MASTER

Design of a new virtual window system based on a sustainable energy solution

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Award date:
2013

non-(CONFIDENTIAL)
as of 13/8/14

2013

Design of a New Virtual Window System Based on a Sustainable Energy Solution

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SUSTAINABLE ENERGY TECHNOLOGY

SMART LIGHTING

TECHNISCHE UNIVERSITEIT EINDHOVEN

PHILIPS RESEARCH

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8/9/2013

Key words

Virtual Window, Daylight, Control Patterns, Solar Cell

Preface

With this thesis I will finish my master study of Sustainable Energy Technology at Eindhoven University of Technology. This project was within the group of Human Interaction & Experience at Philips Research at Eindhoven. I would like to express my sincere gratitude to my supervisors, Evert van Loenen, Myriam Aries, Bernt Meerbeek and Rizki Mangkuto for their continuous support. Besides my supervisors I would like to thank my colleagues who helped me with the prototyping at Philips. Last but not least, I would like to thank my family and friends for their supporting behind.

Abstract

Window plays an important role in human physical and psychological well-beings, in places where real windows are not available, virtual windows can be a substitute plan and provide people with window-like experiences. This current paper raises a newly designed virtual window plan to replace the existing virtual window made by Philips. By this design, the virtual window is able to provide functional lighting with a blurred view and direct light. Also via certain control methods, the virtual window can realize a dynamic lighting variation on daily basis and yearly basis. In an ideal case, the virtual window system is integrated with solar cells, and use solar energy to power the whole system. Experimental results in this paper indicate that this virtual window system can meet the expected requirement but still is limited by light sources.

Contents

1. Introduction

In the history of human evolution, sunlight plays a very important role. It is widely accepted that sunlight has a positive physical and psychological effect on human beings, mainly through our eyes. Sunlight can provide high illuminance, permits excellent color discrimination, and has a color rendering around which our visual life is built. It also affects our inherent circadian rhythms via the third kind of photo sensitive cells in the eyes (ipRGCs) (David M.Berson, 2003).

With the development of electric lighting, people spend most of their time in artificially lit indoor spaces. However, they still prefer places next to windows naturally because windows can enable them to be close to daylight; also windows have positive effects on people's psychological and physical well-being (Finnegan et al., 1981). Also meanwhile, by observing the view from a window, one can perceive some extra external information like time of the day and present lighting level conditions, which can alleviate the feelings of being isolated from the external world (Boyce et al., 2003)

However, not every area in a building has access to the natural light. For these reasons virtual windows (VW) and virtual skylights (VS) are developed by Philips Research to provide an alternative lighting solution for windowless spaces, for example corridors, meeting room or metro stations, and spaces with insufficient daylight such as hospital rooms or offices. Compared with normal artificial lights, the VW/VS sets try to create an experience similar to that of real windows and skylights, in order to improve people's visual comfort and accommodate the psychological desire to be in daylight conditions.

During an internship at Philips Research the lighting performance and energy consumption of an existing virtual window prototype from Philips was tested and discussed (Shen, 2013). It was found that this existing state of the art has satisfying lighting performance compared with real window situations, but that in order to keep the VW working, hundreds of watts are consumed continuously under different lighting scenes. Since we are living in a world which is short of traditional energy and the price of traditional energy is increasing, it is time to think about ways of combining a new sustainable energy source with VW systems in order to satisfy both people's demand for windows and energy saving.

The main purpose of this study is to design a more energy efficient virtual window by applying new energy sources and energy-saving light sources. Meanwhile the lighting performance will be maintained or improved as much as possible, and the relationship between view patterns and energy consumptions will be studied.

For this virtual window study, two possible control patterns for the virtual window system were analyzed. They are the "Mimicking" mode and "Compensating" mode. Mimicking mode stands for the situation that the lighting level of virtual "sky" through the virtual window is mimicking the lighting level of the outside ideal condition, and compensating mode is the way that showing the contrary level of the ideal outside lighting condition. Lighting performance and energy performance of each mode are studied in the following sections to make the comparison.

In this study, certain new energy solutions and energy-related use patterns were explored in the design of a new energy scenario. This energy scenario is made to optimize the energy efficiency of the new virtual window system, which also needs to meet some application requirements like limited volume, high applicability, etc. Besides the energy aspect, another important factor that affects both energy and lighting performance is the light source. In this energy saving virtual window study, the light source should meet the requirements like high luminous efficiency, high color rendering, and short response time. To combine and control the energy source and the light source and realize functions of the new virtual window, relevant connection circuits were designed in this study. The circuits are supposed to be highly efficient, easily controllable, and with quick response.

In order to create window-like experiences, smart scenarios were designed to meet the users' requirements. Basically the scenarios can be divided into two parts, which are the "Mimicking outside lighting condition" and "Compensating outside lighting condition". These two scenarios are selected as main use cases for the study because they relate to energy consumption. These two basic scenarios were realized in a preset scene with different scaling factors, which were determined in this study. By controlling the circuit themselves, users can have "window" experiences with their preferred scenes.

Since the usage patterns of virtual windows will vary with the application environment and in order to make these plans comparable and applicable, a standard application environment is defined which a standard office is.

This research aims at answering the following research questions:

- How to realize a more energy-efficient virtual window than the current state of art/the currently available systems?
- What is the energy consumption of the new virtual window system under different lighting modes (mimicking/compensating) when combined with solar energy?
- What is the lighting performance of the new virtual window system?

2. Literature review

2.1. Types of virtual windows

The window started its history when people started to learn building shelters. Virtual windows also have a quite long history. The early examples are made to create some pretend views. These types are mostly paintings with detailed features to look realistic. The advantage of these virtual windows is that it can provide very detailed pleasing "views" when the actual wall is blocking light, sound, and heat. But it does not contain one of the most important functions of a window; that is the lighting function. More recently, a number of commercial efforts are being developed to create virtual windows which can provide both view and lighting. For example, the TESS round skylight (TESS *Virtual Windows, 2008)* or Sky Factory Luminous Virtual Windows (*Sky Factory, 2013*) realize both functions. Also there exist other types of virtual window system. For example, at the Experience Lab of Philips Research, prototypes of a Virtual Window (van Loenen et al., 2006) and a Virtual Skylight were developed and applied in an experimental environment. These two systems provide people with a very simple view, and bright diffusive light output.

Another important property of the window is that it gives the sense of depth. This feeling can make people be able to consider the virtual window as a true opening that connects the room with the outside world. When looking at the window surface, the observers will feel better when their eyes are focusing at long distance. To reach such an effect, several methods are considered by virtual window researchers. The easiest method is to enlarge the distance between display surface and the internal wall surface, so the static depth is increased (IJsselsteijn et al., 2008). The other way is to blur the lighting surface so that human eyes can hardly focus on (IJsselsteijnet al., 2008). Besides the static depth cue, there are several cues to enhance the experience of depth which are "Blur", "Occlusion", and "Movement parallax". Each of them can reach different "see through experience" levels, as shown in figure 1, taken from IJsselsteijn et al. (2008).

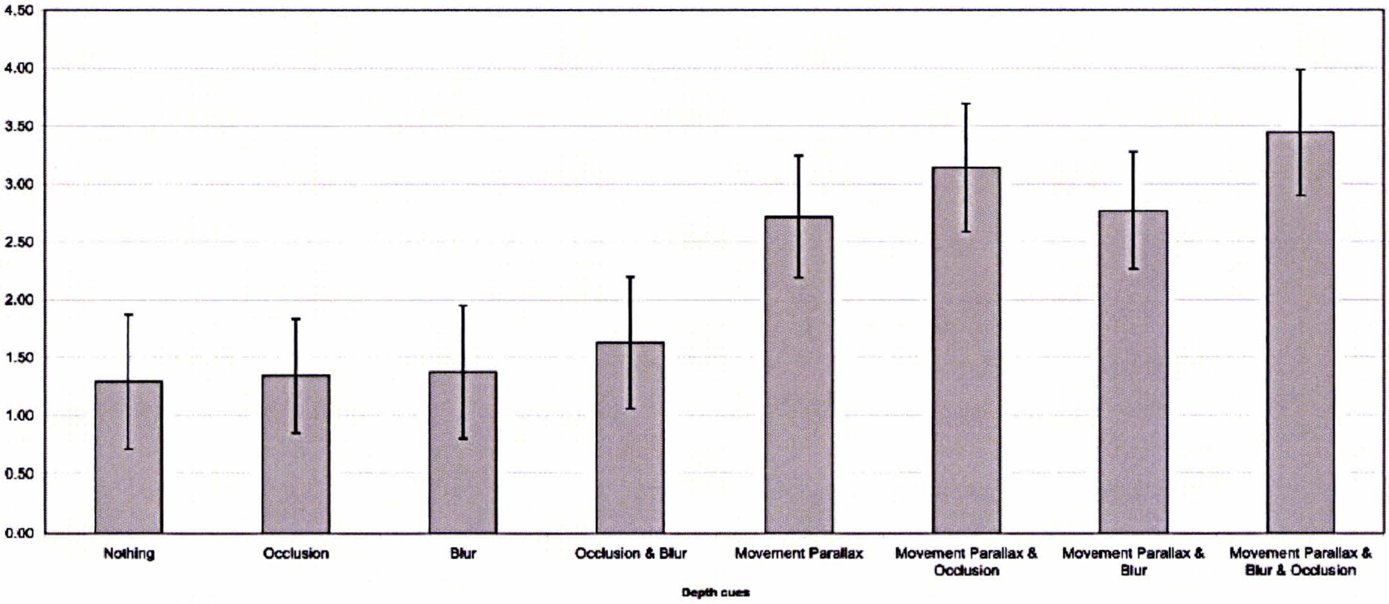

Figure 1 Mean scores and 95% confidence intervals for each of the eight experimental conditions, averaged across participants and images. (Wijnand et al., 2008)

2.2.The original Philips virtual window system

A first version of a virtual window system prototype developed by Philips (van Loenen et al., 2006) was studied and tested during a preceding internship project (Shen, 2012). This version of the virtual window uses Red-Green-Blue (RGB) fluorescent light sources in a luminaire called "Strato Rainbow" behind a highly diffusive panel. In order to increase the depth, the light diffusing surface was installed 350mm away from the "window's" glass plane. Besides the fluorescent lamps, the system had a virtual "sun" system to mimic the position of a sun beam during a day. The "sun" is mimicked by one High-Intensity Discharge (HID) lamp of 70 watt, which is fixed on a moveable track.

The original virtual window is controlled by a Digital Addressable Lighting Interface (DALI) protocol. The 12 fluorescent lamps are divided into four groups; each group has three tubes which emit red, green, and blue light. Each lamp has its own ballast so that it can be dimmed independently. By assigning dimming values to each of the ballasts, the light distribution on the diffusor can be changed to present different scenes.

The instant power consumption was measured under three lighting scenes. For the "clear sky" condition, the system consumes 475 Watt, for the "Partly cloudy" condition 550 Watt, and 315 Watt for the "Overcast" condition.

Figure 2 shows photo of this original virtual window prototype developed by Philips:

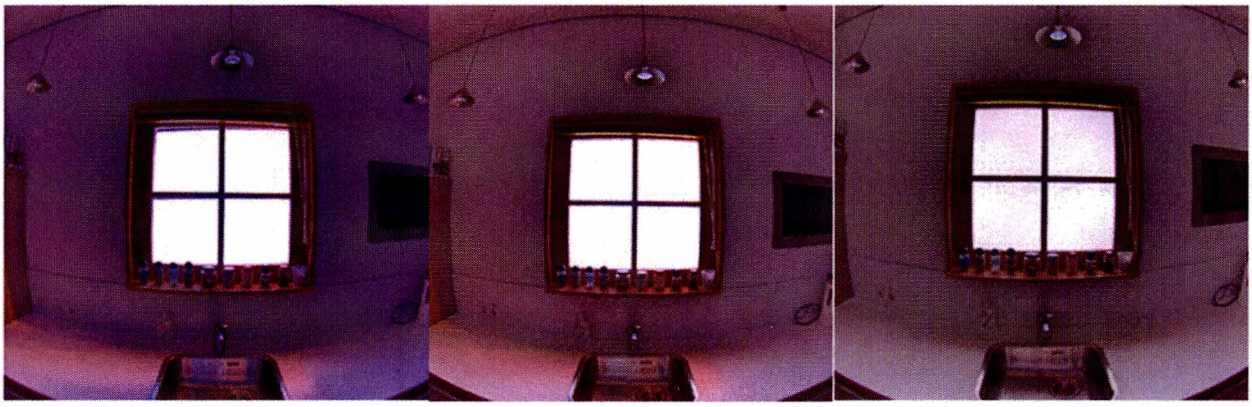

Figure 2 Original virtual window made by Philips of three scenes (Clear sky; Partly cloudy; Overcast) (Shen, 2012)

3. Method for designing a new virtual window

3.1.Introduction

This chapter discusses the methods used to design a new virtual window system. The framework became the basis for the subsequent measurements and tests. The design is discussed in six different functional aspects, which are:

1) Standard test environment plan
2) Energy sources plan
3) Light sources plan
4) Control circuit plan
5) System structure plan
6) Programming and settings

The first step is used to determine under what conditions the new virtual window will be installed and tested; the following five steps are mainly about constructions and setup methods of the virtual window system itself. The research followed this particular order to make sure that each step can match the previous one. Finally by these methods, the functional virtual window will be built and ready for tests in a standard environment.

3.2.Standard test environment

A standard office test room has been built in the new Experience Lab of Philips at the High Tech Campus in Eindhoven, the Netherlands, to provide an experimental application environment for the Virtual Window system. The dimension of the office room is 6813mm ×3625mm ×2700mm (L×W×H). Two real window openings are placed on one short side of the room to enable daylight to come through. On the opposite side of the room the virtual windows are installed. (See also figures 3a and 3b).

In order to avoid daylight entering from outside during the measurement of virtual window, in all experiments and measurements, the two real windows were blocked with two white boards. Therefore, the south wall can be considered as an entire wall without any openings. The virtual window prototype is installed on the outside surface of the north wall behind the window openings so that the light will come through. The top view and side view of the whole test room (with blocked real windows) are shown in figure 3a and 3b:

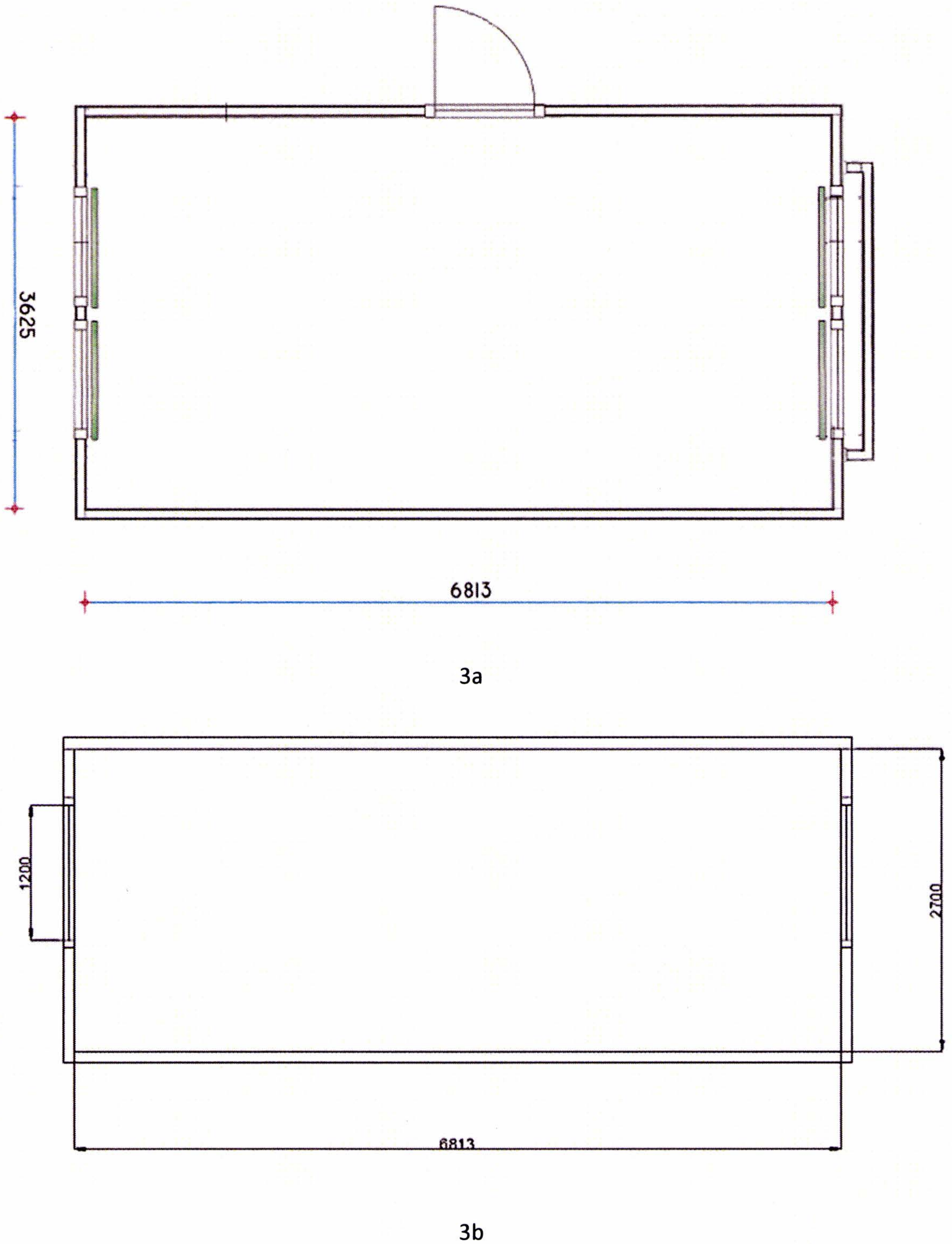

Figure 3 Floor plan (a) and cross section (b) of the standard test environment

Figure 3 shows that, in the test room the virtual window system is installed opposite to the real window as mentioned. The dimension of the openings for the virtual windows is 90cm (width) × 120cm (height) each excluding window frames, the distance from the floor to the window bottom is 93cm, and they are placed on the wall symmetrically. The distance between the two openings frames was 25cm. Figure 4 shows the virtual window openings and the wall's layout:

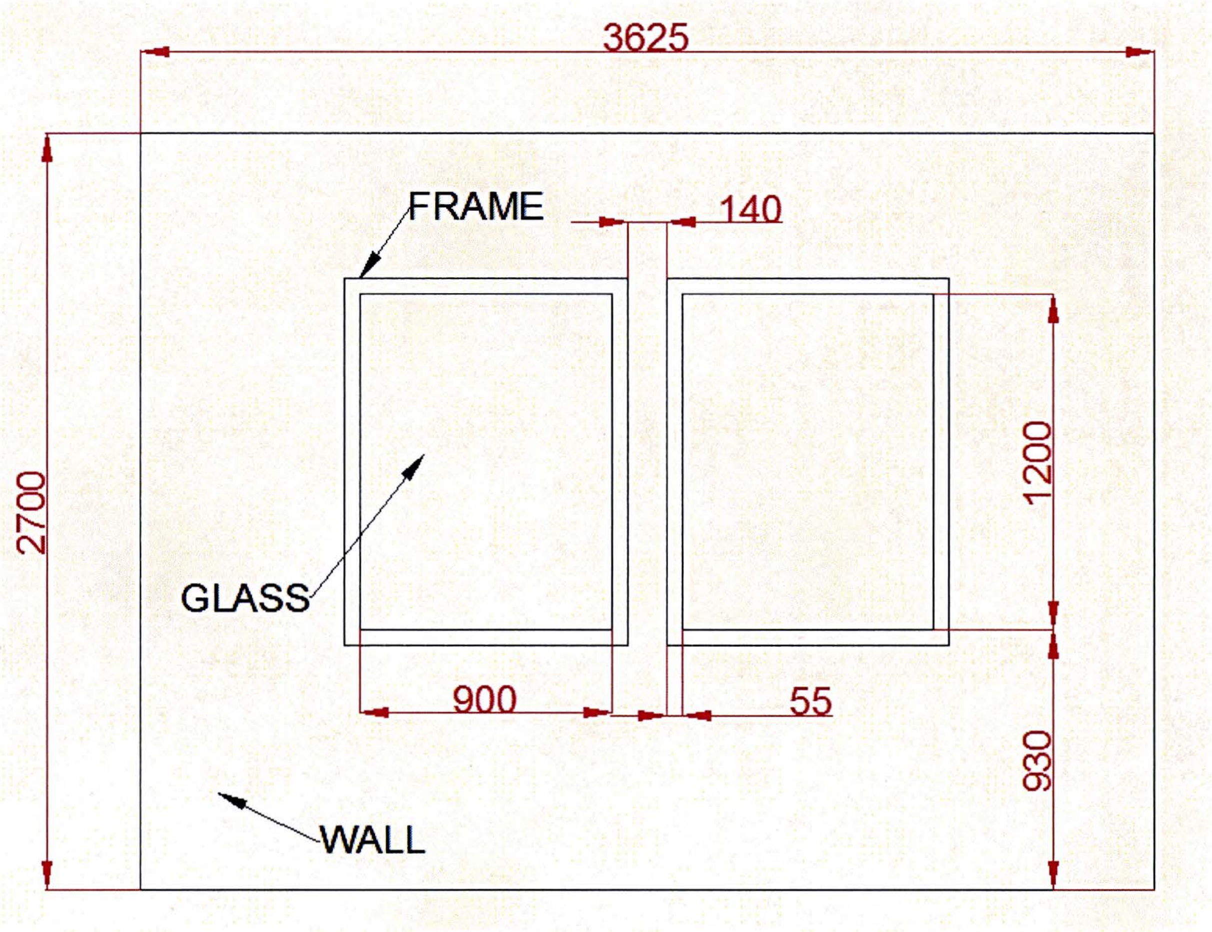

Figure 4 Front view of the back wall and openings for virtual windows

3.3. Energy sources plan

In order to realize an energy-efficient virtual window system, a combination with a sustainable energy source to provide the system with power was considered theoretically. Several power source candidates have been considered. Energy sources that can be used are wind power, solar power, and hydropower and Hydrogen fuel battery. These four options can all produce electricity in a sustainable way, but hydrogen cells need refuelling at certain time points, in terms of building maintenance this is not very convenient. Hydropower and wind power have the shortcoming that they are normally not applicable in a building environment. Solar energy (Photovoltaic) doesn't need refuelling and is easier to apply and maintain. After comparison of these sustainable energy sources, solar energy was selected as energy source to focus on for this research.

There is another reason why solar energy was selected.. What solar panels and real windows have in common is that their performances rely on daylight. When they are combined directly, the output of the solar panel will vary with the daylight level/amount, and this variation will be reflected in the light output of the virtual window, potentially leading to a natural "Mimicking" behavior of the virtual window. However, since a more general analysis is aimed for, applicable to "Mimicking" as well as "Compensating" modes, indirect coupling of solar panels to the Virtual Window system is considered in the remainder of the work.

In the actual prototyping process, grid power is used to provide energy to the virtual window system to make sure that the power supply is stable and sufficient. The energy consumed by the virtual window was measured and provides reference for the calculation of the solar-power virtual window situation.

To avoid the shortcomings of solar cells, the mains grid is integrated in the power source solution to ensure the power requirement can be fulfilled. Grid electricity can solve the problem of insufficient power when a low lighting level outside is experienced.

By the integration of solar power and grid power, the virtual window system can work in a stable manner. The purpose of the thesis study is to investigate the relationship between virtual window view and usage patterns, energy consumption, and solar power gains, so the research focus on understanding the solar power gain under various situations and what is the power needed from external sources (mains grid) under various virtual window operation scenes.

3.4. Light source plan

3.4.1. Basic concept

For a real window, the view to the outside changes continuously depending on the time of the day, weather, and so forth. For a virtual window, we have decided to use Light Emitting Diodes (LED) as the basic light source, because of its outstanding properties, like its long life time, high efficiency, multiple color choices and high application flexibility. The luminaire elements should be able to fulfill the functions of a frosted glass window look and providing a dynamic blurred view of "outside". So the light source should be able to provide white light with high color renderings, and also be able to present different basic colors. Beside the color requirements, the light sources should be dimmable and controlled individually.

In order to create certain "views" on the virtual window, a combination of lighting "pixels" was assigned. The requirements for the "pixels" are listed below:

- Each single pixel should contain red, green, blue lighting components

This requirement enables the virtual window to display colorful effects.

- Each color in a pixel should be separately controllable and dimmable

This requirement enables the virtual window to display certain images.

- The pixel should have a uniform lighting appearance

This requirement is made to assure the surface uniformity of the virtual window

- The pixel should have a good suitability in structure and control

This requirement will provide more convenience to system construction and control.

In a daylight environment, direct "sunlight" and an acceptable level of glare should be present to enhance people's experience of real ambient daylight. So in this case, extra direct light and glare design will be applied to the virtual window set. This could not be realized with the LED-system only, and therefore additional lamps are applied. The requirements for the extra lamps are defined and listed below:

- The direct light sources should be able to generate light with high color rendering.

This requirement is because real daylight has high color rendering.

- The direct light sources should be dimmable to fit the real daylight situation

This requirement is made to mimic different lighting level conditions.

- The spot created by the extra light sources should be able to change incoming angle with time

Because in real daylight condition, the different position of sun will result in different incoming angles.

- The glare created by the extra light sources should be visible but not disturbing.

This requirement is based on the fact that sometimes sunlight through the window could be glary.

3.4.2. Display and basic luminaire selection

To meet all these requirements for the lighting "pixels" and based on luminaire availability, the Philips Origami BPG762 model was incorporated and acts as pixels in the virtual window. The BPG762 squared luminaire tile consists of four individually controllable circular LED modules. For each of these circular LED modules, 27 LUXEON power LEDs are distributed in three concentric circles, where the inner circle contains three LEDs, the middle circle contains eight LEDs, and the outer circle contains 16 LEDs. These LEDs are covered by three layers of diffusors with different properties to ensure uniform light output distribution. The three groups of RGB LEDs can be controlled by DALI or DMX independently, which makes color and output change possible. The tiles can display a virtually limitless range of dynamic changing colors at high light output. Because the luminaire is designed to be a uniform edge-free lighting tile, it can be joined to other tiles to form an array of pixel units.

