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Influence of DDLC window (Dye-Doped-Liquid Crystal) adaptive façade system and control strategies on visual environment and performance

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INFLUENCE OF DDLC WINDOW (DYE-DOPED LIQUID CRYSTAL) ADAPTIVE FAÇADE SYSTEM AND CONTROL STRATEGIES ON VISUAL ENVIRONMENT AND PERFORMANCE

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GRADUATION PROJECT

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ABSTRACT

Automated daylighting systems in highly glazed facades are a key factor to obtain a pleasant visual environment and high-performance in office buildings. Switchable glazing as DDLC (Dye-Doped Liquid Crystal) allow dynamic control of daylight but, due to the lack of appropriate control system, these devices are not widely employed. In this study, daylighting control strategies for the enhancement of visual comfort and room ambiance were developed, implemented and then the performance were assessed for an office façade array with DDLC windows.

Different methodologies are employed to fulfill research objectives and provide qualitative and quantitative proof about the potential of the system: an analytical study, Radiance daylighting simulations, and a pilot study application.

An innovative approach for automatic daylighting systems, the GPC control strategies, is developed with the aim to provide protection against direct glare while maximizing daylight admittance and view to the outside.

Obscuring daylight with the entire façade array results not to provide effective benefits for user's glare protection; therefore, ‘Pixel’ strategy prevails on the other approaches in light of the greater daylight admittance, view to the outside and savings from electrical lighting. ‘Pixel’ control system is smoothly implemented in the pilot study and effective protection from direct daylight, on occupants and workstations inside a single office room, is demonstrated. DDLC windows seem to provide not enough protection against glare from sunlight; for both ‘Pixel’ and ‘Homogeneous’ approaches despite the partial agreement in daylighting performance resulted from the comparison between real and virtual testing methodologies.

Extended testing activity and a study on Human-technology interaction are required to obtain stronger insights on daylighting performance and user-acceptance of GPC system and DDLC windows. Further optimization would be: for GPC daylighting systems, the integration of thermal balance controls; and for DDLC technology, modification of luminous properties to enhance the shielding from daylighting glare.

GLOSSARY AND ABBREVIATIONS

Background area	Area in the workplace in halls and other spacious room situations where no task area or immediate surrounding area is given (EN12464-1, 2009)
BRTD	Bi-directional Reflectance and Transmittance Distribution
CCT	Correlated Colour Temperature [K]
CIE	International Commission on Illumination
DDLC	Dye-Doped Liquid Crystal
DGI	Daylight Glare Index [-] (Chauvel et al., 1982)
DGI$_{N}$	New Daylight Glare Index [-] (Nazzal, 2005)
DGP	Daylight Glare Probability [%] (Wienold & Christoffersen, 2006)
DGPs|$_{\text{Hviid}}$	Hviid’s Simplified Daylight Glare Probability [%] (Hviid et al., 2008)
DGPs|$_{\text{Wienold}}$	Wienold’s Simplified Daylight Glare Probability [%] (Wienold, 2007)
E	Illuminance [lux = lm/m^2] is the aerial density of luminous flux (EN12464-1 2009)
E_{avg}	Average illuminance on a surface
EC	Electrochromic
eDGPs	Enhanced Simplified Daylight Glare Probability [%] (Wienold, 2009)
E_m	Maintained illuminance [lux], value below which the average illuminance on the specified surface is not allowed to fall depending on the visual task to perform (EN12464-1, 2009)
g value	Total solar energy transmittance [%] (or solar heat gain coefficient) of glazing for solar radiation in the wavelength range between 300 nm and 2500 nm
Glare	A situation in which an unsuitable luminance distribution in the field of view leads to an uncomfortable feeling or the inability to see details or objects (Rosemann, 2015)
GPC	Glare Protection Control (Strategies)
IESNA	Illuminating Engineering Society of North America
Immediate Surrounding Area	Band with a width of at least 0,5 m surrounding the task area within the field of vision (EN12464-1, 2009)
L	Luminance [cd/m^2] is the ratio of the luminous intensity per unit area of light traveling in a certain direction (Rosemann, 2015)

LC	Liquid Crystal
LR	Luminance Ratios [-]
PDLC	Partially Dispersed Liquid Crystal
R & D	Research and Development
R_a	Color Rendering Index [%] describes how colors are rendered under certain lighting conditions
RAULE	Relative Annual Usable Luminous Exposure [%] (DIN 5034-3: 2007-02 E)
RAUT	Relative Annual Usable Luminous Exposure [%] (DIN 5034-3: 2007-02 E)
SG	Switchable Glazing
SPD	Suspended Particle Devices
Task Area	Area within the space where the visual tasks are carried out (Rosemann, 2015)
TC	Transparent Conductor
U_o	Maintained uniformity [-] (EN12464-1, 2009)
U-value	rate of heat transfer (in watts) through one square meter of a structure divided by the difference in temperature across the structure [W/(m2 K)]
Visual Comfort	Comfort is defined as the state of mind when subject express satisfaction with the environment (Gou, Lau and Ye 2014)
ρ	Luminous reflectance [%] is the ratio of total reflected luminous flux to the total incident luminous flux (direct plus diffuse) (Rosemann, 2015)
τ	Luminous transmittance [%] is the ratio of total transmitted luminous flux to the total incident luminous flux (direct plus diffuse) (Rosemann, 2015)
Φ	Luminous Flux [lm] is the measure of the perceived power of light. It is the spectral distribution of the spectral distribution of radiant flux weighted with the eye sensitivity curve and the maximal luminous efficacy of radiation (Rosemann, 2015)

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I INTRODUCTION

This study is part of a research project in cooperation between Eindhoven University of Technology and Heijmans Utiliteit. The aim is to investigate, develop, and test control strategies for DDLC window façade array to guarantee visual comfort and enhanced daylighting in office buildings. First, background information relevant for the study is provided in this chapter; then, research structure, goals, and questions are defined.

I.1 BACKGROUND INFORMATION

Control of solar energy and light in buildings is a key factor for design and management of high-performance buildings. Façade systems able to select and modulate the admittance of radiation and daylight enable the achievement of lower operational consumptions and pleasant environmental conditions (Kleindienst and Andersen,2012; Ochoa et al., 2012; Konstantoglou and Tsangrassoulis, 2016). Also, visual comfort and balanced daylighting have a positive effect on occupants (Veitch et al, 2008; Aries et al., 2013) in combination with view to the outside (Hellinga, 2013; Beute, 2013) and modest risk of glare (Osterhaus, 2002; Carlucci et al., 2015).

Completely transparent envelopes or high window-to-wall ratio facades, allowing the penetration of a considerable amount of daylight, are often employed in office buildings. In addition, the spatial discretion of highly glazed envelopes results in a façade array pattern of perimeter areas, commonly visible in this type of buildings (Figure I-1).

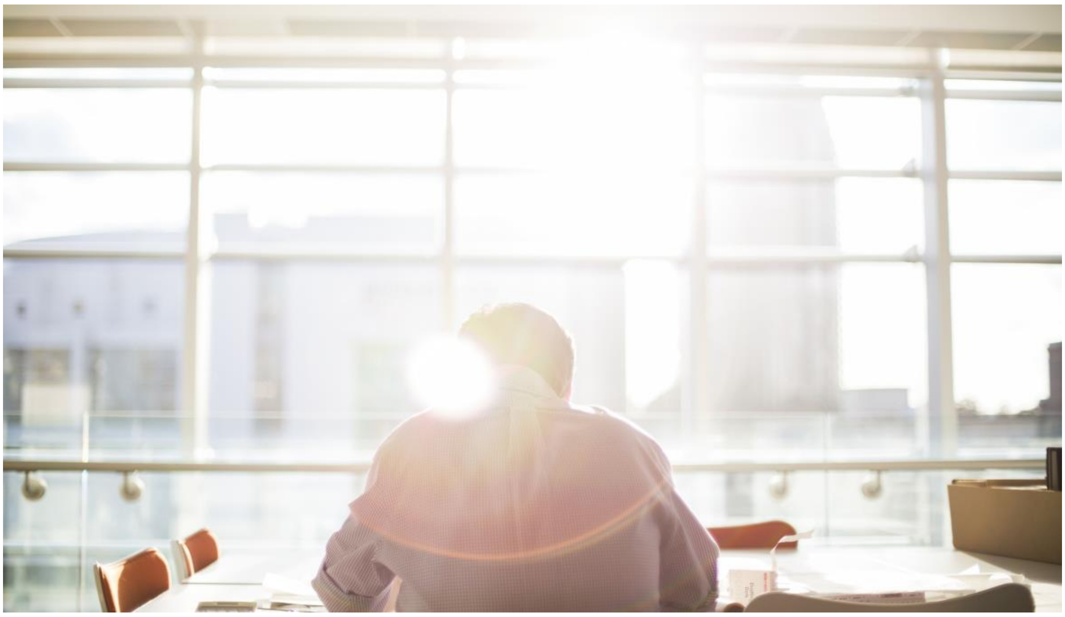

Figure I-1: Glazing façade array[1], commonly employed for office buildings.

In consideration of the significant losses (Gustavsen et al. 2007) and continuous exchange of energy in transparent façades, advanced glazing technologies have a huge potential to provide considerable energy savings and comfort benefits (Jelle et al., 2012) in office buildings for different climates (Bellia et al., 2013; Huang et al., 2014; Singh et al., 2015).

Many high-performance glazing and window technologies enable a robust control of energy and comfort (Cuce and Riffat, 2015); however, to properly handle the dynamic behavior of solar energy, additional systems such as shading devices are often required (Lee et al., 1998; Chaiwiwatworakul et al., 2009; Beck et al., 2010; Bellia et al., 2013). For the purpose of dynamic solar control of radiation and

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[1] https://dealerxpresswindowtinting.com/office-windows-too-much-sun

light various shading solutions are available, and the most commonly employed are: for exterior, overhangs and fins; and for the interior, rolling shades, Venetian blinds, and louvers.

Switchable glazing (SG) technology are an alternative solution, integrating the dynamic shading within the glasses of a façade, which showed benefits on energy and visual comfort (Dussault et al., 2012; Aldawoud A., 2013; Fernandes et al., 2013). The adaptability of SGs in the employment in new building designs but also for retrofitting (Lee et al., 2012) of existing facades makes this technology very promising for an office environment with glazed façade array (Hee et al., 2015).

I.1.1 SWITCHABLE GLAZING (SG)

Switchable glazing allows the variation of properties such as the luminous transmittance, solar factor, and spectrum of light upon the application of an electric current. Adjustment of transmission properties occurs in response to an electric field applied using a transparent conductor (TC), a highly transparent layer with elevated conductivity to produce a low voltage drop over its surface (Baetens et al.,2010).

Compared to conventional shading solutions SGs present some benefits such as less or unperceivable visual obstruction (Hellinga, 2013), the absence of movable parts and operation-related noises (Bakker et al.,2014), and lower maintenance requirements. Ease of integration in building management system and control of individual elements in a façade array make this technology very suitable for office buildings having façade array. Benefits for energy consumptions mainly for cooling and lighting are widely documented (Dussault et al., 2012; Sbar et al.,2012; Aldawoud A., 2013; Ghosh et al.; 2016a) also for visual comfort (Fernandes et al., 2013; Ghosh et al., 2016b). Despite glare protection is often claimed (Sbar et al.,2012), previous research confirms that SGs have a positive influence on glare (Zinzi, 2006; Clear et al., 2006), but complete protection is not achieved or confirmed (Piccolo and Simone, 2009; Piccolo et al., 2009).

Although several techniques allow the development of SGs, it is possible to classify them in three major technology groups: Electrochromic (EC), Liquid Crystal (LC), and Suspended Particle Device (SPD) (see Figure I-2).

(a) (b) (c)

Figure I-2: Major switchable glazing technologies: (a) Electrochromic[2], (b) Liquid Crystals[3], and (c) Suspended Particle Devices[4].

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[2] https://www.sageglass.com

[3] http://www.maxlen.co.uk

[4] www.innovativeglasscorp.com

The difference in SGs technology groups are commonly judged on specific technical factors:

- Transmission Range and Modulation: ECs and SPDs present the broad transmittance ranges, and modulation appear to be promising for dynamic daylight and solar energy control thanks to the wide transmittance ranges and modulation (Baetens et al. 2010). LC devices have a lower transmittance range (Papaefthimiou et al., 2006), and modulation is obtainable (Gardiner et al., 2009).
- Switching Speed: This parameter depends on windows size (Baetens et al., 2010) and TC, but LCs and SPDs can quickly switch from bright to dark and the other way around in the order of few seconds (Cupelli et al., 2009; Ghosh et al., 2016b). Differently, the switching speed of EC devices is slow, between 1 to 30 minutes for full darkening (Lee and Di Bartolomeo, 2002; Lee et al., 2006) compared to the speed of sudden extreme changes in sky luminance, which occur in 1-2 seconds.
- Transparency: ECs and SPDs exhibit full transparency in both states. PDLC (polymer dispersed liquid crystal) technology, the most commercially available LC, scatter rather than absorb light when switched (Cupelli et al., 2009) and can present hazy effect; however, this defect appears to be avoided in newer PDLCs (Gardiner et al., 2009).
- Color Rendering: the bluish effect in the building interior, resulting from ECs and SPDs, was found impact negatively occupant’s comfort and acceptance of the system (Lee and DiBartolomeo, 2002; Mardjalevic et al., 2014). Therefore, further research about the effects of SGs on color rendering is necessary due to the impact on visual comfort (Hellinga, 2013, Beute, 2013).
- Heat gains: All the technologies can reject solar gains but EC use absorption, rather than reflection (Ghosh et al., 2016b). Absorption causes high operational temperature and may lead to possible switching failure (Lee and DiBartolomeo, 2002) when the maximum design temperature is exceeded.
- Power Consumption: constant power is necessary to maintain the clear state for SPDs and LCs, resulting in a power consumption of 3.5 up to 15.5W/m^2 (Baetens et al., 2010); differently draw of power in EC windows occurs only during switching.
- Durability: Amount of switching cycle and long-term UV stability are drawbacks respectively of EC (Ghosh et al., 2016b) and PDLC (Baetens et al., 2010).

SGs are an emerging technology able to deal with the dynamic solar control and improve building performance; making them a potential competitor of conventional shading devices. However, uncertainties on the use as shading device (i.e. risk of discomfort glare) have arisen from literature as well as on the effect for visual comfort. Moreover, performance and comfort from these systems depend strongly on control strategies.

I.1.2 Dye-Doped Liquid Crystals (DDLC) Windows [5]

Current stage DDLC are switchable glasses having a layer of polymer LC materials (see Figure I-3a) to control the transmission of light and radiation. The layer consists of LCs typically employed in displays and a mixture of dyes specifically selected for light and radiation filtering. Switching occurs instantly, continuously and evenly across the surface of the glass. Figure I-3b shows the working principle of DDLC windows:

- At rest, alignment of LCs is homogeneous (i.e. planar) and perpendicular to the propagation direction of the incoming light. Then, the embedded dye molecules absorb incoming light and results in the dark state of the system.
- Consequent to the application of an external voltage, the LCs have a more homeotropic alignment, which is parallel to the direction of the incoming light. This arrangement causes the bright state due to the re-alignment of dye molecules and results in lower light absorption and higher light transmission.

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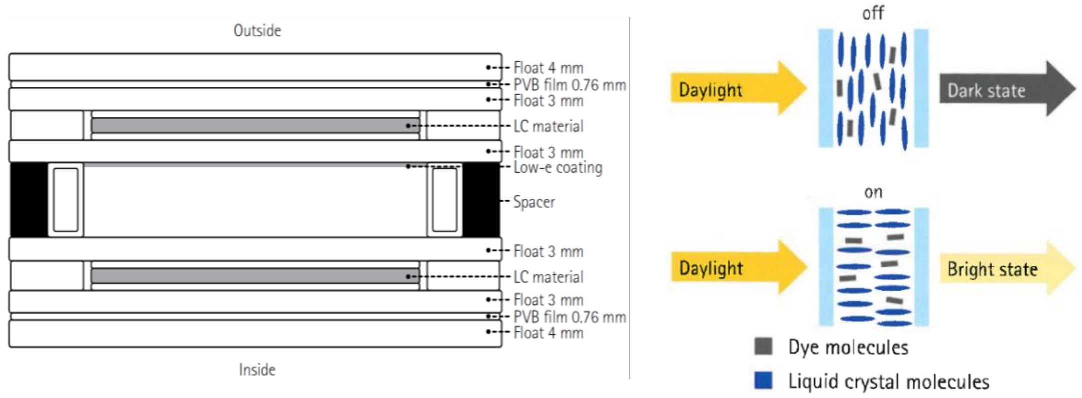
[5] Product specifications and images of section I.1.2 refers to data retrieved from DDLC developer.



(a) *(b)*

Figure I-3: (a) Composition of a DDLC window and position of the LC layers: one LC layer on both sides of the gas chamber. (b) The working principle of DDLC window technology. As can be seen in the upper part, the alignment of LCs at rest is homogeneous (perpendicular to the direction of the incoming light), and the system is in the dark state. When an external voltage is applied the LCs have a more homeotropic alignment (parallel to the direction of the incoming light), as can be seen in the lower part, and causing the bright state.

Figure I-4a summarizes the properties of a double glass DDLC window. Switching occurs evenly and in less than one second for both states, but darkening takes longer, due to the passive removal of the electric field, and makes this parameter depending on window size. Luminous transmittance $\tau_{\perp}$ can decrease up to five times, from 53% to 11%, and the solar factor g-value can be almost halved, from 0.25 to 0.40, when a voltage of 10V is applied to the glass. These ranges can be varied with addition or removal of LC layers or modifications in the composition of the layer. Color appearance is neutral either in the dark and bright state as can be seen from Figure I-4b; furthermore, resulting color rendering index R_a is high for both configurations.

Product specification		
Glass thickness	41 mm (tolerance ± 2 mm)	
U_g value	1.1 W/m^2 K (acc. To EN 673)	
Switching speed	< 1.0 s	
Technical details (acc. to EN 410)		
Color Appearance	Dark	Bright
	■	□
$\tau_{\perp}$	11% (0.11)	53% (0.53)
g-Value	0.25	0.40
R_a	94%	97%
Electrical specification		
Energy usage	< 400 mW/m^2 at 5 V DC	
Glass controller	Int. window controller: 5 V DC analog 0 – 10 V BMS input	

(a)

(b)

Figure I-4: (a) DDLC technical specifications. (b) The appearance of the glazing system in the dark and bright state, respectively on the left and on the right.

Conventional lacks of LC devices such as small transmittance range, modulation, haze, power consumption in bright state and low stability at UV (Baetens et al. 2010) appear to be overcome in the DDLC, which is entirely transparent in both states, UV resistant and allows either a wide transmittance modulation range and considerably lower power consumptions (8 to 30 time less).

DDLC system appears to be superior to other SG technologies about switching speed and effect on color rendering (see section I.1.1). Furthermore, properties such as tunable transmission of radiation, even distribution and possible energy-generation (Debije, 2010) makes this technology a potential next-generation SG.

