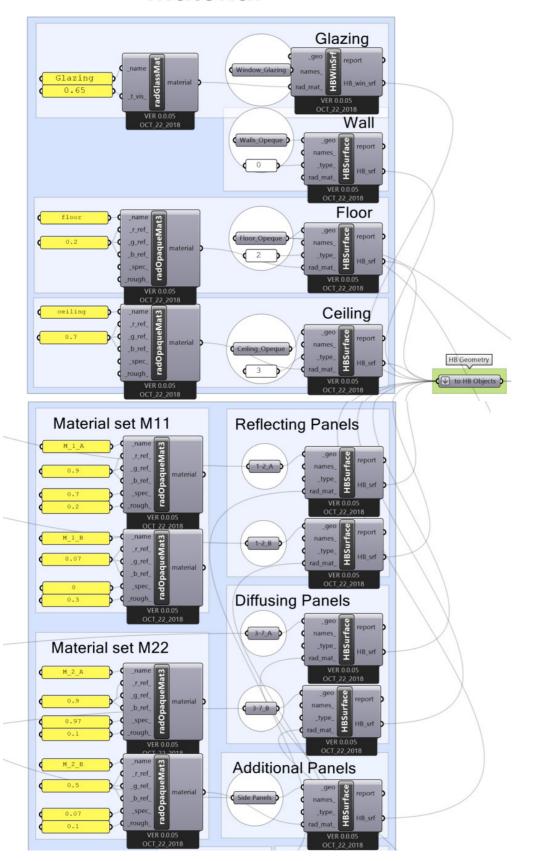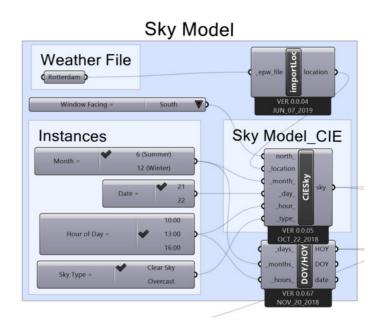
03. Seperating Modules for Parameters & surface to apply material later

Diffusing Panels_All surface seperate for seperate material
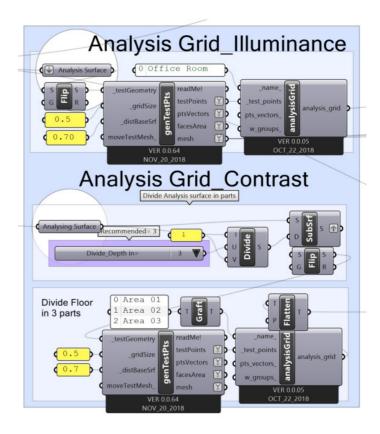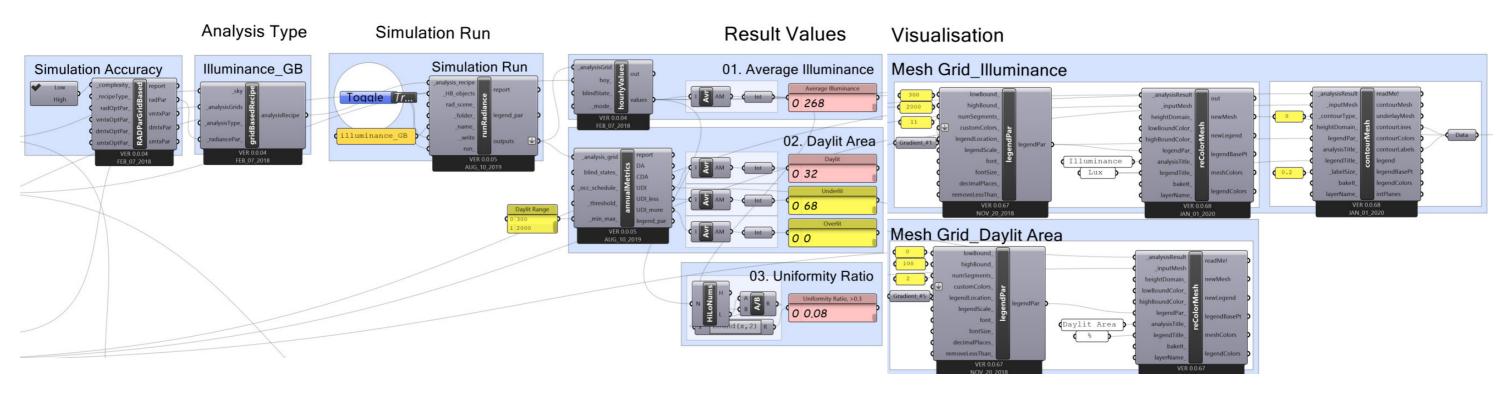
Material
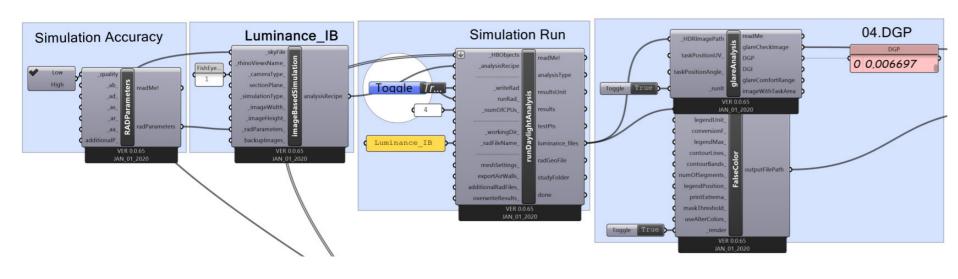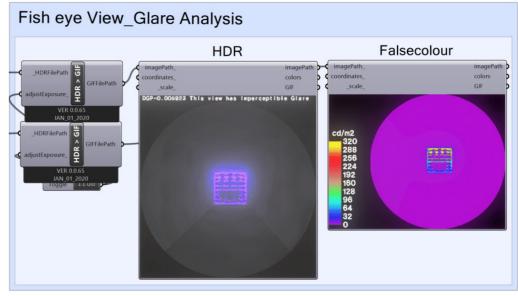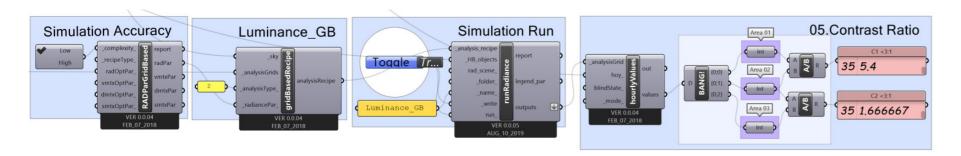
Daylight Simulation