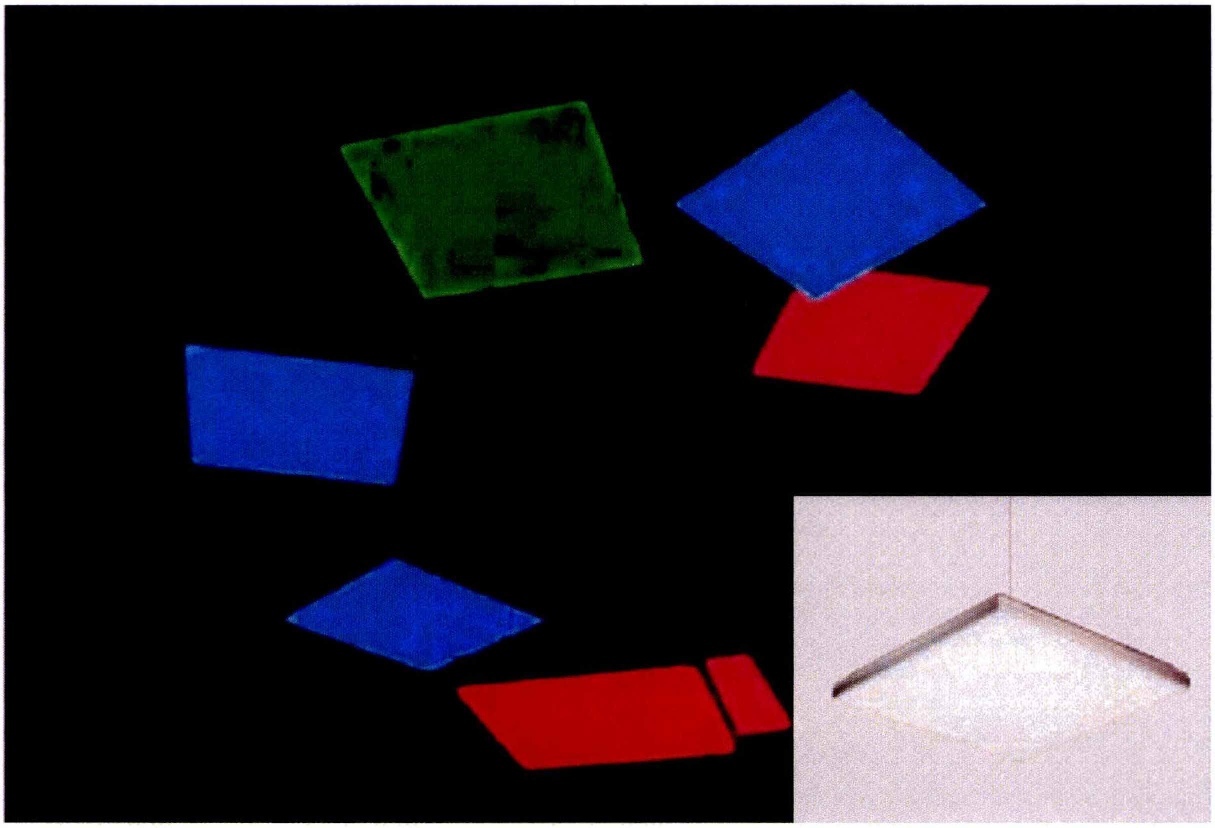

Figure 5 Origami lamps with dynamically changing colors (source: Philips, 2013)

On the power aspect, a single Origami BPG762 tile has a maximum power of 128 watt and it is driven by a DC source of 24 volts. Each tile can be independently controlled by DALI or DMX (Digital MultipleX*)* protocols with proper programming. All the properties of these luminaires meet our requirements for the desired light sources. The detailed specification of the Origami BPG762 is shown in Table 1.

Table 1 Detailed information of the light panel

Type	*BPG762(BPG732×4)*
Dimension	*595mm×595mm×50mm (L×W×H)*
Light source	*108 ×LUXEON(27×4)*
Light color	*RGB*
Power supply	*24V DC*
Power consumption	*128W(32×4)*
Optic/ Cover	*Multi-layer diffuser*
Lifetime	*50,000 hours (70% lumen maintenance)*
Option	*Light controls: Color Chaser DMX* *Color Chaser Wheel*
Material	*Housing: anodized aluminum* *Backplate: steel* *Top cover: PMMA (PC on request)*

Weight(kg)	*15(approx.)*

The dimension of the Origami BPG762 tile is shown in following figure 6:

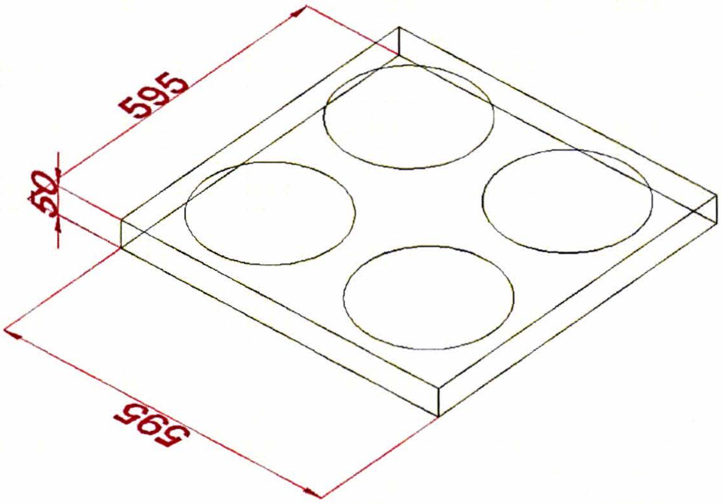

Figure 6.Dimension of Origami BPG762 tile with dimensions in mm

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3.4.3. Display lighting panel integration concept

To fit the total size of the virtual window openings in the standard office room which is 1200mm ×900mm for each plus wall in between, a 4 × 2 BPG762 array was designed as display light source panel. This array contains eight BPG762 tiles and can display a 32 pixels image on the lighting panel. Each BPG762 tile can be controlled by 12 channels, so the whole display and lighting panel can be controlled by 96 channels.

The conceptual structure of the display lighting panel together with window opening is illustrated in figure 7, each red block stands for one BPG762 tile, and black parts show the actual window frame:

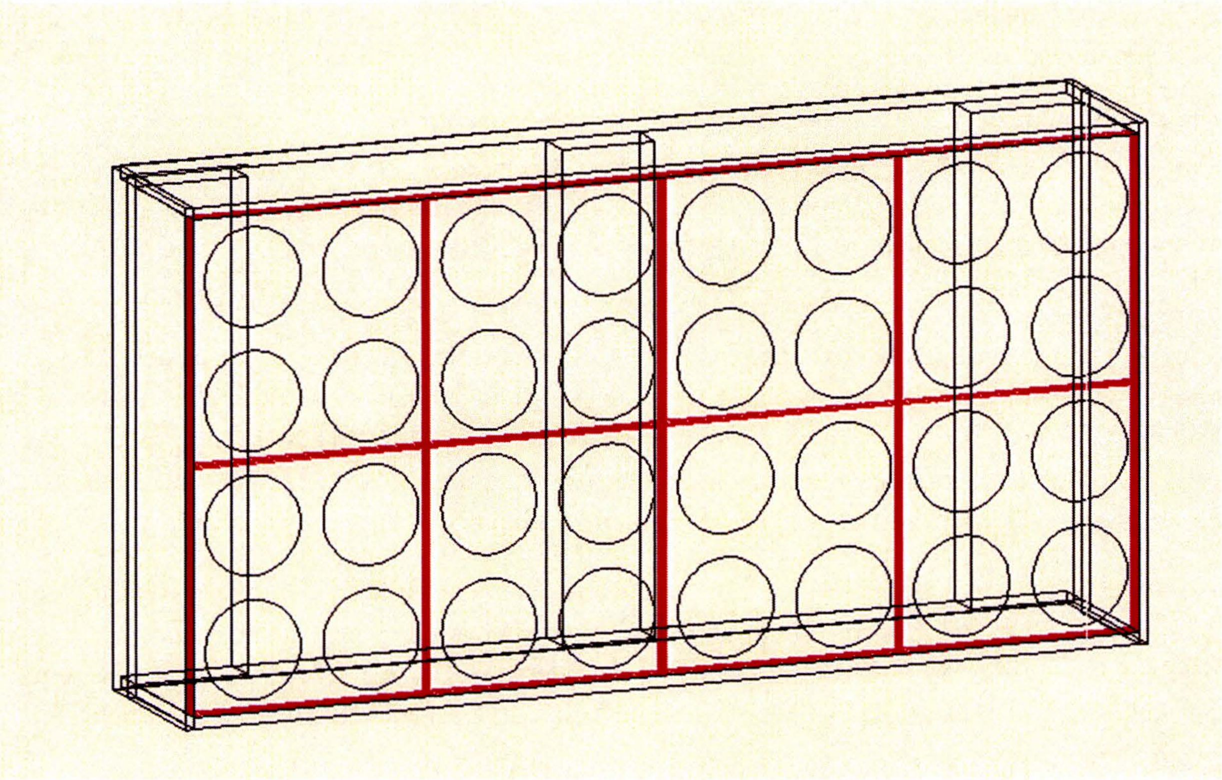


Figure 7 Illustration of relative positions of two openings on the wall and Origami array

3.4.4. Direct light sources plan

Besides the display elements that are used in the virtual window design, additional direct light sources were required to enhance the light output and to realize other functions of the virtual window system such as providing direct sunlight or glare.

The requirements for the direct light sources are:

- The light source shape is linear

This requirement is made to fit the luminaire to the system structure.

- The emitted light should be directional

This requirement is made to generate direct light output.

- The light sources array can be dimmed independently

This function can be able to generate asymmetric light distribution to mimic the position of the sun.

- The color temperature of the light source can be controlled

This function enables the virtual window to show the color temperature variations during the day.

- The beam angle of the light source should enable the light to reach both bottom and top frames

This function enables the virtual window to mimic the situation that all direct light comes through the window openings.

To find a luminaire that meets all the required conditions, several available commercial products were compared. The Philips Color Kinetics iW Cove MX Powercore (wide beam version) was eventually selected. This decision is based on the fact that it meets all the mentioned conditions and it has advantages in luminous efficacy when compared with other lamps from the same product family.

The iW Cove MX Powercore is a high- performance, white light LED fixture that can be applied where adjustable color temperature is required. It has independent channels of warm, neutral, and cool white LEDs to produce color temperatures in a wide range from 2700K to 6500K. This property can help to imitate the effects of real daylight color temperature fluctuations. The rapid and accurate control system can improve the natural imitation performances.

Besides the color temperature range, the dimensional and mechanical properties are also suitable for the study. The length of the iW Cove MX Powercore lamp is 305mm and can be connected in series with other same lamps. In this Virtual Window design, eight iW Cove MX Powercore units are installed above the window openings on the outside to fit the total length and make non-uniform light distributions possible.

Figure 8 and 9 shows the dimensions and actual photo of the iW Coves.

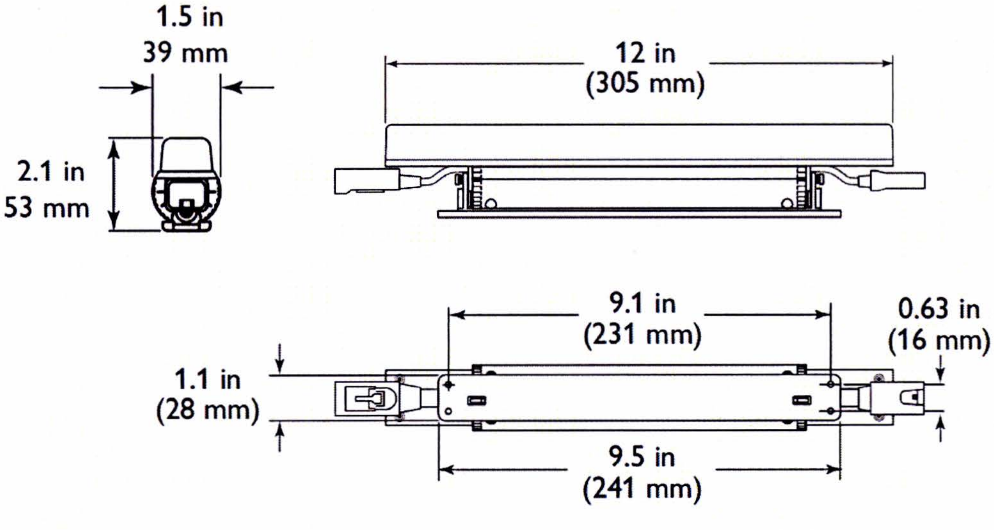


Figure 8 Dimensions and structure of iW Cove MX Powercore (Philips, 2013)

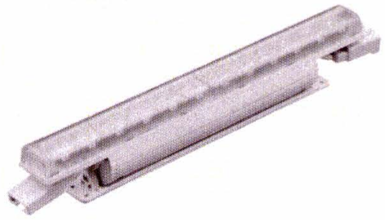


Figure iW Cove MX Powercore s made by Philips (Philips, 2013)

The detailed properties of the kind of luminaires can be found in the reference.

3.5.Control circuit plan

3.5.1. Basic concept

To realize all the supposed functions of the new virtual window system, a control circuit plays a crucial role in the design process. The ideal control circuit design should have a friendly human-machine interface, and various setting possibilities. In this case, the DMX512 protocol was adopted to realize these functions.

DMX512, or "Digital Multiplex with 512 pieces of information", is a standard for digital communication networks that is commonly used to control lighting dimmers. Under this protocol, a digital dimming lighting network can be set up by using DMX512 controllers and a certain control software. Each color channel can be dimmed from the full value of 255 to zero. Compared with the DALI protocol, the advantage of using DMX512 is that each DMX512 controller can control 512 channels at the same time, while each DALI controller can only control 64 channels. As mentioned before, the virtual window light sources need multiple channels each, so the DMX512 is a better choice to simplify the control circuit.

In this case, the purpose is to build up a dimmable and unit-independent controllable lighting system (virtual window) to realize a series of functions, such as independent pixels, various patterns, fast response, and easy control. Moreover, the dimming protocol should be able to process enough addresses or channels at the same time by a single controller. Using DMX512 protocol would be the best solution to meet all the requirements for the virtual window control.

3.5.2. Hardware plan

Compared with a DALI protocol, the system for DMX512 is simpler. The DMX512 modules are already integrated with the Origami tiles and Color Kinetics. However, they are using different DMX protocols. Origamis accept regular DMX (DMX ESTA, or DMX Entertainment Services and Technology Association) signals while Color Kinetics uses DMX Kinetics signals. In order to control both types of lamps, a DMX Splitter (Martin DMX-splitter RS485) is used to split the signal from computer in half and converts it to the suitable DMX formats and transfers the signal to the lamps. By connecting them with a DMX controller, the basic network is formed. Commands can be sent by the computer to control the light emission level of each lighting unit.

In the virtual window prototype, totally there are two general groups of lighting modules, which are the Origami tiles and iW Cove MX Powercores to provide directional lights. For the Origami tiles, totally there were 96 addresses (3 x 4 x 8) that were controlled, and for the iW Cove MX Powercores, there were also three CCT channels for each luminaire, so 24 addresses (3 x 8) that were controlled together with the Origami's. In total for each scene setting, 120 values from 0 to 255 must be determined to present the certain "view" and "lighting level" of the virtual window prototype.

As to the power supply plan, this prototype is powered by the mains grid which is 220V with 50Hz AC source. In order to adapt the power source to Origami's and iW Cove MX Powercores, suitable rectifiers were needed to convert the 220V AC source to a suitable DC source. For the Origami's, four adapters were applied. Each adapter is responsible for two Origami 762 sets and provides a stable 24V DC current. The iW Cove MX Powercores were powered via a Philips Data Enabler Pro which provides integrated DMX signals. Unlike the Origami's, these iW Cove MX Powercores were connected in series.

The conceptual control circuit structure is shown in figure 10, in which blue lines stand for signal circuit and red lines stand for power circuit.

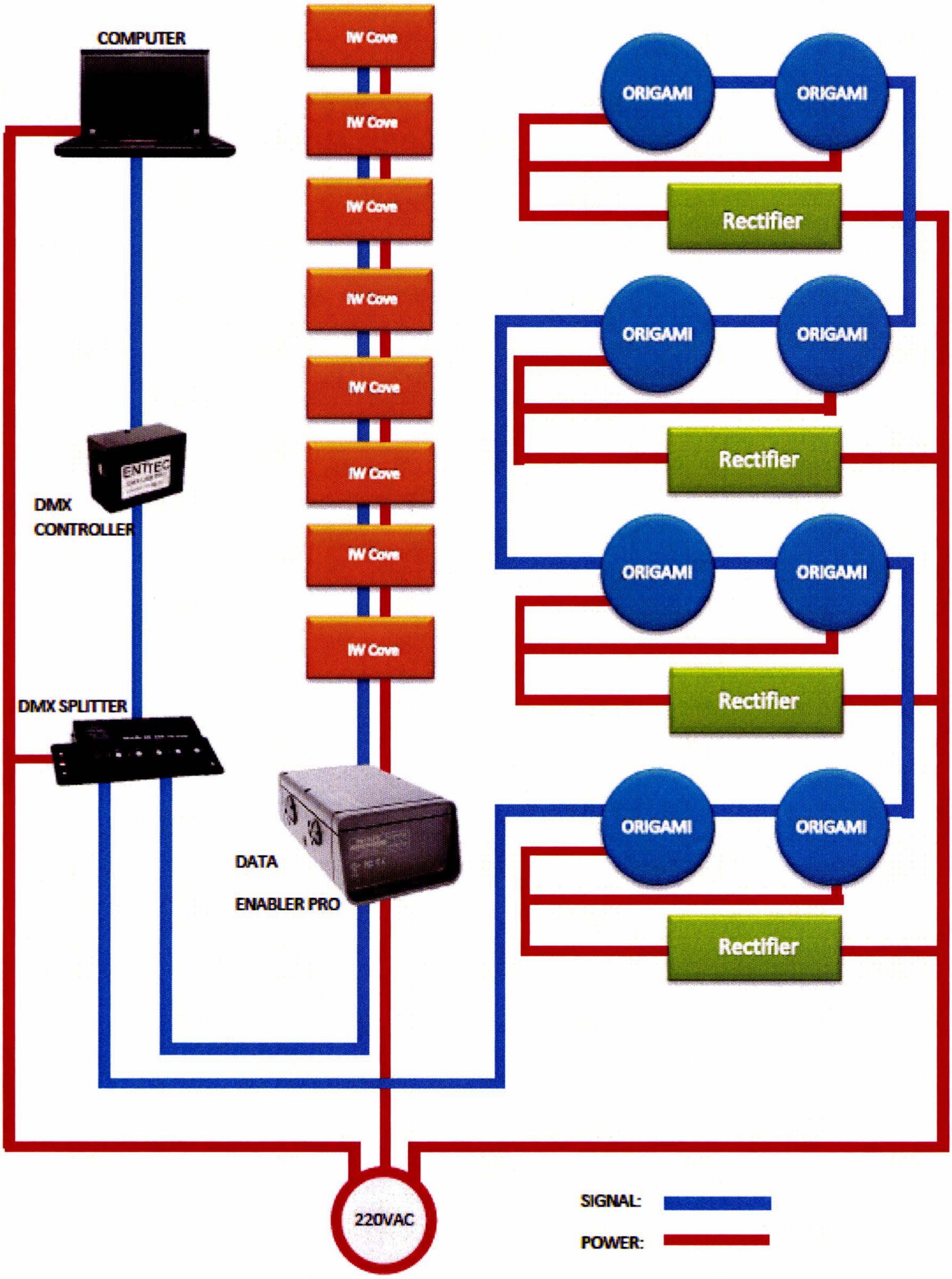


Figure 9 Control and power supply circuits of the new virtual window

3.6. System Structure Plan

At this stage, the light sources, power supply, control circuits, and mechanical structures were integrated together into the total design of the virtual window system. The design was initially built up with CAD modelling methods, then in several rounds of discussions continuously modified and improved. The final plan of the virtual window structure is described in this part of the thesis.

3.6.1. Basic structure

The basic function of the virtual window is to display. Before any mechanical supporting structure is determined, the functional components plan should be made. As already mentioned, the display light source is Origami762 LED tiles, and the direct light source is Colour Kinetics. To increase the light output, the front diffusors of the Origami tiles were taken off, and the original housing was also removed to create an edgeless tile.

According to the design requirement, the display should be blurred and uniform. Therefore, the individual highly diffusive front covers were removed and replaced by a single large diffusive panel in front of the Origami array to eliminate the visibility of LED spots and boundary reflections caused by the metal surrounding edges. To achieve this goal, it is also noticed that the diffusive panel effect mainly depends on two properties: i.e. the diffusion of the panel itself, and the distance between the light-emitting plate and the diffusor. So in order to gain maximum light output, the new diffusive panel should have high transmission, and the diffusion requirement should be made up by enlarging the distance between the Origami's and the diffusor. The PLEXIGLAS SATINICE colourless diffusor (type 0F00SC) was selected. This type of diffusor has a one-sided matte surface and 92% transmission (Plexiglas, 2012). To make the diffusor strong enough to stand by itself and keep straight, a thickness of 5mm is chosen. Since the panel was made of frosted surface material, a variation in thickness does not cause a significant effect on the amount of light loss.

The Origami-diffusor-window glass combination formed the basic structure of the virtual window, which is shown in figure 11. The following designs were all aimed to support the structure.

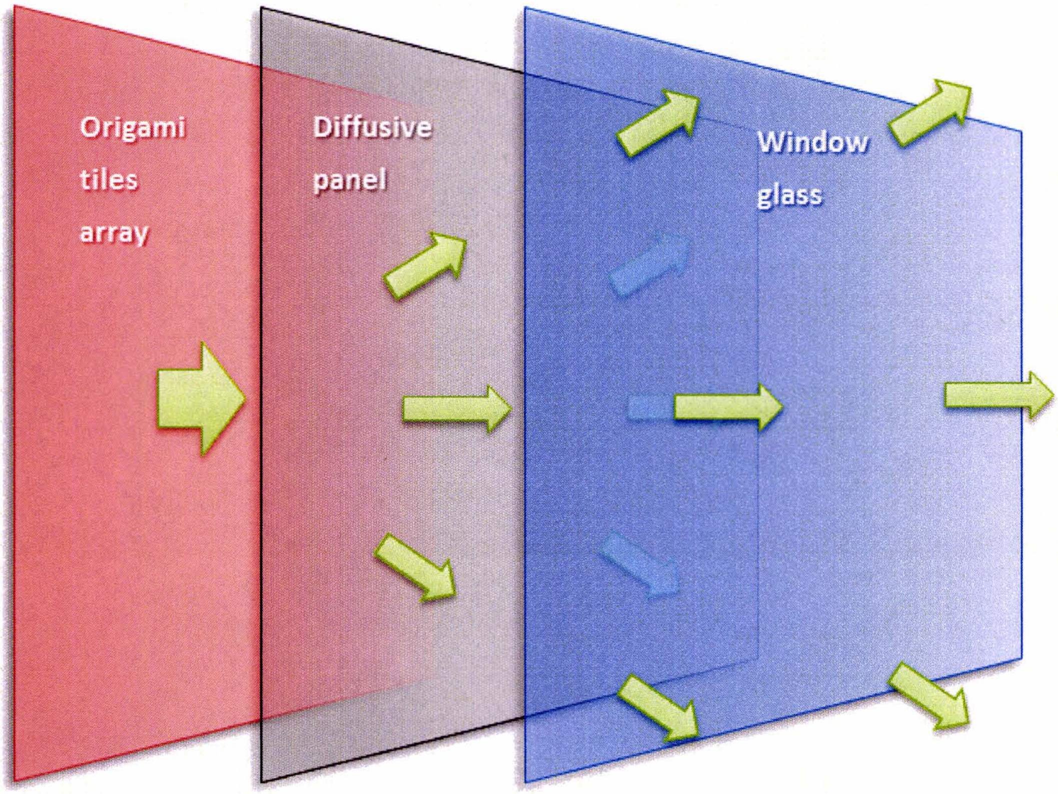


Figure 10 Basic three-layer structure of the virtual window design

3.6.2. Light-emitting plate design

As mentioned before, the light-emitting plate was realized by building up an Origami tiles array. In this case, eight Origami 762 tiles were incorporated; each of them was modified by removing the front diffusor and aluminium frame. All tiles were fixed to a MDF backplane in a 4 X 2 form. The edges were tightly joined against each other to make the boundary between them as thin as possible. The MDF backplane together with the Origami array is shown in figure 11 and 12.

The thickness of the MDF backplane was 18mm, and the length and width were 2400mm and 1200mm, corresponding to the length of four Origami tiles and two Origami tiles respectively. Because in Origami tiles, high-power LEDs were used, a large amount of heat will be generated when they were switched on. In order to not reduce the efficacy of LED chips, a cooling element had to be considered in the design. A MDF plate with four large openings was applied. The openings' size is designed to fit the size of each circular array. With the openings in the back plate, heat generated by LED arrays can be emitted from the back via aluminium conduction and air convection. The opening could not be too big to affect the supporting strength of the back plate. Therefore, the width of the central strips is determined to be 200mm and side strips were 100mm wide after the openings were created.

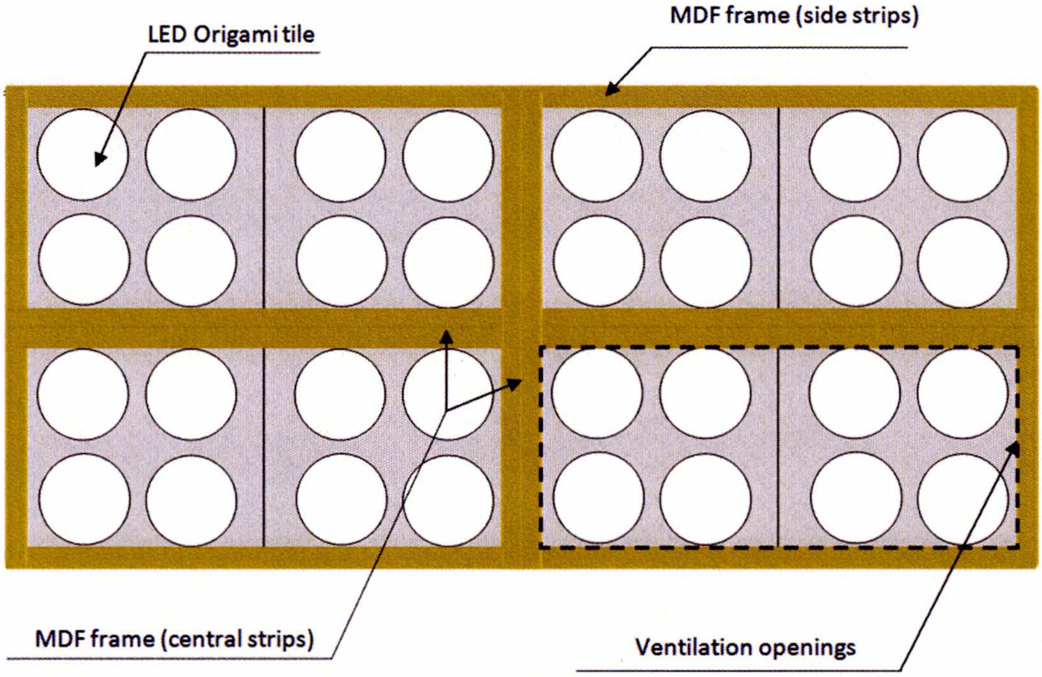


Figure 11 the light-emitting plate illustration

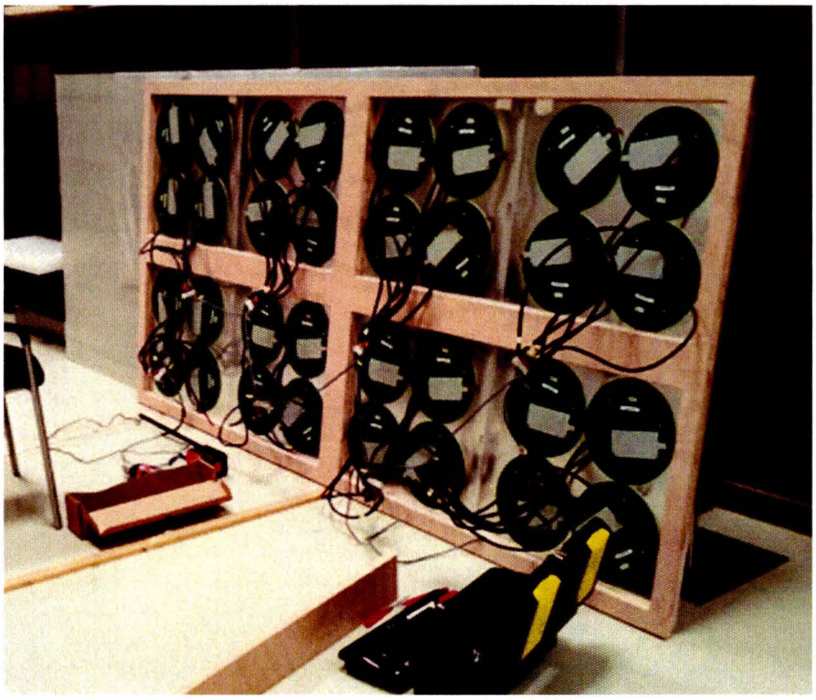


Figure 12 Light-emitting plate under construction

Each Origami 762 tile was surrounded by highly reflective steel strips which were jointed to the backboard and could not be removed. During the demonstration test, we found that the reflection from side strips resulted in two bright "crosses" in the centre of each window. Observed from inside of the standard room, the virtual window view was not convincing enough.