I.1.3 CONTROL STRATEGIES

The control strategy of an automated façade system, such as shadings or SGs, is the key element for achieving energy savings and high-quality visual environment as reported in various studies (Chaiwiwatworakul et al., 2009, Singh et al.,2015). Although high performance can be achieved with single objective approach (Dussault et al., 2012), the multi-objective strategy can evaluate and choose between competitive requirements (Colaco et al., 2008; Konstantoglou and Tsangrassoulis, 2016). In combination with SGs, these systems have enhanced the capability to provide either comfortable conditions and benefits for consumptions (Fernandes et al., 2013; Favoino et al., 2015; Ghosh et al., 2016b).

Various types of control patterns for daylighting control are available (Konstantoglou and Tsangrassoulis, 2016) combining different goals, rules, and technologies. SGs have a significant influence on the visual environment and mainly in intensity and distribution of sunlight (Clear et al., 2006; Piccolo et al.,2009); therefore, according to previous research (Nielsen et al., 2011; Konstantoglou and Tsangrassoulis, 2012, Ochoa et al., 2012) suitable rules for the strategies are weather conditions, illuminance level, and glare. Among office occupants, glare results as the main motivation for closing the shading (O'Brien et al., 2013). Protection from glare is not yet confirmed with SGs (see section I.1.1) although this control rules it be taken into account in many studies (Assimakopoulos et al., 2007; Fernandes et al.,2013). According to IESNA (2000), glare can be defined as "the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance and visibility". Therefore, an automated façade equipped with SGs shall provide a balanced luminance distribution within the field of view of the users (Carlucci et al., 2015).

The discretization of the office façades, as an array (see Figure I-1), enables a flexible control of the single elements to achieve the desired performance. In most of existing automated facades, when the control rule threshold(s) be met the system order the obstruction of all the transparent surfaces (Assimakopoulos et al., 2007; Bülow-Hübe,2007). This often occurs to minimize negative impacts of daylight, causing the darkening of elements more than it is needed (Koo et al., 2010) although no additional protection is obtained and desirable view and daylight contributions (i.e. to reduce electrical lighting) are prevented. Koo et al. (2010) showed that advantages from daylight usage are possible when the control of individual facade elements is enabled rather than control of the entire surface (see Figure I-5).


(a) (b)

Figure I-5: (a) Control of entire façade array versus (b) control of individual element façade array elements.[6]

I.1.4 PROBLEM STATEMENT

Employment of SG in office buildings has a slow expansion since they are associated with high-risk investment from project managers even though the system seems to be promising for new designs and retrofitting (Lee et al., 2012). Higher initial investment, failure costs and uncertainties of maintenance and tangible benefits are the major causes that possible can lead to excessive payback times (Loonen et al., 2013). A new device, called DDLC technology, appears to overcome drawbacks of conventional SGs (slow switchable speed and poor color rendering), but any research has been accomplished yet to estimate the performance of the system, mainly due to its novelty. Furthermore, its effects on the visual environment and glare from daylight are unknown.

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[6] Koo et al.,2012

Although the system appears to enhance building's performance (Sbar et al.,2012; Fernandes et al., 2013), control systems have a large impact on the final outcomes of visual comfort, consumptions and acceptance (Piccolo & Simone, 2009; Lee et al., 2012) in offices.

Control strategies are a key factor in the obtainment of visual comfort and protection against glare (Colaco et al., 2008; Konstantoglou and Tsangrassoulis, 2016) by façade systems. According to O'Brien et al. (2013) in offices "the biggest motivation for closing shades is to prevent glare and other forms of visual discomfort". The geometrical discretization of offices' façade array facilitates the implementation of control strategies based on the concept of individual facade elements control (see Figure I-5) which appears to have benefits on visual comfort and consumptions (Koo et al.,2012).

Despite the potential and the constant development of the SG devices, their application in office building remains limited mainly due to the lack of an integrated control system able to deliver the required performance.

In order to collect the market needs, an innovative control system, able to either provide protection against glare and regulate the incoming light, in combination with DDLC windows may represent a key upgrade for application in the transparent façade array of office buildings.

I.2 RESEARCH GOAL AND QUESTIONS

The problem statement (section I.1.4) highlighted several uncertainties and opportunities offered by the DDLC windows and control systems; consequently, this study aims to evaluate the potential of such combined technology. The primary goal of this research is:

To develop, implement and assess the performance of an innovative control strategy for a façade array with DDLC windows, based on the trade-off between visual comfort (i.e. daylight discomfort glare) and room ambiance (i.e. daylight admittance, illumination level and distribution).

In order to achieve this goal, the following objectives are fulfilled:

- *Development of control strategies that aim at protection against direct glare while maximizing daylight admittance in consideration of a switchable façade array for an office space.*
- *Definition of the most suitable methods to evaluate the operating principles of a combined application of DDLC façade array and conceived controls strategies and estimate its performance and potential.*
- *Appraisal of the combined application for glare protection (according to existing metrics) and analysis of the effects on illumination level and distribution.*
- *Assessment of the performance of the developed control strategy to provide input for further refinements.*

I.2.1 RESEARCH OUTLINE

The project is divided into two parts that logically set the path to meet the goals and answer the questions outlined for this research.

The first part is the preparation phase that outlines the research methodologies, which is realized within the M3 project and discussed in the M3 report. First, the assessment methods for discomfort glare results from a thorough literature review and define the research methodologies and the guidelines for the development of both control strategies and testing environment, either virtual and real.

The second part is the application phase in which the findings result from the implementation of the chosen research methodologies. This study is accomplished for the M4 project and discussed in this report. The first step is the definition of the GPC control strategies; then, each research methodology is applied in the virtual and real testing environment, to assess the objectives and the questions of the study.

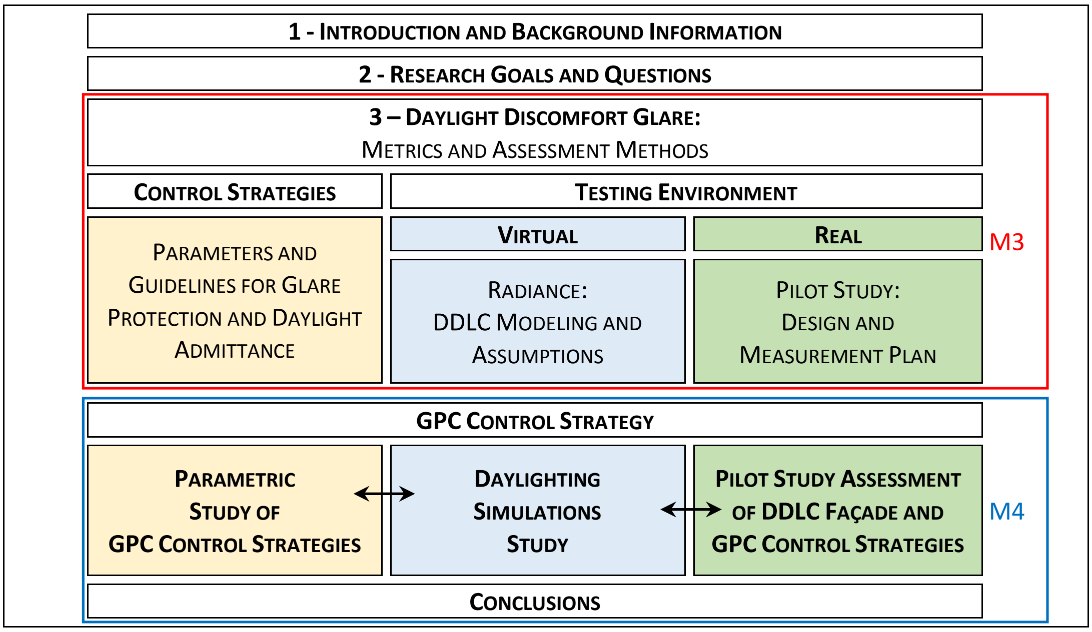

Figure I-6 : Research structure.

I.2.2 M4 GOAL AND QUESTIONS

The primary objective of this part is:

The development and implementation of control strategies to enhance visual comfort and room ambiance, then the assessment of the performance for a façade array with DDLC windows

To fulfill this objective, the following questions are answered:

- *Which of the developed control strategies augments most daylight admittance in consideration of a façade array for variation of sensitive parameters? What is the effect of window position within a façade?*

  In case of a DDLC façade array controlled by the conceived control strategies:

- *Is the system providing protection against glare in discrete days of the year for clear sky conditions and different orientations? What is the effect on illumination level and distribution at work-plane height?*
- *Do the developed strategies effectively provide protection over the desired areas (workstation(s), user(s)) in the pilot study?*
- *Are the results of pilot study measurements comparable with those from daylighting simulations regarding glare assessment, illumination level, and distribution?*

II CONTROL STRATEGY APPROACH AND RESEARCH METHODS

II.1 GPC CONTROL STRATEGIES

II.1.1 GOAL AND PARAMETERS

Automatic daylighting systems allow the adaptation of shading devices to the dynamic behavior of natural light. The resulting visual environment in office buildings has to allow optimal visual performance but also achieve of pleasant luminous conditions.

Therefore, the goal of control strategies under development is to provide protection against direct glare while maximizing daylight admittance (see Figure II-1). The system considers a common configuration of office buildings: a transparent façade array enclosing the interior spaces.

(a) *(b)*

Figure II-1: Goals of control strategies for offices with highly glazed façade arrays: (a) protection from glare experience in buildings[7], and; (b) enhancement of daylight admittance and visual connection to exterior[8].

The first step for the development of control strategies is the analysis of daylighting features and the requirements. A thorough evaluation of the lighting environment for office buildings was accomplished within the M3 project (Capperucci, 2016) through three criteria: occupant requirement, light scene configuration, and light source features. The following points summarize the key findings of the study:

- Geometrical discretization of offices' façade array allows the integrated interface between the light source (sun), the interface (façade) surface and the receiver (Office occupant).In this configuration, the visual functions of the transparent façade are divided for: the upper part, permitting daylighting deep in the building ; the middle part, allowing view to the outside and; the lower part. However, all the parts are potential provide potential risk of glare; mainly from the upper and the middle parts. Also, façade array configuration facilitates the implementation of control strategies based on the concept of individual facade elements control.
- Task area and its immediate surroundings are the zones requiring effective protection from adverse luminous conditions since the visual task is performed over these surfaces.Glare protection, adequate illuminance, and balanced lighting distribution are the main requirements for visual tasks in offices. Metrics for the evaluation and quantification of these requisites are DGP, for glare; E_M for illuminance levels, and; U_0, for illuminance distribution. Automatic controls integrated with artificial lighting can address these demands and widely accepted even tough individual override is necessary for users' satisfaction.
- Control systems for shading devices based on solar coordinates and feedbacks from the sensor for the luminous environment allow proper management of the dynamic nature of daylighting. Luminous conditions change rapidly and consistently; therefore, dynamic shading devices (e.g. DDLC windows) efficiently controlled (e.g. individual control of elements) allow the achievement of an optimum environment.

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[7] www.mrtints.co.uk

[8] http://lqs.omslighting.com/efficiency-2/daylight-sensor/

II.1.2 CONTROL VOLUME CONCEPT

Blockage of direct sunlight, the primary source of glare, is necessary to avoid annoyance and impairment of the view during a task. Office occupants mostly close shading devices to avoid glare (O'Brien et al.,2013) from daylight; either direct, indirect (from reflection on desks or walls), and veiling (on screens). Assurance of appropriate visual performance and protection from this disturbance is essential on the task area and its immediate surroundings, visible in Figure II-2a. Working tasks are habitually accomplished at workstations (i.e. desks) and the user can vary its position to perform different jobs. Also, change of position and view direction take place to adapt to the visual environment and minimize the occurrence of glare. Despite this 'adaptive zone' (Jakubiec & Reinhart, 2012) there is the need of persistent protection on the user, workplace and maneuver area.

Therefore, the author proposes the concept of 'control volume': the user, its workstation and maneuver space are enclosed by a volume (e.g. a box) within which no direct sunlight is allowed. Obstruction of daylight on the 'control volume' result in the avoidance of:

- Direct glare, on occupant seat and position inside the maneuver area, and;
- Indirect and veiling glare, from reflection on workstation and screen.

Figure II.2b displays the 'control volume' concept.

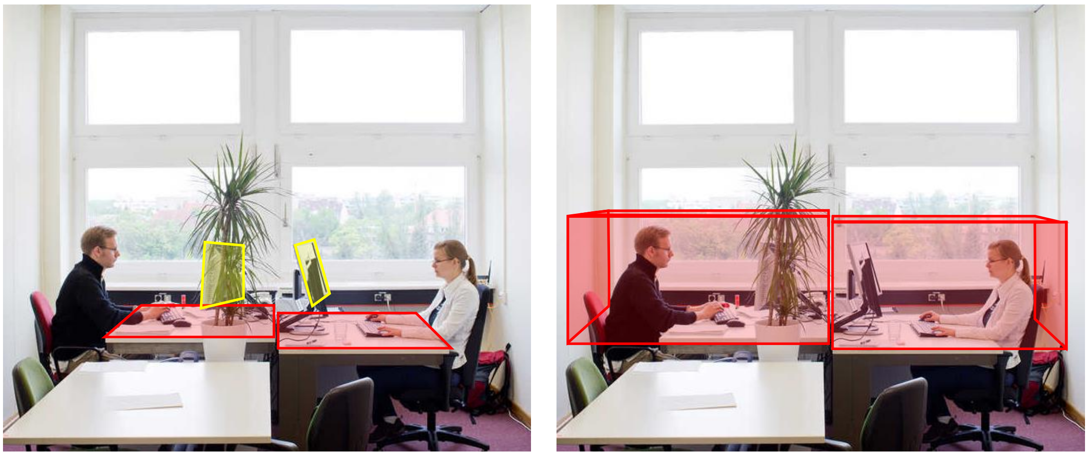
(a) (b)

Figure II-2: Occupant lighting requirements in offices buildings. (a) Conventional approach for task area and its immediate surroundings. (b) 'Control Volume' approach.[9]

II.1.3 APPROACH

Due to requirement for office visual tasks but also the conflicting nature of the goal, the enhancement of luminous conditions for an office with a façade array should be accomplished in the following order:

I First and the main purpose is the avoidance of glare from sunlight; this goal is achieved by shielding the 'control volume(s)' and interior spaces from the access of light (e.g. by shading devices). However, depending on the approach, it reduces or completely blocks both beneficial natural light (i.e. for lighting and users' health) and the visual connection to the outside.

II The following goal is to maximize daylight admittance into space and view to the outside, according to the constraints descending from the previous goal. This scope is accomplished by reducing the light-shielding area as far as glare protection is guaranteed to 'control volumes.'

Conventional control systems command the entire façade (Section 1.I.3) and are based on the use of a reference sun penetration depth. For protection from glare, the system considers the control volume with the least sun penetration for the entire room (see Figure II-3a). Such configuration is not flexible:

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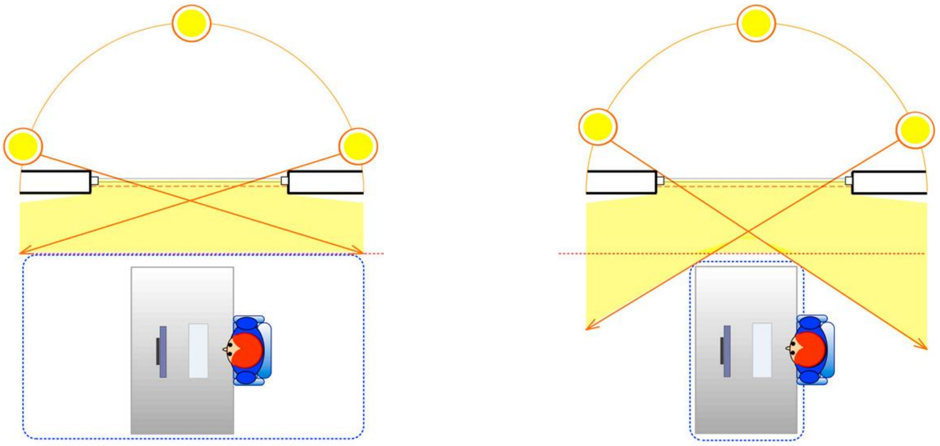
[9] https://officedomain.wordpress.com/tag/office-fitout/

does not enhance daylight admittance and can cause disagreements among the occupants. Users far from the windows may prefer daylight deeper into the room; on the other hand, workers close to the windows may require higher protection.

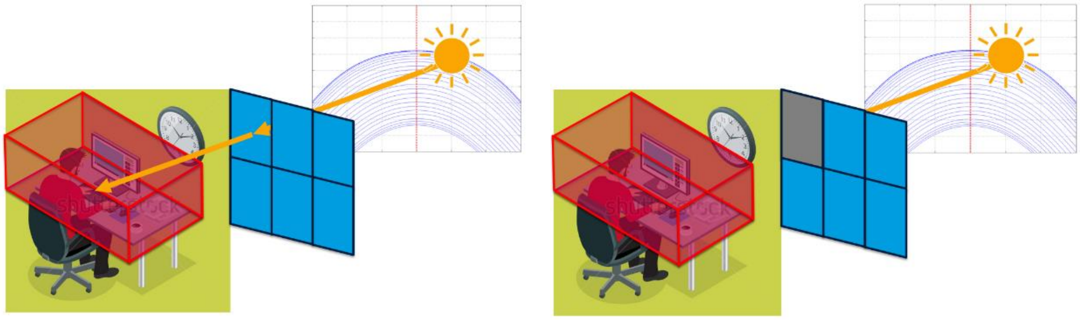
Differently, a controller based on the approach of individual control of façade elements (Section I.1.4) appear the most suitable method in light of its flexibility. To guarantee glare protection, this system considers individual sun penetration for each control volume and only for the extension of the zone (see Figure II-3b). This approach can avoid unnecessary blockage of daylight while providing comfort requirements in different part of the room.



(a) *(b)*

Figure II-3: Sun penetration depth and daylight admittance for daylighting systems controlling (a) the entire façade and (b) the individual elements of the façade; in consideration of a 'control volume'.[10]

In light of the previous considerations, the Glare Protection Control (GPC) strategies implements the individual control of façade elements for the protection of 'control volumes' of office spaces. In consideration of solar position and conditions, a façade array configuration equipped with shading devices can increase the daylight admittance by blocking only the necessary elements to protect working areas. Figure II-4 represents schematically the concept of GPC strategies.



(a) *(b)*

Figure II-4: Schematic representation of GPC strategies approach: (a) when daylight falls on a 'control volume' of an office space, (b) the GPC system blocks only the elements of the façade array allowing light on the 'control volume'.

The GPC strategy approach implements feedbacks from exterior luminous conditions and occupancy (i.e. exterior and interior sensors) but also, as many other daylighting systems, it calculates the solar coordinates. Inputs of the system are geographical location, façade orientation and geometry of the office room. Transparent façade array of the space is composed of rectangular window elements. Windows are the interfacing elements between daylight and control volume(s); therefore, in this strategy they can be regarded as solar shading elements (for example, as blinds). Dimensions of control

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[10] Koo et al., 2010

volume(s) depend whether it is chosen to protect both occupant(s) and workstation(s) or just the occupant(s). Choice of control volume dimension influences daylight admittance. Last input is the position of the control volume(s) (i.e. user(s) and workstation(s)) within the space. With these information, the control algorithm can relate solar coordinates to those of the control volume(s), and it determines which façade element(s) has or have to be obstructed to provide protection against the direct beam of light. The system 'sees' the window array as composed of n rows by m columns of 'pixels' that can be, independently from each other, obstructed or opened. Figure II-5 displays the calculation loop for GPC strategies according to the concept explained above.