Optimisation Step-01

Objectives

Maximise Daylit Area (%)

Maximise where lux is <300 (Lux)

Minimise where lux is >2000 (Lux)

Parameters

01. Rotation

Redirecting Modules

Diffusing Modules

Optimisation   Visualisation
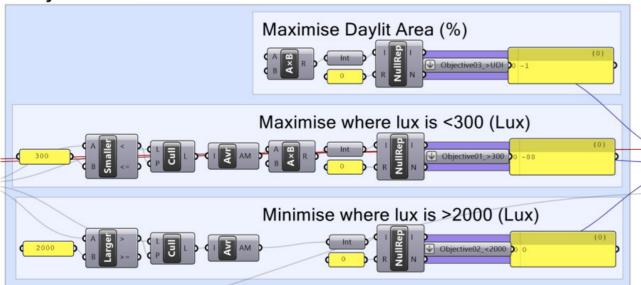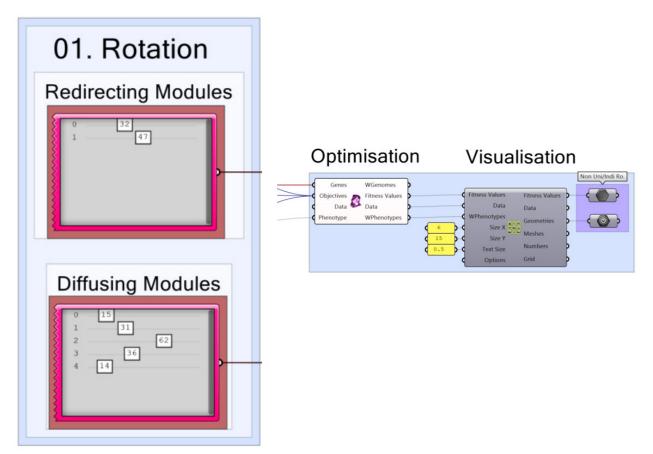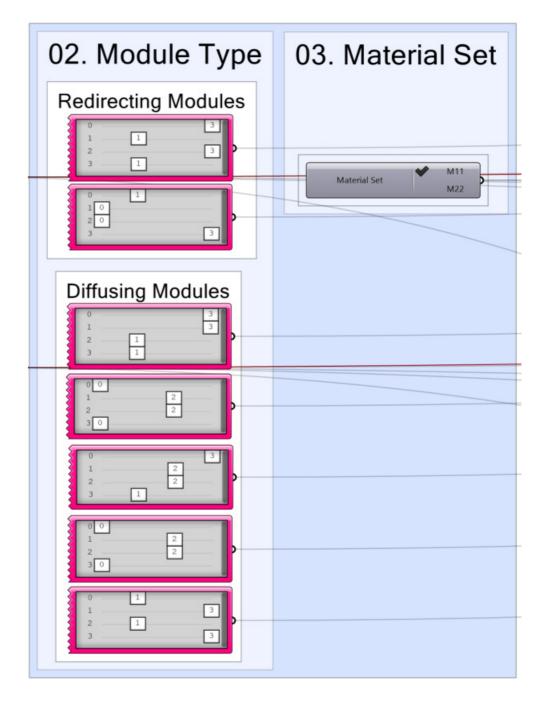
Manual Adjustment - Parameters

02. Module Type

Redirecting Modules

Diffusing Modules

03. Material Set

Material Set   M11   M22
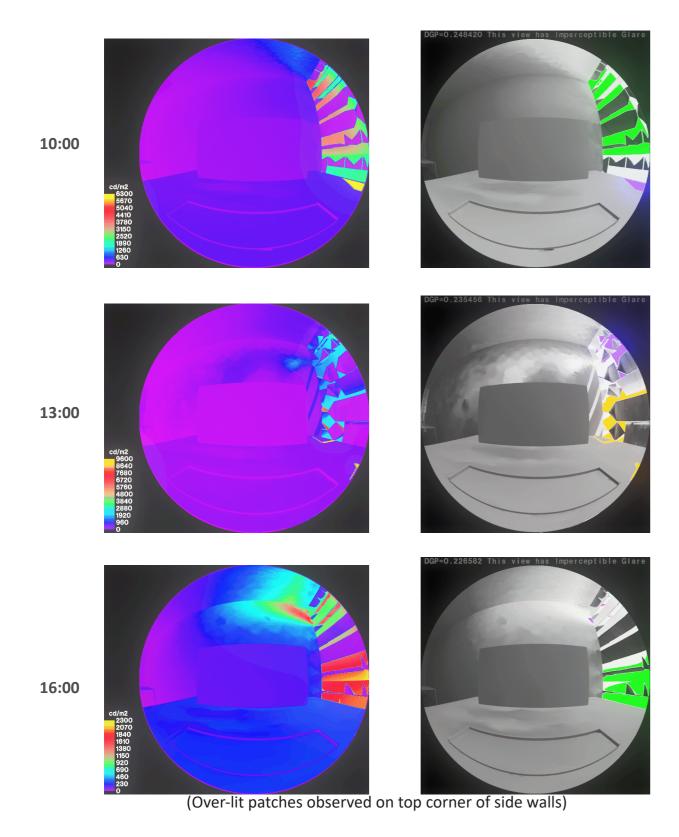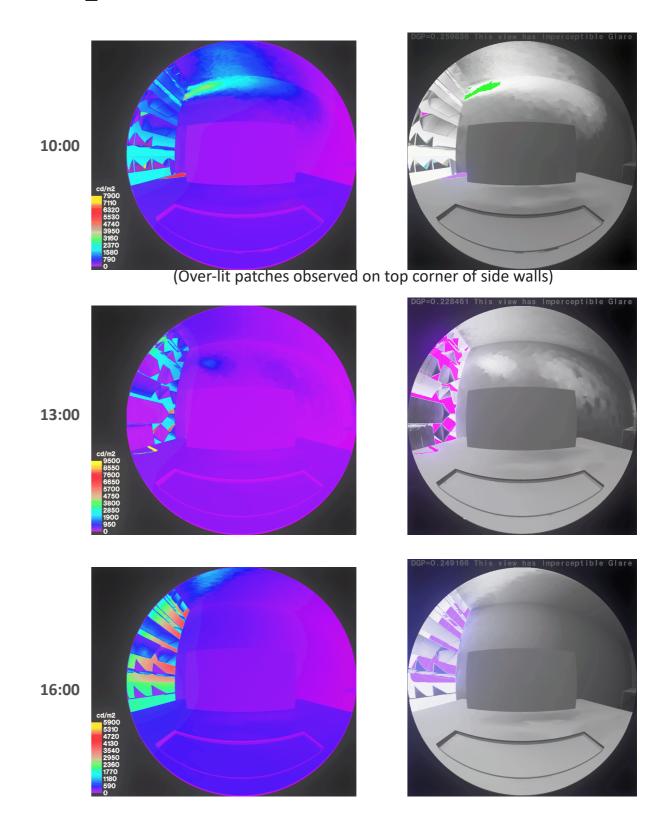
A5.Glare Analysis _ Visualisation