The solution after many trials contained two steps. The first step is to use half-transparent paper strips to cover the steel surroundings perpendicular to the Origami surface. The aim of the step is to reduce the reflection of the steel surroundings and block reflected light from coming back to the Origami diffusor. The second step was placing another additional diffusive strip on the joint boundaries of the Origamis tiles. The function of the diffusive strips is to build up "connections" between neighbouring Origami tiles by its diffusive property so colour transitions were created between these Origami tiles.

3.6.3. Mirror-box design

The Origami tiles-diffusor panel-window combination was supported by the surrounding and back MDF frame. This basic structure generated two inner spaces: the space between light-emitting plate and diffusor, and the space between diffusor and window glass, see Figure 14. In this design, these two spaces were designed to be "mirror boxes" to realize different functions.

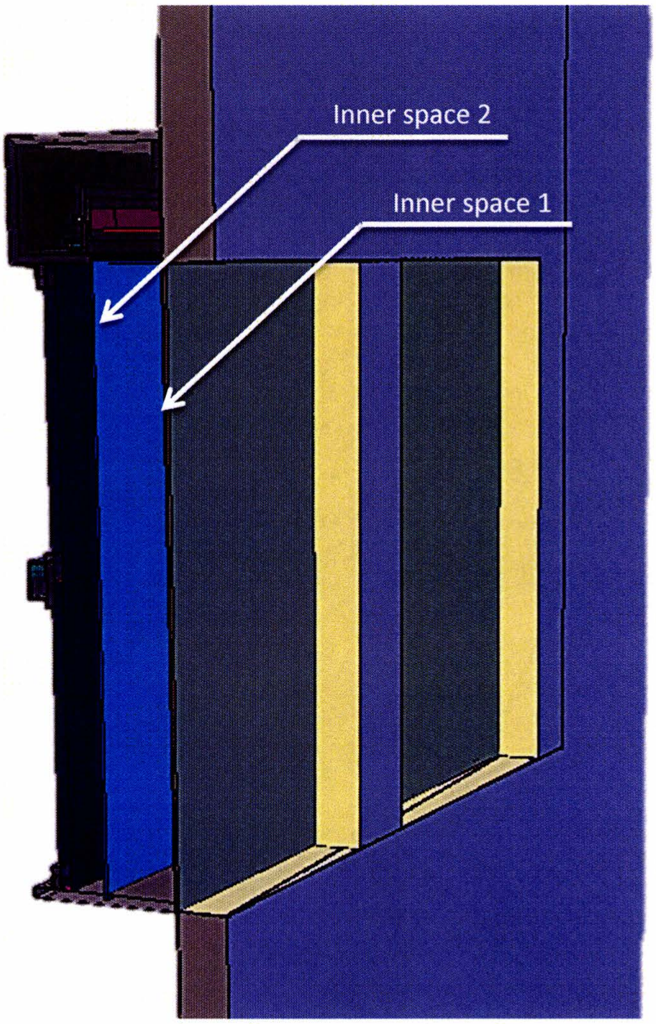


Figure 13 Image with cross section of the two inner spaces

For a real window, one of the key characteristics is that it has an endless view (the "view" is continuous and uninterrupted) if observed from any angle. For the virtual window, we should mimic this property to enable people to observe the virtual view from any possible angle. This is the main purpose of the first mirror box: to eliminate the edge effects and generate an endless view. The mirror plates will cover three sides of the surround structure: the bottom, left side, and right side. The top panel is not included because that it is designed to be an open area to keep space for the

Colour Kinetics. During the building process, the mirrors were attached as close as possible to the diffusor panel so that the boundary between them was less visible.

The next mirror box was in the Origami-diffusor panel space. Unlike the first space, this space could not be directly observed from the test room. The function of these mirrors was to collect light that goes to the side plate and increase the light output so that the system efficiency can be improved. The mirrors attached to the side panels can eliminate the dark shadows on the edges of the diffusor caused by light absorption of the side panels. In this space, there is no external structure and the space is quite closed, so four mirror plates were attached to the four sides. The boundary gap requirement is not as strict as the first mirror box, but the gaps were still made as small as possible. Figure 15 shows where the mirror plates were placed:

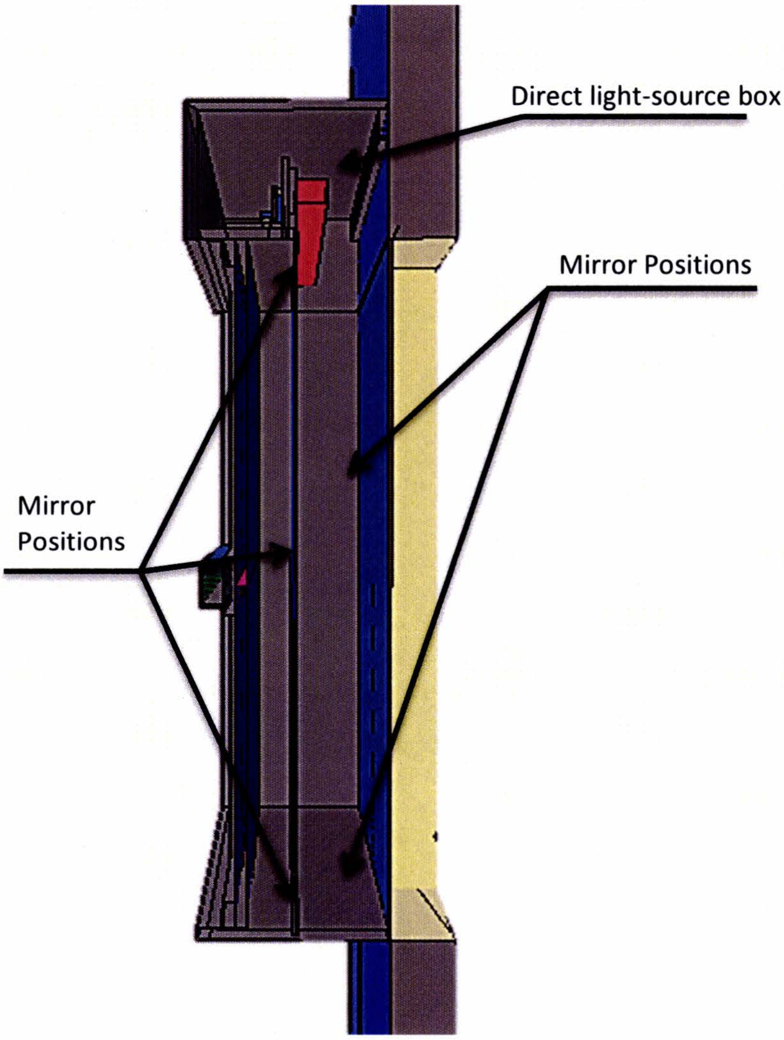


Figure 14 Mirror positions in the two inner "mirror boxes" in the cross section plan

As mirror material, 1mm thick, aluminium-based mirror plate from Philips was used. The high reflectivity was realized by polishing the aluminium material itself. The mirror plates were cut according to the exact dimension of the side panels. All mirror plates were attached to the MDF by using a double-sided tape to keep the surface as flat as possible.

3.6.4. Direct light-source box design

A normal window can usually provide us not only the outside-views but also the direct sunlight when the sky condition is clear. In the virtual window design requirement, it is intended to have an acceptable amount of direct light. However, the direct light source should not affect the view of the main light-emitting panel. To meet the requirement, an additional direct light source box was designed and integrated in the virtual window system. Furthermore, the external box should also be able to house such functions. The direct light source should be adjustable in height and distance from the wall surface. These functions can create a possibility to adjust the angles of the incoming light and beam angles of the direct light.

Based on the total length of the virtual window system, it was determined to use eight iW Coves, and to connect them in a line via the product's special interface. Next, they were fixed to a long wooden strip with a corresponding length and width. The connection method is illustrated in figure 16; this connection contains signal and power cables:

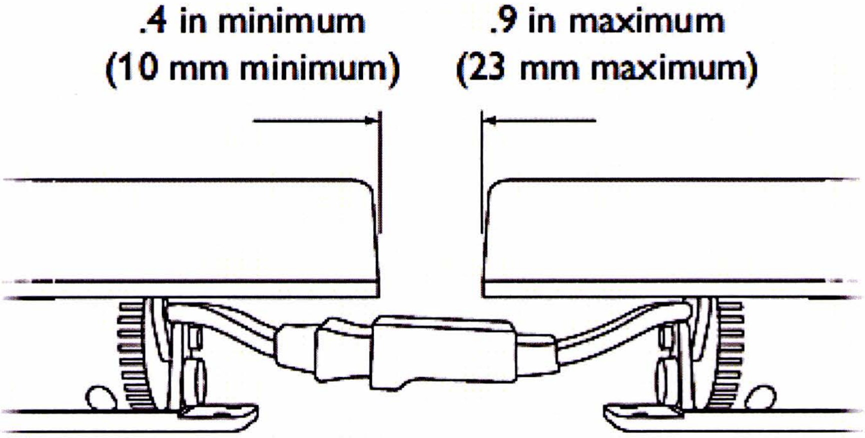


Figure 15 Signal and power connection of iW Coves

The movable-position function was realized by adjusting the position of base wooden strip in two directions, the height and the depth. The wooden strip to which the iW Coveswere fixed was placed on a "L" shaped wooden structure by locating bolts through two long grooves on the vertical side. Thus the height of the strip can be adjusted. The "L" shaped structure is fixed to the top panel of the main virtual window structure by using the same bolts and two long grooves but on the horizontal side, so the depth to the window frame could be adjusted. To avoid the situation that at some points, the vertical bolts and the horizontal bolts would touch each other, the bolts were misaligned along the structure.

In this particular test or future application, the angle of the iW Covescan be adjusted to achieve different light incoming angles. In this design, the MDF box around the iW Covescan therefore be opened. For the following test, the iW Cove lamps were adjusted to a suitable angle and then the box was closed.

3.6.5. System Integration

The main parts of the system were the Origami "box" and the iW Cove "box", and there were some other small components like power supply and supporting structure which serve the main "boxes". According to the dimension of the window opening on the wall of standard test room, the Origami box was designed to be as high as the opening's height, but due to the Origami tile dimensions, the width of the virtual window frame was wider than the width of the two openings. The virtual window was placed behind the openings with aligned centre, and tightly fixed to the wall by angle steels and screws.

According to the design (see appendix), the diffusor plate was placed 100mm from the wall surface. To keep the diffusor straight and tightly joint to the frame, three grooves were carved on the bottom panel and two side panels. The width of the groove was determined to be 7mm, 2mm wider than the diffusor itself so it can be inserted smoothly. When the diffusor's position was fixed, another parameter should be determined to eliminate the boundary effect. That was the distance from Origami tiles surface to the diffusor surface. This distance was determined by moving the 8-Origami plate forward and backward, in the meantime the display effect was observed from the test room. When the distance was large enough to eliminate the bright boundaries and LED spots, the 8-Origamin plate was fixed at that position by angle steels. The actual distance form plate to diffusor became 400 mm.

The iW Coveswere fixed to a structure which contains a long wooden strip and a "L" shaped structure. This has been already explained in the previous sections. To avoid interference from external light, the whole structure with Colour Kinetics was placed in a MDF box. The whole box was placed on the top of the main box with Origamis. The opening of the box was facing the top opening of the Origami box so that the light from the iW Covescan pass into the room.

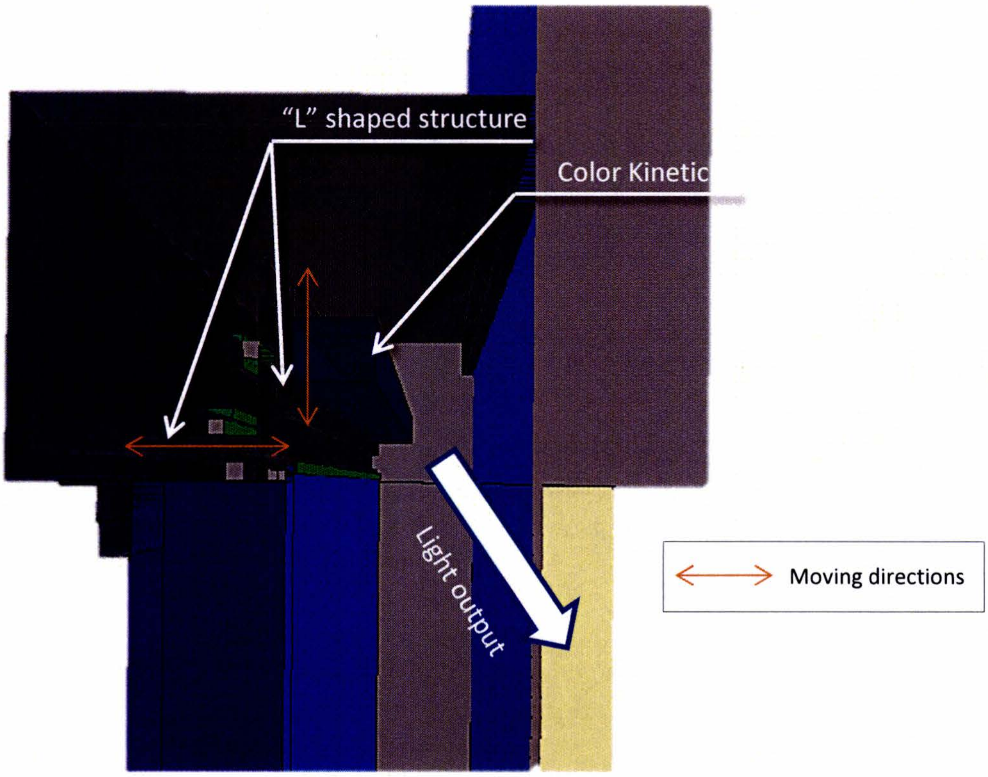


Figure 16 Cross section view and explanation of the direct light box structure

To support such a heavy system on the back of the wall extra supporting structures were needed. We placed several MDF right triangle brackets under the virtual window bottom. Together with the angle steels on the side and on the top, the whole virtual window was tightly connected to the wall and facing the two window openings.

All the ~~electrical~~ lamps used in the project came with a power supply, signal splitter, and data enabler which were shown in conceptual design in figure 10. Totally there were one Data Enabler Pro, one Enttec DMX pro box, one signal splitter, and four power adapters. In the integration plan, they were all fixed to the right-side panel of the virtual window in a line. According to the Dutch electrical specification (NEN-EN 12464-1), the electrical wirings should not be exposed to people, so another small MDF cover was made to cover the service modules up.

The practical construction process follows these mounting steps:

I. Build the basic frame and fix it on the wall, keep the centre and height aligned to the centre and height of window openings. In the meantime the support structure should also be built on the frame.
II. Place all service modules (power supply, DMX splitter, Data Enabler, etc.) on the right side of the panel.
III. Place the mirror plates in the first "space" of the structure which is between the window glass and the diffusor grooves.
IV. Insert the diffusor from the top into the grooves. Remove all the protection foils.
V. Place the mirror plates in the second "space" of the structure, which is behind the diffusor, the mirrors should cover top, bottom and two sides of the space.
VI. Place the Origami array plate on the back of the structure, fix it with temporary methods.
VII. Place the Colour Kinetics box on the top of the frame and fix.
VIII. Connect all the power cables and signal cables and make sure that the system can be turned on.
IX. Determine the suitable distance from Origami array to the diffusor by observation, and fix the Origami array to the frame.

Figure 18 shows the sectional view of the virtual window system, the three-layer structure, mirror boxes and top iW Coves box:

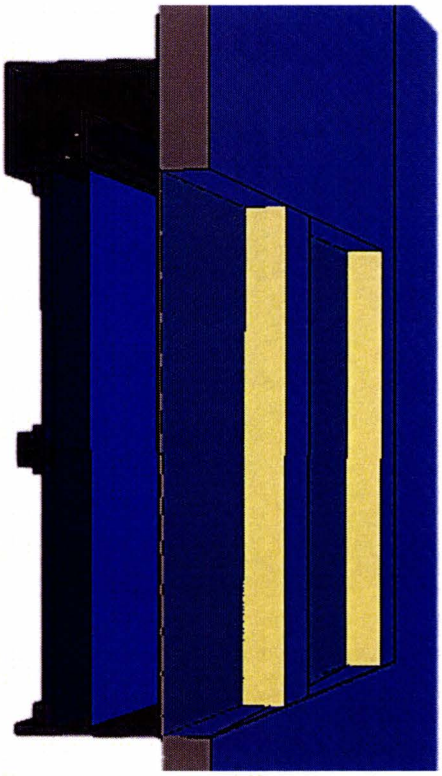


Figure 17 Cross section view of the virtual window system

By following the designed construction procedure, the virtual window prototype was built up in the standard test room (office) in the Experience Lab of Philips Research. Figure 19 and 20 show the virtual window's appearance from outside and inside of the test room:

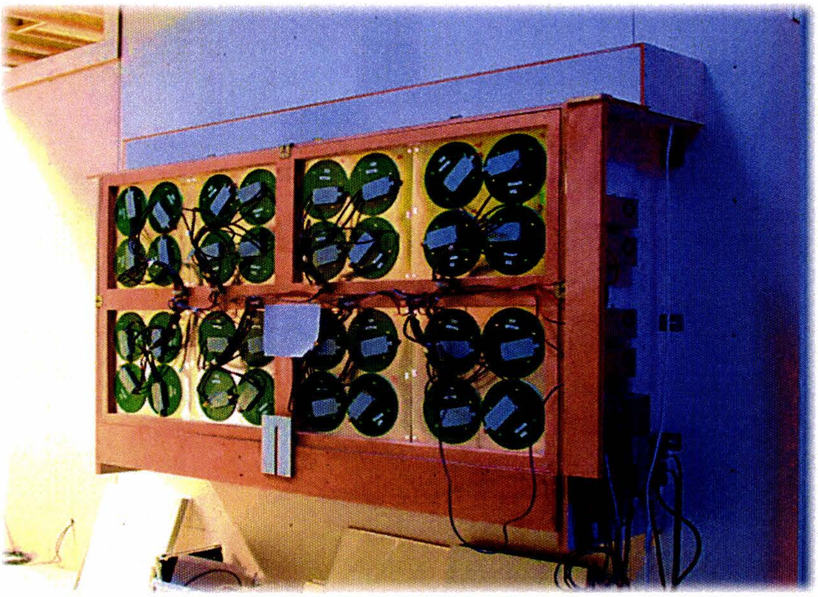


Figure 18 Finished virtual window structure was installed on outside of test room

Figure 19 Virtual window structure observed from inside of the test room

3.7.Programming and settings

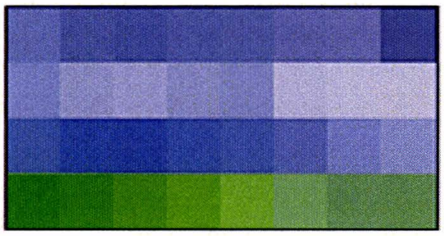
3.7.1. Introduction

After the construction of the virtual window prototype, the next thing to do was to determine the display program and relevant settings. By assigning values to the 120 DMX addresses, each lighting module can display differently and form the intended scene on the virtual window. However, since the amount of pixels is limited, the current prototype could not display very detailed pictures. Therefore a detailed picture should be converted to a 32 pixels picture, which can be described by 120 values and displayed on the virtual window.

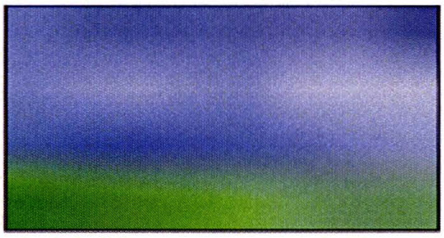
Three steps were necessary to generate a group of data that is readable to DMX512 processor. In this section each step is briefly introduced by using one photograph as an example. These principles of choosing original photographs were listed:

- Since the aspect ratio of the virtual window is 2:1, the aspect ratio should match, no matter how many pixels the original picture has.
- The horizon in a real window view is at eye height. Since people were supposed to sit in office, with an eye height of about 1.20 m, on the four-pixel height, the best proportion should be around 75% sky, thus the proportion of the land should occupy no more than a quarter of the whole display area.
- Light output should mainly come from the sky, and generally the appearance of sky is composed of blue sky and white clouds. In the real situation, even a blue sky without any cloud would emit white light, this is relatively difficult to realize with artificial lighting. Therefore, to increase the white light output, it was found that clouds should take more than half of the sky area even when the scene is meant to be sunny.

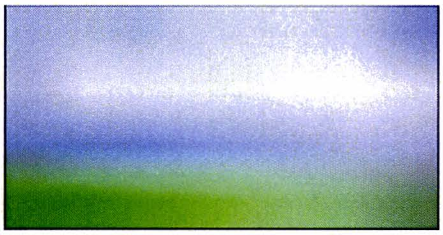
Select a picture that meets the principles of picture selection.



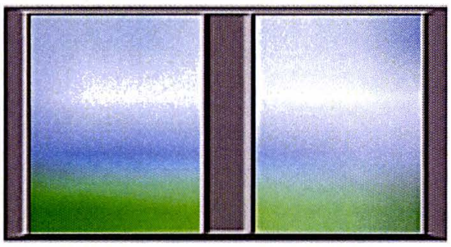
Use sophisticated image processing software (e.g., Adobe Photoshop) to change the pic into 32 pixels or mosaics, and then use the color picker function in the program to get RGB values of each pixel.



Use "Blur" function to mimic the effect of adding diffusor. This step can be used to check the final display on diffusing plate.



Apply the RGB values to the virtual window. Determine the direct source distribution and brightness of Origamis tiles by observation. (Effect image)



Add the frame and check if the final effects are satisfying and record the values for each address. (Effect image)

Figure 20 Process to convert a picture to 96 RGB values for each address

In order to make the addresses easier to manage, each of the pixels were assigned with a code. For the Origami units, the code consists of a letter, a number and another letter. The first letter stood for the row it belongs to, the following number showed the column it belongs to, and the last letter showed the color that the address controls (in this case only R, G, and B).

For the direct lamps, the codes were similar. They started with "P" indicating the lamp type is "Powercore Color Kinetics", and followed by number from 1 to 8 indicating the position of the lamp from left to right, the final letter "W" or "N", or "C" shows the color temperature property of the address (warm, neutral, cold). The coding plan is shown below in the example pic:

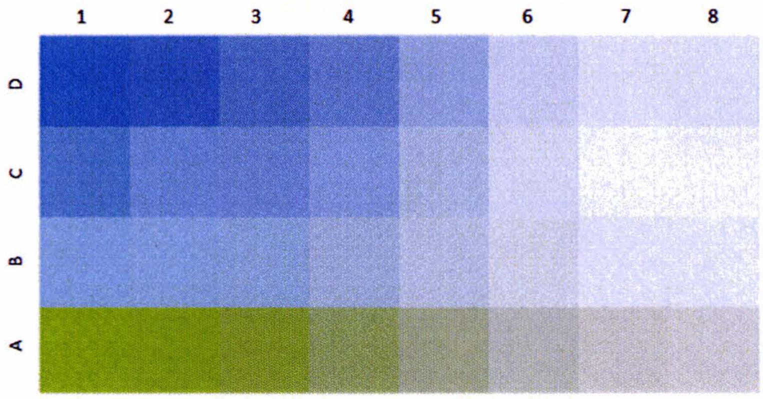


Figure 21 Codes for lighting modules (the "pixels") of Origami tiles

In the actual process of assigning RGB values to each address, it is not only based on computer processing on original picture, but also adjusted via people's observations. This step is necessary because the different display pattern between computer screen and Origami tiles may lead to color deviation. When the original values were input to the system, we invited people to the test room to have an initial experience and give their opinions on how to adjust each parameter to achieve their impression of a real window. This users' experience test principally is not very strict, but it helped us to find a more satisfying setting for a convincing virtual window. In total N = 10 people assessed the system.