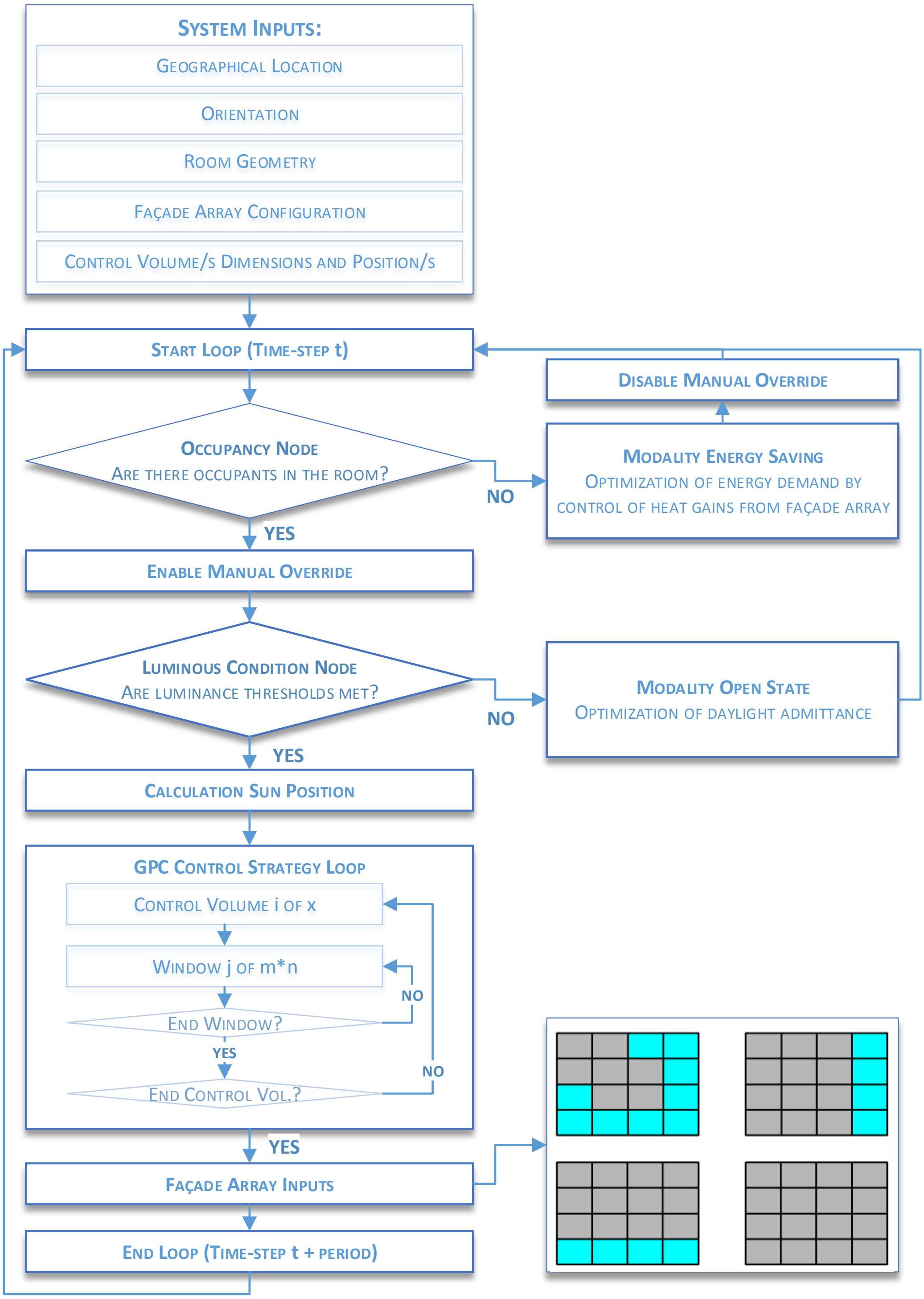


Figure II-5: Calculation loop for GPC strategies with multiple control volumes and with feedbacks from occupancy and luminous conditions.

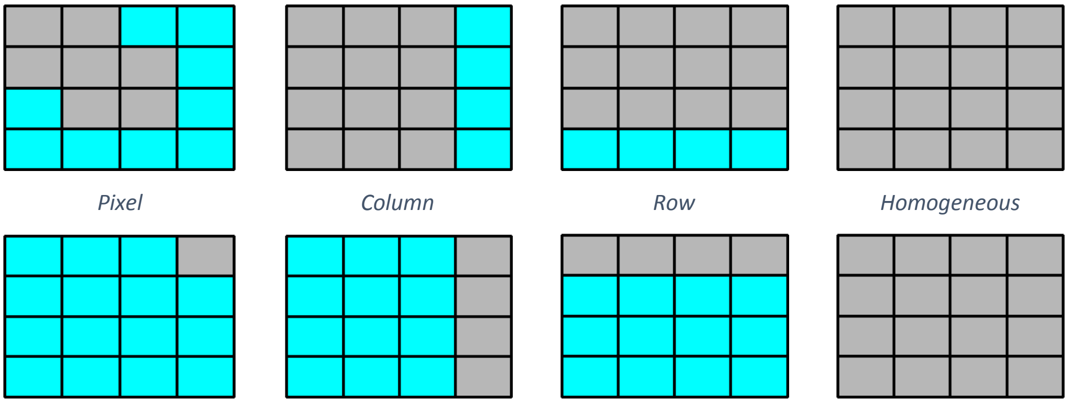
The feedbacks from occupancy sensors are used in homonym node. If no user is found in the space the system has to switch to ‘Energy Saving Modality’ and disable the manual override. Differently, when presence is detected, the system should enable the manual override and continue to the next node. The ‘Luminous Condition’ node utilize feedback from exterior sensors of luminous environment. When the thresholds (e.g. luminance or irradiation on the considered surface) are not met the system switch to ‘Open State’ modality, that opens all the shading devices to allow maximal daylight admittance. On the other hand, if thresholds are met, the algorithm computes the solar coordinates and triggers the GPC loop to provide protection against the adverse luminous conditions.

II.1.4 STRATEGIES

In light of GPC approach, the following four control strategies were developed according to geometrical constraints about the array of windows:

- Pixel: To maximize the area allowing daylight access (i.e. open state) the system will obscure only the necessary ‘pixels’ of the array to provide shading over the control volume(s). The obscuring occurs regardless of geometrical constraint on the resulting pattern of dark and bright elements in the window façade.
- Column: This approach improves daylight admittance by darkening all the columns (elements from top to bottom) of the array necessary to protect the control volume(s). Differently from the previous strategy, this approach has the geometrical constraint to provide the feeling of vertical evenness in the façade array.
- Row: Similar to the previous approach, the strategy increases the amount incoming light through the darkening of all the rows (from left to right) of ‘pixels’ necessary to protect the control volume(s). In this case, the aim is to offer the feeling of horizontal evenness in the façade array.
- Homogeneous: This strategy is relatively straightforward since its goal is to block the whole array when the beam of sunlight reaches the geometrical limits fixed by the control volume(s).

Figure II-6 presents some examples of possible façade configuration achievable in consideration of the developed strategies and their concepts.



Pixel *Column* *Row* *Homogeneous*

Figure II-6: Visualization of possible configuration resulting from the employment of a DDLC façade array in combination with ‘Pixel’, ‘Column’, ‘Row’ and ‘Homogeneous’ control strategies.

Pixel is the only strategy applying effectively the GPC approach, since the rest do not minimize the obstructed façade elements. Column, Row and, Homogeneous are designed to provide more uniform geometrical pattern of the façade when shading devices are closed.

Moreover, these strategies (mainly Row and Homogeneous) reproduce the conditions achievable with conventional daylighting controllers; using the partially or the complete façade approach. This allow the comparison of Pixel and GPC approach with more existing daylighting system.

II.2 METHODS

Methodologies for the development and the assessment of a combined application of DDLC façade array and control strategies have been defined for the scope of this research (Capperucci, 2016). Analytical method as well as virtual and real testing environment are prepared to fulfill research objectives. To provide qualitative and quantitative proof about the potential of the system three types of investigations are carried out:

- Analytical method: Parametric study of the control strategies
  Purpose of the research is to investigate the effectiveness of the GPC control strategies, for switchable windows or automatic shading devices, in increasing the daylight admittance for an office room equipped with façade array. Sensitive parameters such as location, orientation, façade grid refinement, and dimensions of protection volume are varied to test the robustness of each strategy. Moreover, the relation between daylight admittance and window position within façade array is evaluated.

- Virtual Testing Environment: Daylighting simulation study
  A set of simulations in Radiance is performed to research the effect on the visual environment (i.e. daylight glare assessment, illumination level, and distribution) from a combined application of control strategies and DDLC façade array. The effects above are analyzed for clear sky conditions (i.e. high glare probability) in a discrete part of the year (i.e. different daylighting conditions) and different orientation of transparent surfaces.

- Real Testing Environment: Pilot study assessment of DDLC façade and control strategies
  In the pilot study room, equipped with a DDLC façade array and control strategies, the effective operation of the system (i.e. protection of user and workstation from direct sunlight) is tested. Measurements of luminance distribution within user's field of view and illuminance distribution in the room are taken to validate the daylighting performance of the system, in comparison with those resulting from the virtual testing environment.

These studies are reported in the following Chapter III as stand-alone investigations, but each part complementary to the others, to provide a wide range of information about the system.

III RESEARCH STUDIES

III.1 PARAMETRIC STUDIES OF GPC CONTROL STRATEGIES

III.1.1 GOALS AND PERFORMANCE INDICATORS

The main purpose of the part is to evaluate the effectiveness of GPC control strategies, for switchable windows or automatic shading devices, in the enhancement of daylight admittance.

The effectiveness of the control strategies developed for this project is evaluated through performance indicators representative of the annual amount of time in which the entire façade and each element should be darkened to provide protection to the control volume(s). Two different sets of calculations, depending on relevant parameters, are defined:

III.1.1.1 SET I | DAYLIGHT ADMITTANCE POTENTIAL OF CONTROL STRATEGIES

In this set of calculations, the most effective control strategy in daylight admittance is investigated. Three parameters will be varied in this set: location, orientation, and façade array refinement (the parameters will be discussed in the following chapter). The index D is defined as it follows:

$$D = \frac{\sum_{i=t}^{T}\left(\frac{\sum_{j=1}^{(n*m)} Input(i,j)}{n*m}\right)}{(T-t)} * 100 \tag{1}$$

Where: n = number of rows of windows in the façade array; m = number of columns of windows in the façade array; t = beginning time; T = end time; Input(i,j) = system input: 1 for bright state (i.e. no protection), 0 for dark state (i.e. protection).

The index averages the area of façade having light or open elements (input equal to 1) over the total area (consider all items are having input equal to 1), obtaining the ratio of surface allowing the access to daylight. Then, the ratios are summed and averaged over the time frame considered in the calculations; resulting in D, daylight admittance percentage.

III.1.1.2 SET II | DAYLIGHT ADMITTANCE POTENTIAL OF WINDOW POSITION IN FAÇADE ARRAY

The goal of this part is to investigate which windows (i.e. their positions within the façade array) allows the greatest and the least amount of daylight in the space. Refinement of the grid is constant, and the parameters that will vary are the location and the orientation. In this set only 'Pixel' strategy is investigated. The index D_W is defined as it follows:

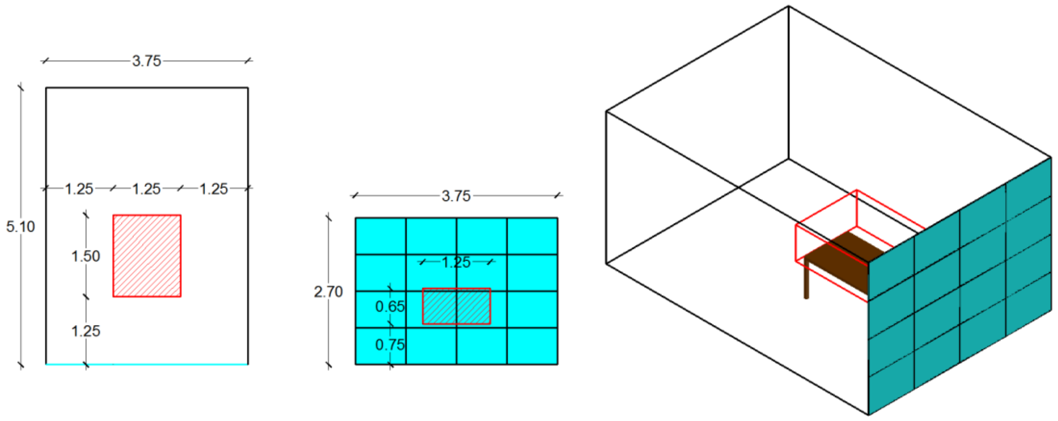
$$D_W(i) = \frac{\sum_{i=1}^{(n*m)}\left(\sum_{j=t}^{T} Input(i,j)\right)}{(T-t)} * 100 \tag{2}$$

D_W sum up all the states (i.e. 1's and 0's) over the time frame and divide the amount by the time frame, for each component of the façade array. The result is the time percentage in which the element is in an open state.

III.1.2 METHODOLOGY

Parametric calculations are done to evaluate the control strategy approach that allows the higher amount of light into space over a year. A space sized to typical single offices dimensions (height=2.70 m; width=3.75 m; length=5.10 m), and equipped with a fully transparent façade (3.75 m by 2.7 m) is used for the calculations. The façade is composed of an array of windows subdividing the area by the same number of an element either vertically and horizontally.

A single workstation is considered for the calculations. Two type of control volume are implemented depending on the degree of protection; the first one for both user and workstation while the second only for the user. In the first typology is implemented one box placed centrally in the room at 1.25 m from the façade. Differently, the user case implements two smaller boxes in correspondence to user's head. Dimensions of the control volume based on the size of a standard office table plus the operating space for user's movement, covering from workstation height to over user's head. Figure III-1 and III-2 illustrate room and control volume dimensions and arrangement. Both configurations consider that user's main view is parallel to the glazed surface (i.e. view direction toward the right or left wall); even though view preferences depends on individuals, this configuration is the most common in office buildings.



(a) *(b)*

Figure III-1: (a) Planar and (b) 3D view of room geometry and control volume for user and workstation used in the calculations.

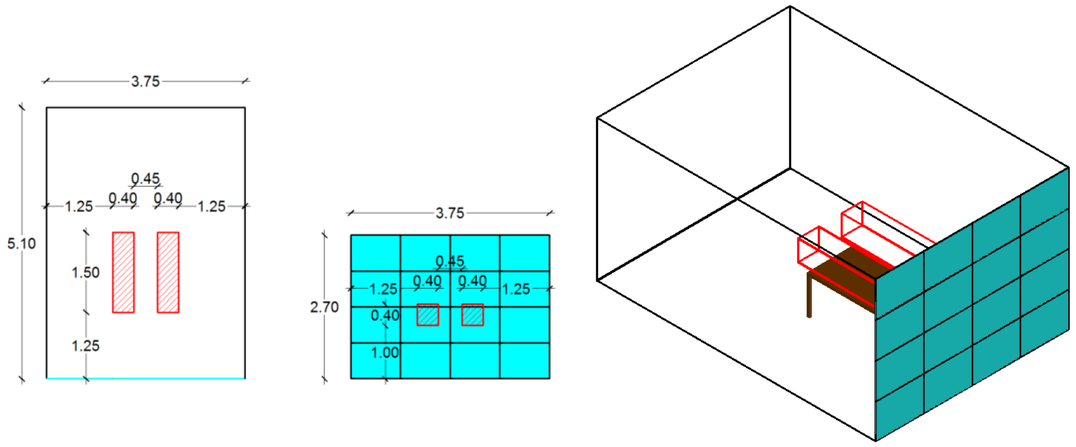


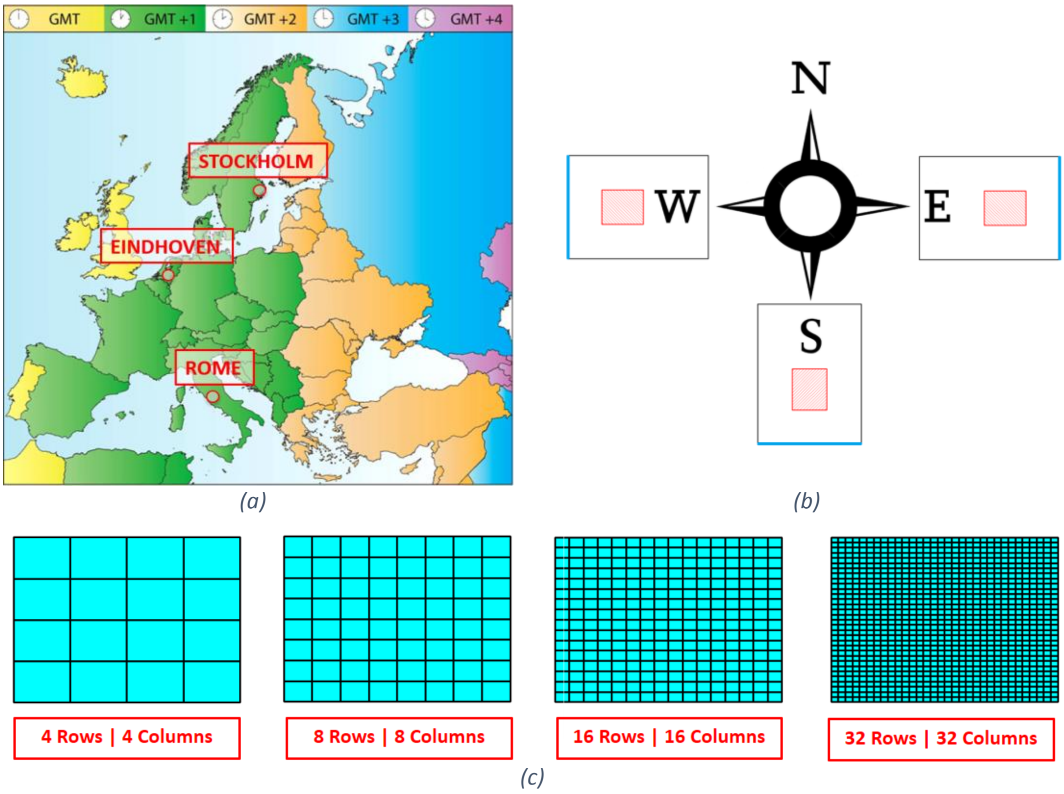
Figure III-2: (a) Planar and (b) 3D view of room geometry and control volume for the user employed in the calculations.