SU - CS _ O11
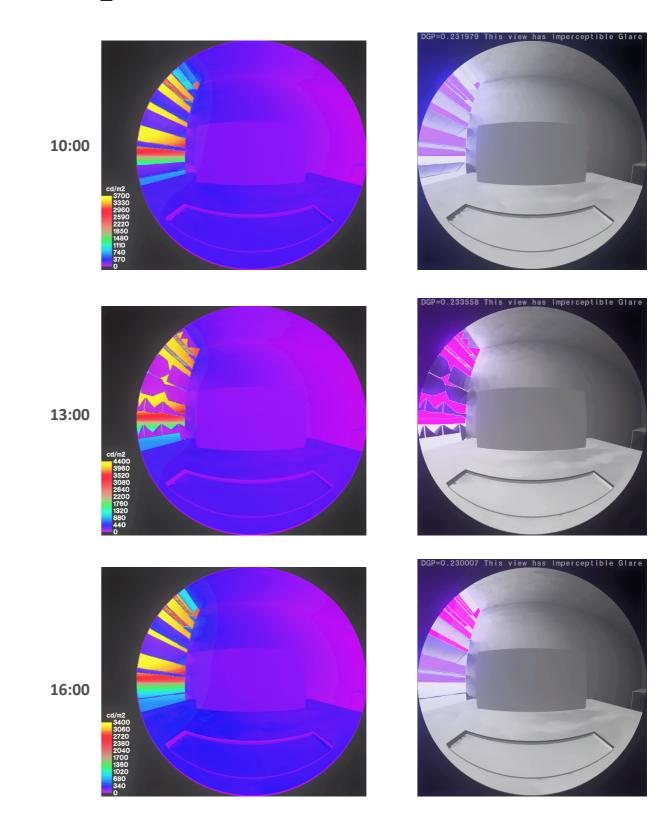
10:00

13:00

16:00

(Over-lit patches observed on top corner of side walls)

NOTE: All simulations made are with 'High' accuracy settings

SU - CS _ O12

10:00

(Over-lit patches observed on top corner of side walls)

13:00

16:00

NOTE: All simulations made are with 'High' accuracy settings

SU - OC _ O11
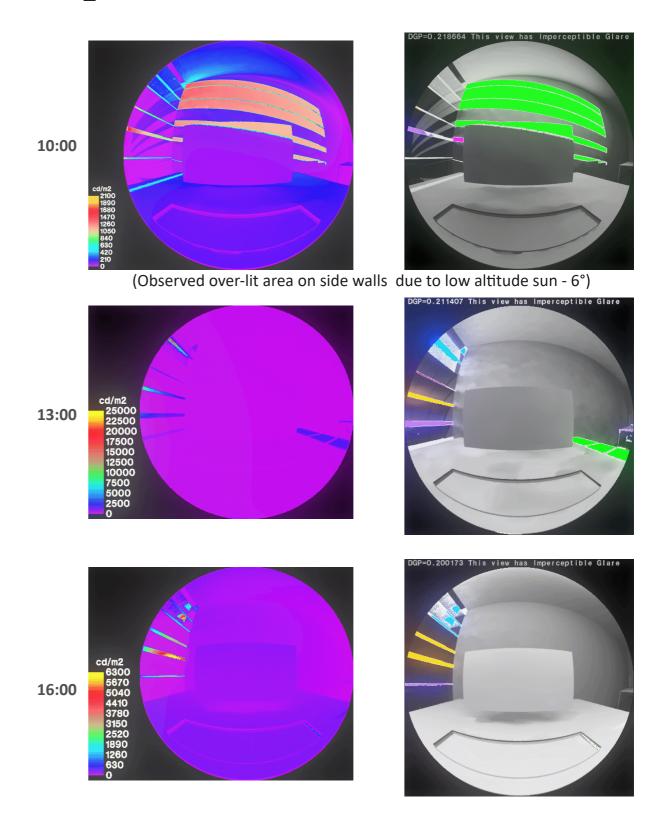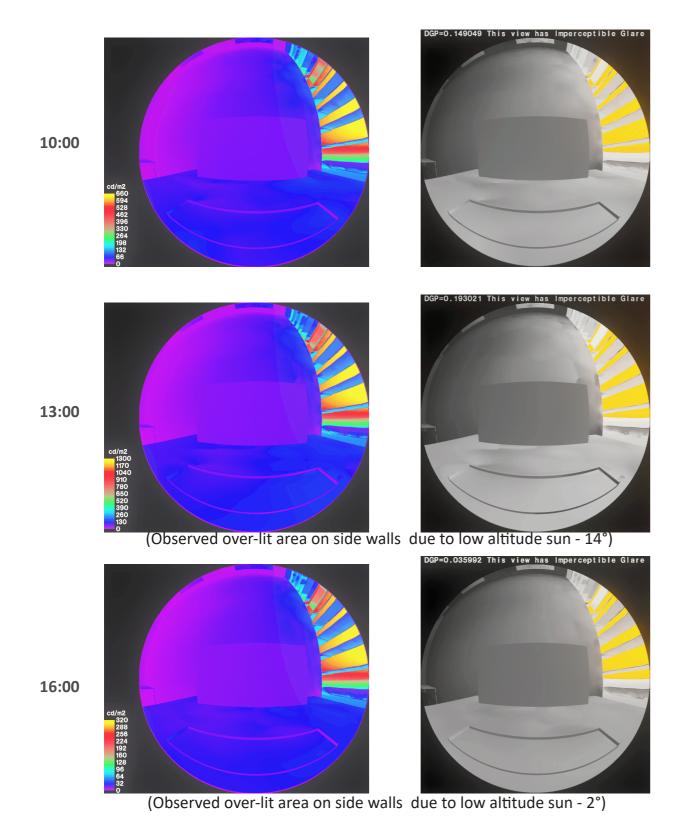
10:00