Finally, the parameters for each address were determined to be the maximum setting, during the entire "year" circle, this setting is the peak that the prototype can reach. The final display picture (original and blurred) and its detailed table are shown below in Figure 22, 23 and Table 2:

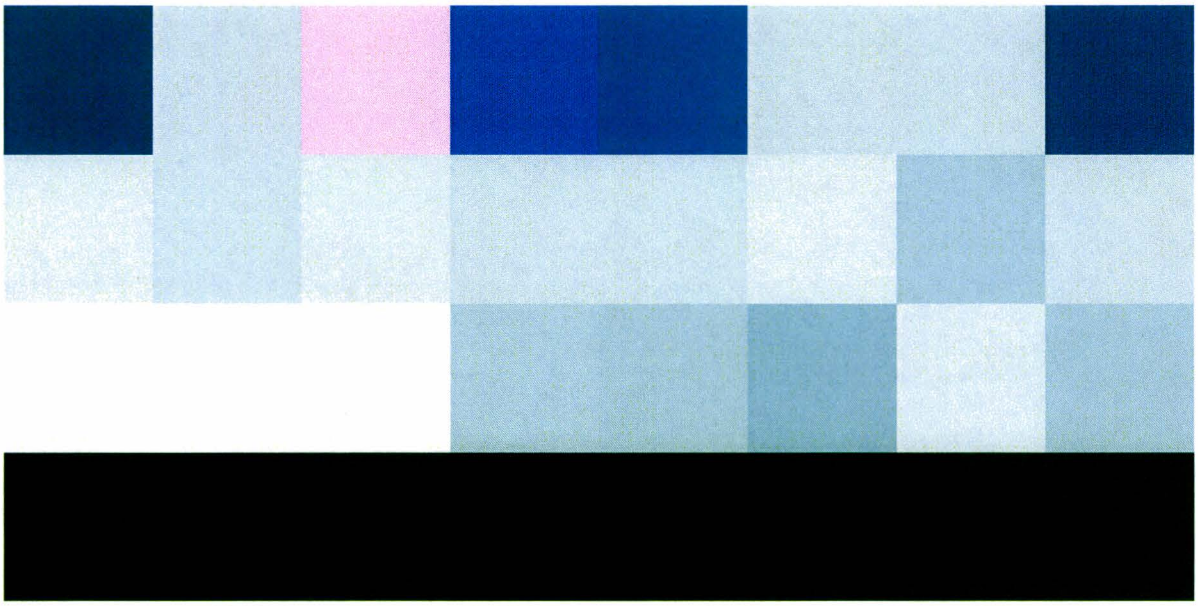


Figure 22 Original display image on the Origami array (preset scene)

Figure 23 Final blurred display image on the virtual window (preset scene)

Table 2 DMX values for each address of the virtual window display (default)

Position	P1		P2		P3		P4		P5		P6		P7		P8	
2700K	201	150	204	200	207	225	210	255	213	225	216	200	219	200	222	200
4000K	202	175	205	200	208	255	211	255	214	200	217	200	220	200	223	200
6500K	203	200	206	200	209	255	212	225	215	200	218	200	221	200	224	200
Position	D1		D2		D3		D4		D5		D6		D7		D8	
R	85	20	88	220	55	255	58	26	37	25	40	220	97	220	103	25
	86	255	89	255	56	230	59	233	38	255	41	255	98	255	104	248
B	87	230	90	255	57	255	60	255	39	255	42	255	99	255	105	227
Position	C1		C2		C3		C4		C5		C6		C7		C8	
R	94	230	91	220	52	230	49	220	46	220	43	230	100	200	106	220
	95	255	92	255	53	255	50	255	47	255	44	255	101	255	107	255
B	96	255	93	255	54	255	51	255	48	255	45	255	102	255	108	255
Position	B1		B2		B3		B4		B5		B6		B7		B8	
R	115	255	118	255	127	225	130	205	82	200	79	180	70	230	61	200
	116	255	119	255	128	255	131	255	83	255	80	255	71	255	62	255
B	117	255	120	255	129	255	132	255	84	255	81	255	72	255	63	255
Position	A1		A2		A3		A4		A5		A6		A7		A8	
R	112	0	109	0	124	0	121	0	76	0	73	0	67	0	64	0
	113	200	110	216	125	221	122	215	77	227	74	224	68	225	65	229
B	114	100	111	10	126	10	123	10	78	10	75	10	69	10	66	10

▨ Address
🟨 Position
🟧 DMX Value

3.7.2. Display patterns settings

3.7.2.1. Daily lighting level scenarios

For each scene setting, three daily lighting level scenarios were determined. These lighting level conditions were realized by scaling the default image settings. These three “lighting level” conditions were named “**summer**”, “**spring**”, and “**winter**” settings. These three profiles are abbreviated as “**SM**”,”**SP**” and “**WT**” in the following texts.

In order to make “lighting levels” settings more lifelike and convincing for a specific displayed scene, the “SM” level design is determined according to observations from several observers which we have mentioned in the last section.

After the “SM” profile setting was made, “SP” and “WT” modes were also determined by applying certain scale factors on the “SM” profile. To make the proportions to be simple and representative, luminance value of three typical real skies were selected as reference. These three luminance values are: 8000 cd/m^2 for the real “SM” lighting level sky, 5000 cd/m^2 for the “SP” lighting level sky, and 2000 cd/m^2 for the “WT” lighting level sky. Thus the proportion between the three scenes was 1: 0.625: 0.25.

3.7.2.2. General control patterns

In the real application where both real and virtual windows are present, the display of the virtual window should likely be related with the real outside conditions. The issue is then how to create the right combination of real and virtual window experiences throughout the year.

In the virtual window settings, three lighting level scenarios were determined. Assuming that the outdoor lighting level conditions could be also classified in those three levels, for annual use, two usage modes/patterns were introduced:

- **Mimicking mode**
  - Mimicking mode is that the light output of the virtual window follows the basic lighting tendency of an ideal real sky condition. It is only related with the lighting-level change.
- **Compensating mode**
  - Compensating mode is that the light output of the virtual window follows the opposite lighting tendency of an ideal real sky condition. It is only related with the lighting-level change.

Table 3 explains the operating mechanisms of the two modes.

Table 3 Two modes of lighting level control patterns

REAL LIGHTING LEVEL CONDITIONS	VIRTUAL WINDOW LIGHTING LEVEL PATTERNS	
	MIMICKING MODE	COMPENSATING MODE
SM	SM	WT
SP	SP	SP

WT	WT	SM

Both modes have their advantages and disadvantages. In the mimicking mode, the user can experience similar weather conditions from both window sets, but the effects of the real lighting condition might be amplified too much. In the compensating mode, the advantages and disadvantages are quite the opposite. Compensating mode can keep the lighting level consistent and stable, but the user may experience a contradicting view and perception from both windows.

In the real situations, the lighting level largely varies within minutes, even seconds. To apply this fact to the virtual window would certainly increase the control's complexity. Therefore, to simplify the calculations in this case, there was only one lighting level scenario in each day: SM, SP or WT.

3.7.2.3. *Daily- level control methods*

A country of high-latitude, like the Netherlands (52°N), has different daylight duration/hours throughout a year. Based on solar radiation data from Amsterdam, daylight in June can last for 15 hours and in December the daylight can only sustain for 7 hours. Since the selected standard application environment is an office room, the normal schedule followed the work timetable, which is from 9am to 5pm.

A real window has one function that the virtual window should be able to mimic, which is that the window should always remind people of the time of day by showing different outside lighting levels. In the design the virtual window should be able to realize this function to provide people the impression of time of the day automatically.

Generally the outside illuminance will increase with time in the morning, it will reach a peak value around 1 PM, and after that the illuminance will start to decrease with the approach of the night. In the virtual window daily settings, it still follows the natural pattern of changing lighting levels, but in a more controllable/controlled way.

However, in the context chosen, the virtual window is only operational during office hours, every day exactly eight hours; from 9am till 5pm. So the display curve will be converted into eight stages. For each stage a certain set of dim values are determined just to fit the luminance level changes.

For the daily control curves determination three "lighting level" conditions of the virtual window were distinguished. In the virtual window settings, we used different dimming levels to distinguish different scenarios. This section discusses how dimming levels of different lighting levels were determined. The method we used in this project is using solar radiation in three days to represent three lighting level scenarios. These three days are: March 21, June 21, and December 21, corresponding to SP, SM, and WT.

On the global level, because of the latitude difference and geological environment difference, the daily solar radiation situation varies from location to another. For people in each location, they are more used to the solar radiation pattern of their location. So it is hard to say that a universal yearly lighting level pattern could be found to meet all people's demand. In this study, in order to make the patterns to be simpler but representative enough, it is decided that all the possible application regions are categorized into five climate regions based on Köppen Climate Classification. For each region, a representative location is picked to represent the daily solar radiation situation of the corresponding region. Among these five climate regions, the polar climate is an exception and was not taken into consideration because that there is no large cities or population in this region. So in these daily patterns and the next yearly patterns, the polar climate was removed. And the mild temperature climate is divided into two sub-climate types, which are the Oceanic climate and the Mediterranean climate. To distinguish them, they are given the code of Cfb and Csa. These five climate regions and the representative cities are listed in table 4:

Table 4 Five climate regions and their representative cities

Group Code	Climate type	Typical City	Country
Af	Tropical/mega thermal climates	Singapore	Singapore
Bwh	Dry (arid and semiarid) climates	Cairo	Egypt
Cfb	Oceanic climate of Mild Temperate	Amsterdam	The Netherlands
Csa	Mediterranean climate of Mild Temperate climate	Sevilla	Spain
Dfb	Continental/micro thermal climate	Chicago	The U.S.

In most situations windows are placed vertically on the wall, so in order to mimic/ compensate the real lighting conditions from the window, vertical illuminance on the external wall of the five locations were taken as reference. These hourly vertical illuminance data at each location was gained by using Radiance models. In this model, the orientation of the measurement vertical point was determined to be south.

Before calculating data from Radiance model, first thing to be decided is which sky type should be taken. The options are clear sky, overcast sky and partly cloudy sky. From the climate data from Energy Department of the US, The hourly statistics for total sky cover percentage are available, combining this information, the sky type of the five cities can be determined in Radiance software. In the "gensky" function of radiance, these sky types are defined as:

Table 5 Sky types of five typical cities in Radiance models

Climate type	Typical City	"gensky" option	Sky type
Af	Singapore	-c	Standard CIE overcast sky
Bwh	Cairo	+i	Intermediate sky with sun
Cfb	Amsterdam	-i	Intermediate sky without sun
Csa	Sevilla	+i	Intermediate sky with sun
Dfb	Chicago	+i	Intermediate sky with sun

By applying the typical city locations and the sky types in Radiance, the south-orientated vertical illuminance distributions are listed in the following graphs:

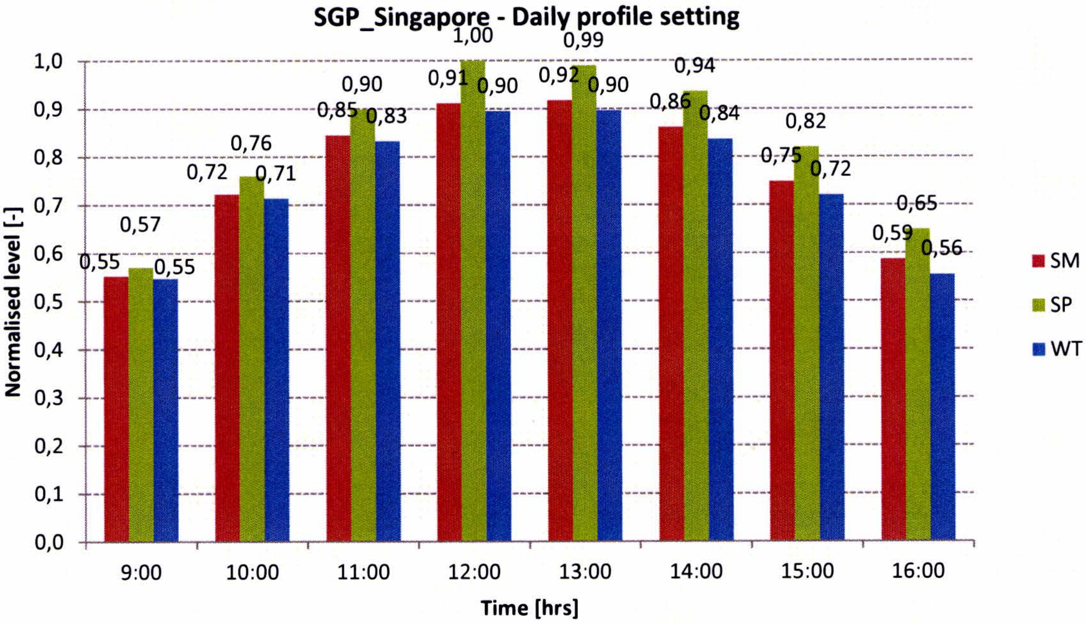


Figure 24 Normalized vertical illuminance levels in Mar21, Jun21 and Dec21 of Singapore

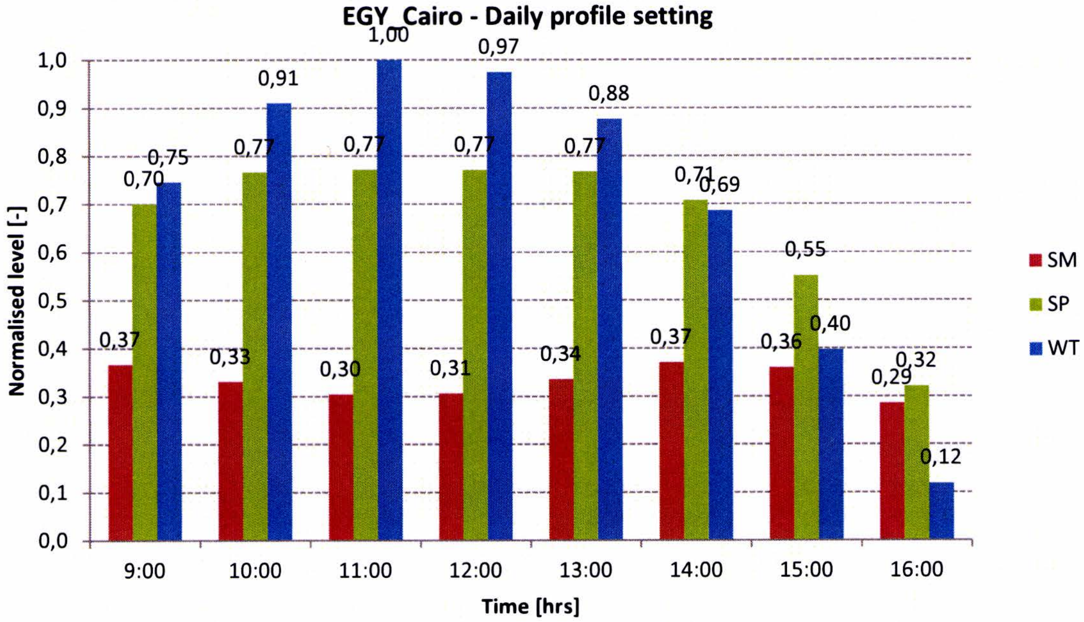


Figure 25Normalized vertical illuminance levels in Mar21, Jun21 and Dec21 of Cairo

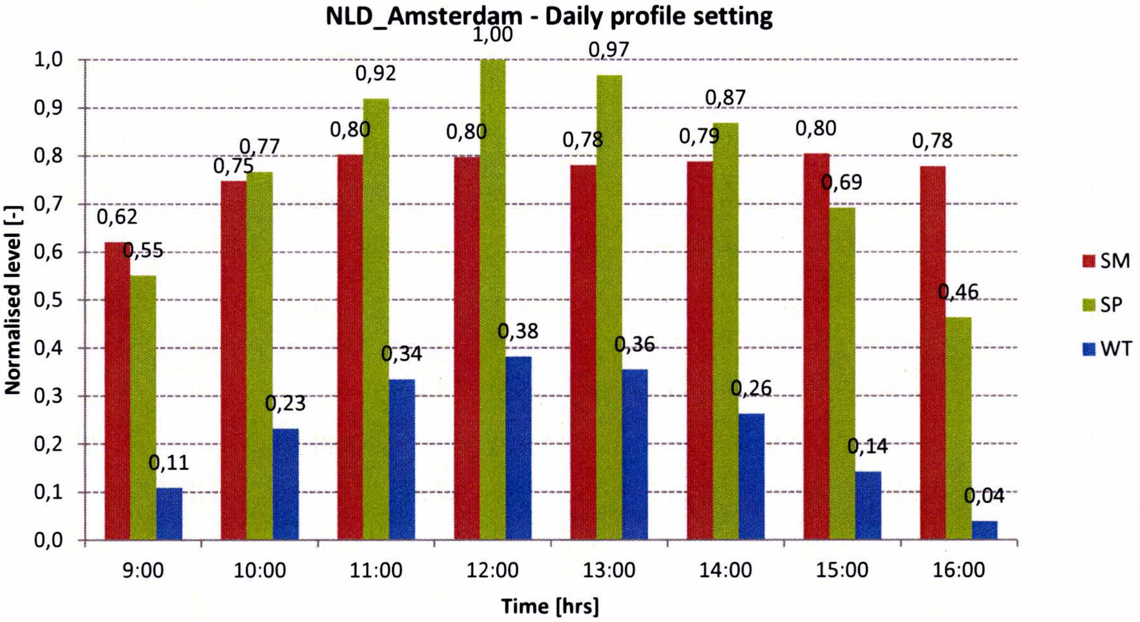


Figure 26 Normalized vertical illuminance levels in Mar21, Jun21 and Dec21 of Amsterdam

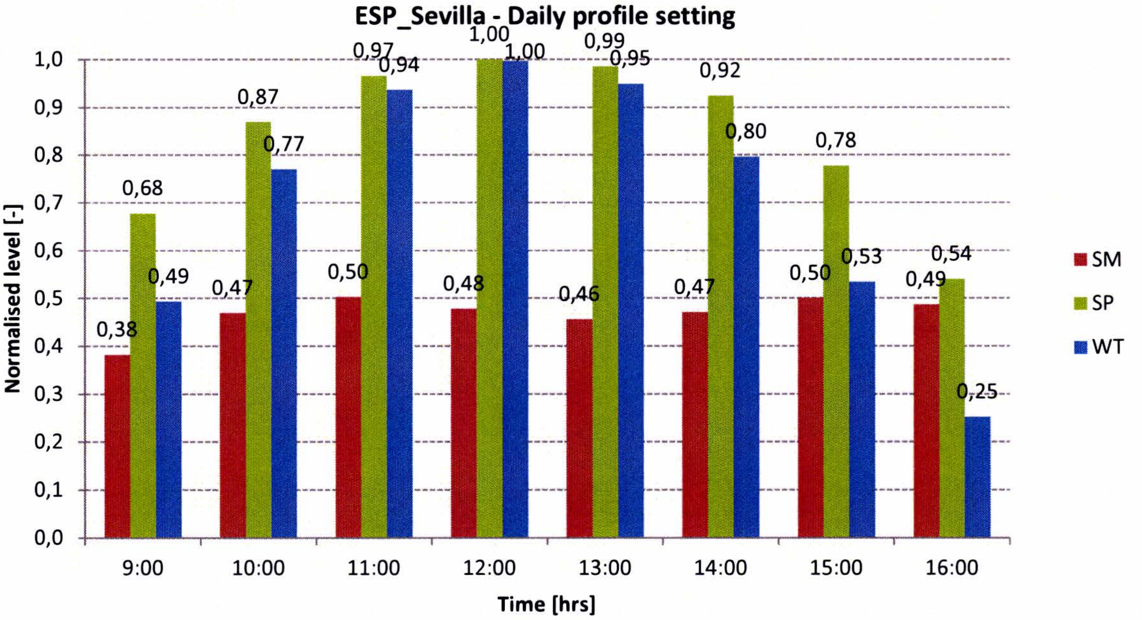


Figure 27 Normalized vertical illuminance levels in Mar21, Jun21 and Dec21 of Sevilla

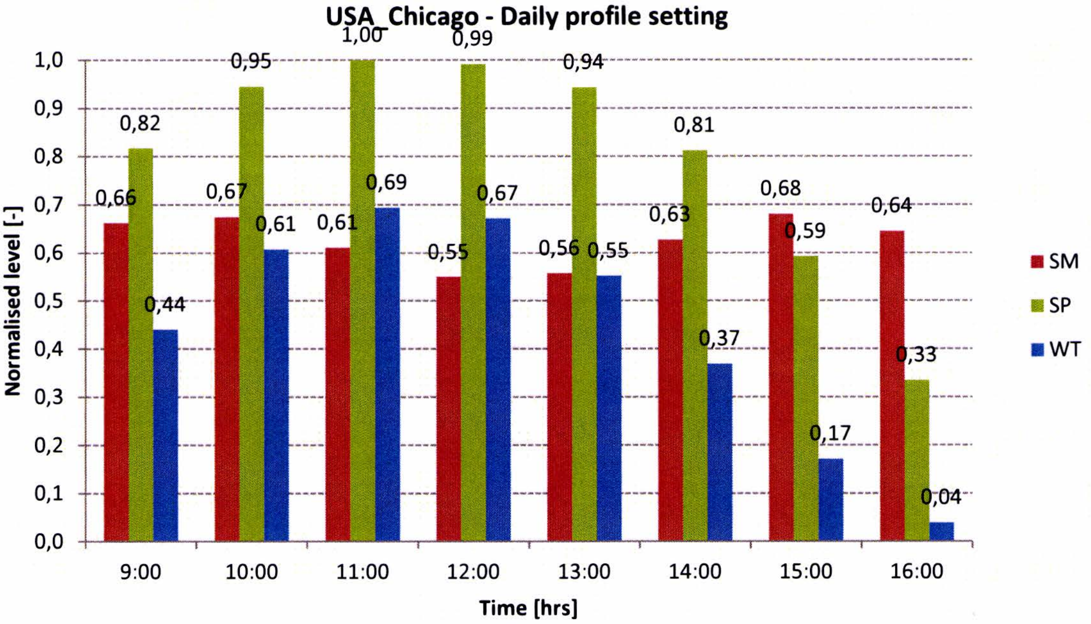


Figure 28 Normalized vertical illuminance levels in Mar21, Jun21 and Dec21 of Chicago

From Figure 24 to Figure 28 we can see how the lighting level varies throughout a day in the three representative scenes. From the figures it can be noticed that the values are in a big variable range. For instance, the luminance level of a bright sky is four to five times higher than the level in overcast sky. Comparing with the other two months, the average solar radiance level in December is really low in the target work time, but for the human perception there exists a difference between actual luminance variations and perceived brightness variations. This divergence of objective and subjective observations is caused by a physiological phenomenon, which is the non-linear relationship of human visual acuity and actual illuminance on the retina. S.S. Stevens (1963) proposed that the relationship follows a power function. The typical relationship is described in the following figure:

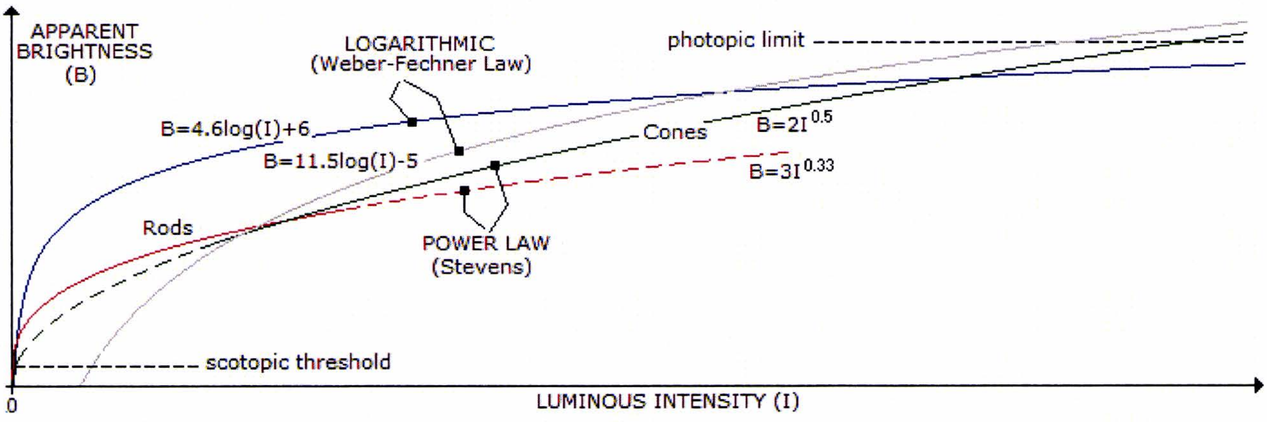


Figure 29 Range of subjective brightness sensations showing a particular adaptation level (http://www.telescope-optics.net/)

One thing to notice is, that the brightness range of real daylight conditions is much larger (L $\approx$ 2000 - 8000 cd/m^2) than the brightness range we are able to present on the virtual window screen (L $\approx$400 - 1600 cd/m^2). Under real daylight, the horizontal illuminance in the unobstructed open field is always much higher than we can reach via artificial light sources. Thus in this high lighting intensity range, although the illuminance of a summer day might be ten times higher than that of a winter day, the subjective brightness perception could tell our brain a much smaller difference. In the low lighting intensity situation a virtual window would provide the slope of subjective brightness. The actual light intensity is higher than high lighting intensity situations of the virtual window. In order to reach a similar sense of lighting level differences, we explored if the lighting level "curves" can be "compressed" or if the low lighting level parts had to be increased to reasonable extents.

In order to create more convincing visual experience and simplify the setting process at the meantime, Steven's power law is taken in this study, so we can keep the original ideal proportion from real sky and directly apply it to the following profile settings without making any change. This conclusion will also be taken in the following yearly profile settings.