The two sets perform the calculation for an entire at steps of 30 minutes during working hours, between 8:00 and 18:00. This study assumes clear sky conditions since the aim is to compare the strategies and identify the most effective. The following parameters have been investigated:

- Location: Longitude and latitude coordinate of the site influences sun position (i.e. heavily for the altitude) and the length of the day. Three location within the same time zone, UTC +01:00, but at different latitudes have been chosen for this study as displayed in Figure III-3a: Eindhoven (location of the pilot study; latitude=51°.44, longitude=-5°.26), Rome (latitude=41°.89, longitude=-12°.51) and Stockholm (latitude=59°.33, longitude=-18°.06).
- Orientation: Planar transparent surfaces in buildings are influenced differently, depending on the amount of sun that is received, by the direction of the surface. Therefore, the orientation of the glazed surface is set toward East, South and West orientation (see Figure III-3b) in light of the differences of daylighting conditions at which they are exposed.
- Façade Array Refinement: Office buildings often employ façade composed of an array of windows (section I.1), and the degree of refinement of such grid might have a relevant influence on daylight admittance in combination with the control strategy. The following arrays are

implemented in the calculations to estimate the impact of grid discretization: 4x4, 8x8, 16x16 and 32x32 elements (see Figure III-3c).

- Control Volume Size: User and workstations define the geometrical constraints for the state of the shading device, which represents the interface between them and sunlight. Position and dimensions of the space to protect influences maximization of daylight admittance; however, the position is not a controllable parameter since it depends on the choice of the room layout. Dimensions of the control volume vary with the degree of protection: for both user and workstation (see Figure III-1) or only for the user (see Figure III-2).



(a)

(b)

(c)

Figure III-3: Calculation parameters: (a) Location, (b) Orientation, and (c) Façade Array Refinement.

III.1.3 RESULTS AND DISCUSSION

In this chapter, the results are presented and discussed. Due to similarities in trends between different locations, in this section only displays the graphs for Eindhoven, complete plots for all location are reported in Appendix VI.1.

III.1.3.1 SET I | DAYLIGHT ADMITTANCE POTENTIAL OF CONTROL STRATEGIES

The first set of calculations aimed to vary all the parameters mentioned in section III.1.2 to investigate which control strategy provides the higher amount of daylight admittance using the index D. The results displayed in Figure III-4 show a clear trend between the control strategies; 'Pixel' strategy allows the most daylight admittance in the space for all computation conditions in all locations. 'Column' and 'Row' control strategies resulted in the second most performing strategies in all sets depending on the orientation while 'Homogeneous' guaranteed the least daylight admittance.

Location effect is visible relative to room orientation; as a matter of fact, as the latitude increases the values of D for South orientation slightly reduces in all configurations whereas in East and West orientation small improvements are obtained. Southern orientation highlights once more the benefits of 'Pixel' strategy, which yields increases in D index respectively from 14% to 23% compared to both Column' and 'Row' strategies and from 87% to 143% to 'Homogeneous'. These outcomes are caused by differences in sun position: either solar altitude and solar azimuth. However, the latter also depends on location's longitude that occurs to vary between the three chosen locations so no real conclusions can effectively be drawn on effects for East and West configurations.

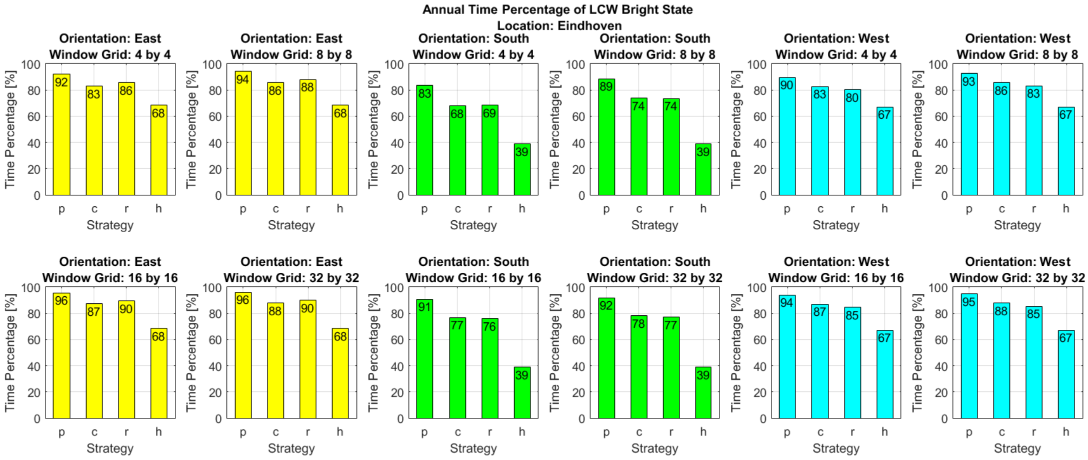


Figure III-4: Annual time percentage of open state for control volume on user and workstation. Results for each control strategy, window grid, and orientation are shown for Eindhoven. Results for other location are visible in Appendix VI.1.

Façade array refinement produces a growth of the index for all the settings, from the lower to the higher discretization, apart from 'Homogeneous' that remains constant due to strategy's criteria. Improvements reach the maximal value of 15% compared to the base grid of 4x4, with limited improvements for 'Pixel' approach. However, with more workstations hence more control volumes and different positions, the constraints will be more. Multiple constraints on each window might turn façade array refinement into an added value for augmenting income of daylight. In the latter situation, 'Pixel' approach will maximize the benefits of its concept by creating patches of dark elements specifically sized to protect the configuration of multiple control volumes.

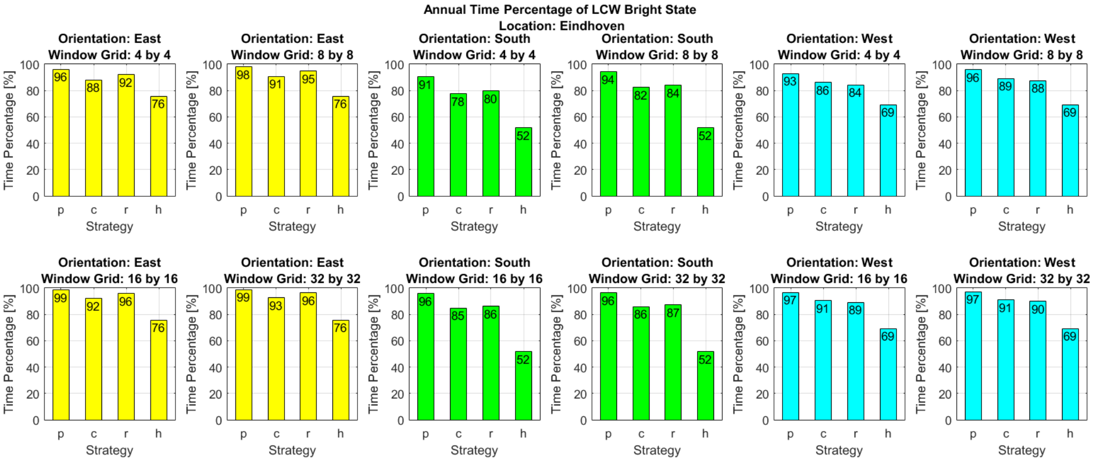


Figure III-5: Annual time percentage of open state for control volume on the user. Results for each control strategy, window grid, and orientation are shown for Eindhoven. Results for Rome and Stockholm are visible in Appendix VI.1.

Figure III-5 shows that when the control volume is reduced only to the user, D index increases significantly in all the settings. Results for 'Homogeneous' strategy as expected have risen the most, but with 'Pixel' approach peaks of 99% have been achieved. The most consistent improvements are obtained for South orientation with similar magnitude in each location. Refinement of façade array has shown to be more efficient compared with smaller control volumes.

III.1.3.2 SET II | DAYLIGHT ADMITTANCE POTENTIAL OF WINDOW POSITION IN FAÇADE ARRAY

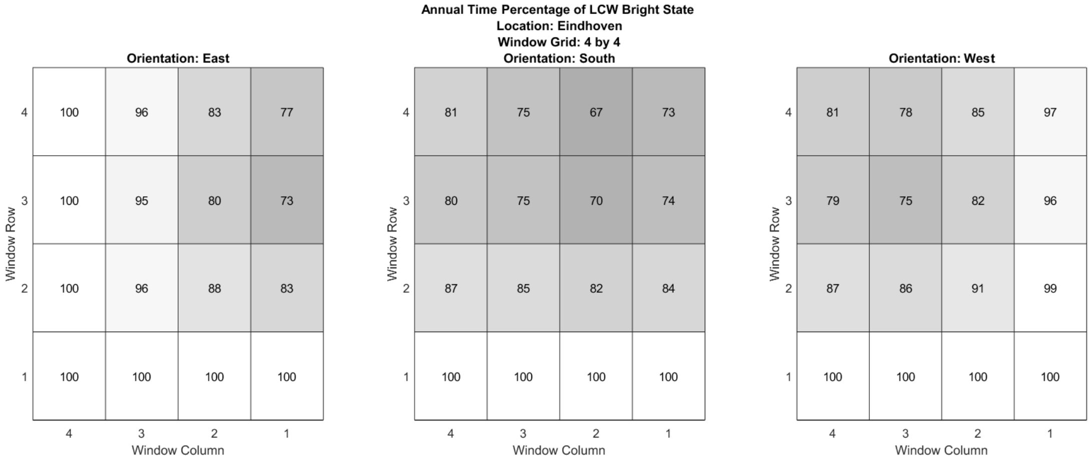


Figure III-6: Annual time percentage of open state for control volume on user and workstation. Results for each window and orientation with grid refinement equal to 4 are shown for Eindhoven. Results for other Rome, Stockholm, and grid refinement equal to 8 are visible in Appendix VI.1.

The second set of calculations aimed to investigate the effect on daylight admittance of windows positioning within façade array, through the index DW. The results displayed in Figure III-6 are valid for the configuration with a control volume placed centrally in the room. Since these strategies are based on the geometrical position of the user(s) different results and trend are expected with various workstation's positions. Results show that D_W has low values mainly in the top windows due to the obvious relation with sun elevation angle. The height of control volumes leads to D_W values equal to 100 % for each element of the first row in all the configurations, meaning that never turn to the dark state during the entire year. Also, this relation will maximize the daylight admittance through the lower rows when the refinement of façade array is going to be increased. Differently, the effect of orientation results in D_W values up to 100% on the left end of the façade for East orientation and on the right end of the façade for West orientation in all locations. This effect is due to the azimuth angle of the sun in relation to time frame considered in this calculations (i.e. from 8:00 to 18:00) as well as location's longitude. A reduction of DW values for West orientation and mainly in the right end is visible between Eindhoven, Rome, and Stockholm. The cause of this decrease and shift of low D_W to the right end is due to the decreasing trend of longitude angles from the western location (Eindhoven) to the eastern location (Stockholm) within the same time zone.

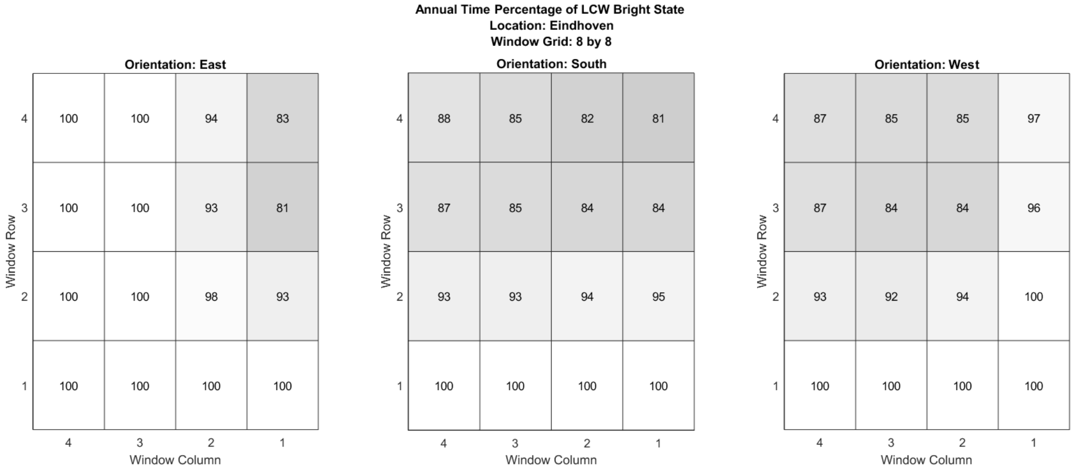


Figure III-7: Annual time percentage of open state for control volume on the user. Results for each window and orientation with grid refinement equal to 4 are shown for Eindhoven. Results for other Rome, Stockholm, and grid refinement equal to 8 are visible in Appendix VI.1.

As expected, when the size of the control volume decreases the index of openness for each window position increases (see Figure III-7). Similar to the previous set the major improvements are obtained for South orientation, and the effects due to the position of control volume (i.e. height) are even more pronounced.

Doubling façade array refinement from 4x4to 8x8 produces an increase in number of rows and columns presenting a D_W equal to 100%; therefore, of the equivalent façade area constantly in an open state. Results are reported in Appendix VI.1.

III.1.4 CONCLUSIONS

The study above meant to highlight the effectiveness regarding annual daylight admittance of each control strategy developed for the DDLC technology. Also, the effect of annual daylight admittance on window position is investigated. However, a preliminary consideration to the conclusion is necessary:

- The developed strategies are strictly dependent on workstation number and their position; therefore, findings and comparison are valid in consideration of the geometry and positions chosen for the calculations. Moreover, in reality, sky condition are various and should be implemented to identify and quantify the benefits from GPC strategies.

The following conclusions can be drawn from these two set of calculations:

- ‘Pixel’ approach allows the greatest amount of daylight into a standard office for each location, orientation, and grid refinement. The best performances are achieved for South orientation where the results for index D are significantly higher than in other strategies.
- Orientation and location influence importantly the effectiveness of the control strategies, showing clear guidelines for each parameter.
- Refinement of the façade array seems to provide limited benefits for a single workstation; however, some improvements are obtained with smaller control volumes. Moreover, with multiple users and constraints, concrete improvements can be achieved.
- The dimension of control volumes can influence the goals of the control strategies massively: with complete control volumes protection against glare might be safer (against direct sunlight and workplace reflections) compared to protection only on the user. However, the latter provides significantly better results regarding light admittance.
- Window position effectiveness is strictly related to orientation and control volume’s height; these parameters define the parts in which daylight access is available during the whole year.
- Advantages such as shading devices constantly kept in an open state (maximal daylight admittance), as well as removal or substitution of the application (for example switchable windows with standard glasses), can be maximized with finer grids or orientation choices.

As a remark for future investigations, a loop evaluating sky condition from meteorological data (i.e. IWEC weather file) shall be implemented in the calculation procedure. This way the system can “override” the GPC strategy in overcast condition and relate the potential of GPC strategy to operative conditions.

III.2 DAYLIGHTING SIMULATION STUDY

III.2.1 GOALS AND PERFORMANCE INDICATORS

The primary goal of the study is to assess the performance of GPC control strategies in combination with a DDLC façade array. Fulfillment of the goal is studied by daylighting simulations in Radiance virtual environment, involving two types of investigation:

- Assessment of discomfort glare from daylight, and;
- Room illumination quality, by means of illuminance level and distribution.

To estimate the potential of the GPC control strategies two of them are compared: Pixel and Homogeneous. Section III.1 revealed that Pixel allows the maximal daylight admittance compared to other GPC approaches. Differently, Homogenous is designed to provide a more uniform visual environment by obscuring the entire array, which also resembles the criteria of existing daylighting strategies (section I.1.3). Discrete part of the year and different orientations are simulated to account for the difference in luminous conditions and solar positions.

III.2.1.1 DISCOMFORT GLARE ASSESSMENT

The most reliable index for daylight glare evaluation is the Daylight Glare Probability (DGP) due to scientific evidence and lower reliability of other metrics (Capperucci, 2016). DGP is established on a different glare detection approach compared to other available indices; it is determined by comparison of bright luminance areas against the total vertical eye illuminance. The innovation introduced in the method of Wienold & Christoffersen (2006), enables the evaluation of glare sources also from specular reflections and avoid the detection of false disturbing scenes, such as with a dim sky view. Moreover, the illuminance term allows glare detection in an extremely bright scene having little contrast.

$$DGP = 5.87 \cdot 10^{-5} E_v + 0.0918 \cdot \log_{10}\left[1 + \sum_{i=1}^{n}\left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right)\right] + 0.16 \qquad (3)$$

Where: E_v is the vertical eye illuminance resulting from the light scene; $L_{s,i}$ is the luminance of the i-light source; $\omega_{s,i}$ is the solid angle of the i=light source as seen from the observer's point of view and P is the position index expressing the change in experienced glare relative to an angular position between the light source and observer's line of sight.

This method appears to have a better correlation with datasets (Wienold & Christoffersen,2006; Suk et al., 2013) compared to conventional metrics. DGP enables a relatively quick evaluation from luminance pictures either from real or simulated (Jakubiec & Reinhart, 2012) daylighting scenes. Computation is obtained from *evalglare* (Wienold, 2004), an appositely designed software that can calculate the index from a pixel evaluation of an 180° fish-eye daylighting scene. Also, recent research (Hoffmann et al., 2015) have shown that *evalglare* in combination with DGP can evaluate glare from complex fenestration systems (CFS), such as DDLC windows. Although this method has various advantages, it was found that can underestimate glare under certain light configurations (Van Den Wymelemberg & Inanici, 2014). The following Figure III-8 shows an accepted scale of ranges of DGP.

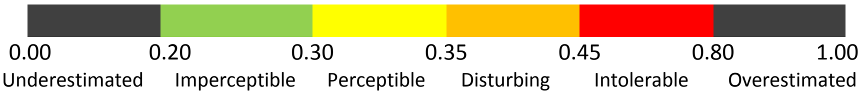


Figure III-8: Four-point sensation scale (Carlucci et al., 2015).

III.2.1.2 ILLUMINATION LEVEL AND DISTRIBUTION

The level of illumination and its distribution are widely known to influence the visual performance of a task; therefore, depending on the typology of work to perform different requirements are set by the standards. For interior environments such as an office, the requirements for lighting (from daylighting, electrical lighting or mixed) are established by the norm EN 12464-1 "Light and Lighting - Lighting of work places - Part 1: Indoor work". Two type of areas are subject to requirements; the task area and the surrounding area, to provide a balanced distribution in the field of view.

The first condition regards the average illuminance E_{avg} on the considered area, which should not be less than a particular maintained illuminance E_m .

$$E_{avg} \geq E_m \tag{4}$$

The second requirement is about the Uniformity U_0 of illumination on the surface (relates the minimal illuminance E_{min} to the average illuminance E_{avg}), which should not be less than a maintained value $U_{0,m}$.

$$U_0 = \frac{E_{min}}{E_{avg}} \geq U_{0,m} \tag{5}$$

Requirements for offices depend on type tasks as displayed in Table III-1a, for this study is chosen activity 3.2 (writing, typing, etc.) since it is the most common configuration. Requisites for task and surrounding area of maintained illuminance and uniformity are displayed in Table III-1b.