13:00

16:00

SU - OC _ O12

10:00

13:00

16:00

WI - CS _ O11

10:00

13:00

(Observed over-lit area on side walls due to low altitude sun - 14°)

16:00

(Observed over-lit area on side walls due to low altitude sun - 2°)

NOTE: All simulations made are with High accuracy settings

WI - CS _ O12

10:00

(Observed over-lit area on side walls due to low altitude sun - 6°)

13:00

16:00

NOTE: All simulations made are with High accuracy settings

WI - OC _ O11

10:00

13:00

(Observed over-lit area on side walls due to low altitude sun - 14°)

16:00

(Observed over-lit area on side walls due to low altitude sun - 2°)

NOTE: All simulations made are with High accuracy settings

WI - OC _ O12

10:00

(Observed over-lit area on side walls due to low altitude sun - 6°)

13:00

16:00
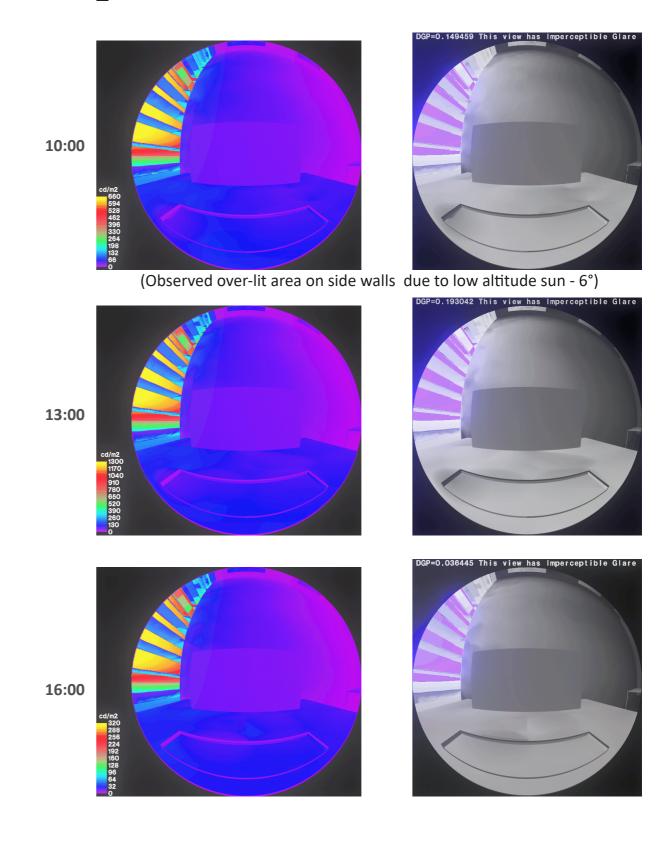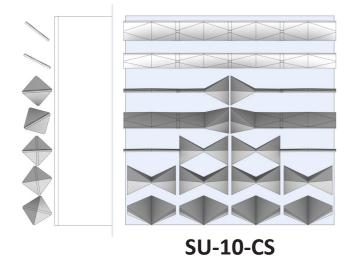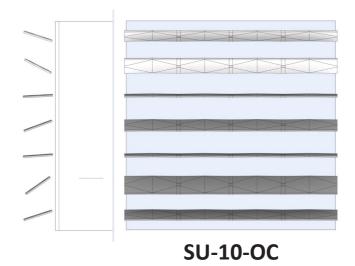
NOTE: All simulations made are with High accuracy settings
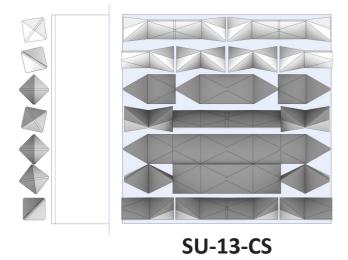
A6.Schedule of Configuration for Summers
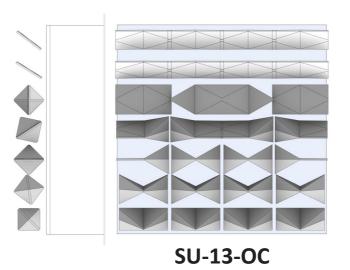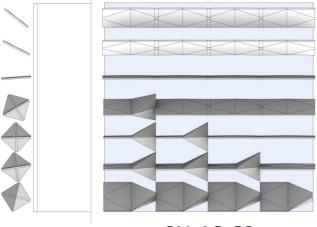
SU-10-CS

D	D	D	D
D	D	D	D
D	C	B	D
D	C	B	D
D	A	A	D
A	A	A	A
A'	A'	A'	A'