According to the power-function relationship developed by S. S. Steven (1961), for a large subject like the virtual window, which may lead to an image on the retina of about 60° around the central fovea applying logarithmic weigh factors, the relationship between luminance and objective brightness becomes:

$$\psi = \mathrm{k}\,(\phi - \phi_0)^{\beta}$$

Where ψ is brightness, ϕ is luminance, ϕ_0 is a constant that seems to depend upon the visual threshold of start perceiving brightness, k is a constant that depends upon the choice of units, and β is the exponent (Stevens, 1961). Under retinal locus is around 60° condition of this case (Marks, 1966):

$$\beta = 0.33$$

$$\mathrm{k}=1.19$$

$$\phi_0=0.0045$$

3.7.2.4. *Yearly lighting level control patterns*

Normally yearly control methods are more complicated than the daily methods since seasons and latitude are getting involved. The basic concept is still combining daily patterns to the yearly pattern. In this prototyping project, the yearly patterns are tightly related to the total energy consumption estimation, and therefore we can make the year patterns much simpler. To get an initial basic understanding of the influence of the outside light level variations on energy consumption of the virtual window, horizontal solar radiation of twelve months in the five locations (ref: U.S.DoE) were categorized into three lighting level situations. This simplification assumes that for each day in a given month there will be only one lighting level scenario that corresponds to its average illuminance level. Figure 30 shows how global horizontal solar radiance varies throughout a year in the five representative locations:

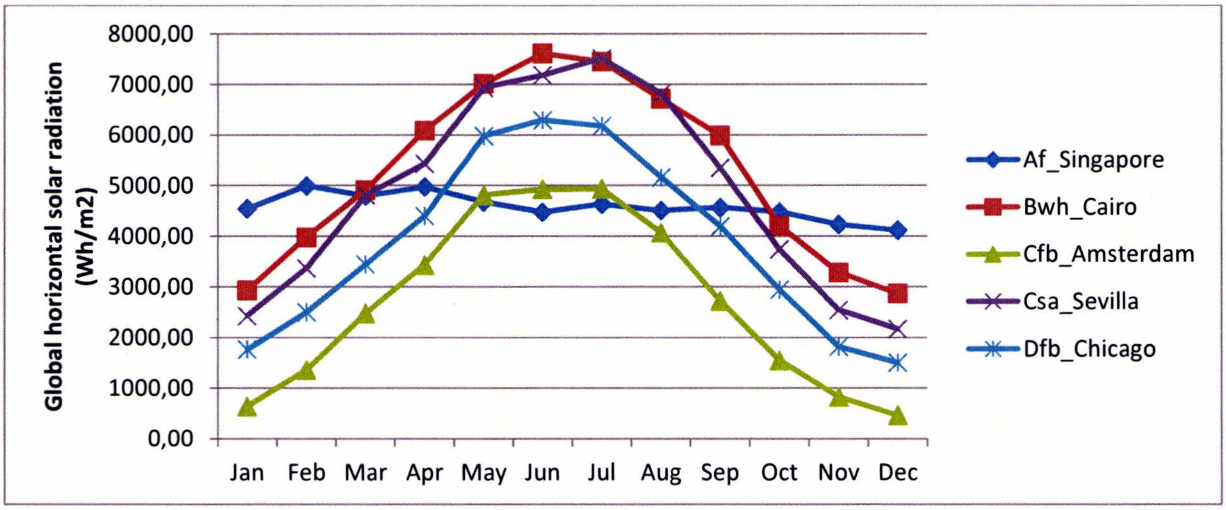
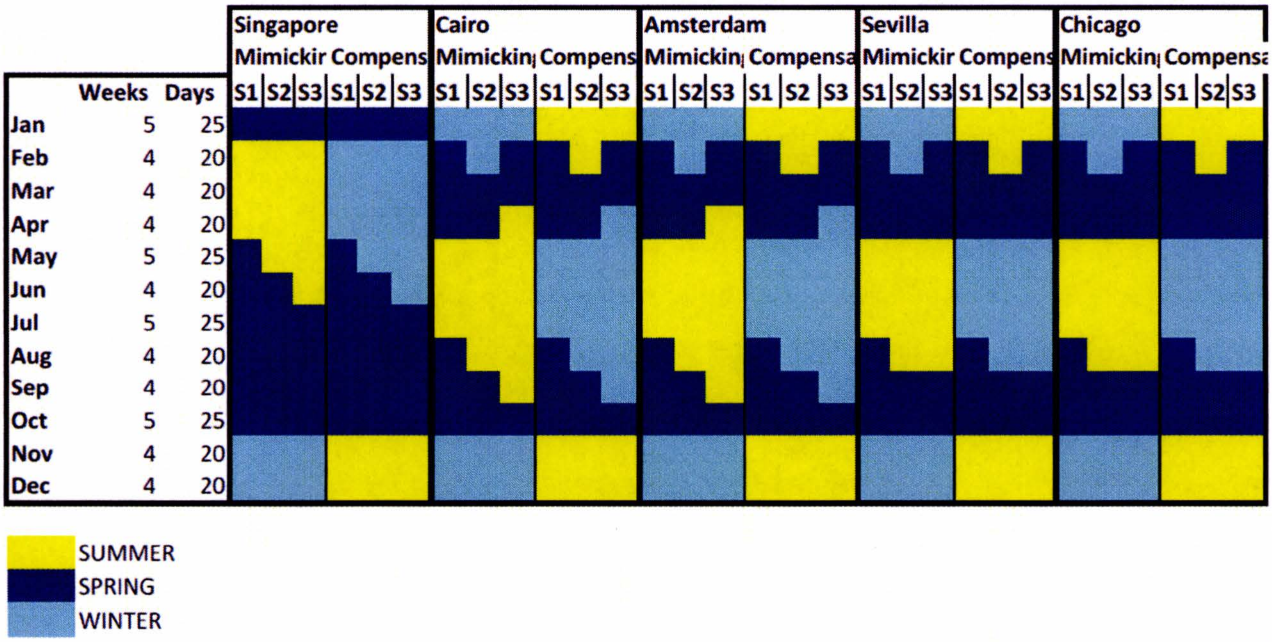


Figure 30 Annual solar radiation curves in five locations

For each location, assigning lighting-levels to each "virtual window" month by looking at the yearly curve can be very flexible. And different yearly profiles lead to different energy consumption results. So in order to show more possibilities and find out how different yearly patterns influence final energy consumption, for each location, three close scenarios are made. Each scenario contains its "Mimicking" mode and the corresponding "compensating" mode. The scenario assumptions are listed in Table 6, where terms S1, S2 and S3 refer to Scenario 1, Scenario 2 and Scenario 3.



			Singapore						Cairo						Amsterdam						Sevilla						Chicago					
			Mimickir			Compens			Mimickin			Compens			Mimickin			Compensa			Mimickir			Compens			Mimickin			Compensa		
	Weeks	Days	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
Jan	5	25	⬛	⬛	⬛	⬛	⬛	⬛	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨
Feb	4	20	🟨	🟨	🟨	🟦	🟦	🟦	⬛	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	🟨	⬛
Mar	4	20	🟨	🟨	🟨	🟦	🟦	🟦	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
Apr	4	20	🟨	🟨	🟨	🟦	🟦	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
May	5	25	⬛	🟨	🟨	⬛	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦
Jun	4	20	⬛	⬛	🟨	⬛	⬛	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦
Jul	5	25	⬛	⬛	⬛	⬛	⬛	⬛	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦
Aug	4	20	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟨	🟨	⬛	🟦	🟦	⬛	🟨	🟨	⬛	🟦	🟦	⬛	🟨	🟨	⬛	🟦	🟦	⬛	🟨	🟨	⬛	🟦	🟦
Sep	4	20	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	🟨	⬛	⬛	🟦	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
Oct	5	25	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛
Nov	4	20	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨
Dec	4	20	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨	🟦	🟦	🟦	🟨	🟨	🟨

🟨 SUMMER
⬛ SPRING
🟦 WINTER

Table 6 Lighting level scenarios for each month in a year

4. Methods for evaluating the lighting and energy performance

4.1.Measurement items

We measured lighting performance and power consumption of the new virtual window system. Lighting performance can be classified as luminance and illuminance distribution, uniformity, etc.; Power consumption of the system includes all light sources and service modules. The items were listed below:

1. Power-DMX value relationship

   This item was about the relationship between power readings of the system and the corresponding DMX values. It is noteworthy that the measurement was taken under the determined scene profile.

2. DMX value-luminance relationship

   This item measured the relationship between virtual window surface luminance and the corresponding DMX values. The measurement was taken under "full white" settings to avoid non-uniformity.

3. Luminance distribution on the virtual window surface

   The luminance map on the virtual window surface was measured.

4. Maximum and minimum illuminance and uniformity on the working plane

   This item measures the illuminance distribution on the working plane in the test room, it was taken under different patterns which were determined before.

5. Vertical illuminance from observer's position

   The vertical illuminance on standard observer's eye-height position was measured in this item.

6. Test room surface properties

   The reflectance of each surface in the test room was measured in this item.

7. Power consumption under different scenes

   This item measured the real-time power readings of the whole virtual window system under three lighting-level scenes.

4.2.Equipment used

1. Spectra Duo 680 spectrometer

This instrument measures spectral energy distribution and luminance in a small solid angle range ((1°, 0.5°, 0.25° and 0.125°) (Photo Research, 2013). In this measurement plan it was used to measure luminance and provide calibration reference to other instruments.

2. DSLR camera with special firmware (Canon 50D, Sigma 4.5mm f2.8)

   This camera together with fisheye lens and special firmware measures luminance distribution map in 180 degrees. Before use, the camera is calibrated by SpectraDuo 680 spectrometer.
3. ELV EM800 energy monitor

   This energy monitor can measure real time power, current, voltage and ϕ of certain electric equipment. In this case it measures power consumption of the virtual window device.
4. LUTRON LX-1118 light meter

   This device measures illuminance values. Before use, it is calibrated by SpectraDuo 680 spectrometer.
5. Standard Lambertian body panel

   This Lambertian body panel is an approximate ideal Lambertian reflector which obeys the Lambert's cosine law. By using SpectraDuo 680 spectrometer to measure luminance value on a point of the panel, and then multiply the result with π, the product is the illuminance value on that point.

4.3.Measurement steps

The measurement process will mainly include these following steps:

1. Measurement spots distribution in the virtual window test room

A measurement grid was set up on the working plane 750mm from the floor and the illuminance value on each point was measured and analyzed by using a LUTRON LX-1118 illuminance meter. The grid is designed to be 13 x 7 points the distance from one point to the next point is constant 0.5m. The central line of the grid is aligned to the center of the two window openings. The reference point of the grid is located right in the center of the grid, on the half distance position from window to the backwall. The grid has a uniform height of 750mm, which is the height of office desk. The layout of the grid is shown in the following floor plan:

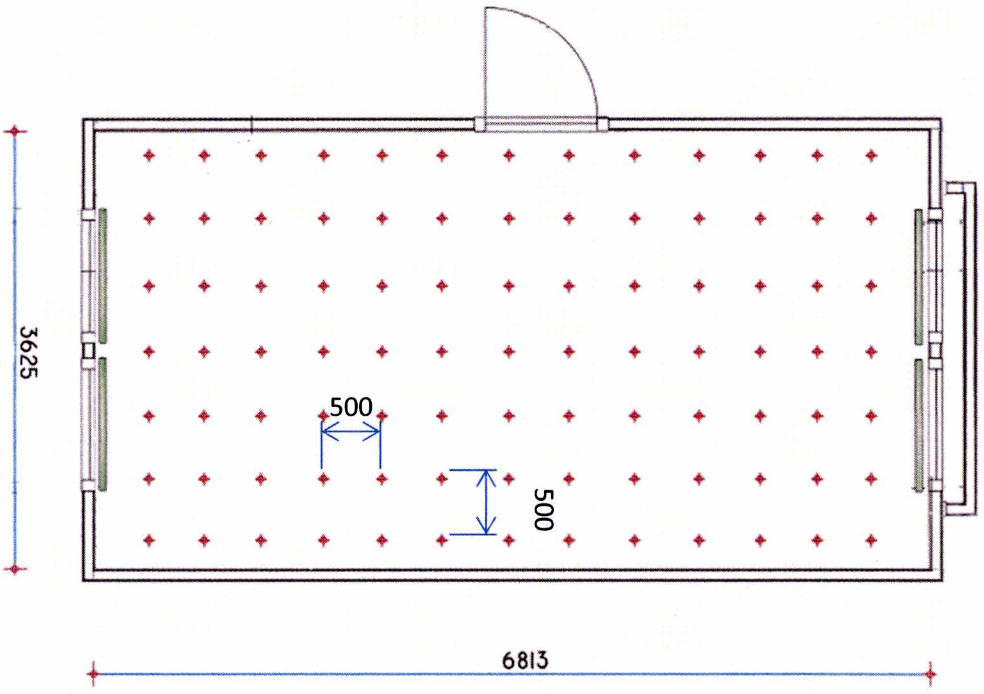


Figure 31 Horizontal illuminance grid distribution on the working plane height

2. Measure of the surface reflectance in the test room

The surface reflections properties were measured using a LUTRON LX-1118 illuminance meter by obtaining the ratio between incoming and reflected light from a certain surface. The principle of this measurement was to find the ratio between incoming light and reflected light from a certain surface. The rough reflectance result gives us a straightforward impression of the test room inner surfaces.

3. Determine observer's positions& height

This step determined where the observers' positions were, so that we can determine how their objective feeling is when different scenes were on. Related to average body height data, the standing eye height in this experiment will be fixed to 1.65m. At these height and positions the luminance camera will be placed. This following figure shows the standard observer's positions and directions in the test room:

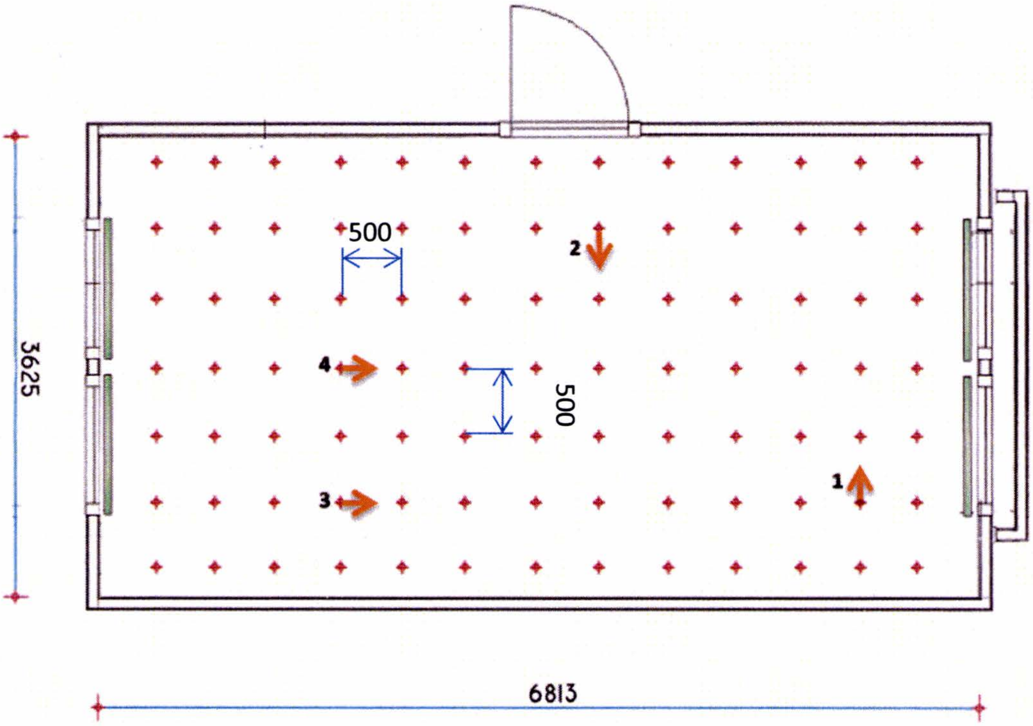


Figure 32 Observer's positions and directions in the test room

4. Measure the luminance distribution and corresponding parameters after calibration

After determining the observers' positions and directions, the DSLR camera with a fisheye lens (Sigma 4.5mm f2.8) and special firmware and processing software (Photolux 3.1) was used to act as observers' eyes at the determined positions. After calibration with a SpectraDuo 680 spectrometer, the DSLR camera will start to take photos. For each position under a certain lighting scene, then the luminance distribution was calculated and plotted by using Photolux 3.1 software.

5. Measure the illuminance distribution at the grid

Under each scene setting, the LUTRON lux meter is placed horizontally on the measurement points at the working plane height to get the corresponding illuminance values.

6. Measure the surface luminance as a function of DMX setting at full-white condition

During the measurement, the virtual window was set to display a full-white scene. The DMX value was changed from 5 to 255 in ten steps, for each step, the luminance at two sides of the virtual window was measured with the SpectraDuo meter. The relationship of the DMX value of the system and average luminance value on the virtual window surface was calculated from the measurement results. During the process, all the iW coves were turned off to avoid extra influences. This means that luminance values can be higher in the real test situation as both lighting systems will be on in that situation.

7. Measure the total power consumption as a function of DMX setting at scene-display condition

By plugging the ELV EM800 energy monitor in the socket of the entire system, the power consumption data could be directly obtained from the monitor screen directly. We got power, current, voltage, and cosφ values of different scenes in this measurement.

This measurement was taken when the preset scene was displayed. The scene DMX scale factor was changed from 0% to 100% in 9 steps. At each step, power consumptions were read and recorded. The relationship of DMX value of the system and system power consumption was calculated from measurement results.

5. Methods for calculating the potential energy consumption

5.1. Introduction

In the prototyping and testing process, the project environment was fully dependent on the mains power, but our ultimate goal is to combine the virtual window system with solar cell technology, after the practical setup is finished and actual energy-consumption patterns were determined. In this section the methods for calculating the potential of running virtual windows sustainably by combining the virtual window system with solar cells were discussed.

5.2. Suitable battery system design

The level of solar energy that can be harvested is dependent on the level of solar radiation, and so is the lighting performance of a real window facing outside. In different environments (depending on time zone, latitude, weather conditions, sun altitudes, obstructions, etc.), there will be large deviations for both energy gain and indoor lighting levels.

Because the uncertainty of weather, temperatures, or material properties, the actual power output from solar cells is highly fluctuant. It is generally hard to accurately predict the energy output of solar cells. In order to guarantee stable and continuous output, a "buffer" should be built in between the solar cells and virtual window system. This "buffer" is normally a storage battery. A battery system is necessary to store overflow of energy or provide power when the solar radiation is at a low level.

In case the solar radiation level is very low and the battery is empty, the solar cell could not support a virtual window system. To avoid this situation, the mains grid power should be integrated to the battery system and provide electricity when the solar energy is not sufficient. The hybrid solar energy system for the virtual window can have two conceptual designs:

- The first design provides 24V DC power a storage battery, and the battery is charged separately by solar cells and mains. The current from a solar cell is a variable DC current, and the current is processed by a charge controller to become more stable. While the mains grid gives 220V AC current, by applying an AC/DC adapter the current is turned into 24V DC. In the prototype project the mains were used as the power supply. If this solar power plan was to be used, then there would no longer be a need to use any power adapters.

- The second design is more suitable for larger scale applications. The system structure is simpler than the first design. In this plan, the virtual window system still gets its power from the mains grid like we did in the experiments, and solar-generated current from solar cells is adapted to 220VAC and is imported to the grid. In this plan the solar cells and virtual window system were almost isolated, but if the energy usage and energy gain reach even in a year, this plan has more adaptability and can be promoted to a larger scale application.

5.3.Environment requirements for solar-powered virtual window

As mentioned before, solar power production is influenced by many factors, hence the high degree of uncertainties. For this virtual window prototype, using the defined settings, the power consumption throughout a year is a constant.

Assuming that all energy demand of the virtual window needs in a year can be fully provided by solar energy, and given the yearly consumption data and the solar cell's efficiency, the required solar radiation throughout the target year can be estimated. A quality of currently available solar cells is that efficiency hardly changes with the solar radiation, so the solar cells' efficiency is considered as constant. The required total annual solar radiation can be expressed as:

$$[\text{TOTAL ANNUALSOLAR RADIATION DEMAND}] = \frac{TOTAL\ ANNUAL\ ELECTRICITY\ DEMAND}{EFFICIENCY\ OF\ SOLAR\ CELLS}$$

Solar radiation gain is the effective solar radiation that falls on the solar cell surface. By knowing the required solar radiation amount, users from different places of the world can adjust the combination of solar cell efficiency, cell's effective area, orientation angles etc. to achieve the required solar radiation amount.

In the discussion section, several ways to estimate annual solar radiation amount were introduced

6. Results

6.1.Relationship virtual window luminance and DMX values

The DMX values we set in the measurement are:

DMX: 5 10 30 55 105 155 185 205 225 255

The virtual window was turned on with the full-white mode and after diffusions the light output was quite uniform. We measured the centres of the two openings and calculate the average luminance value for two windows. The final results are shown inTable 7.

Table 7 Results of surface luminance and corresponding DMX values at full-white condition

DMX	right window	left window	Average

	(cd/m²)	(cd/m²)	(cd/m²)
255	1658	1456	**1557**
225	1416	1289	**1353**
205	1364	1170	**1267**
185	1227	1078	**1153**
155	1011	868	**939**
105	657	595	**626**
55	377	335	**356**
30	221	191	**206**
10	86	77	**81**
5	48	43	**46**

The graph showing the relation between the average window surface luminance and the DMX values is shown in figure 27.

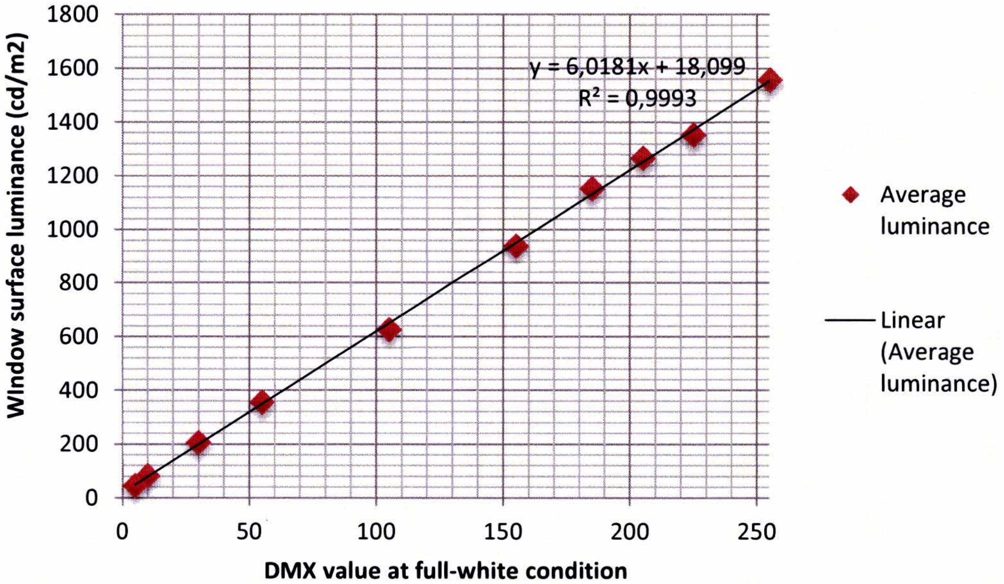


Figure 33 The DMX-surface luminance relationship curve at full-white condition

Figure 27 shows the relationship between window surface luminance and DMX values, the relationship is almost perfectly linear (R^2=0.9993).

6.2.Relationship system power consumption and DMX scale factors

In this measurement, the displayed "scene" was applied instead of the full-white mode. The peak DMX profiles for all addresses (scale factor=1) were considered as one whole profile, and by scaling the peak profile, the total power consumption at different scales could be observed. The results are listed in table 6:

Table 8 the results of system power consumption at different scale factors

Scale factor	0%	10%	25%	40%	62.5%	70%	80%	100%
Power (W)	126	172	249	321	436	479	574	640

The graph showing the relation between the total power consumption and the scale factor is shown in Figure 28:

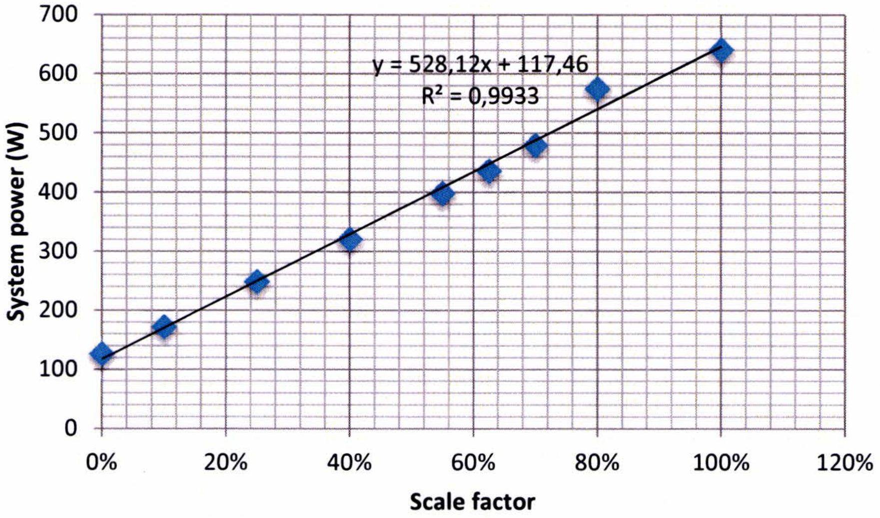


Figure 34 The system power consumption-scale factors relationship curve at preset scene condition

Figure 28 shows a R^2 value of larger than 0.99, which means a linear relationship between the system power and scale factors. When the scale factor is at 0%, which means all the DMX values were zero, and all light sources were turned off, the system is still consuming 126 Watt power. This phenomenon is caused by the service modules, the power adapter, data splitter, and their cooling fans. These parts of the system were still working when the lamps were switched off. By fitting a curve we get the approximate linear relationship which is indicated in the figure. By applying this linear relationship, we can calculate the power consumption for any scale factor in the following yearly power consumption estimation.

Besides the system power consumption at pre-set scene condition, the power consumption of full-white Origami tiles was also measured in order to estimate the efficacy of the current Origami tiles. The measurement results are:

Table 9 the results of total full-white Origami tiles power consumption at different scale factors

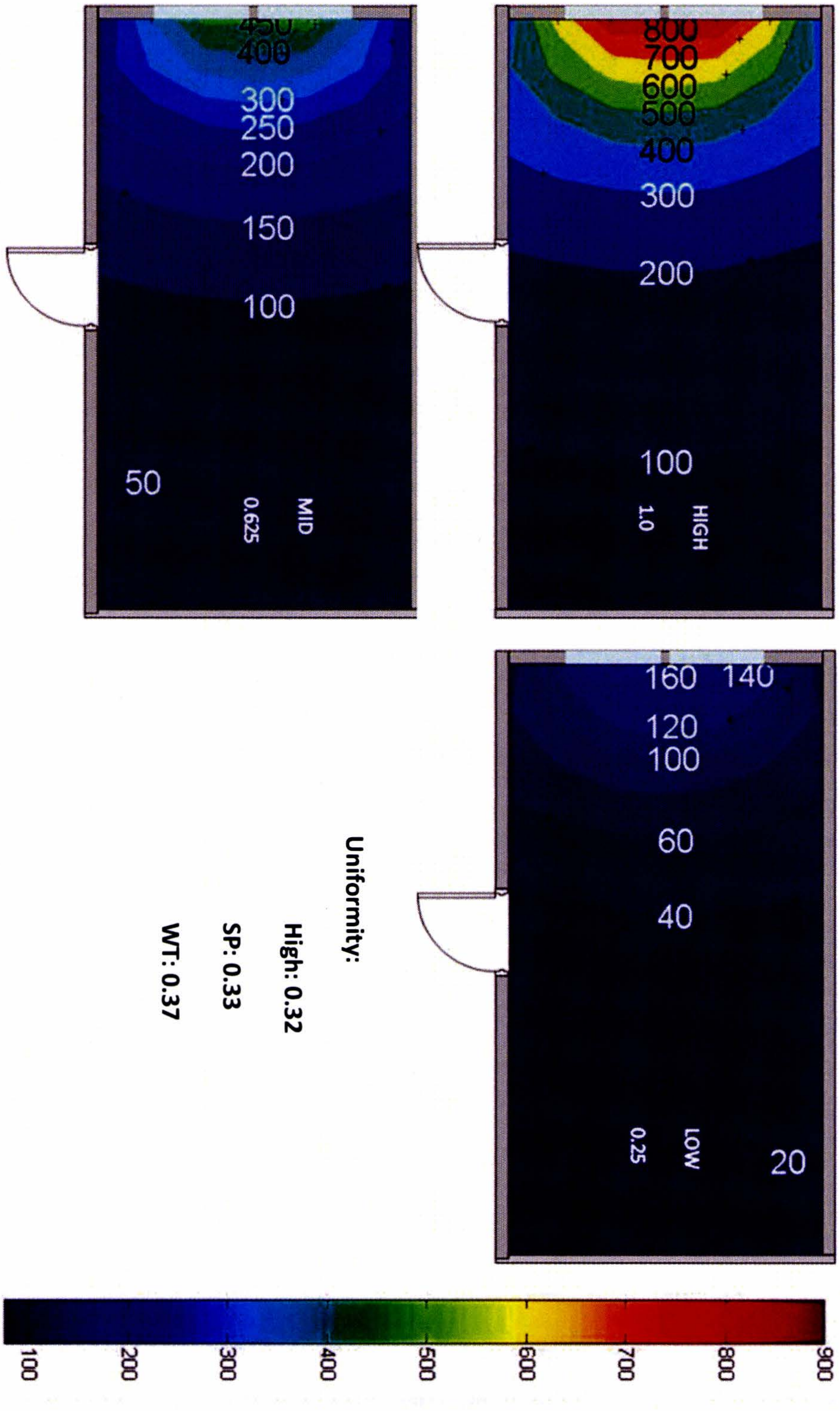
Scale factor	**0%**	**8%**	**24%**	**39%**	**59%**	**78%**	**88%**	**100%**
Power (W)	128.4	169.7	258.2	346.4	455.3	566.1	620.3	686.3

From Table 7 the net energy consumption of the Origami tiles can be calculated. Since in the measurement only the Origami tiles and the power adapters and DMX controllers were consuming energy, when the Origamis were completely switched off (0%), the power reading was 128. 4 watts, which was consumed by the power adapters and DMX controllers. So the net power consumption of Origami tiles at full-white setting and 100% scaling is 558 watts.