Table III-1: (a) Lighting requirements for offices depending on interiors, tasks and activities.
(b) Requirements for task area and surrounding area of offices.(EN 12464 – 1)

(a)

Offices			
Type of interior, task or activity	E_m [lx]	UGR_L [-]	R_a [-]
3.1 | Filing, copying, etc.	300	19	80
3.2 | Writing, typing, reading, data proc.	500	19	80
3.3 | Technical drawing	750	16	80
3.4 | CAD work stations	500	19	80
3.5 | Conference and meeting rooms	500	19	80
3.6 | Reception desk	300	22	80
3.7 | Archives	200	25	80

(b)

Illuminance E [lx]	
Task Area	Surrounding Areas
≥ 750	500
500	300
300	200
≤ 200	E_{task}
Uniformity U_0 [-]	
≥ 0,7	≥ 0,5

The standard does not provide metrics to evaluate illuminance distribution in the room; it only requires to provide a well-balanced luminance field. However, the spatial distribution of daylighting in the space is an essential factor for daylight dependent controls of electric lighting and determination of energy savings potential with space distribution. Dimming and switching in these systems are based on the natural lighting condition within the area to be lit; hence it provides the amount of illumination to meet the requirements mentioned above. The modulation of the power drawn based on the free contributions from the sun can allow important energy savings. Two performance indicators (DIN 5034-3:2007-02 (E)) are available:

I - Relative Annual Utilization Time (RAUT):

$$RAUT = \sum_{i=1}^{n} \frac{U_{t,i}}{B_{t,i}} \tag{6}$$

Where: $U_{t,i}$ = Utilization time of i-day, is the time interval in which the average illuminance E_{avg} caused by daylight is equal or higher than required maintained illuminance E_m; $B_{t,I}$ = Base time related to $U_{t,I}$, generally the working hours.

II - Relative Annual Usable Luminous Exposure (RAULE):

$$RAULE = \sum_{i=1}^{n} \left(\int_{B_{t,initial}}^{B_{t,final}} \frac{LE_i\,(t)}{LE_{req,i}(t)} dt \right) \tag{7}$$

Where: $LE_{,i}$ (t) = Luminous exposure from daylight of i-day, is the integral of illuminance from daylight during the base time B_t (working hours). When E_{avg} is higher than required maintained illuminance E_m it is replaced by E_m , to prevent overestimation of daylight contributions; $LE_{,req,i}$ (t) = Luminous exposure needed for i-day, is the integral of the required illuminance (E_m) during the base time B_t (working hours).

RAUT expresses the amount of energy that can be saved compared to a typical situation in which the lighting system is continuously switched on. This index is valid for all lighting system, but the dimming of lighting is not considered.

RAULE expresses the amount of energy can be saved in consideration of a lighting system supplying the exact additional illumination to meet the requirements. Different from RAUT this metric allows the evaluation of dimmable lighting system.

Figure III-9 illustrates the principles of RAUT and RAULE performance indicators.

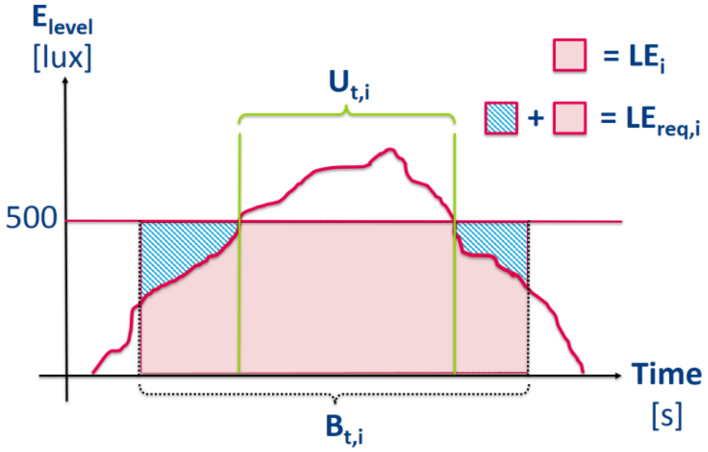


Figure III-9: RAUT compares the utilization time (green lines) with the base time (dotted lines), typically the working hours. RAULE compares the luminous exposure from daylight (red fill) with the required luminous exposure (red fill plus striped fill).

III.2.2 METHODOLOGY

III.2.2.1 APPROACH

The validated Radiance backward ray-tracing software is selected to assess research goals (section II.2). Radiance software allows the computation of HDR luminance pictures and illuminance grid values, needed for the calculation of performance indicators. A standard-sized office equipped with a facade array, of four columns by two rows, of DDLC windows and controlled by GPC strategies is simulated with the façade oriented toward East, South and West. The location chosen for the calculation is Eindhoven, the Netherlands. Simulations are done between 8:00 and 18:00 local time (i.e. working hours) with steps of 60-minutes. Six discrete days of the year, the 21st of the month from January to June, are chosen in order to include Summer Solstice and Spring Equinox.

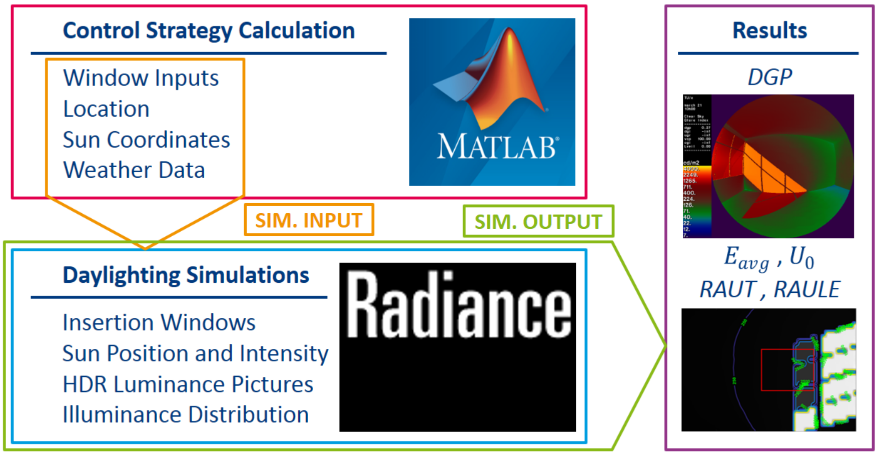
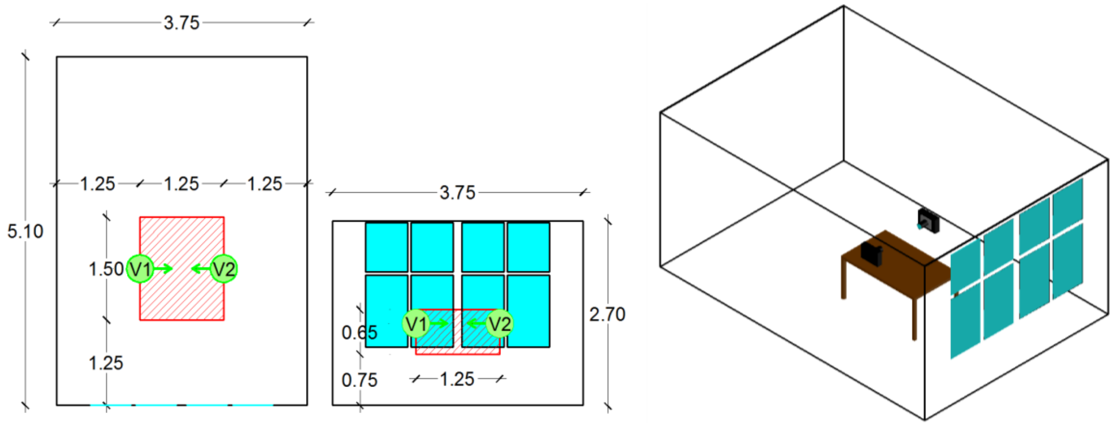


Figure III-10: Flowchart of the workflow for daylighting simulations in Radiance.

A flowchart of the simulation process is displayed in Figure III-10. Simulation of the DDLC façade in combination with control strategy is realized using a c-shell script in Radiance. The code reads the outputs from Matlab control strategy calculations and uses it as inputs for Radiance. Then, each window in the bright or dark state is inserted in model's façade depending on calculation output. In this way, other variable inputs are inserted such as location and sun coordinates but also data from climate files (for example, direct normal and diffuse horizontal irradiance); the latter shall be implemented for long-term simulation since it can model the stochastic conditions of illumination and irradiation.

III.2.2.2 Model

The space modeled in the simulation tool is the pilot study room whose dimensions (see Figure III-11a) are typical for standard single offices. A single workstation, hence one control volume is protecting both user and workstation, is implemented in the model geometry. The control volume is a box-shaped volume placed centrally in the room at 1.25 m from the façade, its dimensions are displayed in Figure III-11a. The positioning of the workstation considers that user's primary view is parallel to the glazed surface; despite view preferences depends on individuals, this is regarded as the most common in office buildings. The volume encloses two viewpoints used for glare assessment at eye-position (height h=1.20 m), one toward the right wall and one toward the left wall. Opposite viewpoints are necessary to evaluate the worst glare configuration, hence the position which gets hit most from direct sunlight, since it depends on room's orientation. The façade is an array of 4 columns by two rows of windows having the same length (l≈0.60m) but different height depending on the row (bottom row h≈1.05m, top row h≈0.70m). Room, control volume and viewpoints geometry employed in this simulation study are presented in Figure III-11.



(a) *(b)*

Figure III-11: (a) Planar and (b) 3D view of model geometry, control volume (red) and viewpoints in Radiance.

III.2.2.3 Settings and Assumptions

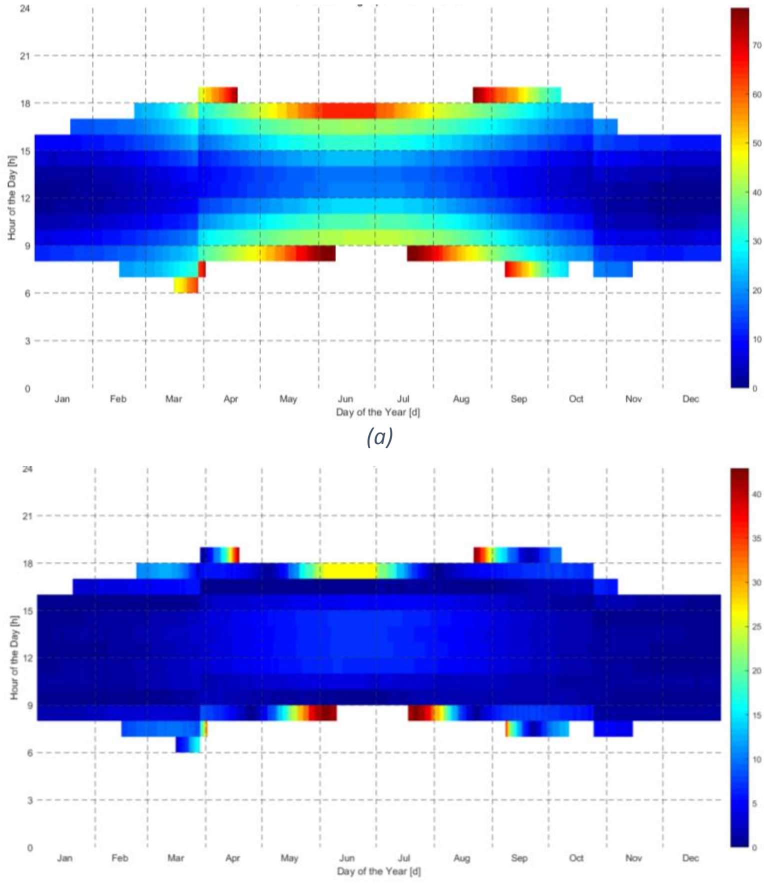
Luminous conditions resulted from the sky model generated by the 'gensky' Radiance program, producing the CIE standard sky distribution at the given month, day and time. The option +s was chosen to utilize a sunny sky with sun source description corresponding to the CIE clear sky model. Another solution could be the 'gendaylit' Radiance program, which describes the angular distribution of the daylight sources (direct and diffuse) using the Perez et al. sky luminance distribution model. The sky description can be based on measurements of atmospheric conditions, hence the direct and diffuse component of the solar radiation. The CIE clear sky model was chosen because it describes the most demanding conditions in terms of discomfort glare, to test DDLC window properties when used as shading devices.

Radiance model employs material properties of the pilot study because they satisfy the requirements of standard EN 12464-1. The luminous reflectance of opaque surfaces was measured by a spectrophotometer Minolta CM-2600d in the XYZ color space coordinates. Then, the results were converted into RGB values by multiplication with conversion matrix and finally computed with constants into the reflectance factor ρ. Differently, the direct luminous transmittance of the DDLC windows is measured through a less conventional process due to lack of equipment. The process of measurement involved an assumed parallel light source providing an illuminance field relatively constant over a small surface and evaluated the ratio between total and transmitted luminous flux. Detailed information and results are presented M3 report (Capperucci, 2016) of this project. The resulting luminous reflectance and direct transmittance for each surface are displayed in Table III-4.

Table III-2: Measured material properties utilized in Radiance

Surface	Material Property	Color & Reflection Type	Value [%]	Reflectance [%] EN 12464-1
Wall	Luminous Reflectance ρ	White - Diffuse	80	30 – 80 ✓
Floor	Luminous Reflectance ρ	Gray - Diffuse	20	10 – 50 ✓
Ceiling	Luminous Reflectance ρ	White - Diffuse	85	60 – 90 ✓
Desk	Luminous Reflectance ρ	Gray - Diffuse	45	20 – 60 ✓
Façade Wall	Luminous Reflectance ρ	White - Diffuse	80	30 – 80 ✓
Ceiling Box	Luminous Reflectance ρ	White - Diffuse	65	60 – 90 ✓
DDLC Bright	Direct Luminous Transmittance $\tau_{\perp}$	/	53	/
DDLC Dark	Direct Luminous Transmittance $\tau_{\perp}$	/	11	/

To model DDLC in Radiance, two materials are available: standard *glass* material or *BRTDfunc* (Bi-directional Reflectance and Transmittance Distribution). Material *glass* models an infinitely thin element (i.e. no computation of internal reflections) having a transmissivity derived from light transmittance, varying accordingly with basic Fresnel coefficients (Ward, 2004). Differently, *BRTDfunc* (B) material models specular and diffuse interactions for both reflectance and transmittance, from measured data of the glazing system (Ward, 2004). *Glass* material represents the simplest solution with much lower computational costs and time compared to *BRTDfunc*; however, the latter model provides a much more realistic response of the system. An investigation on the differences of Fresnel function between DDLC window and standard clear glass was conducted to understand which solution should be implemented in the Radiance model (Capperucci, 2016). Absolute and relative deviation of Fresnel coefficients between DDLC and normal glass functions are analyzed versus the relative sun position coordinates. This method allows the identification depending on time, location and orientation of the deviations. In Figure III-12 the results for South direction are presented.



(a)

(b)

Figure III-12: Relative deviation of Fresnel function for DDLC window in (a) bright and (b) dark state, orientation is South.

The greatest relative deviations, for both bright and dark state DDLC and all orientations, always occur when sun profile angle is high in combination with azimuth angle close to the extremity of the angular field (-90° and +90°). Influence of deviation on DGP and illumination level and distribution appear to be limited in light of sun positions mentioned in the previous point. Considering DGP, the index is not affected by these conditions because the office workstations are rarely implemented very close (i.e. less than 0.5 m) to the façade. Similarly, for illumination level and distribution the impact is low because the area influenced by the deviation is always marginal, due to obvious geometry constraints on angles, compared to room surface. In consideration of these results the 'glass' material is chosen since errors impact is assumed to be relatively low in consideration of the time-frame selected for the simulation. Additional motivations are the lower computational costs and the lack of BRTD measurements for the glazing system. Detailed information can be found in the M3 report (Capperucci, 2016) of this project.

A hemispherical fisheye was chosen in the viewpoints used for DGP calculation from HDR luminance pictures since this view provides a greater amount of information about the visual field.

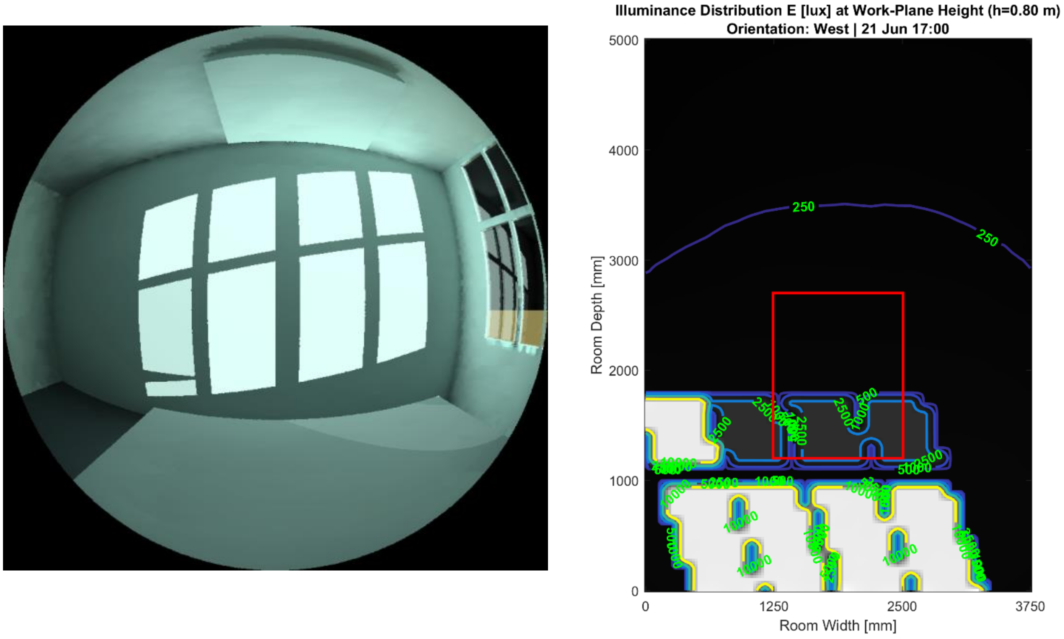
Computation of luminance images and estimate of illuminances is based on several parameters. The choice of Radiance parameters relies on a brief review of papers (Wienold,2009; Jakubiec and Reinhart, 2012) about DGP settings, the resulting set employed in the simulations in presented in Table III-3.

Table III-3: Radiance simulation parameters

Radiance Simulation Parameter	
Ambient Bounces (-ab)	5
Ambient Accuracy (-aa)	0.08
Ambient Divisions (-ad)	1024
Ambient Super-Samples (-as)	512
Ambient Resolution (-ar)	512

III.2.3 RESULTS AND DISCUSSION

The outputs from Radiance simulations are HDR luminance pictures with DGP results and room illuminance value at work-plane height (h=0.80 m). Post-processing by a Matlab script enables the computation of performance indicators and plots of illuminance at work-plane height. Figure III-13 show a sample HDR picture and an illuminance plot.