SU-10-OC

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

SU-13-CS

B	C	B	C
C	A	A	B
B'	B'	C'	C'
A	D	D	A
B'	D'	D'	C'
A'	D'	D'	A'
C	B	C	B

SU-13-OC

D	D	D	D
D	D	D	D
D'	B'	C'	D'
C	B	C	B
C	A	A	B
A	A	A	A
A	A	A	A

SU-16-CS

D	D	D	D
D	D	D	D
D	D	D	D
C	D	D	D
C	C	D	D
C	C	C	D
C	C	C	C
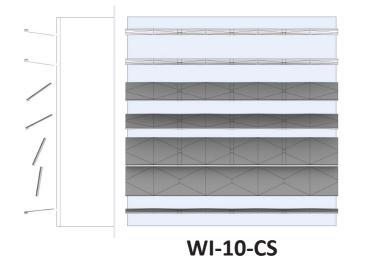
SU-16-OC

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
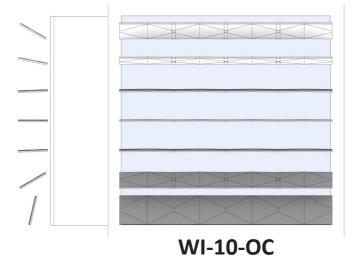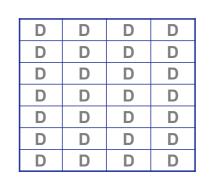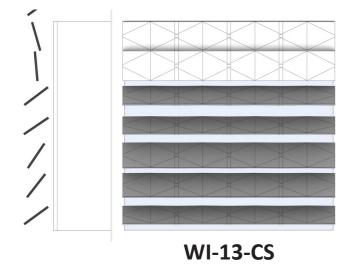
A6.Schedule of Configuration for Winters

WI-10-CS

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

WI-10-OC

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

WI-13-CS

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

WI-13-OC
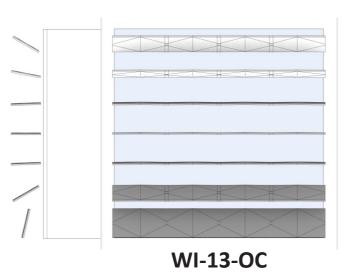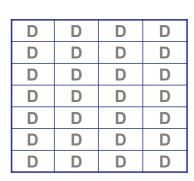
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

WI-16-CS

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

WI-16-OC

D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D
D	D	D	D

View to outside - with finalised configurations

SU-10-CS

SU-10-OC

SU-13-CS

SU-13-OC

SU-16-CS

SU-16-OC

* The view does not represent the daylight quality, as the actual daylight quality can be obtained only through simulation renders.

* The view does not represent the daylight quality, as the actual daylight quality can be obtained only through simulation renders.

View to outside - with finalised configurations

WI-10-CS

WI-10-OC

WI-13-CS

WI-13-OC

WI-16-CS

WI-16-OC

* The view does not represent the daylight quality, as the actual daylight quality can be obtained only through simulation renders.
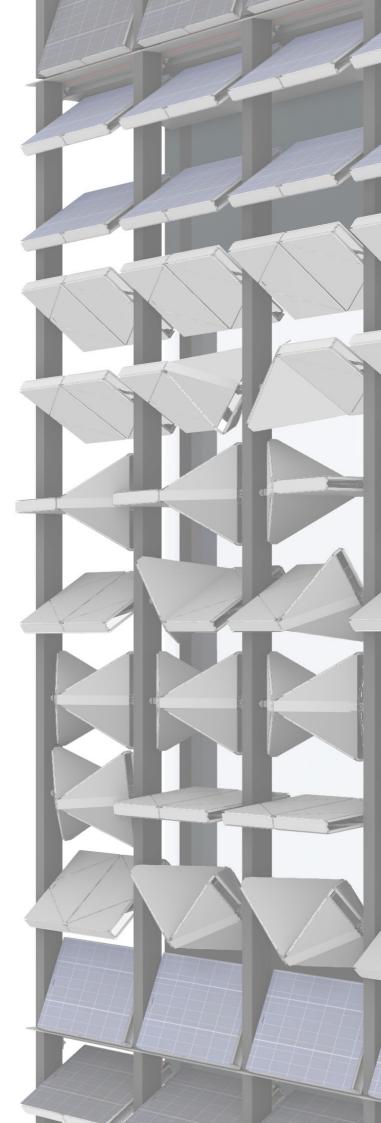
* The view does not represent the daylight quality, as the actual daylight quality can be obtained only through simulation renders.
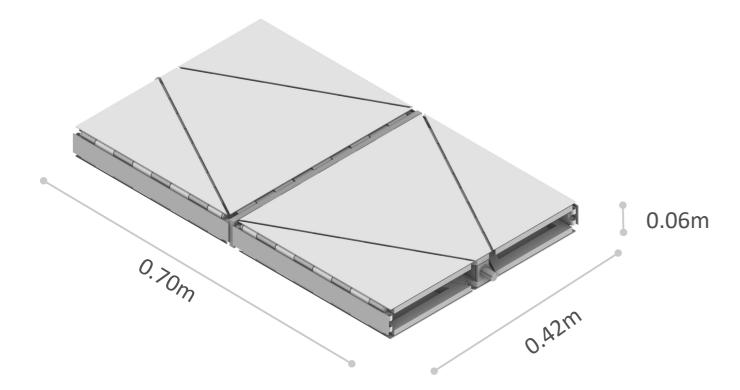
A7.Manual for Facade Module
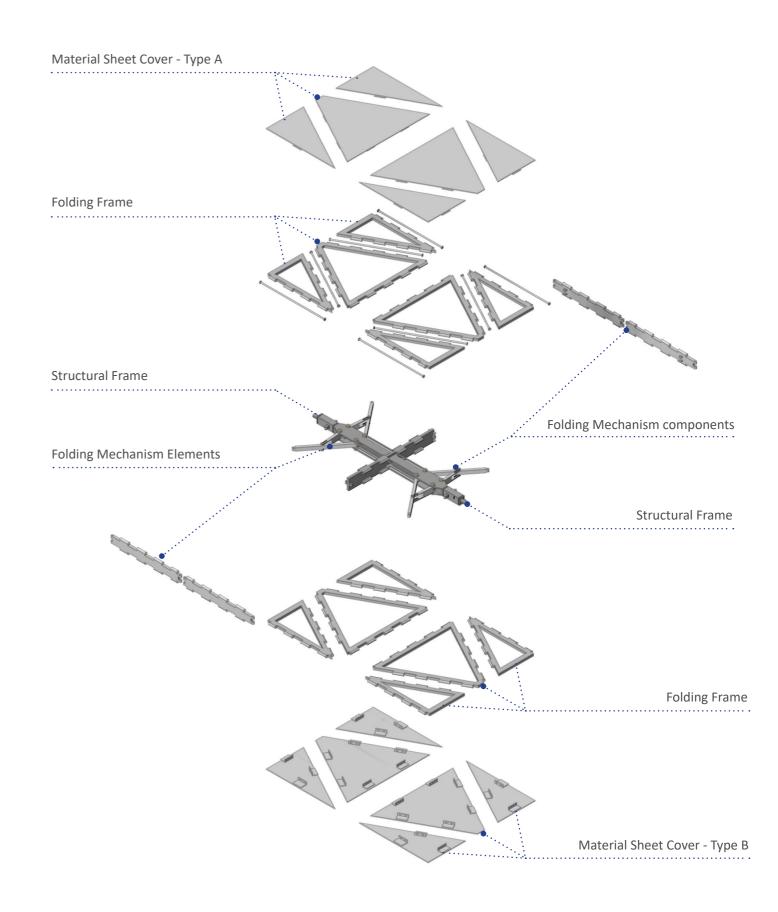
FACA-◁▷-LIT