6.3. Illuminance distribution under three scenes

As a virtual window, its lighting performance is the most important function, so when the virtual window is switched to one of the three pre-set scenes, the illuminance distributions on the working plane of the test room were interesting for this study. Figure 29 shows the horizontal illuminance distribution results in an isolux diagram. The numerical results are listed in the appendix. In the following diagrams, a certain colour stands for a certain range of illuminance.

The three scenes were measured at the peak setting of their daily profiles, the ratio of window luminance under the High, Medium, and Low settings are 1: 0.625: 0.25.



Uniformity:

High: 0.32

SP: 0.33

WT: 0.37

Figure 35 Illuminance distribution on working plane under three lighting-level settings (lux)

6.4.Virtual window surface luminance distribution under three scenes

The test was performed under the three different scale settings: High, Medium, and Low. The measurement equipment is the luminance camera with a fisheye lens on a tripod. By using Photolux 3.1 software, the luminance distribution in 180° range is plotted and relevant parameters were calculated. It should be noted that a fisheye view could not represent the actual human-eye's view range. The results of luminance and vertical illuminance values are shown in the Table 8, while the corresponding luminance maps are shown in Figure 30.

In table 7 it is seen that the maximum luminance of several scenes is surprisingly high. This high luminance value was caused by the direct light sources, in this case the LED luminaire with no diffusive optical modules. The LEDs were small and produce a large light output, hence the extremely high luminance.

Table 10 Luminance measurement summary for three settings from four observers' positions

LUMINANCE MEASUREMENT SUMMARY	**Position 1**			**Position 2**			**Position 3**			**Position 4**		
	High_1	**Med_1**	**Low_1**	**High_2**	**Med_2**	**Low_2**	**High_3**	**Med_3**	**Low_3**	**High_4**	**Med_4**	**L**
Min Luminance (cd/m^2)	2.94	2.44	1.09	1.57	1.88	0.69	1.8	1.13	0.44	2.58	1.48	
Avg Luminance (cd/m2)	255	155	60	89	49	18.5	55	34	13	55	34	
Max Luminance (cd/m2)	320000	143000	57000	36000	17500	3060	2270	1740	480	2130	1310	
Standard deviation (cd/m2)	1930	840	274	380	188	60	179	117	42	182	114	
Vertical Illuminance (lux)	660	400	157	224	119	47	295	182	70	303	187	

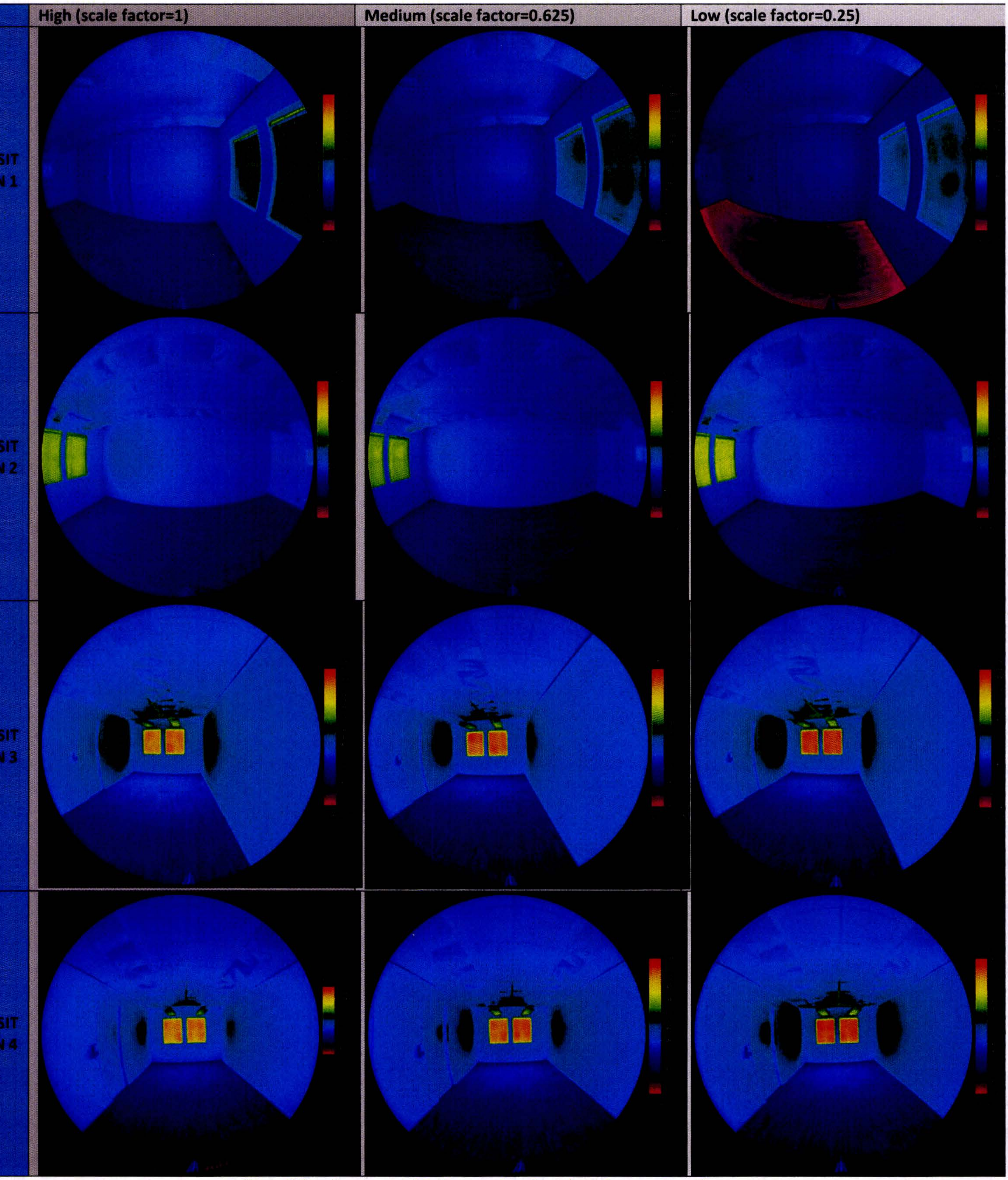


Figure 36 Luminance map for three settings from four observers' positions

6.5. System power consumption under three scenes on daily and yearly levels

The daily and annual calculations were based on the obtained relationship between power and the scene scale factors. As mentioned before, the daily and yearly profiles follow the time schedule of normal office hours between 09.00-17.00 hrs.

Based on the measurement, the estimated linear relationship between the total power consumption and scene scale factors is:

$$\mathbf{TOTAL\ POWER} = \mathbf{528.12} \times [\mathbf{SCALE\ FACTOR}] + \mathbf{117.46}$$

Applying this function, all power consumption can then be estimated as shown in Table 11:

Table 11 Estimated power and energy consumption on a daily basis

	Singapore			**Cairo**			**Amsterdam**			**Sevilla**			**Chicago**		
OFFICE HOURS	SM	SP	WT	SM	SP	WT	SM	SP	WT	SM	SP	WT	SM	SP	WT
SYSTEM ENERGY (Wh)	3364	3616	3285	1523	2948	3133	3350	3408	1099	2097	3678	3144	2762	3518	1989

In the yearly/annual mode, three different scenarios were determined for each location in Table 6. Just like the daily profile, the yearly profile is also based on working schedule, so for each month, only the working days were taken into consideration. The results are shown in Table 12-16:

Table 12 Estimated energy consumption on a yearly basis of Singapore

			Mimicking			**Compensating**		
	Weeks	**Days**	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Jan	5	25	90	90	90	90	90	90
Feb	4	20	67	67	67	66	66	66
Mar	4	20	67	67	67	66	66	66
Apr	4	20	67	67	67	66	66	66
May	5	25	90	84	84	90	82	82
Jun	4	20	72	72	67	72	72	66
Jul	5	25	90	90	90	90	90	82
Aug	4	20	72	72	72	72	72	72
Sep	4	20	72	72	72	72	72	72
Oct	5	25	88	88	88	88	88	88
Nov	4	20	66	66	66	67	67	67
Dec	4	20	40	40	40	67	67	67
Total [kWh]	52 weeks	260 days	**883**	**877**	**872**	**908**	**899**	**885**

Table 13 Estimated energy consumption on a yearly basis of Cairo

			Mimicking			**Compensating**		
	Weeks	**Days**	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Jan	5	25	78	78	78	38	38	38
Feb	4	20	59	63	59	59	30	59
Mar	4	20	59	59	59	59	59	59
Apr	4	20	59	59	30	59	59	63
May	5	25	38	38	38	78	78	78
Jun	4	20	30	30	30	63	63	63
Jul	5	25	38	38	38	78	78	78
Aug	4	20	59	30	30	59	63	63
Sep	4	20	59	59	30	59	59	63
Oct	5	25	74	74	74	74	74	74
Nov	4	20	63	63	63	30	30	30
Dec	4	20	63	63	63	30	30	30
Total [kWh]	52 weeks	260 days	**679**	**654**	**593**	**687**	**662**	**698**

Table 14 Estimated energy consumption on a yearly basis of Amsterdam

			Mimicking			**Compensating**		
	Weeks	**Days**	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Jan	5	25	27	27	27	84	84	84
Feb	4	20	68	22	68	68	67	68
Mar	4	20	68	68	68	68	68	68
Apr	4	20	68	68	67	68	68	22
May	5	25	84	84	84	27	27	27
Jun	4	20	67	67	67	22	22	22
Jul	5	25	84	84	84	27	27	27
Aug	4	20	68	67	67	68	22	22
Sep	4	20	68	68	67	68	68	22
Oct	5	25	85	85	85	85	85	85
Nov	4	20	22	22	22	67	67	67
Dec	4	20	22	22	22	67	67	67
Total [kWh]	52 weeks	260 days	**732**	**685**	**728**	**721**	**673**	**582**

Table 15 Estimated energy consumption on a yearly basis of Sevilla

			Mimicking			**Compensating**		
	Weeks	Days	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Jan	5	25	79	79	79	52	52	52
Feb	4	20	74	63	74	74	42	74
Mar	4	20	74	74	74	74	74	74

Apr	4	20	74	74	74	74	74	74
May	5	25	52	52	52	79	79	79
Jun	4	20	42	42	42	63	63	63
Jul	5	25	52	52	52	79	79	79
Aug	4	20	74	42	42	74	63	63
Sep	4	20	74	74	74	74	74	74
Oct	5	25	92	92	92	92	92	92
Nov	4	20	63	63	63	42	42	42
Dec	4	20	63	63	63	42	42	42
Total [kWh]	52 weeks	260 days	**811**	**769**	**779**	**816**	**774**	**805**

Table 16 Estimated energy consumption on a yearly basis of Chicago

			Mimicking			**Compensating**		
	Weeks	Days	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Jan	5	25	50	50	50	69	69	69
Feb	4	20	70	40	70	70	55	70
Mar	4	20	70	70	70	70	70	70
Apr	4	20	70	70	70	70	70	70
May	5	25	69	69	69	50	50	50
Jun	4	20	55	55	55	40	40	40
Jul	5	25	69	69	69	50	50	50
Aug	4	20	70	55	55	70	40	40
Sep	4	20	70	70	70	70	70	70
Oct	5	25	88	88	88	88	88	88
Nov	4	20	40	40	40	55	55	55
Dec	4	20	40	40	40	55	55	55
Total [kWh]	52 weeks	260 days	**762**	**717**	**747**	**759**	**713**	**728**

🟨	SUMMER
🟦	SPRING
▨	WINTER

7. Discussion

7.1.Lighting performance discussion

The highest luminance on the virtual window is around 1600 cd/m^2, while the actual sky luminance is several times higher. By applying the "same proportion" method, the virtual window can still mimic the real day lighting condition to some extent. According to horizontal illuminance measurement and calculation, when only using the virtual window, the illuminance uniformity on the working plane of the "SM" scene is 0.32, while that of "SP" and "WT" is 0.33 and 0.37.

However, this lighting performance could be improved with the same power consumption. One factor of this project we should consider is that the Origamis were manufactured in the year of 2008; LED efficacy has been improved a lot since they were produced. The actual efficacy of the Origami tiles were not indicated in the product catalogue, in order to have a clear concept of the luminaire, simple calculation could be done to estimate the efficacy of the Origamis in the virtual window system.

Before the estimation, one assumption should be made, the diffusor in the virtual window should be considered as approximate Lambertian body, which obeys the Lambert's cosine law. The calculation formula of the efficacy is listed:

$$\text{ORIGAMI EFFICACY} = \frac{LUMINANCE\ \times TOTAL\ AREA\ \times 2\pi}{ORIGAMI\ POWER}$$

Where the average luminance at full power is 1557 cd/m^2 from the previous measurement, the total area of the diffusor is 2.88 m^2 (1.2m × 2.4m). The full-white maximum net power of the Origami tiles is 558 watts from the previous measurement. Hence the approximate efficacy of the Origami tiles is 50.5 lm /watt.

As to the iW Cove MX Powercore luminaires, the efficacy data can be available from Philips product catalogue. For the wide-beam version used in this project, the efficacy for each group of LEDs is listed below in Table 17.

Table 17 Efficacy information of the iW Cove MX Powercore luminaires

iW Cove MX Powercore	2700K	4000K	6500K	All Channels
Efficacy (lm/W)	22.1	26.1	31.1	38.8

The efficacy of iW Cove is higher than the Origami tiles, but still both of them are below 40lm/watt. Compared with this result, nowadays LEDs with efficacy higher than 100lumen/watt or even 200lumen/watt are available. For instance, efficacies of the CXA product family (blue LED +phosphors) from CREE are already above 100lm/watt. And what's more, by April of 2013, Philips succeeded in developing a prototype LED lamps hitting an efficiency of 200 lm /watt. This LED prototype uses RGB modules to realize white light output. This shows its possibility to be applied on this virtual window to replace Origamis as display light sources. With the efficacy of 200 lm /watt, the light output of the virtual window could be eight times higher in display and three times higher in direct lighting under the same power consumption situation. This shows that the maximum surface luminance would be able to increase from around 1600cd/m^2 to 8000cd/m^2, which is already high enough to mimic most actual sky situations.

From the appearance of the virtual window, the modified Origami tiles combined with the diffuser panel can successfully generate a display scene without visible boundaries in the form of dark or bright lines. The application of the two mirror boxes reduces light loss and increases the visual experience at the same time. The display shows a blurred scene, which can give people the experience of grass and sky through the "window", and makes it hard to focus on the lighting plate thus creating a sense of depth.

The displayed "scene" together with the direct light effect in shown in Figure 37 and the direct light-only effect is shown in Figure 38:

Figure 37 Effect of the virtual window with display and direct light functions

Figure 38 The direct light can create "sun patterns" on the sidewalls (iW Coves only)

Compared with a real window scene, the virtual window still has some shortcomings in displaying and directing light. The amount of pixels limits the ability of showing more complicated views. The second shortcoming is that the color display is not convincing enough, especially the display of green grass was not very realistic. The third shortcoming is about the direct light, because of the special positioning of the direct light sources, the light is not parallel like real sunlight. And the light intensity is not yet high enough so that sometimes the direct light patterns can be "covered" by light from Origami tiles. As mentioned before, these shortcomings are mainly resulted from the shortcomings of the light sources used in this prototype. If the virtual window design can be combined with the latest LED technology, the light output could be magnificently higher (efficacy could be improved from 25.25 lm/W to approx.200 lm/W). In terms of display effect, there is also large space to get improved. In this project the Origami tiles were selected because of the current storage availability. The main limitation of the Origami tiles is the size of the pixel unit, which makes higher-resolution display impossible. If in the future the next generation of virtual window will be built, a good recommendation could be choosing LEDs with high efficacy and the ability to constitute small-sized pixel units.

7.2.Energy performance discussion

From the measurement and reasonable assumptions, we get the three estimated energy consumption of the virtual window system in five locations, which is listed in from Table 12 to Table 16. All these estimated energy consumptions are summarized in Table 18 to make this clearer:

Table 18 Summary of annual energy consumption estimation

		Mimicking			Compensating		
Climate code	**Location**	S1[kWh]	S2[kWh]	S3[kWh]	S1[kWh]	S2[kWh]	S3[kWh]
Af	**Singapore**	**883**(Max)	**877**	**872**(Min)	**908**(Max)	**899**	**885**(Min)
Bwh	**Cairo**	**679**(Max)	**654**	**593**(Min)	**687**	**662**(Min)	**698**(Max)
Cfb	**Amsterdam**	**732**(Max)	**685**(Min)	**728**	**721**(Max)	**673**	**582**(Min)
Csa	**Sevilla**	**811**(Max)	**769**(Min)	**779**	**816**(Max)	**774**(Min)	**805**
Dfb	**Chicago**	**762**(Max)	**717**(Min)	**747**	**759**(Max)	**713**(Min)	**728**

From table 18, the energy consumption range in these three scenarios for each location is available. In Singapore, the energy consumption varies from 872kWh to 908kWh; In Cairo, the energy consumption varies from 593kWh to 698kWh; In Amsterdam, the energy consumption varies from 582kWh to 732kWh; In Sevilla, the energy consumption varies from 774kWh to 816kWh; In Chicago, the energy consumption varies from 713kWh to 762kWh. This range will be considered in the solar panel area estimation.

In order to find the minimum solar panel area we need in a year, the efficiency of the solar cell data is required. The efficiency means the ratio of the electrical output of solar cell to the incident energy in the form of sunlight. Current solar cell energy conversion efficiencies for commercially available multicrystalline Si solar cells were around 14-19% (Fraunhofer, 2013).In this estimation process, in order to keep safe, the solar cell efficiency is determined to be 14%. As long as the solar cells at each location can receive such amount of effective solar radiation in a year, the virtual window could be driven entirely on solar power.

For a user who intends to apply a new virtual window system, the first thing he/she should consider is how much effective area there is available on the roof or façade to place solar cells and collect energy. If the application environment is a high office building, the usable area for a single office unit is its own façade. If the virtual window will be installed in a family house, then the usable area can be the roof. For any location in the world, there is an optimum angle to get the best radiation input. This value varies from place to place, when the application environment changes, the solar cells' optimum tile angle is also different. When considering installing a solar powered virtual window, this factor (angle) should always be taken into account. In this case, the solar cells were considered to be installed horizontally.

We need the annual solar irradiance to estimate how much the energy density is at a certain location on Earth. By using the weather data from Energy Department of the US, the monthly sum of global solar radiance data of the five involved locations was collected and summarized. Table 19 shows the yearly sum of global irradiance which includes both direct and diffusive irradiance in the five locations.

Table 19 Annual sum of global horizontal irradiance in the five locations (source: DoE. U.S.)

	Average daily solar radiation sum (kWh/m^2)												Yearly Sum (kWh/m^2)
Location	**Jan**	**Feb**	**Mar**	**Apr**	**Mei**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Singapore	4.5	5.0	4.8	5.0	4.7	4.5	4.6	4.5	4.6	4.5	4.2	4.1	1666.9
Cairo	2.9	4.0	4.9	6.1	7.0	7.6	7.5	6.7	6.0	4.2	3.3	2.9	1916.3
Amsterdam	0.6	1.4	2.5	3.4	4.8	4.9	4.9	4.1	2.7	1.6	0.8	0.5	981.9
Sevilla	2.4	3.4	4.8	5.4	6.9	7.2	7.5	6.8	5.3	3.7	2.5	2.2	1773.7
Chicago	1.8	2.5	3.4	4.4	6.0	6.3	6.2	5.2	4.2	2.9	1.8	1.5	1404.9

From the table showing the yearly sum of global irradiance density, the tropical climate collects the most amounts of solar radiations. Amsterdam, which stands for the oceanic climate, gets the least solar radiation. This result does not only depend on the latitude of the location but also the sky cover ratio and other climate factors.

Also assuming that the horizontally placed solar efficiency is 14% and the virtual window will fully depend on the solar energy gain via solar cells. Then the area needed for solar cells can be calculated. It is noteworthy that the solar cell area calculation is based on a monthly basis, and after the calculation, the maximum area is picked to be able to support all monthly conditions. The estimation process example is shown in Table 20, which is based on the data of Singapore.

Table 20 Solar cell area estimation on a monthly basis in Singapore

Singapore	I [Wh/m^2]	**Mimicking**						**Compensating**					
		S1		S2		S3		S1		S2		S3	
		W [kWh]	A [m^2]	W [kWh]	A [m^2]	W [kWh]	A [m^2]	W [kWh]	A [m^2]	W [kWh]	A [m^2]	W [kWh]	A [m^2]
Jan	4545	90	5.7	90	5.7	90	5.7	90	5.7	90	5.7	90	5.7
Feb	4994	67	4.8	67	4.8	67	4.8	66	4.7	66	4.7	66	4.7
Mar	4798	67	5.0	67	5.0	67	5.0	66	4.9	66	4.9	66	4.9
Apr	4972	67	4.8	67	4.8	67	4.8	66	4.7	66	4.7	66	4.7
May	4675	90	5.5	84	5.1	84	5.1	90	5.5	82	5.0	82	5.0
Jun	4472	72	5.8	72	5.8	67	5.4	72	5.8	72	5.8	66	5.2
Jul	4633	90	5.6	90	5.6	90	5.6	90	5.6	90	5.6	82	5.1
Aug	4508	72	5.7	72	5.7	72	5.7	72	5.7	72	5.7	72	5.7
Sep	4566	72	5.7	72	5.7	72	5.7	72	5.7	72	5.7	72	5.7
Oct	4480	88	5.6	88	5.6	88	5.6	88	5.6	88	5.6	88	5.6
Nov	4230	66	5.5	66	5.5	66	5.5	67	5.7	67	5.7	67	5.7

Dec	4117	40	3.5	40	3.5	40	3.5	67	5.8	67	5.8	67	5.8
Avg.	4583		**5.3**		**5.2**		**5.2**		**5.4**		**5.4**		**5.3**
SD			0.7		0.7		0.6		0.4		0.4		0.4
Max			**5.8**		**5.8**		**5.7**		**5.8**		**5.8**		**5.8**

Table 20 shows how the total solar cell area is estimated on a monthly basis. In order to keep safe, usually the maximum solar cell area is used. For the application in Singapore, the least solar cell area is 5.8 m^2. In the previous sections, two solar cell integration plans were introduced. Since in this estimation, the monthly gain equals to the monthly consumption, so this result corresponds to the storage battery plan, which is that electricity from solar cell is firstly stored in storage and then used by the virtual window system. The duration of the independent usage depends on the capacity of the storage battery. In this case, the battery should be able to sustain for one month.

The solar cells area estimations of all the location on a monthly basis (first solar cell integration plan) is summarized in Table 21:

Table 21 Maximum solar cells area in the five locations based on monthly data (storage battery integration plan)

Storage battery integration plan	**Mimicking**			**Compensating**		
Maximum Solar cell area in:	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Singapore (m^2)	5.8	5.8	5.7	5.8	5.8	5.8
Cairo (m^2)	7.8	7.8	7.8	5.3	5.0	5.3
Amsterdam (m^2)	17.9	17.0	17.9	51.7	51.7	51.7
Sevilla (m^2)	10.4	10.4	10.4	7.8	7.0	7.8
Chicago (m^2)	10.1	9.4	10.1	13.1	13.1	13.1

The other solar integration plan is that the power from solar cells directly goes to the grid, and then the virtual window system gets all the needed power from grid. To make a comparison with the first integration plan, the needed solar cell area is also estimated. This area values are calculated on a yearly basis, by using this following equation:

$$\text{SOLAR CELL AREA} = \frac{YEARLY\ ENERGY\ \text{CONSUMPTION}}{YEARLY\ SOLAR\ RADIATION\ DENSITY \times DEFAULT\ SOLAR\ CELL\ EFFICIENCY}$$

Where for each location the yearly energy consumption and solar radiation density are available, and the default solar cell efficiency is 14%. Thus the Table 22 is concluded from the calculations:

Table 22 Maximum solar cells area in the five locations based on yearly data (grid integration plan)

grid integration plan	**Mimicking**			**Compensating**		
Maximum Solar cell area in:	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
Singapore (m^2)	3.8	3.8	3.7	3.9	3.9	3.8
Cairo (m^2)	2.5	2.4	2.2	2.6	2.5	2.6
Amsterdam (m^2)	5.3	5.0	5.3	5.2	4.9	4.2
Sevilla (m^2)	3.3	3.1	3.1	3.3	3.1	3.2
Chicago (m^2)	3.9	3.6	3.8	3.9	3.6	3.7

Table 22 shows a different result from the result of the first solar cell integration plan. It is not difficult to tell the fact that the second plan reduces the need solar cell area to a large extent. For instance in Amsterdam, the compensating mode of scenario 3 needs 51.7 m^2 in the first integration plan while the same situation in the second integration plan only requires 4.2 m^2. For all the locations under all scenarios and modes, the total solar cell of the storage battery integration plan is in the range from 5.0 m^2 to 51.7 m^2; for the grid integration plan, the range is from 2.2 m^2 to 5.3 m^2. By this estimation based on measurement and realistic assumptions, it can be concluded that: In real situation, solar cells can be placed in an optimally way to maximise yearly energy yield.

8. Conclusions and recommendations

In this graduation project, a new virtual window system was designed and constructed based on current availability, and its relevant control patterns and possible application examples were developed and discussed. In this section, its performance in terms of lighting performance and energy performance are concluded. Also based on the current design, there are large spaces to keep improving the system. Several recommendations are also made to help people in the future to proceed with the virtual window systems.

One of the objectives of this project is to provide a newly designed virtual window system with better lighting and energy performances than the earlier versions. This is also the first research question: How to realize a more-efficient virtual window? In this study, a new virtual window prototype has been successfully designed and built based on power LEDs. Compared with the first version of virtual window built by Philips, This virtual window realized functions such as delivering direct light and providing "through- window" views and dynamic controls. Although a real users' experience study has not been conducted to quantify the visual comfort, there was positive responses from visitors during the preliminary observations.

The second research question is about the total energy consumption under the two annual control patterns (Mimicking and compensating). To make this energy consumption result suitable for more locations, five representative locations in five climate region were selected and assumed to be the ideal application sites. The daily energy consumption of each location was summarized in Table 18. And based on the yearly solar radiation amount, two solar cells integration plans were introduced, and necessary solar cell areas of each corresponding integration plans were calculated. The result showed that the best plan to integrate the solar cell to the virtual window is to connect the virtual window and solar cells to the mains grid. According to all the assumptions and calculations, the needed solar cell area varied from 2.2 m^2 to 5.3 m^2. Methods for improving the energy performance were listed in Table 23, the recommendation list.