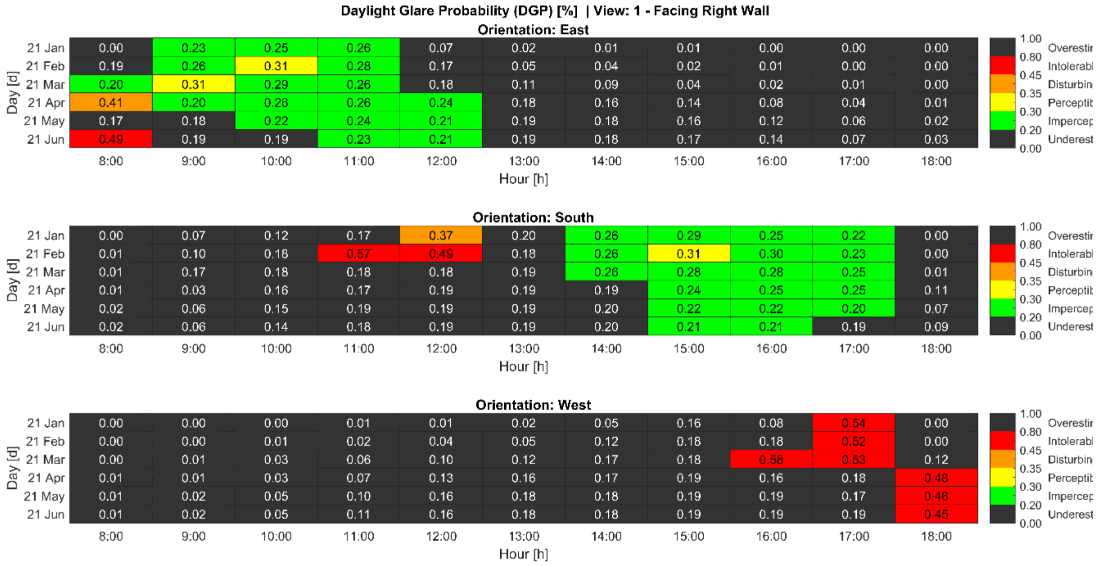


(a) (b)

Figure III-13: Radiance daylighting simulations output. (a) HDR luminance picture and (b) work plane illuminance distribution.

III.2.3.1 DISCOMFORT GLARE

Results of discomfort glare assessment for viewpoint one, respectively for Pixel and Homogeneous control strategy, are presented in Figure III-14.



Daylight Glare Probability (DGP) [%] | View: 1 - Facing Right Wall

Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.23	0.25	0.26	0.07	0.02	0.01	0.01	0.00	0.00	0.00
21 Feb	0.19	0.26	0.31	0.28	0.17	0.05	0.04	0.02	0.01	0.00	0.00
21 Mar	0.20	0.31	0.29	0.26	0.18	0.11	0.09	0.04	0.02	0.01	0.00
21 Apr	0.41	0.20	0.26	0.26	0.24	0.18	0.16	0.14	0.08	0.04	0.01
21 May	0.17	0.18	0.22	0.24	0.21	0.19	0.18	0.16	0.12	0.06	0.02
21 Jun	0.49	0.19	0.19	0.23	0.21	0.19	0.18	0.17	0.14	0.07	0.03

Hour [h]

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.07	0.12	0.17	0.37	0.20	0.26	0.29	0.25	0.22	0.00
21 Feb	0.01	0.10	0.18	0.57	0.49	0.18	0.26	0.31	0.30	0.23	0.00
21 Mar	0.01	0.17	0.18	0.18	0.18	0.19	0.26	0.28	0.28	0.25	0.01
21 Apr	0.01	0.03	0.16	0.17	0.19	0.19	0.19	0.24	0.25	0.25	0.11
21 May	0.02	0.06	0.15	0.19	0.19	0.19	0.20	0.22	0.22	0.20	0.07
21 Jun	0.02	0.06	0.14	0.18	0.19	0.19	0.20	0.21	0.21	0.19	0.09

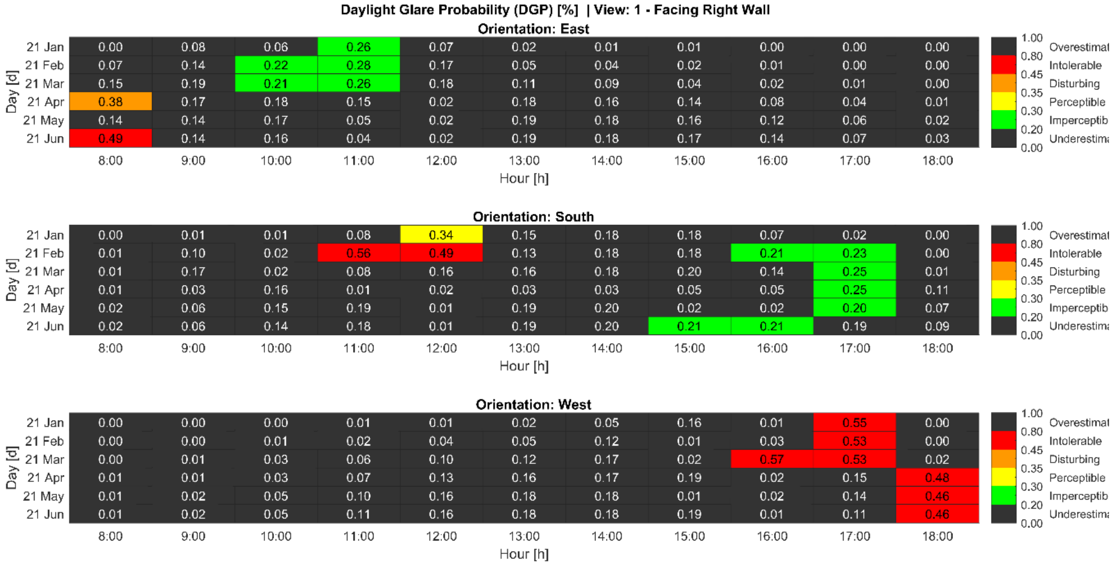
Hour [h]

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.00	0.01	0.01	0.02	0.05	0.16	0.08	0.54	0.00
21 Feb	0.00	0.00	0.01	0.02	0.04	0.05	0.12	0.18	0.18	0.52	0.00
21 Mar	0.00	0.01	0.03	0.06	0.10	0.12	0.17	0.18	0.58	0.53	0.12
21 Apr	0.01	0.01	0.03	0.07	0.13	0.16	0.17	0.19	0.16	0.18	0.48
21 May	0.01	0.02	0.05	0.10	0.16	0.18	0.18	0.19	0.19	0.17	0.46
21 Jun	0.01	0.02	0.05	0.11	0.16	0.18	0.18	0.19	0.19	0.19	0.45

Hour [h]

(a)



Daylight Glare Probability (DGP) [%] | View: 1 - Facing Right Wall

Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.08	0.06	0.26	0.07	0.02	0.01	0.01	0.00	0.00	0.00
21 Feb	0.07	0.14	0.22	0.28	0.17	0.05	0.04	0.02	0.01	0.00	0.00
21 Mar	0.15	0.19	0.21	0.26	0.18	0.11	0.09	0.04	0.02	0.01	0.00
21 Apr	0.38	0.17	0.18	0.15	0.02	0.18	0.16	0.14	0.08	0.04	0.01
21 May	0.14	0.14	0.17	0.05	0.02	0.19	0.18	0.16	0.12	0.06	0.02
21 Jun	0.49	0.14	0.16	0.04	0.02	0.19	0.18	0.17	0.14	0.07	0.03

Hour [h]

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.01	0.01	0.08	0.34	0.15	0.18	0.18	0.07	0.02	0.00
21 Feb	0.01	0.10	0.02	0.56	0.49	0.13	0.18	0.18	0.21	0.23	0.00
21 Mar	0.01	0.17	0.02	0.08	0.16	0.16	0.18	0.20	0.14	0.25	0.01
21 Apr	0.01	0.03	0.16	0.01	0.02	0.03	0.03	0.05	0.05	0.25	0.11
21 May	0.02	0.06	0.15	0.19	0.01	0.19	0.20	0.02	0.02	0.20	0.07
21 Jun	0.02	0.06	0.14	0.18	0.01	0.19	0.20	0.21	0.21	0.19	0.09

Hour [h]

Orientation: West

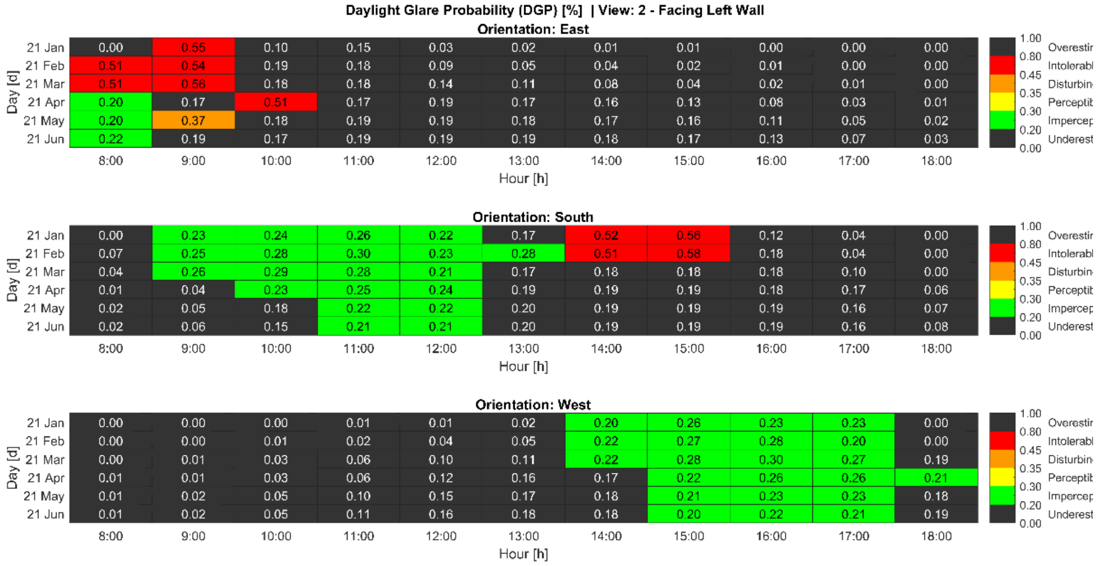
Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.00	0.01	0.01	0.02	0.05	0.16	0.01	0.55	0.00
21 Feb	0.00	0.00	0.01	0.02	0.04	0.05	0.12	0.01	0.03	0.53	0.00
21 Mar	0.00	0.01	0.03	0.06	0.10	0.12	0.17	0.02	0.57	0.53	0.02
21 Apr	0.01	0.01	0.03	0.07	0.13	0.16	0.17	0.19	0.02	0.15	0.48
21 May	0.01	0.02	0.05	0.10	0.16	0.18	0.18	0.01	0.02	0.14	0.46
21 Jun	0.01	0.02	0.05	0.11	0.16	0.18	0.18	0.19	0.01	0.11	0.46

Hour [h]

(b)

Figure III-14: DGP for viewpoint one respectively for (a) Pixel and (b) Homogeneous control strategy.

Results of discomfort glare assessment for viewpoint two, respectively for Pixel and Homogeneous control strategy, are presented in Figure III-15.



Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.55	0.10	0.15	0.03	0.02	0.01	0.01	0.00	0.00	0.00
21 Feb	0.51	0.54	0.19	0.18	0.09	0.05	0.04	0.02	0.01	0.00	0.00
21 Mar	0.51	0.56	0.18	0.18	0.14	0.11	0.08	0.04	0.02	0.01	0.00
21 Apr	0.20	0.17	0.51	0.17	0.19	0.17	0.16	0.13	0.08	0.03	0.01
21 May	0.20	0.37	0.18	0.19	0.19	0.18	0.17	0.16	0.11	0.05	0.02
21 Jun	0.22	0.19	0.17	0.19	0.19	0.19	0.18	0.17	0.13	0.07	0.03

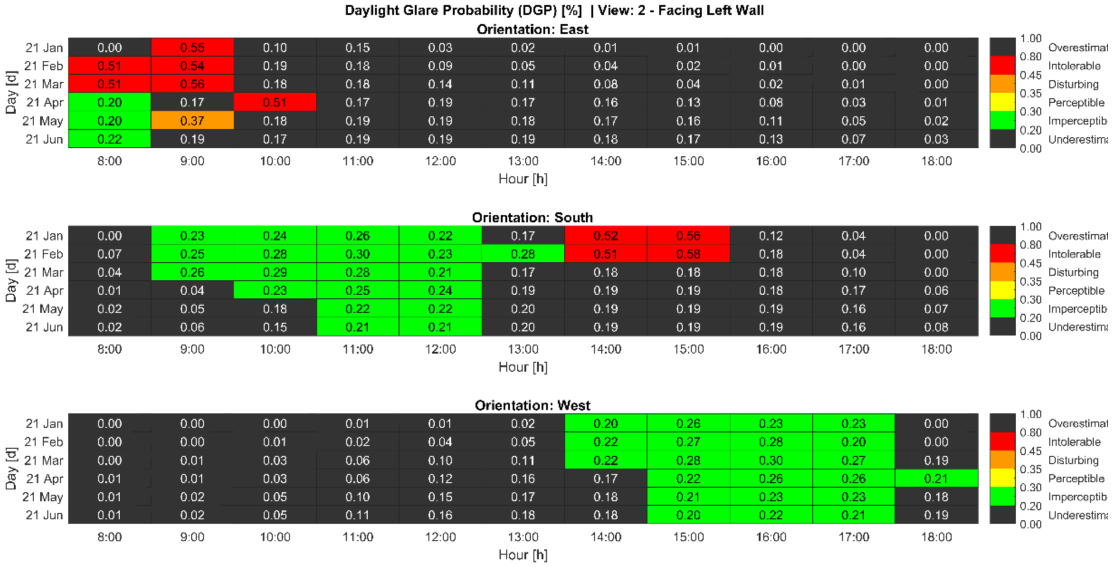
Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.23	0.24	0.26	0.22	0.17	0.52	0.56	0.12	0.04	0.00
21 Feb	0.07	0.25	0.28	0.30	0.23	0.28	0.51	0.58	0.18	0.04	0.00
21 Mar	0.04	0.26	0.29	0.28	0.21	0.17	0.18	0.18	0.18	0.10	0.00
21 Apr	0.01	0.04	0.23	0.25	0.24	0.19	0.19	0.19	0.18	0.17	0.06
21 May	0.02	0.05	0.18	0.22	0.22	0.20	0.19	0.19	0.19	0.16	0.07
21 Jun	0.02	0.06	0.15	0.21	0.21	0.20	0.19	0.19	0.19	0.16	0.08

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.00	0.01	0.01	0.02	0.20	0.26	0.23	0.23	0.00
21 Feb	0.00	0.00	0.01	0.02	0.04	0.05	0.22	0.27	0.28	0.20	0.00
21 Mar	0.00	0.01	0.03	0.06	0.10	0.11	0.22	0.28	0.30	0.27	0.19
21 Apr	0.01	0.01	0.03	0.06	0.12	0.16	0.17	0.22	0.26	0.26	0.21
21 May	0.01	0.02	0.05	0.10	0.15	0.17	0.18	0.21	0.23	0.23	0.18
21 Jun	0.01	0.02	0.05	0.11	0.16	0.18	0.18	0.20	0.22	0.21	0.19

(a)



Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.55	0.10	0.15	0.03	0.02	0.01	0.01	0.00	0.00	0.00
21 Feb	0.51	0.54	0.19	0.18	0.09	0.05	0.04	0.02	0.01	0.00	0.00
21 Mar	0.51	0.56	0.18	0.18	0.14	0.11	0.08	0.04	0.02	0.01	0.00
21 Apr	0.20	0.17	0.51	0.17	0.19	0.17	0.16	0.13	0.08	0.03	0.01
21 May	0.20	0.37	0.18	0.19	0.19	0.18	0.17	0.16	0.11	0.05	0.02
21 Jun	0.22	0.19	0.17	0.19	0.19	0.19	0.18	0.17	0.13	0.07	0.03

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.23	0.24	0.26	0.22	0.17	0.52	0.56	0.12	0.04	0.00
21 Feb	0.07	0.25	0.28	0.30	0.23	0.28	0.51	0.58	0.18	0.04	0.00
21 Mar	0.04	0.26	0.29	0.28	0.21	0.17	0.18	0.18	0.18	0.10	0.00
21 Apr	0.01	0.04	0.23	0.25	0.24	0.19	0.19	0.19	0.18	0.17	0.06
21 May	0.02	0.05	0.18	0.22	0.22	0.20	0.19	0.19	0.19	0.16	0.07
21 Jun	0.02	0.06	0.15	0.21	0.21	0.20	0.19	0.19	0.19	0.16	0.08

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.00	0.01	0.01	0.02	0.20	0.26	0.23	0.23	0.00
21 Feb	0.00	0.00	0.01	0.02	0.04	0.05	0.22	0.27	0.28	0.20	0.00
21 Mar	0.00	0.01	0.03	0.06	0.10	0.11	0.22	0.28	0.30	0.27	0.19
21 Apr	0.01	0.01	0.03	0.06	0.12	0.16	0.17	0.22	0.26	0.26	0.21
21 May	0.01	0.02	0.05	0.10	0.15	0.17	0.18	0.21	0.23	0.23	0.18
21 Jun	0.01	0.02	0.05	0.11	0.16	0.18	0.18	0.20	0.22	0.21	0.19

(b)

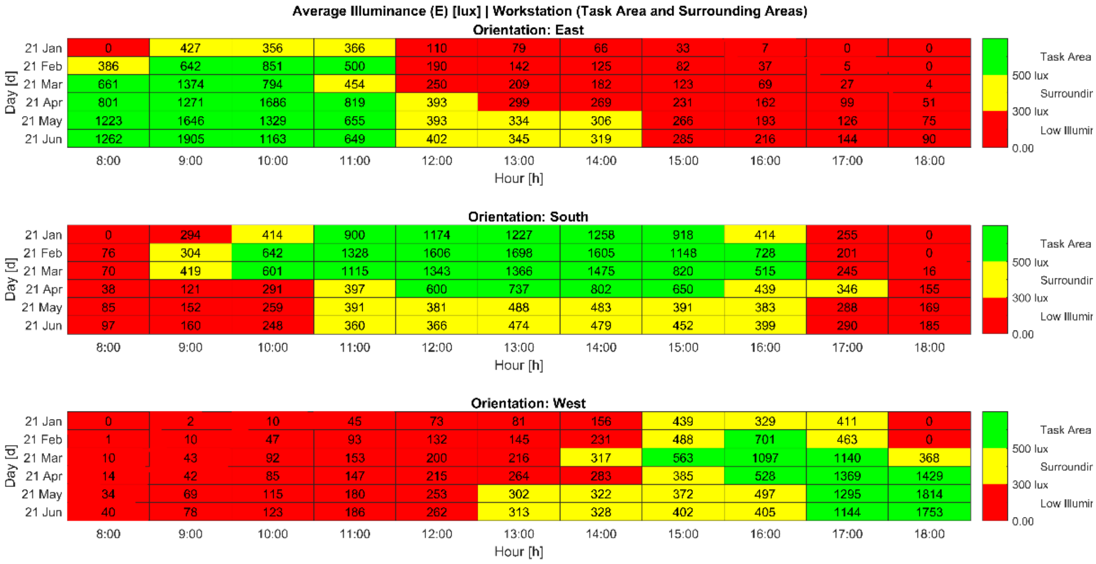
Figure III-15: DGP for viewpoint two respectively for (a) Pixel and (b) Homogeneous control strategy.

The DGP index reaches values considered to provide intolerable discomfort, at various time of the year and for both viewpoints and control strategies, as can be seen in Figure III-14 and Figure III-15. Only for west orientation and viewpoint two, the system was found to provide adequate protection against glare in the relatively short time domain. The set has highlighted that the extreme DGP values occur when the sun is low and shining directly toward each of the points of view, depending on room orientation. The current luminous transmission properties of DDLC window appear to be too high to fully prevent glare discomfort due to direct sun.