**Assembly instruction
Manual for
FACADE MODULE**

Akash Changlani I 4813715
TU Delft

A Module

0.70m

0.42m

0.06m

Layers

Material Sheet Cover - Type A

Folding Frame

Structural Frame

Folding Mechanism Elements

Folding Mechanism components

Structural Frame

Folding Frame

Material Sheet Cover - Type B

Components

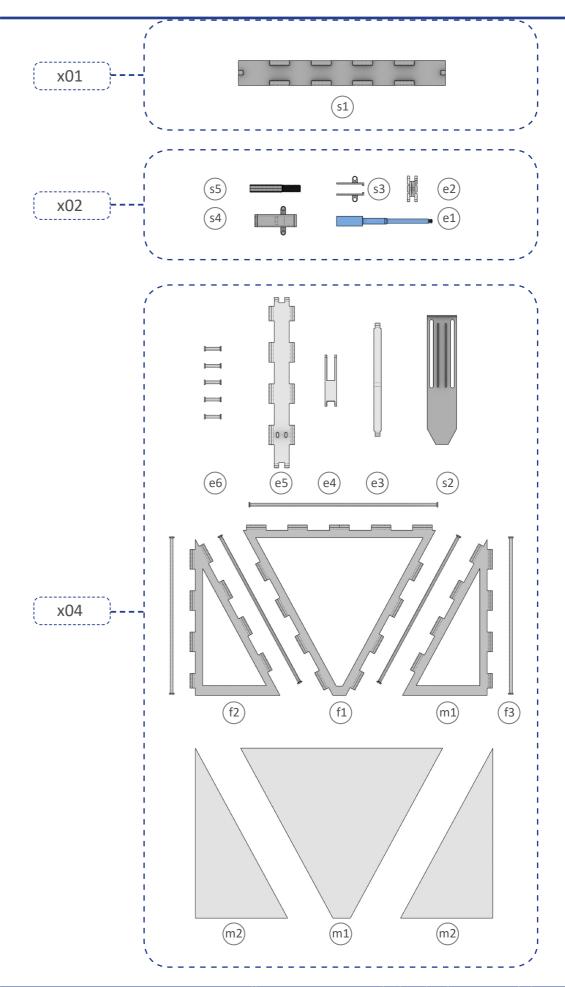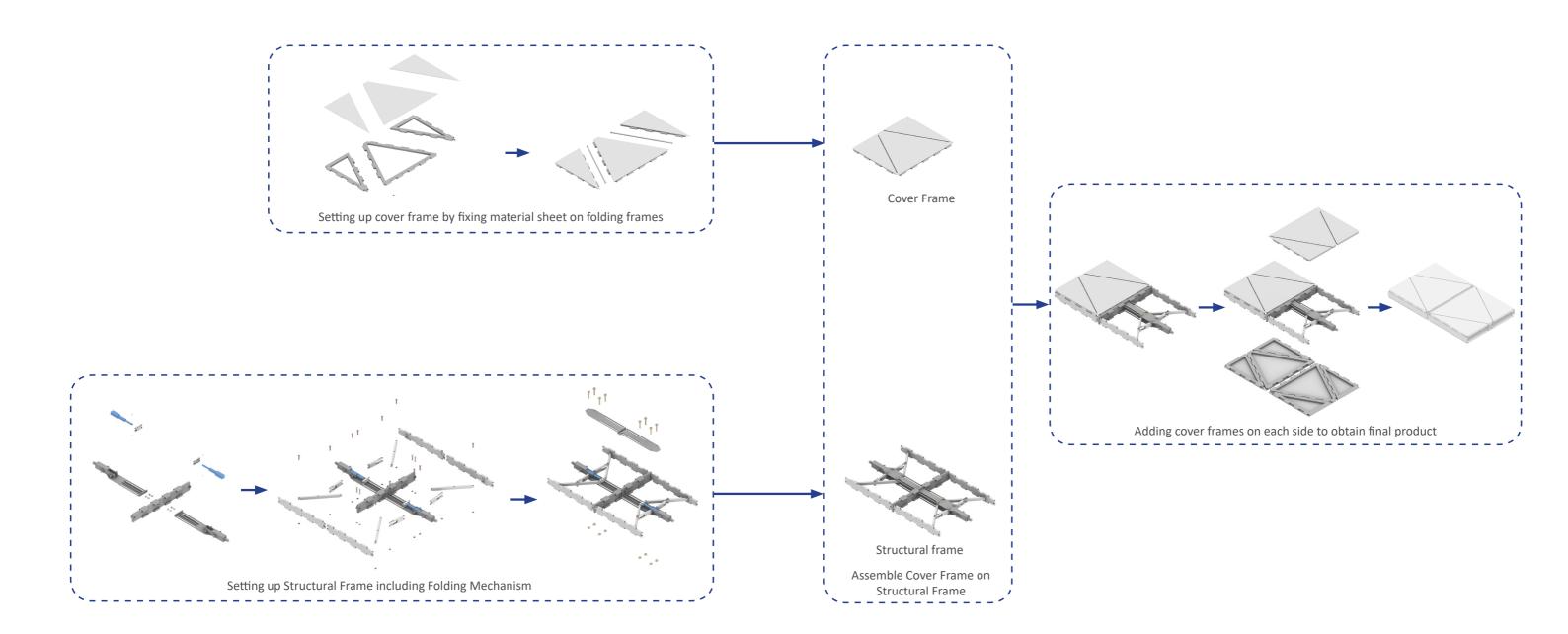| Element	Code	Components	Quantity
Material Sheets	m1	Trepezoid	4
	m2	Triangles	4 (x2)
Folding Frame	f1	Trepezoid	4
	f2	Triangles	8
	f3	Hinge Rods	20
Folding Mechanism Component	e1	Actuator	2
	e2	Sliding Connector	2
	e3	Sliding Bar	4
	e4	Inner bar	4
	e5	Outer Bar	4
	e6	Hinge Rods	20
Structural Frame	s1	Primary Element	1
	s2	Sliding Track Cover	4
	s3	Actuator Cover Plates	2
	s4	Bolt Box	2
	s5	Bolt	2