The third research question is about the lighting performance of the virtual window. From the measured illuminance distribution, only part of the room under "SM" and "SP" can reach the European standard (NEN-EN 12464-1) for typical writing tasks in office, which is 500lx of work plane illuminance. It is noticed that using only the virtual window prototype cannot provide sufficient amount of light for working tasks, hence some additional task luminaires should be also installed at the relevant spots in the space, as is typically also the case with real windows. Nonetheless, it is expected that in the future the LED efficiency will become higher, resulting in a better lighting performance and a lower total energy power consumption. The following paragraphs show the recommendation of the virtual window design and development in the future.

In the aspect of system design recommendation, since this prototype was constructed on the back side of the wall in an open area, so actually the depth of the prototype was not such a concern as light output. Thus the diffusor used in this prototyping was the one with the most transparency; hence the depth of the virtual window must be enlarged to get enough blurred effects. Finally the depth of the virtual window was more than 400mm, which is larger than most of the common walls. In the future, if the virtual window will come to people' lives someday, a suitable virtual window should be thin enough to be mounted into a wall, which should be the thinner the better. When the virtual window is going to be thinner, the diffusor should be more diffusive to eliminate possible display short comings. But more diffusive panel leads to less light output, so the light output of the light sources should be also improved at the same time.

The display design also has large space to get improved in the future. As mentioned before, one of the important reasons for why the Origami tiles were picked is the current availability, and the main limitations are the efficacy of the LEDs and the size of the pixels. With the latest LED technology, a more efficient with smaller-sized pixel is available nowadays and surely in the future. By applying more advanced LEDs, it is possible to display more detailed images with higher light output.

In this prototype, the displayed image on the virtual window is static, but in real skies, clouds could be moving with the wind and the corresponding illuminance falling on the window surface can be fluctuating. My recommendation of this aspect is that dynamic images can be introduced in the future via certain programming. The dynamic image can increase people's "window" experiences if the display is smoothly controlled.

Table 23 List of recommendations for the virtual window systems in the future

ITEMS	CURRENT PROTOTYPE SHORTCOMINGS	RECOMMENDATIONS
System structure	• Large depth	• The depth of the virtual window should be small enough to be mounted into a normal wall
Display light source	• Low efficacy • Large pixel size • Limited color space	• Efficacy should be much higher. 200lm/W is already able to mimic actual sky under the same energy consumption. • Using smaller-sized pixel unit to display image with higher resolution. • Using RGB LEDs with larger color space to display more realistic images.
Image display	• Low resolution • Static image	• By combining suitable light sources and proper programming, the image could have higher resolution, but too high resolution can help people to focus on the window surface, which is not helpful to improve "window experience". So excessive resolution is not recommended. • By reprogramming the static image, the image is better to be dynamic with time. Also the displayed landscape
Direct light source	• Low efficacy • Insufficient output	• Choosing luminaires with higher efficacy. • The light output should be higher, comparable to the

	• Unable to change positions via remote control	display light source. • Better be able to change positions or beam angles via remote or automatic control methods.
Solar cell integration	• No solar cell was integrated • Assumed solar cell has low efficiency of 14% • Assumed solar cells were placed horizontally	• Connecting the virtual window directly to the grid. • Connecting the solar cells to the grid, upload the power to the grid. • Previous estimations of suitable solar cell area of the five climate regions can be taken as a reference. • Using solar cells with higher efficiency can reduce the needed area to a large extent. • Placing the solar cells at optimized angle. It is even better to use sun-tracking technology on the solar cell systems.

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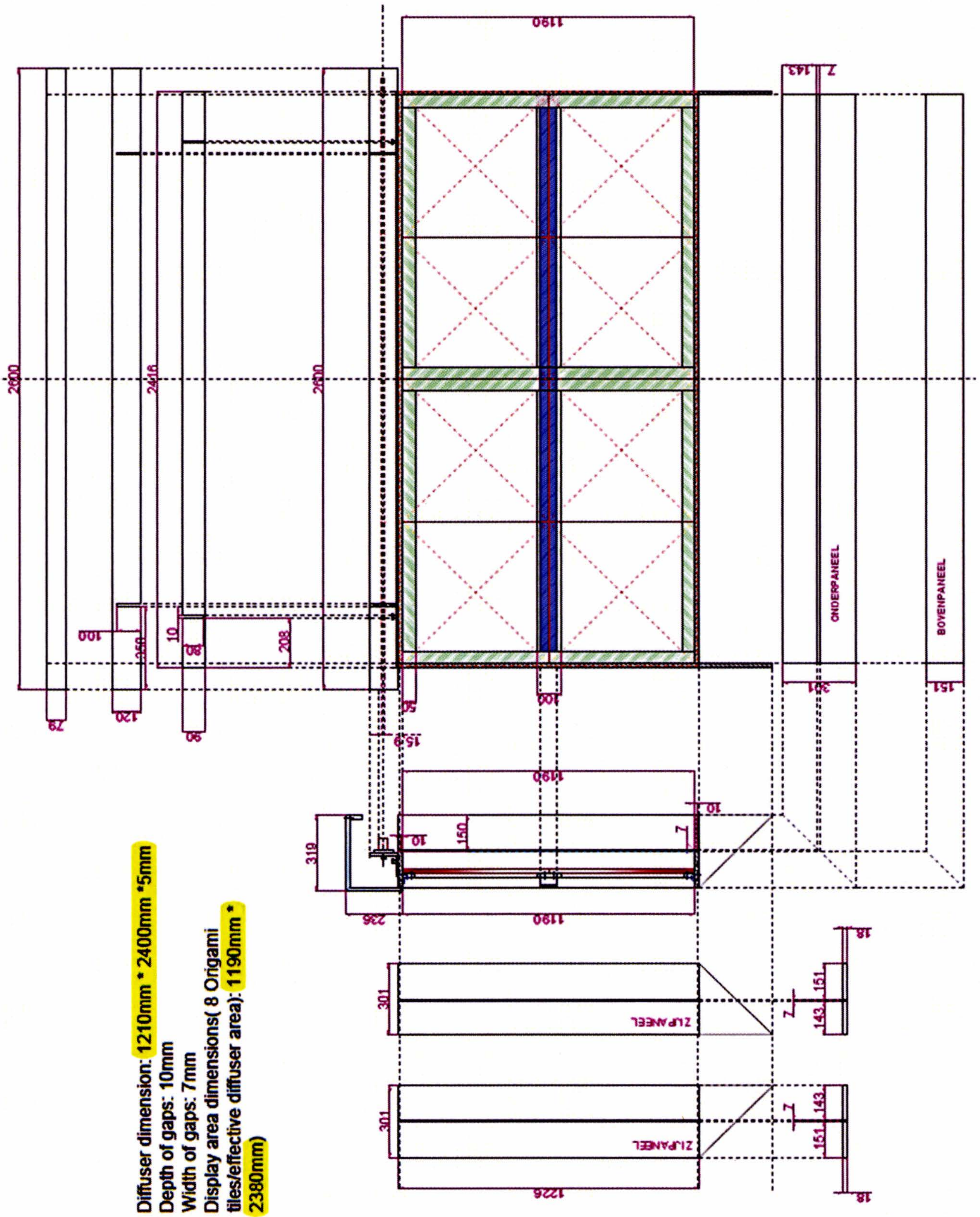
Appendix

1. Plan of virtual window (see .pdf also)



Diffuser dimension: 1210mm * 2400mm *5mm
Depth of gaps: 10mm
Width of gaps: 7mm
Display area dimensions(8 Origami tiles/effective diffuser area): 1190mm * 2380mm)

2. Power-DMX function under full-white condition

POWER MEASUREMENT	**POWER: W** **UNIFORM**			
DMX		POWER OF SYSTEM	POWER OF Origami	POWER OF iW COVE
0		128	128,4	128,4
5		138,1	137,7	128,6
10		146,7	147,7	128,8
20		170,7	169,7	129,3
40		218,8	213,9	131,8
60		267	258,2	136,5
80		316,5	302,7	140,7
100		364,4	346,4	145,3
125		428,5	398,7	152,2
150		488,7	455,3	158,5
175		553,5	509,1	169,2
200		621,9	566,1	182,3
225		692,3	620,3	196,5
255		782,1	686,3	216,6

3. Illuminance measurement result

LUX_SM	1	2	3	4	5	6	7	
1	343,3	632	866	858	903	670	337	
2	382	524	637	677	650	518	378	
3	342,7	404	460	480	458	398	329	
4	283,9	316,5	339,6	349,5	337,3	304,3	273,4	
5	226,9	241,4	249,4	254,2	247,5	234,4	218,5	
6	186,5	196,2	203,4	204,3	202,5	192	178	
7	153,6	159,8	163,4	163,4	158,7	153	146,4	
8	126,5	132	134,7	135,1	134,1	129	123,7	
9	106,8	111,2	111,4	111,5	109,7	109,1	104,8	
10	94,5	97,8	99,5	98,4	98,4	94,6	91,2	
11	85,3	87,2	86,8	88	86,3	84,5	83,1	
12	75,9	80,9	81,3	81,5	81,7	80,5	75,6	
13	83,4	84,2	84,5	84,4	83,6	80,2	82,7	
MIN	75,9	80,9	81,3	81,5	81,7	80,2	75,6	75,6
AVG	191,6385	235,9385	270,5385	275,7923	273,1385	234,4308	186,2615	238,2484
POWER	**640**						UNI	0,317316

LUX_MID	1	2	3	4	5	6	7	
1	192,5	351,1	470	459	484	364	191	
2	223,4	302,2	362	382,3	366,4	303,7	213,5	
3	196,5	230	260,6	271,6	258,1	229,2	194	
4	160,5	182,2	195,7	203,1	196	180,5	161,9	
5	128,8	141,6	151,8	154,6	150	142,6	133,1	
6	104,4	111	115,8	118,7	118,2	113,4	107	
7	85,8	90,4	93,2	94,4	93,2	91,3	87,9	
8	72,1	75,9	77,8	78,8	78,5	77,1	74,8	
9	61,2	64,1	65,4	66,5	66,4	65,6	63	
10	57,7	56	57,3	56,6	57,3	56,5	54,8	
11	47,4	49,8	50,3	50,8	51,2	50,4	49,1	
12	46,5	47,9	48,9	49,1	47,3	48,5	44,9	
13	46,8	47,9	47,6	47,2	47,3	45,7	46,9	
MIN	46,5	47,9	47,6	47,2	47,3	45,7	44,9	44,9
AVG	109,5077	134,6231	153,5692	156,3615	154,9154	136,0385	109,3769	136,3418
POWER	**435,8**						UNI	0,32932

LUX_WT	1	2	3	4	5	6	7
1	65,8	126,6	170,7	165,4	175,4	131,8	65,6

2	79,5	106,1	130	137,1	131,5	105,3	76,6	
3	68,9	82,3	93,1	96,6	92,1	81,1	68,1	
4	56,1	62,8	68,9	70,8	68,3	61,8	55,6	
5	44,7	48	51,4	52,2	51,2	48,3	45,5	
6	36,4	38,8	40	40,7	40,4	38,8	37,1	
7	32,8	34,2	35	35,5	35,3	34,6	33,7	
8	27,4	28,7	29,1	29,2	29,2	29	28,4	
9	23,7	24,6	25	25,3	25,2	25,1	24,3	
10	20,6	21,7	21,7	21,9	22,2	21,9	21,3	
11	18,6	19,3	19,7	19,7	20,1	19,7	19,3	
12	19,2	18,9	19,5	19,8	19,9	19,6	18,9	
13	19,3	20	19,8	19,7	19,5	20,1	20,5	
MIN	18,6	18,9	19,5	19,7	19,5	19,6	18,9	18,6
AVG	39,46154	48,61538	55,68462	56,45385	56,17692	49,00769	39,60769	49,28681
POWER	**248,6**						UNI	0,377383

4. Reflectance measurement of the standard test room

Carpet	9%
Wall	79%
Door	78%
White board	71%
Ceiling	91%

5. DMX settings for three scenes

SM	SP	WT
201=150	201= 94	201= 38
202=175	202= 109	202= 44
203=200	203= 125	203= 50
204=200	204= 125	204= 50
205=200	205= 125	205= 50
206=200	206= 125	206= 50
207=225	207= 141	207= 56
208=255	208= 159	208= 64
209=255	209= 159	209= 64
210=255	210= 159	210= 64
211=255	211= 159	211= 64
212=225	212= 141	212= 56
213=225	213= 141	213= 56
214=200	214= 125	214= 50
215=200	215= 125	215= 50
216=200	216= 125	216= 50
217=200	217= 125	217= 50
218=200	218= 125	218= 50
219=200	219= 125	219= 50
220=200	220= 125	220= 50
221=200	221= 125	221= 50
222=200	222= 125	222= 50
223=200	223= 125	223= 50

224=200	224= 125	224= 50
85=20	85= 13	85= 5
86=255	86= 159	86= 64
87=230	87= 144	87= 58
88=220	88= 138	88= 55
89=255	89= 159	89= 64
90=255	90= 159	90= 64
94=230	94= 144	94= 58
95=255	95= 159	95= 64
96=255	96= 159	96= 64
91=220	91= 138	91= 55
92=255	92= 159	92= 64
93=255	93= 159	93= 64
55=255	55= 159	55= 64
56=230	56= 144	56= 58
57=255	57= 159	57= 64
58=26	58= 16	58= 7
59=233	59= 146	59= 58
60=239	60= 149	60= 60
52=230	52= 144	52= 58
53=255	53= 159	53= 64
54=255	54= 159	54= 64
49=220	49= 138	49= 55
50=255	50= 159	50= 64
51=255	51= 159	51= 64
	0	0
	0	0
37=25	37= 16	37= 6
38=248	38= 155	38= 62
39=247	39= 154	39= 62
	0	0
40=220	40= 138	40= 55
41=255	41= 159	41= 64
42=255	42= 159	42= 64
	0	0
46=220	46= 138	46= 55
47=255	47= 159	47= 64
48=255	48= 159	48= 64
	0	0
43=230	43= 144	43= 58
44=255	44= 159	44= 64
45=255	45= 159	45= 64
97=220	97= 138	97= 55
98=255	98= 159	98= 64

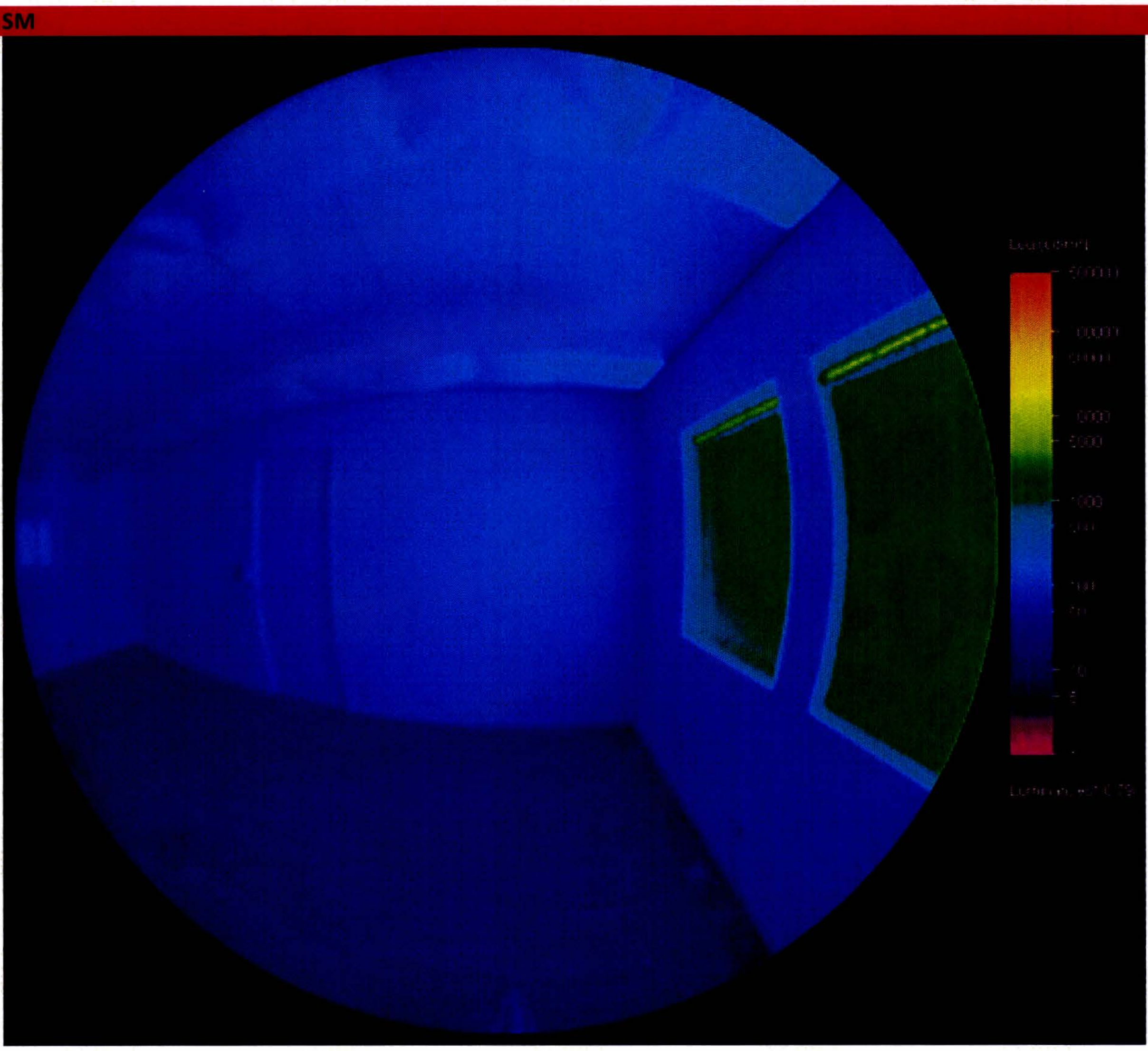
99=255	99= 159	99= 64
103=25	103= 16	103= 6
104=248	104= 155	104= 62
105=227	105= 142	105= 57
100=200	100= 125	100= 50
101=255	101= 159	101= 64
102=255	102= 159	102= 64
106=220	106= 138	106= 55
107=255	107= 159	107= 64
108=255	108= 159	108= 64
115=255	115= 159	115= 64
116=255	116= 159	116= 64
117=255	117= 159	117= 64
	0	
118=255	118= 159	118= 64
119=255	119= 159	119= 64
120=255	120= 159	120= 64
112=0	112= 0	112= 0
113=200	113= 125	113= 50
114=100	114= 63	114= 25
109=0	109= 0	109= 0
110=216	110= 135	110= 54
111=10	111= 6	111= 3
127=225	127= 141	127= 56
128=255	128= 159	128= 64
129=255	129= 159	129= 64
130=205	130= 128	130= 51
131=255	131= 159	131= 64
132=255	132= 159	132= 64
124=0	124= 0	124= 0
125=221	125= 138	125= 55
126=10	126= 6	126= 3
121=0	121= 0	121= 0
122=215	122= 134	122= 54
123=10	123= 6	123= 3
82=200	82= 125	82= 50
83=255	83= 159	83= 64
84=255	84= 159	84= 64
79=180	79= 113	79= 45
80=255	80= 159	80= 64
81=255	81= 159	81= 64

73=0	73= 0	73= 0
74=224	74= 140	74= 56
75=10	75= 6	75= 3
76=0	76= 0	76= 0
77=227	77= 142	77= 57
78=10	78= 6	78= 3
70=230	70= 144	70= 58
71=255	71= 159	71= 64
72=255	72= 159	72= 64
61=200	61= 125	61= 50
62=255	62= 159	62= 64
63=255	63= 159	63= 64
67=0	67= 0	67= 0
68=225	68= 141	68= 56
69=10	69= 6	69= 3
64=0	64= 0	64= 0
65=229	65= 143	65= 57
66=10	66= 6	66= 3