Moreover, the set has highlighted that the two strategies (with DDLC at the current stage) perform equally for glare protection since the results are almost identical. No real benefits concerning glare protection are obtained by turning the entire façade array on the dark state, as it happens with the Homogeneous control strategy. In light of this finding, Pixel strategy's advantages for daylight admittance and view makes this solution the most preferable.

III.2.3.2 Illumination Level and Distribution

First, the results of average workstation illuminance compared to the required maintained illuminance, respectively for Pixel and Homogeneous control strategy, are presented in Figure III-16.



Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	427	356	366	110	79	66	33	7	0	0
21 Feb	386	642	851	500	190	142	125	82	37	5	0
21 Mar	661	1374	794	454	250	209	182	123	69	27	4
21 Apr	801	1271	1686	819	393	299	269	231	162	99	51
21 May	1223	1646	1329	655	393	334	306	266	193	126	75
21 Jun	1262	1905	1163	649	402	345	319	285	216	144	90

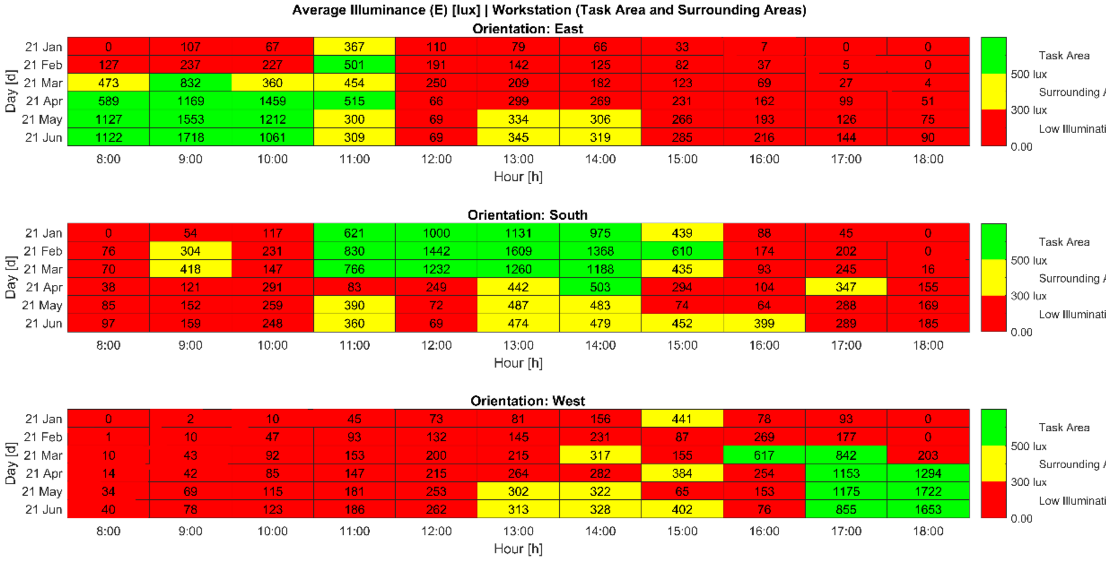
Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	294	414	900	1174	1227	1258	918	414	255	0
21 Feb	76	304	642	1328	1606	1698	1605	1148	728	201	0
21 Mar	70	419	601	1115	1343	1366	1475	820	515	245	16
21 Apr	38	121	291	397	600	737	802	650	439	346	155
21 May	85	152	259	391	381	488	483	391	383	288	169
21 Jun	97	160	248	360	366	474	479	452	399	290	185

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	2	10	45	73	81	156	439	329	411	0
21 Feb	1	10	47	93	132	145	231	488	701	463	0
21 Mar	10	43	92	153	200	216	317	563	1097	1140	368
21 Apr	14	42	85	147	215	264	283	385	528	1369	1429
21 May	34	69	115	180	253	302	322	372	497	1295	1814
21 Jun	40	78	123	186	262	313	328	402	405	1144	1753

(a)



Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	107	67	367	110	79	66	33	7	0	0
21 Feb	127	237	227	501	191	142	125	82	37	5	0
21 Mar	473	832	360	454	250	209	182	123	69	27	4
21 Apr	589	1169	1459	515	66	299	269	231	162	99	51
21 May	1127	1553	1212	300	69	334	306	266	193	126	75
21 Jun	1122	1718	1061	309	69	345	319	285	216	144	90

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	54	117	621	1000	1131	975	439	88	45	0
21 Feb	76	304	231	830	1442	1609	1368	610	174	202	0
21 Mar	70	418	147	766	1232	1260	1188	435	93	245	16
21 Apr	38	121	291	83	249	442	503	294	104	347	155
21 May	85	152	259	390	72	487	483	74	64	288	169
21 Jun	97	159	248	360	69	474	479	452	399	289	185

Orientation: West

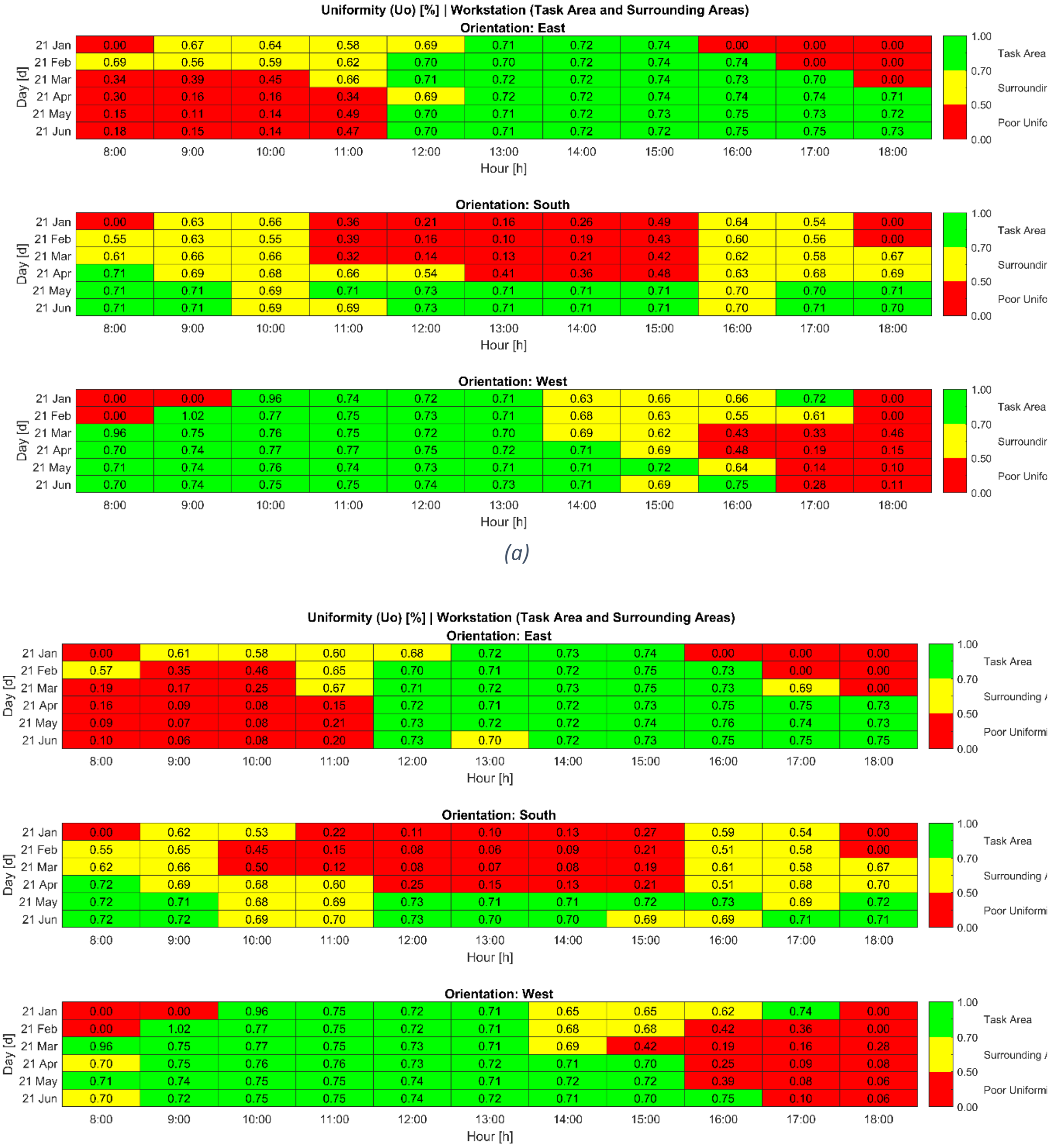
Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0	2	10	45	73	81	156	441	78	93	0
21 Feb	1	10	47	93	132	145	231	87	269	177	0
21 Mar	10	43	92	153	200	215	317	155	617	842	203
21 Apr	14	42	85	147	215	264	282	384	254	1153	1294
21 May	34	69	115	181	253	302	322	65	153	1175	1722
21 Jun	40	78	123	186	262	313	328	402	76	855	1653

(b)

Figure III-16: Workstation average illuminance compared to the required maintained illuminance respectively for (a) Pixel and (b) Homogeneous control strategy.

Requirements of average illuminance on the workstation appears to be achieved by both control strategies in each orientation. In this case, DDLC's luminous transmission is an advantage since it allows daylight to reach room interior and lit the space, differently from the case of conventional shading systems (for example, blinds). As can be seen from Figure III-16, electrical lighting is still required to provide the necessarily maintained illuminance during those hours in which daylight does not shine over the façade. Pixel provides the most interesting outcomes with approximately 40-50% more time steps meeting the requirements of illumination on task area or surrounding area compared to Homogeneous strategy.

Second, the results of workstation uniformity compared to the required maintained uniformity, respectively for Pixel and Homogeneous control strategy, are presented in Figure III-17.



Uniformity (Uo) [%] | Workstation (Task Area and Surrounding Areas)

Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.67	0.64	0.58	0.69	0.71	0.72	0.74	0.00	0.00	0.00
21 Feb	0.69	0.56	0.59	0.62	0.70	0.70	0.72	0.74	0.74	0.00	0.00
21 Mar	0.34	0.39	0.45	0.66	0.71	0.72	0.72	0.74	0.73	0.70	0.00
21 Apr	0.30	0.16	0.16	0.34	0.69	0.72	0.72	0.74	0.74	0.74	0.71
21 May	0.15	0.11	0.14	0.49	0.70	0.71	0.72	0.73	0.75	0.73	0.72
21 Jun	0.18	0.15	0.14	0.47	0.70	0.71	0.72	0.72	0.75	0.75	0.73

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.63	0.66	0.36	0.21	0.16	0.26	0.49	0.64	0.54	0.00
21 Feb	0.55	0.63	0.55	0.39	0.16	0.10	0.19	0.43	0.60	0.56	0.00
21 Mar	0.61	0.66	0.66	0.32	0.14	0.13	0.21	0.42	0.62	0.58	0.67
21 Apr	0.71	0.69	0.68	0.66	0.54	0.41	0.36	0.48	0.63	0.68	0.69
21 May	0.71	0.71	0.69	0.71	0.73	0.71	0.71	0.71	0.70	0.70	0.71
21 Jun	0.71	0.71	0.69	0.69	0.73	0.71	0.71	0.71	0.70	0.71	0.70

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.96	0.74	0.72	0.71	0.63	0.66	0.66	0.72	0.00
21 Feb	0.00	1.02	0.77	0.75	0.73	0.71	0.68	0.63	0.55	0.61	0.00
21 Mar	0.96	0.75	0.76	0.75	0.72	0.70	0.69	0.62	0.43	0.33	0.46
21 Apr	0.70	0.74	0.77	0.77	0.75	0.72	0.71	0.69	0.48	0.19	0.15
21 May	0.71	0.74	0.76	0.74	0.73	0.71	0.71	0.72	0.64	0.14	0.10
21 Jun	0.70	0.74	0.75	0.75	0.74	0.73	0.71	0.69	0.75	0.28	0.11

(a)

Uniformity (Uo) [%] | Workstation (Task Area and Surrounding Areas)

Orientation: East

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.61	0.58	0.60	0.68	0.72	0.73	0.74	0.00	0.00	0.00
21 Feb	0.57	0.35	0.46	0.65	0.70	0.71	0.72	0.75	0.73	0.00	0.00
21 Mar	0.19	0.17	0.25	0.67	0.71	0.72	0.73	0.75	0.73	0.69	0.00
21 Apr	0.16	0.09	0.08	0.15	0.72	0.71	0.72	0.73	0.75	0.75	0.73
21 May	0.09	0.07	0.08	0.21	0.73	0.72	0.72	0.74	0.76	0.74	0.73
21 Jun	0.10	0.06	0.08	0.20	0.73	0.70	0.72	0.73	0.75	0.75	0.75

Orientation: South

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.62	0.53	0.22	0.11	0.10	0.13	0.27	0.59	0.54	0.00
21 Feb	0.55	0.65	0.45	0.15	0.08	0.06	0.09	0.21	0.51	0.58	0.00
21 Mar	0.62	0.66	0.50	0.12	0.08	0.07	0.08	0.19	0.61	0.58	0.67
21 Apr	0.72	0.69	0.68	0.60	0.25	0.15	0.13	0.21	0.51	0.68	0.70
21 May	0.72	0.71	0.68	0.69	0.73	0.71	0.71	0.72	0.73	0.69	0.72
21 Jun	0.72	0.72	0.69	0.70	0.73	0.70	0.70	0.69	0.69	0.71	0.71

Orientation: West

Day [d]	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
21 Jan	0.00	0.00	0.96	0.75	0.72	0.71	0.65	0.65	0.62	0.74	0.00
21 Feb	0.00	1.02	0.77	0.75	0.72	0.71	0.68	0.68	0.42	0.36	0.00
21 Mar	0.96	0.75	0.77	0.75	0.73	0.71	0.69	0.42	0.19	0.16	0.28
21 Apr	0.70	0.75	0.76	0.76	0.73	0.72	0.71	0.70	0.25	0.09	0.08
21 May	0.71	0.74	0.75	0.75	0.74	0.71	0.72	0.72	0.39	0.08	0.06
21 Jun	0.70	0.72	0.75	0.75	0.74	0.72	0.71	0.70	0.75	0.10	0.06

(b)

Figure III-17: Workstation uniformity compared to the required maintained uniformity respectively for (a) Pixel and (b) Homogeneous control strategy.

The uniformity requirement for workstation surfaces is fulfilled at various time steps for both control strategies. According to its definition, Homogeneous approach should provide a much more uniform distribution of illuminance in the room, but surprisingly the results are very close to those from Pixel approach, which initially was supposed to lack in this property. However, the highest uniformities are mainly achieved when the sun is not shining directly in the room or when is at high altitudes. Therefore, electrical lighting may be supplied also when maintained illuminance requirement is met to balance the distribution on the workstation.

Third, the difference in relative annual utilization time (RAUT) and relative annual usable luminous exposure (RAULE) between Pixel and Homogeneous control strategy for each room zone are presented respectively in Figure III-18 and Figure III-19; DDLC façade is in the first row.

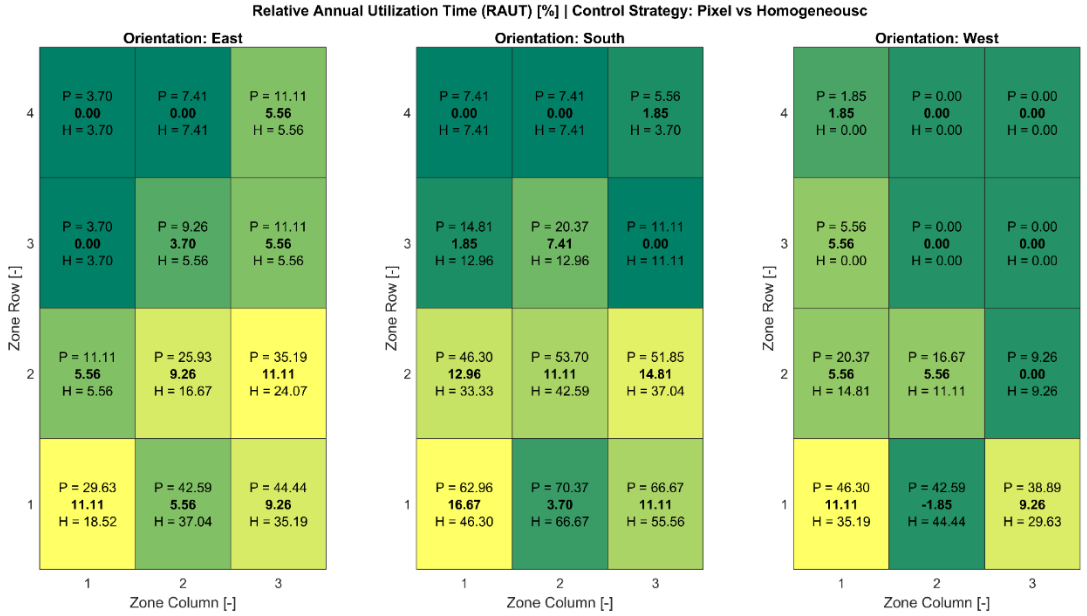


Figure III-18: Difference in relative annual utilization time (RAUT) between Pixel and Homogeneous for each room zone, DDLC façade is in the first row.

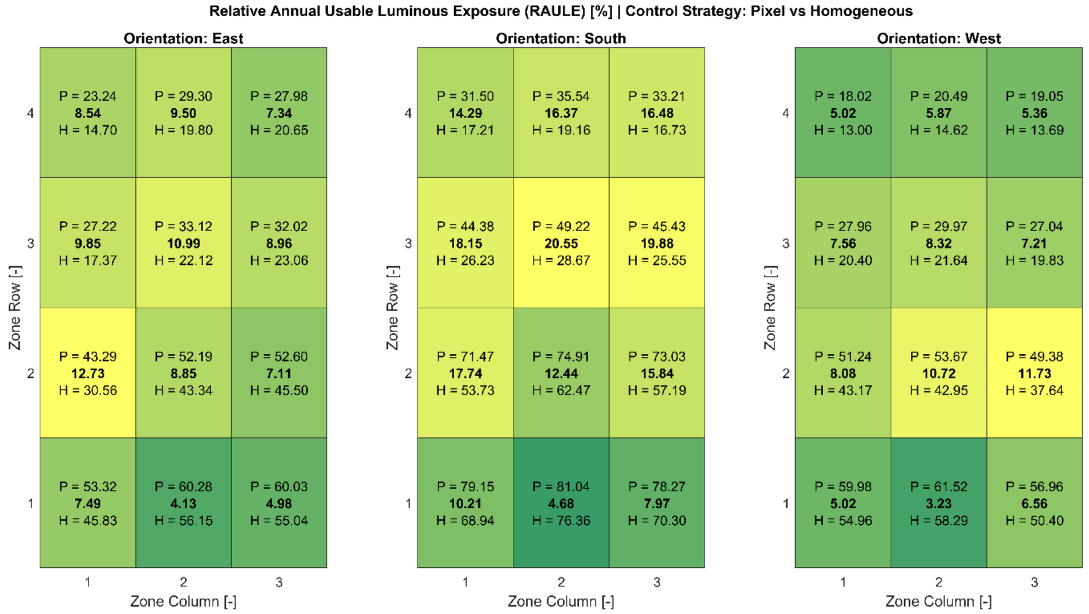


Figure III-19: Difference in relative annual usable luminous exposure (RAULE) between Pixel and Homogeneous for each room zone, DDLC façade is in the first row.