Table 7.1 Components of Module and quantity

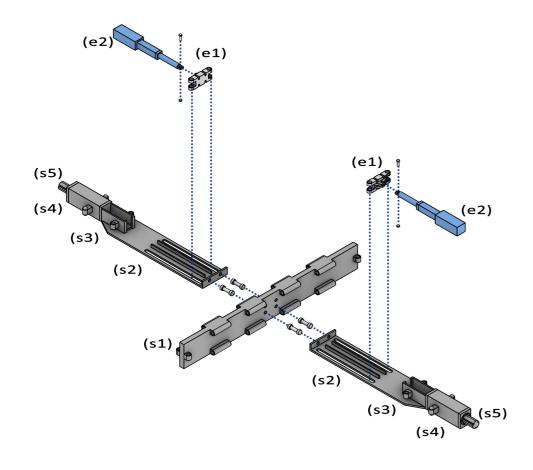*Figure.7.10 All components needed to built one module*

Assembly Sequence

Setting up cover frame by fixing material sheet on folding frames

Cover Frame

Adding cover frames on each side to obtain final product

Setting up Structural Frame including Folding Mechanism

Structural frame

Assemble Cover Frame on Structural Frame

m1	Material Sheet-Trepezoid		4
m2	Material Sheet-Triangle		8
f1	Folding Frame-Trepezoid		4
f2	Folding Frame-Triangle		8
f3	Folding Frame-Hinge Rods		10
			10
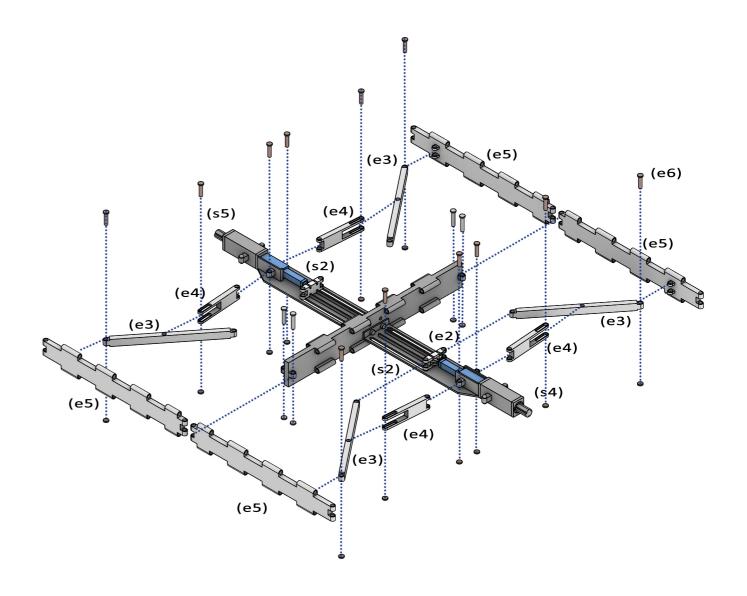
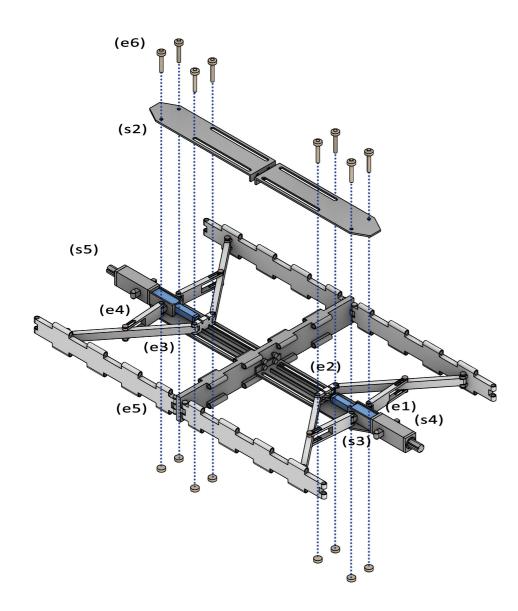|			
e1	Folding Mechanism-Actuator		2
e2	Folding Mechanism-Sliding Connector		2
e3	Folding Mechanism-Sliding Bar		4
e4	Folding Mechanism-Inner Bar		4
e5	Folding Mechanism-Outer Bar		4
s1	Folding Frame-Triangle		1
s2, s3, s4, s5	Sliding Track + Cover plate + Bolt box + Bolt		2