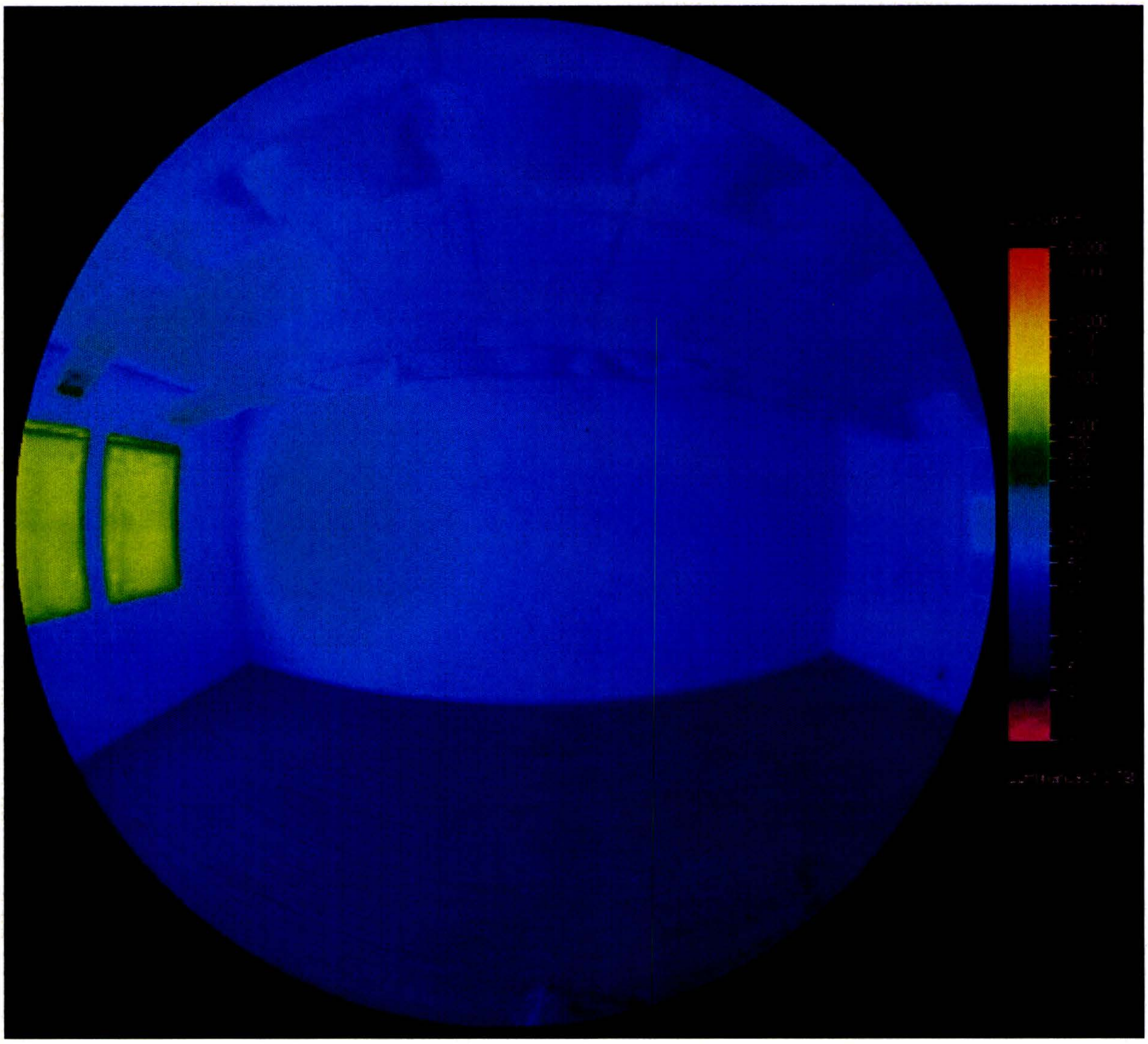
6. Luminance camera measurement results

SM

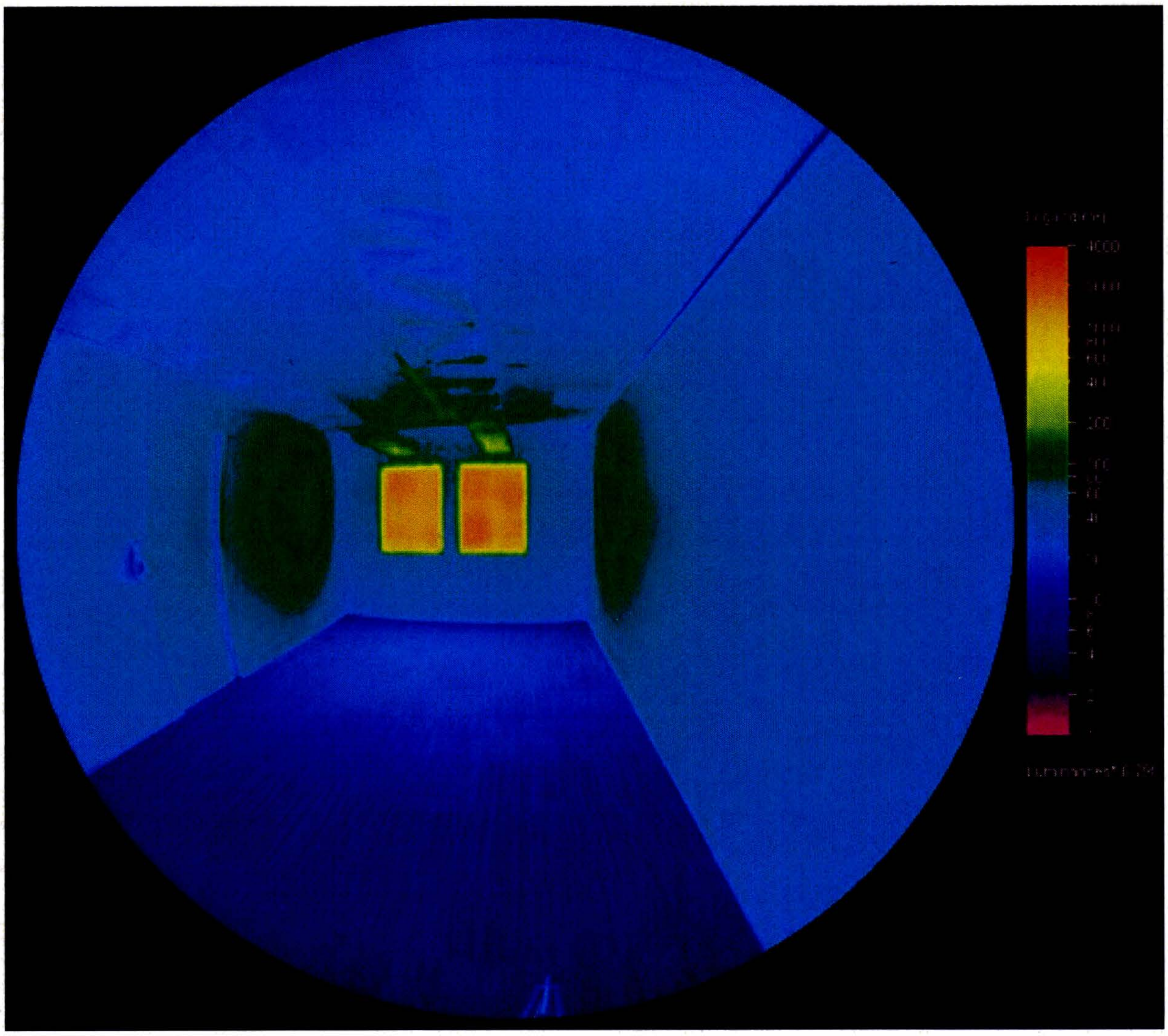
SM POSITION 1



SM
POSITION
2



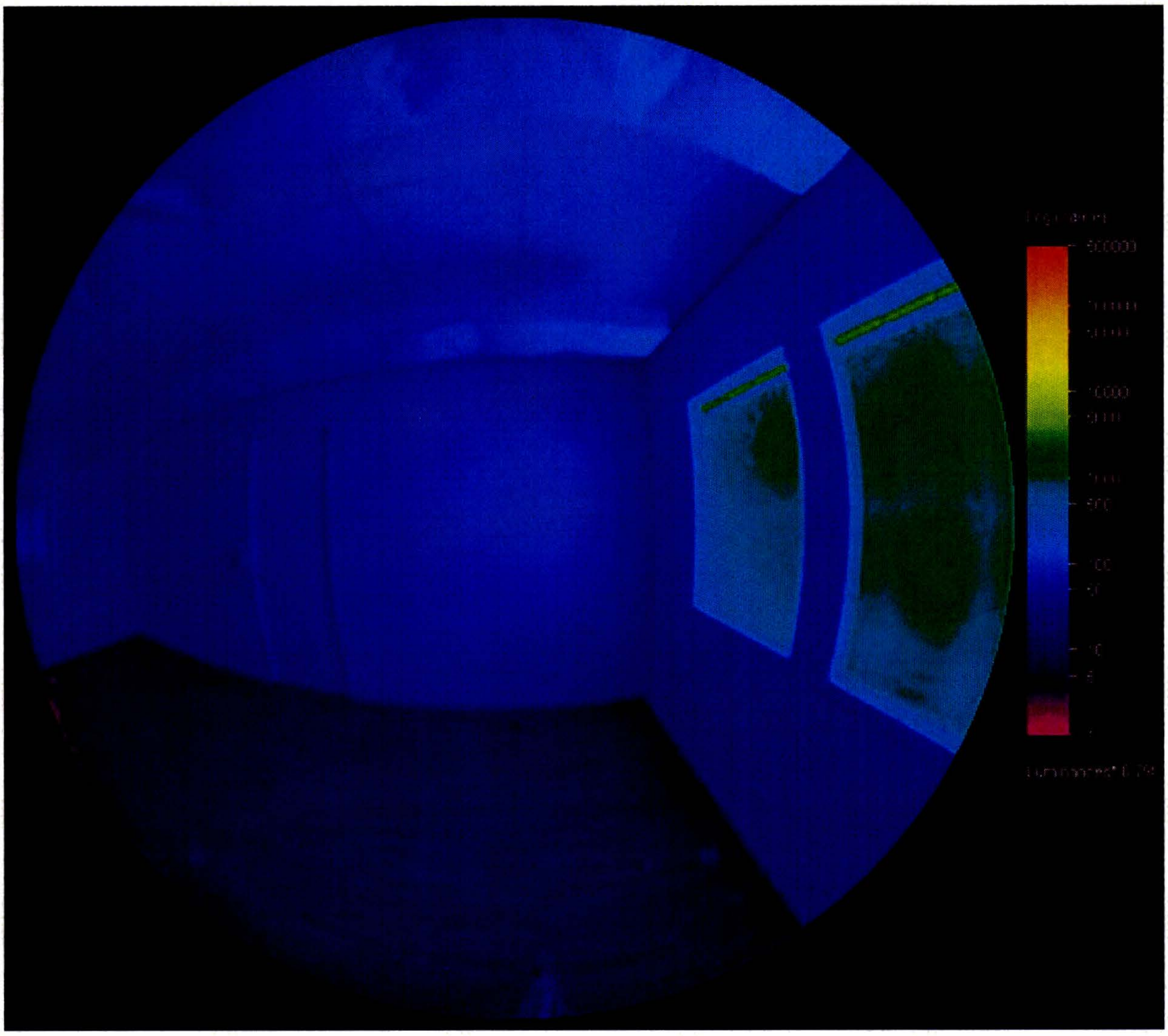
SM
POSITION
3



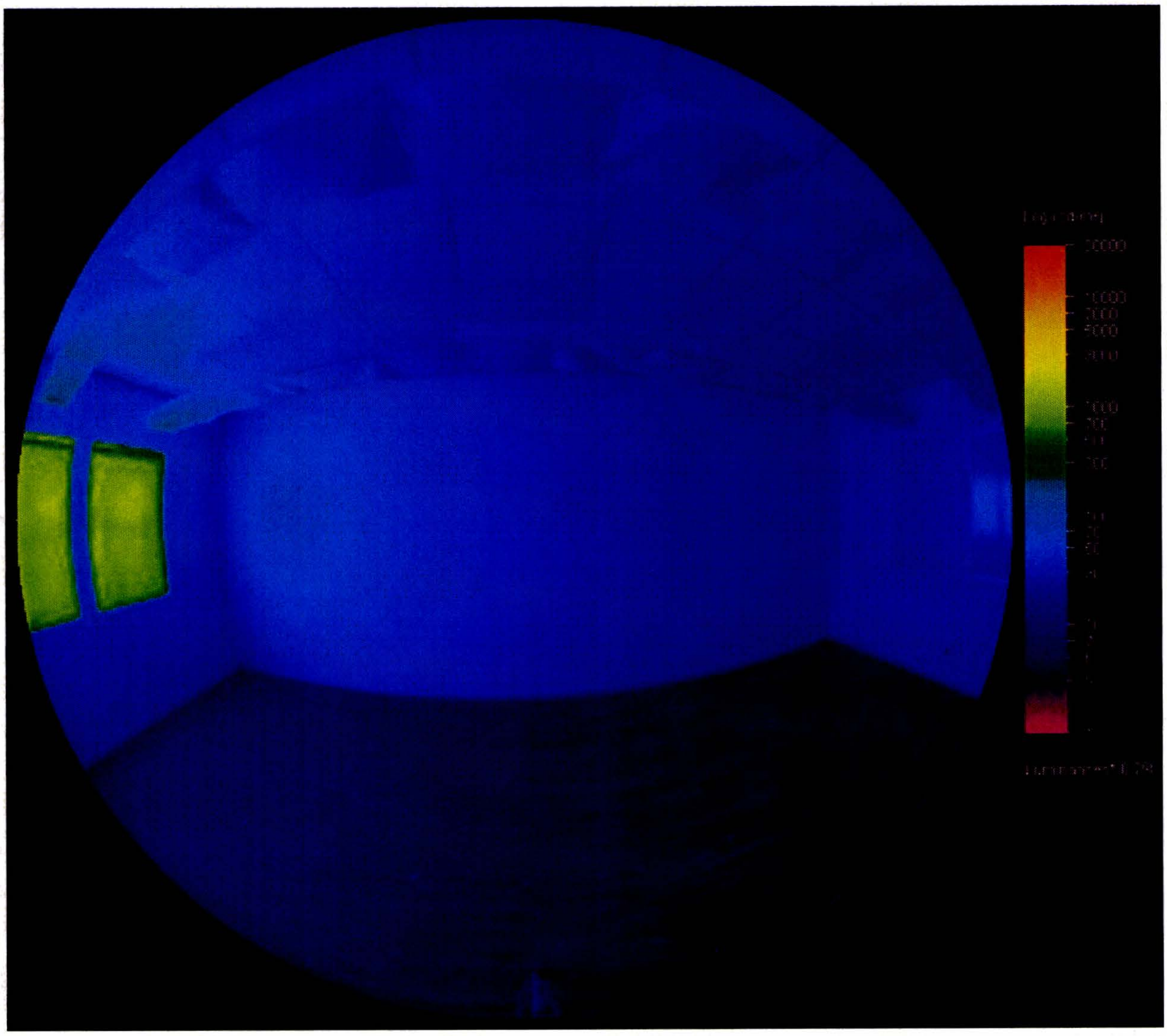
SM
POSITION
4

SP

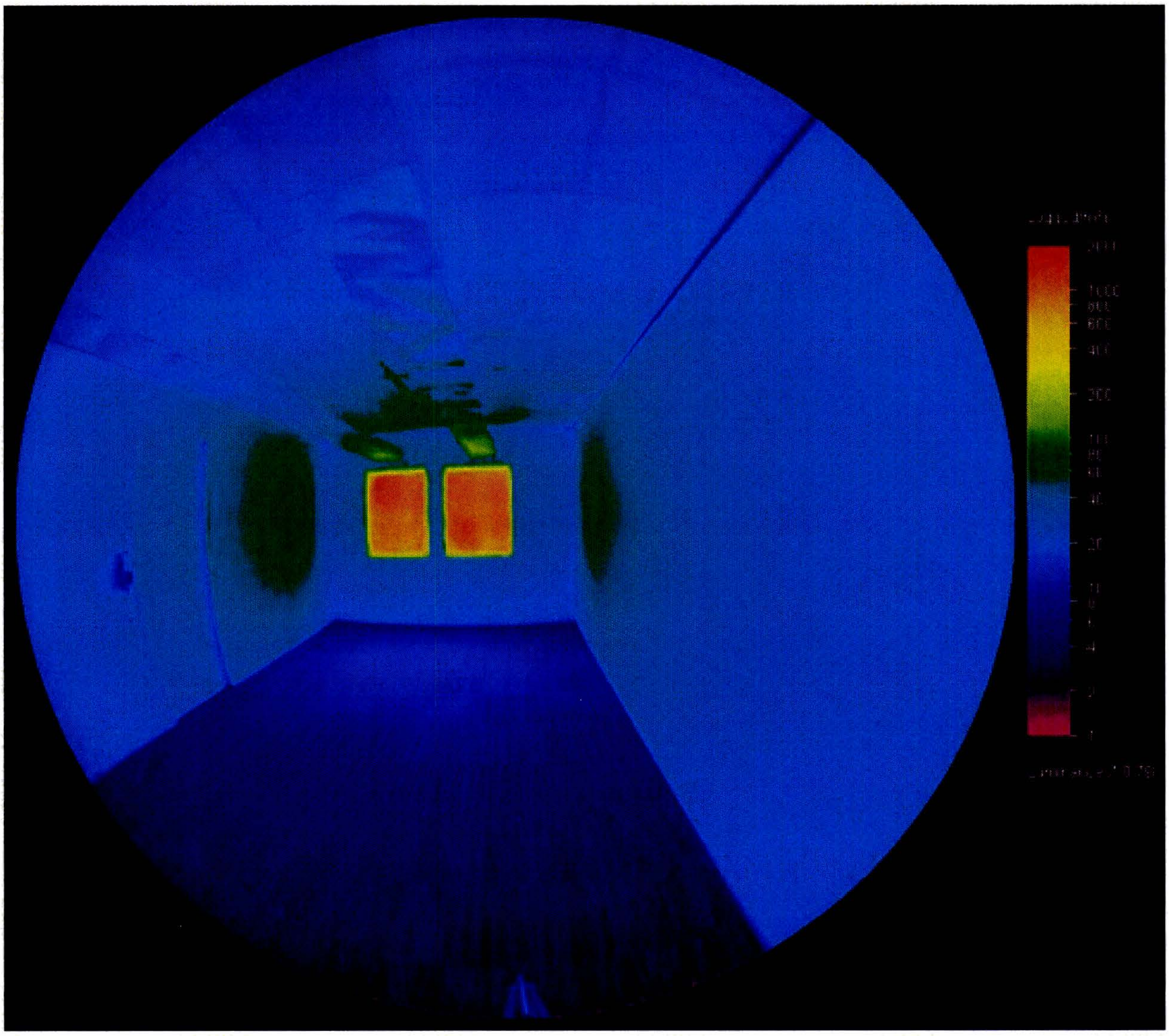
SP POSITION 1



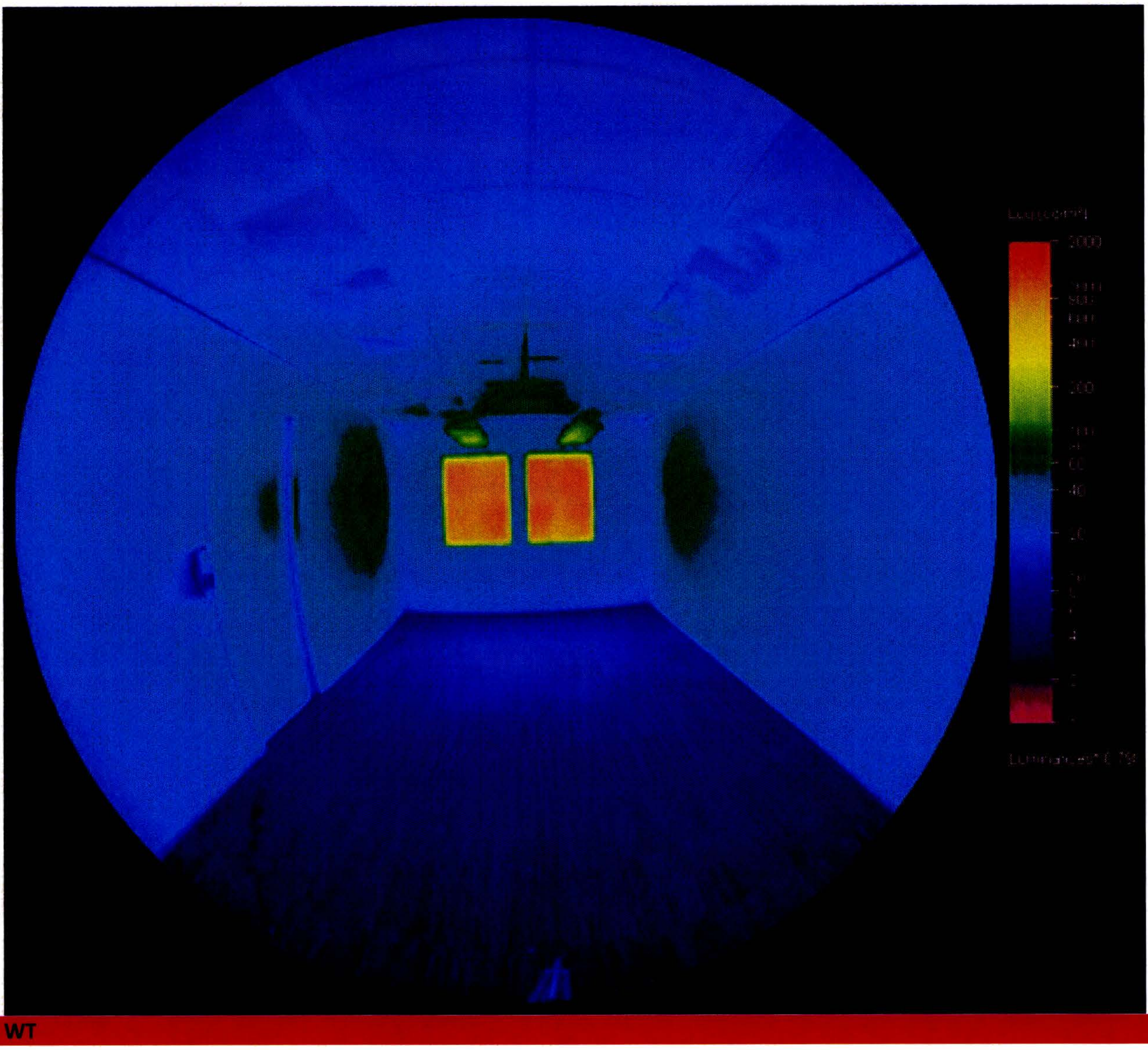
SP POSITION 2



SP POSITION 3

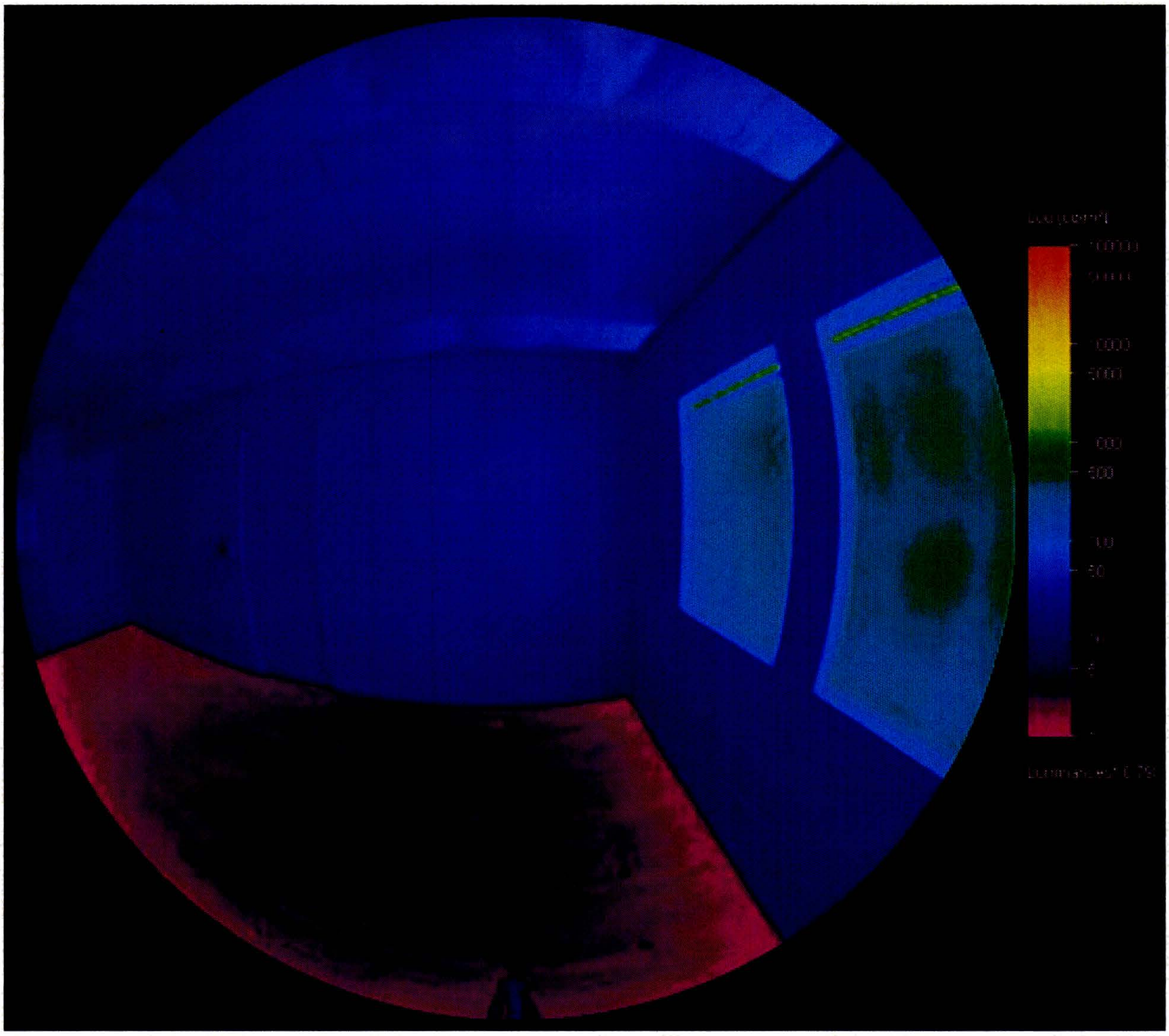


SP POSITION 4

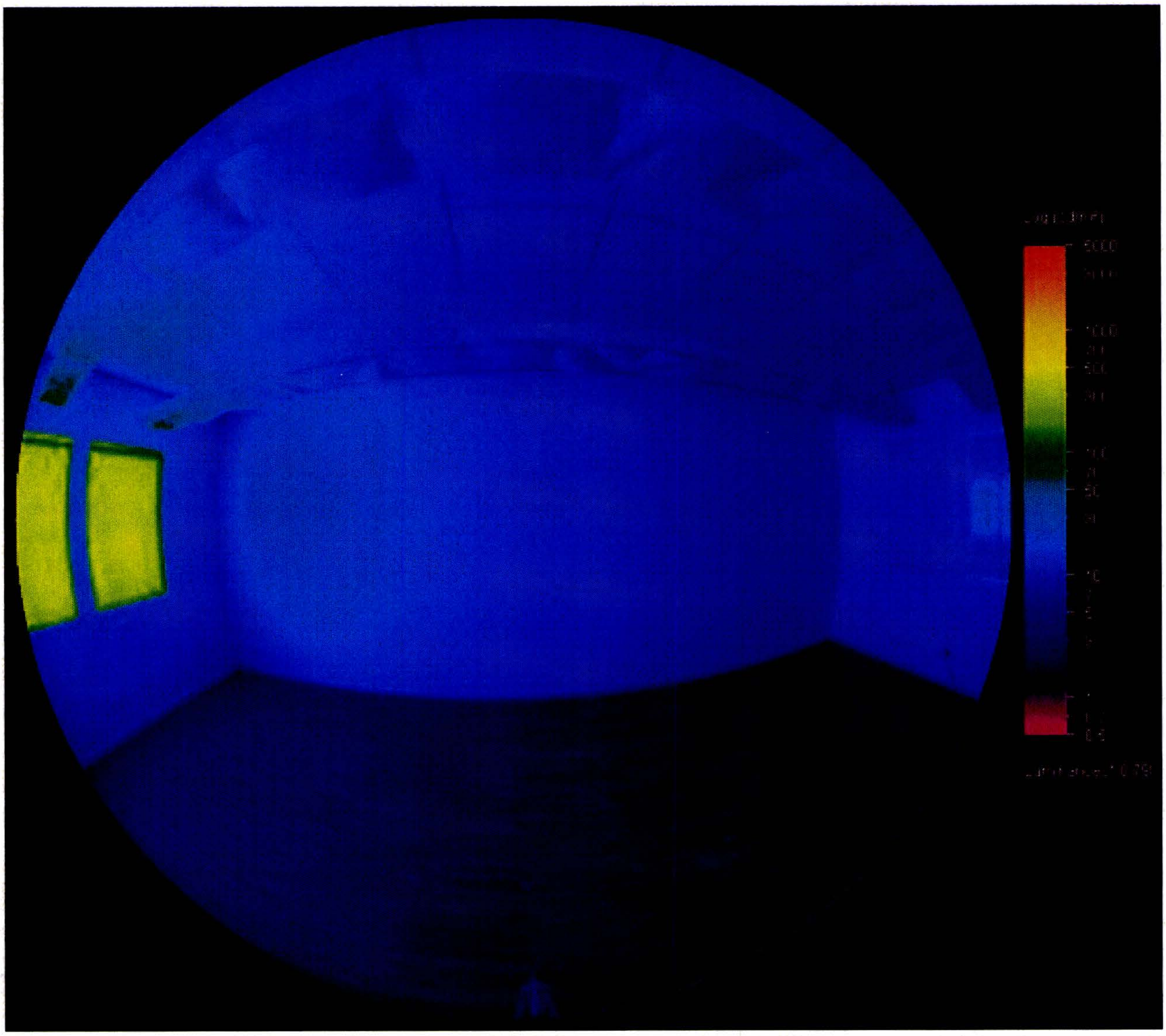


WT

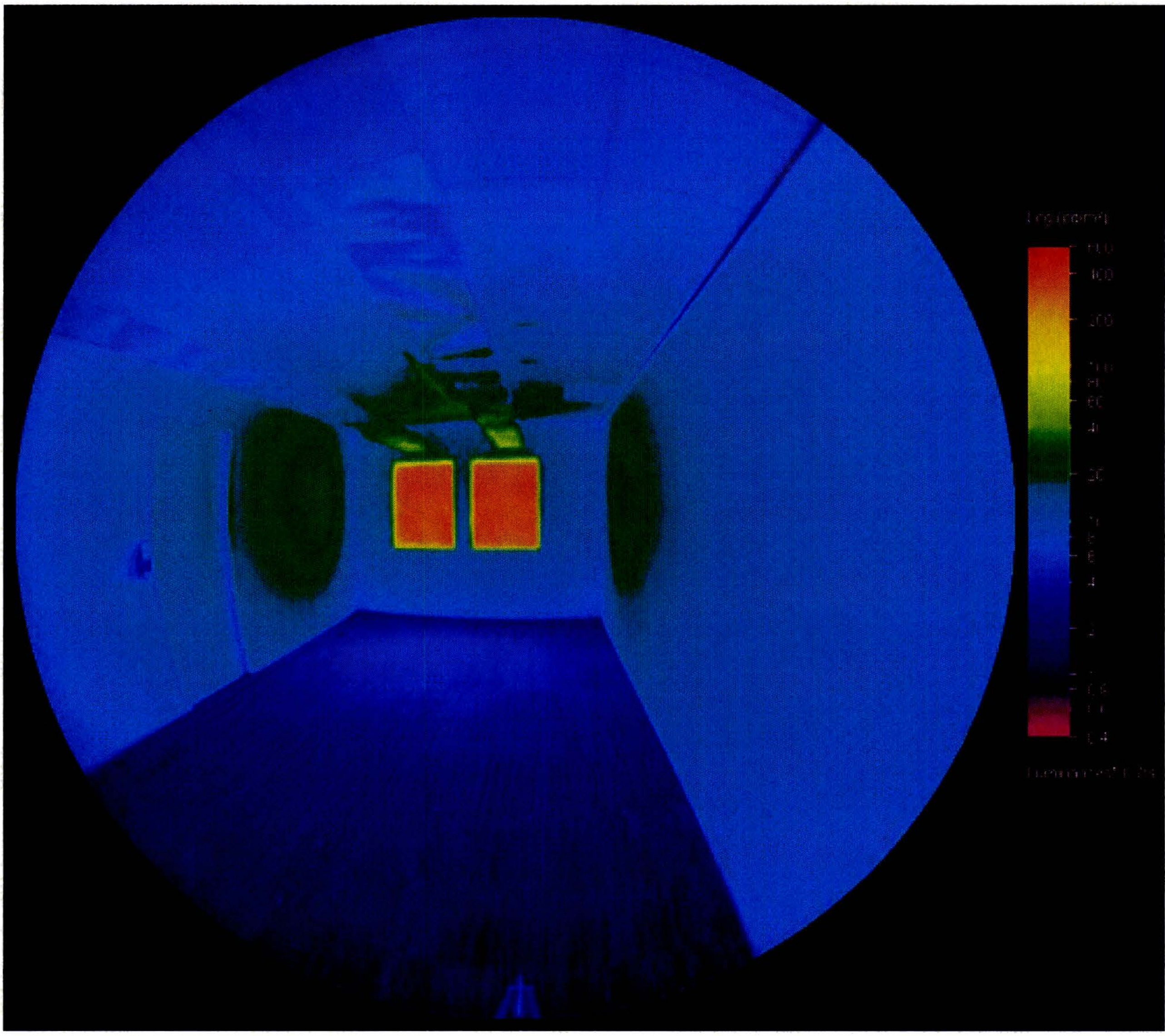
SP POSITION 1



SP POSITION 2



SP
POSITION
3



SP
POSITION
4