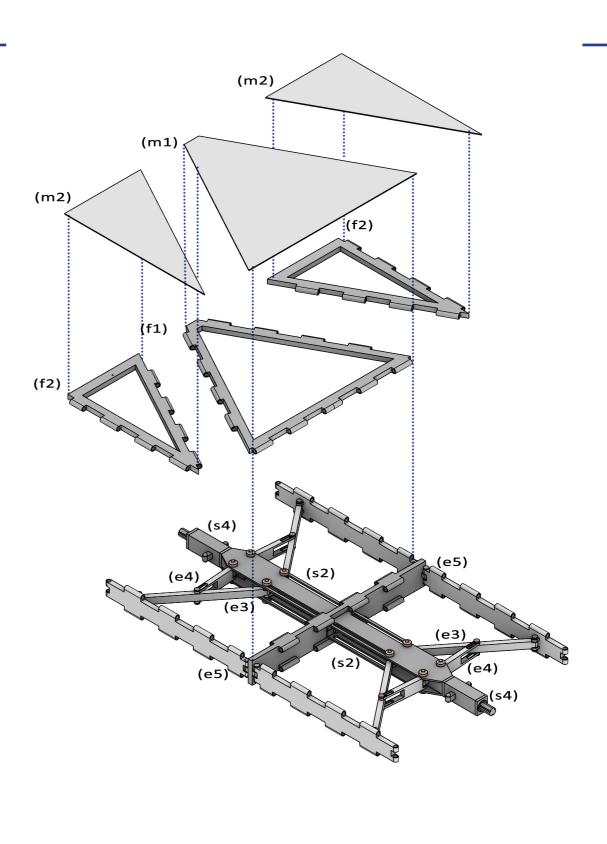# Assembly Sequence - In steps

(i)
Preparing structural frame
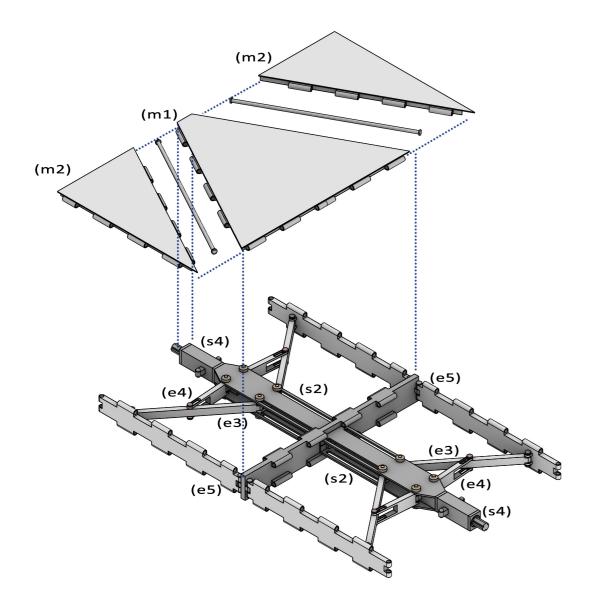
(ii)
Fixing Folding mechanism components within structural frame
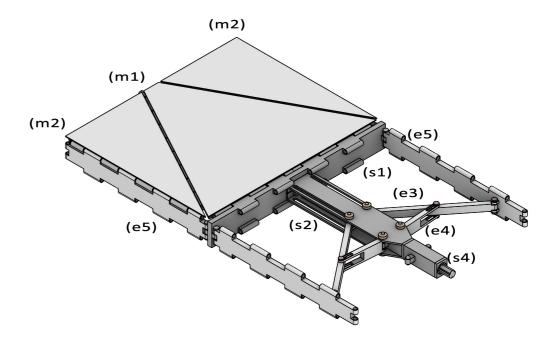
(iii)
Fixing of sliding cover plate n structural frame
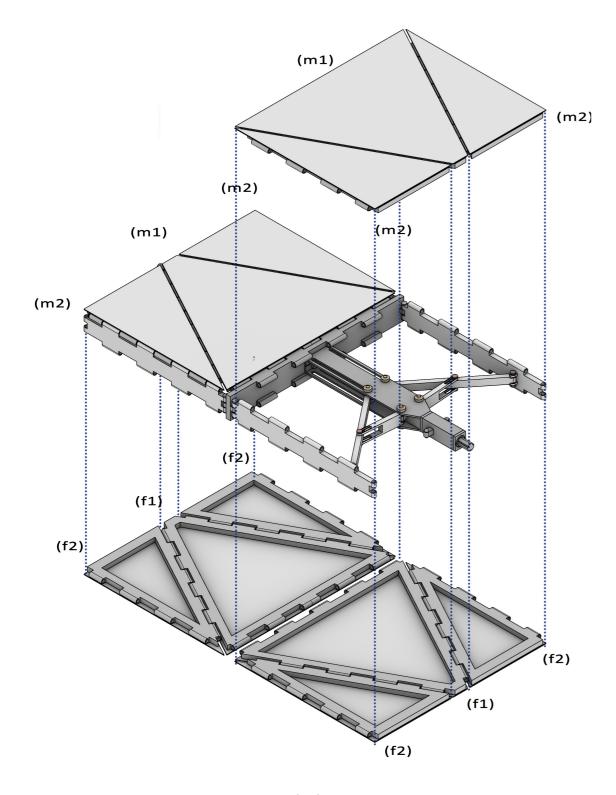
(iv)
Fixing of folding frame with material sheet

(v)
Connecting folding frame with each other and fixing it on structural frame

(vi)
Structural frame with a cover frame

(m1)

(m2)

(m2)

(m1)

(m2)

(m2)

(f2)

(f1)

(f2)

(f2)

(f1)

(f2)

(vii)
Fixing of other cover frames

(ix)
Final module

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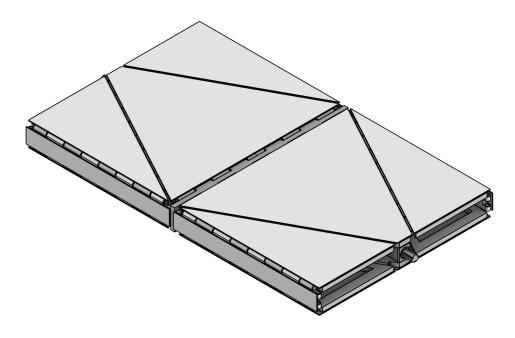
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