Figure III-18 and III-19 show the differences in results between Pixel and Homogeneous strategies respectively for relative annual utilization time and relative annual usable luminous exposure. As can be inferred from the relatively short time frame used for this set of simulation, these results cannot be considered valid for the entire year, but they can provide some guidelines on the electrical lighting savings achievable with Pixel strategy. The results show that both RAUT and RAULE index presents improvements almost in the whole room compared to Homogeneous strategy. RAUT results demonstrate the percentage of time in which the electrical lighting system is not required thanks to the contribution from daylight. In this case, Pixel saves up to 14 % of energy with an average of 5% per room zone; however, in the deeper parts of the room where daylight is required the savings are little. Differently, RAULE calculates the energy saved in consideration of a dimmable lighting system which can match the exactly missing illumination. Savings for this index are more consistent, up to 20% with an average of 12%, and most important the highest energy savings are obtained in the deeper part of the room. These results emphasize the advantages of the Pixel strategy which minimize the element to obscure allowing natural light to get in the space and diffuse toward the darker interior of the room.

III.2.4 CONCLUSIONS

An investigation on the effect of a combined system of DDLC windows and control strategies for glare protection is done using daylighting simulations with Radiance software. The investigated effects were discomfort glare as well as illumination level and distribution; which have been evaluated according to international standards when available or most suitable performance indicator from literature. The final conclusions that can be drawn are:

- At the current stage DDLC windows appear to provide not enough protection against glare from direct sunlight; therefore, their employment as shading device is not yet advised. Results from Pixel and Homogeneous control strategy have highlighted that when the sun is low and hitting the user directly (i.e. viewpoint) the DGP index reaches values that are considered to provide intolerable disturbance. Obscuring the entire façade seems not to provide practical benefits to the user's glare protection, so the benefits in terms of greater daylight admittance and view to the outside make Pixel prevailing on the other approaches.
- Pixel and Homogeneous strategy allow a considerable amount of daylight into space which also reaches illumination level on workstation required by international standards. Moreover, uniformity requirement is also often obtained but with the relatively poor match with illumination level from daylight. However, Pixel appears to provide a more desirable luminous condition in consideration of both comfort and reliance on electric lighting. Electric illumination is still needed to support daylighting illuminance or correct its distribution.
- RAUT and RAULE index, in consideration respectively of standard and dimmable lighting system, have confirmed that Pixel allows a larger amount of savings due to additional electrical lighting.

In light of these conclusions and in consideration of the potential of the employed methodology the following suggestion for further investigations, with the current settings of the simulations, are suggested:

- Simulation with DDLC façade constantly in the bright state, to estimate the benefits for the reduction of glare discomfort offered by the dark state of the glass but also the effective diminishment of daylight admittance with the employment of 'Pixel' strategy.
- Simulation of a façade array controlled by 'Pixel' strategy and equipped with conventional glazing and shading devices capable of blocking direct light (i.e. $\tau \approx 0$). This set should demonstrate that office space with the low or absent risk of glare can be obtained by with the protection only of 'control volume(s)'. Also, illuminance distribution can be compared with the DDLC façade configuration, to provide additional insights about the beneficial effect of DDLC glass on daylight admittance.

III.3 PILOT STUDY ASSESSMENT OF DDLC FAÇADE AND GPC CONTROL STRATEGIES

III.3.1 GOALS AND PERFORMANCE INDICATORS

The aim of the study is to assess, in a real testing environment, the effective operation of GPC control strategies and validate the performance when combined with a DDLC façade array. A pilot study is set up for the achievement of the goal: a single office equipped with a DDLC façade array and GPC control strategy 'Pixel'. Within this part, two different objectives are researched:

- Effective operative condition of GPC control strategy 'Pixel';
- Validation of the daylighting performance (glare assessment, illumination level, and distribution) in a DDLC façade array controlled by 'Pixel' strategy, in comparison with the virtual testing environment.

Assessment of GPC operations do not necessitate of performance indicators but it requires adequate proofs about the successful protection from direct sunlight on the implemented control volume(s).

Differently, the validation of daylighting performance utilizes three performance indicators: DGP for glare (Section III.2.1.1), E_m and U_0 for illumination level and distribution (Section III.2.1.2).

III.3.2 METHODOLOGY

Real testing environment is the main methodology of this study and used for both investigations, but also the virtual method is employed.

The process for the first objective to provide significant proof about the protection on control volume from direct sunlight in operative conditions and for real daylighting scenes.

For the fulfillment of the second objective the two methods are compared in consideration of the performance and for the validation of the virtual testing environment. For the comparison, the geometrical (room and workstation configuration), lighting (luminous properties of opaque and transparent surfaces) and the daylighting (clear sky) conditions are specified for being equal in both approaches. Two days with clear sky conditions (18th and 19th of July 2016) are measured, simulated and compared.

The following sections present the working principles and the settings of the real testing environment, whereas those for the virtual testing environment are the same as in Section III.2.2.

III.3.2.1 APPROACH

The operation of DDLC façade array according to GPC control strategy is the core of the pilot study. Therefore, a setup system is realized and operated using a software and a hardware group.

A Matlab algorithm implements the concept and the rules of the developed control strategies (Section II.1). Based on inputs of geometry and time, the software supplies outputs for a façade are in the form of a digit: 1 for 'ON' and 0 for 'OFF' state of the shading device LabVIEW software provides the interface function between the hardware group and GPC strategies in Matlab. A graphical user interface (GUI) is realized to control the flow of information, and it is displayed in Appendix VI.2.1. Fieldpoint is a modular distributed input/output device creating the desired output signal. Last, the DDLC façade array is the shading device, its elements receive an individual signal output and a low power supply. Figure III-22 shows the components and the workflow of the pilot study system.

LabVIEW triggers periodically (t=10 s) the Matlab algorithm that produces the outputs and transmits it back. In our case with a DDLC façade array, it translates respectively into a 1 for the bright state (i.e. 10V applied) and 0 for the dark state (i.e. 1V applied). Then LabVIEW commands the creation of individual signals to FieldPoint, which translates the calculation outputs into the desired DC voltage. Last, the DC voltage is converted into a 60 Hz AC voltage by a 'driver' to provide a linear relation between the DC voltage input (i.e. 1-10V) and windows' luminous transmission (i.e. 11-53%).

In the current version of the control system no feedback from sensors of occupancy and luminous conditions are implemented. During the measurements in this research, the pilot study is considered to be always occupied (i.e. to trigger GPC algorithm) and the required luminous conditions (i.e. clear sky) would meet the luminance thresholds.

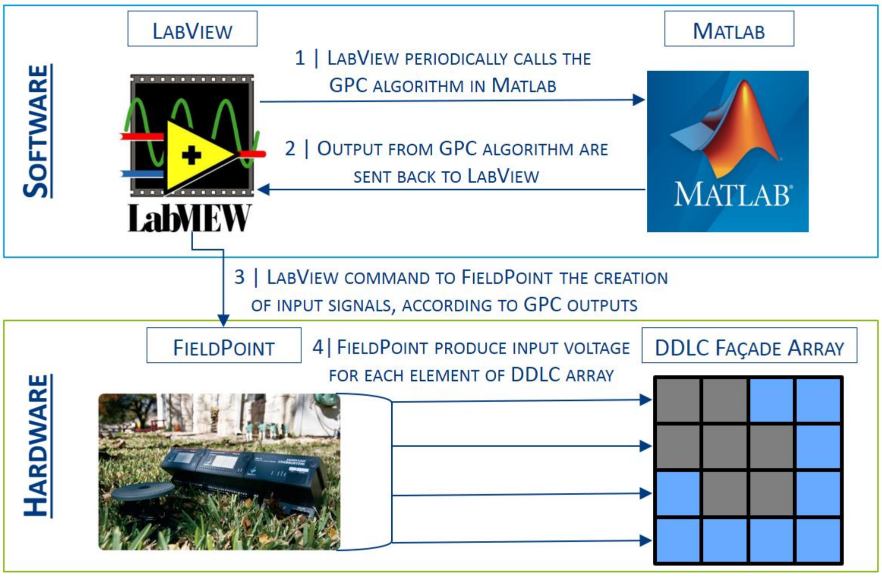


Figure III-20: Flowchart and organization of the pilot study system for the control of DDLC façade array according to GPC control strategy.

III.3.2.2 Model

The pilot study application of a single office is set up in the laboratory of the department of 'Built Environment' at the Eindhoven University of Technology (TU/e), the Netherlands. Dimensions of the room are the width of 3.75 m, the length of 5.1 m and, the height of 2.7 m. A façade array of two rows by four columns of DDLC glasses is realized internally to the existing façade, according to the design presented in Appendix VI.2.2. The transparent array ($A \approx 4.5\ m^2$) is composed by a lower row, useful to mazimize view to the outside (bigger glasses, $h \approx 1.05m$) and an upper row, for daylight admittance (i.e. smaller glasses, $h \approx 0.70m$), having the same width ($l \approx 0.60m$).

(a) *(b)*

Figure III-21: (a)(b) Final set-up of the pilot study implementing: the DDLC façade array controlled by GPC control strategy 'Pixel', the workstation, the view point (i.e. luminance camera and sensor), and the grid of sensors. (b) The laptop enabling the control system is placed under the desk to avoid disturbances to the measurements.

The room has one workstation, placed and oriented to make the 'control volume' vulnerable to direct daylight. The workstation is positioned in correspondence of the middle of the room, at 1.25m from the façade. Moreover, the workstation is composed of a desk, a view-point (luminance camera) and a computer. The computer implements the control system (presented in Section III.3.2), triggers the measurements (discussed in the next Section), and collects the data output. Figure III-21 shows the complete set-up of the designed pilot study.

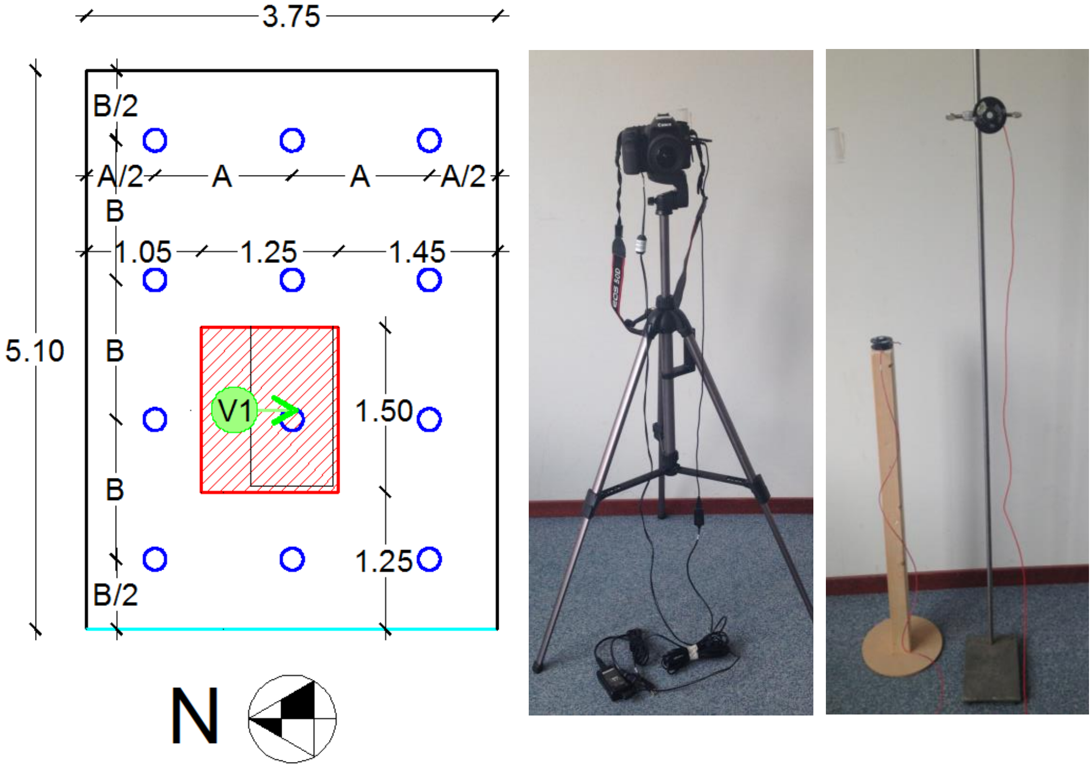
III.3.2.3 SETTINGS AND ASSUMPTIONS

Proof of the effective operation of GPC system and assessment of discomfort glare require clear sky conditions. Therefore, these objectives are assessed respectively on May 2nd and July 18th and 19th 2016. The measurements necessary for the validation of daylighting performance are done from 14:00 to 20:00 (i.e. hours with direct sunlight for West orientation) at steps of 15 minutes.

Luminous reflectance of room and workstation surfaces was measured with a spectrophotometer Minolta CM-2600d and resulted to meet the standards required from EN 12464-1 (Section III.2.2.3).

The presence of the existing façade with a HR++ glass reduces the luminous transmittance of DDLC; to avoid this issue the input voltage was modified. Voltage input for the dark state is adjusted from 1V to 3.25 V in the control system (Section III.3.2.1), according to results from previous investigation of the M3 project (Capperucci, 2016).

Figure III.22 displays the planar view of the pilot study, the workstation and the distribution of measurement devices. The control volume, in red, encloses the desk and the user (that is represented by viewpoint V1) starting from 0.70 m to 1.40 m above floor level.



(a) (b) (c)

Figure III-22: (a) Planar view of the pilot study realized for this research. In red, the 'control volume' is sized to protect the user and the workstation, under the hatch the contour of the desk is visible. In green, the point of view (with view direction) at eyes' height (h=1.20m), representing the user, implements a (b) luminance camera for glare analysis and a (c) vertical illuminance sensor. A grid of four row (B=1.275m) by three columns (blue) of (c) sensors measures the horizontal illuminance in the room, at work-plane height (h=0.80m).

To evaluate the daylighting performance two type of measurements are done in the pilot study:

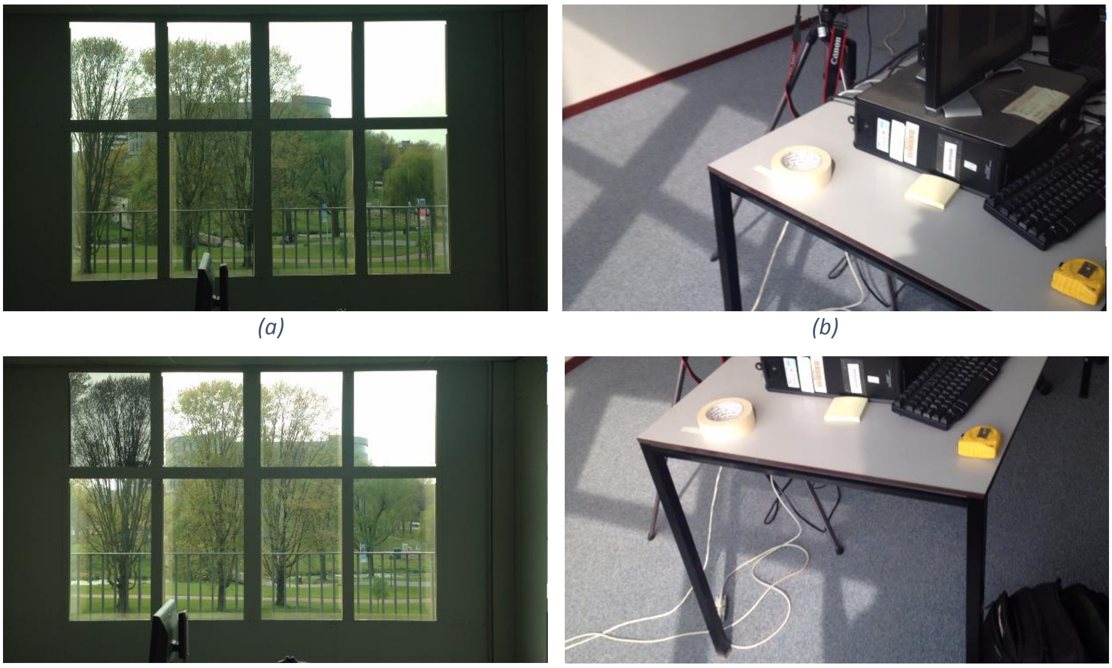
- Discomfort glare: Daylight Glare Probability (DGP) can be extrapolated from HDR (High Dynamic Range) luminance pictures, as mentioned in Section III.2.1.1. A calibrated CCD color camera Canon EOS 50D provided with a 180° circular fish-eye lens Sigma EX (Figure III-22b) is employed to take HDR pictures of lighting scenes. The pictures are then post-processed in Radiance with *evalglare* software to identify the source of glare obtain the DGP value of the daylighting scene. Also, vertical illuminance at eye level $E_{V,eye}$ are measured by an Hagner illuminance meter positioned vertically at a height of 1,20 m from the floor (Figure III-22c, device on the right). This measurement is done to monitor DGP correlation with the retinal illuminance E_V. Both luminance camera and illuminance meter are positioned in the viewpoint V1, represented by the green filled dot in Figure III-22a.
- Illumination level and distribution: Maintained illuminance E_m and uniformity U_0 can be computed from room illuminances. Pilot study illuminances are measured by an array of Hagner illuminance meter (Figure III-22c, device on the left) placed horizontally $E_{H,point}$ at workplane height (i.e. 0.8 m above the floor). Multilab-light is employed because it is a device controlling and recording data from 16 Hagner illuminance sensors at the same time. Figure III-22a displays the distribution of the array of 12 illuminance sensors, represented by the blue dots. The array has three columns equally distributed between the side walls (i.e. A=1.25m) and four rows equally distributed from the facade to the internal wall (i.e. B=1.27m).

Figure III-21 provides an overview of the measurement devices and their distribution within the room.

III.3.3 RESULTS AND DISCUSSION

III.3.3.1 *EFFECTIVE GPC OPERATION*

The designed control system is successfully integrated and operated into the pilot study. Figure III-23 prove that GPC control strategy can provide protection against glare on a determined ‘control volume’.



(a) (b)

(c) (d)

Figure III-23: Protection of ‘control volume’ by GPC control strategy (Pixel) and DDLC façade array at 16:30 of May 2nd 2016. (a)(b) Initially GPC control system is not operating, the façade array is entirely in open state and direct sunlight reaches the desk inside the control zone. (c)(d) GPC control system is started, one element of the array is turned in close state to block the light reaching the desk, and effectively protect it from direct sunlight.

The figure above shows two different situations: when GPC control system is off (a, b) and when it is turned on (c, d). The control system is set according to pilot study configuration (i.e. dimensions, location and orientation) and ‘control volume’ dimensions and coordinates.

Initially, when the control is disabled the entire façade is in open state (Figure III-23a) and direct daylight from the sun hits the desk (Figure III-23b). In Figure III-23b, the shadow of the façade array shows that the direct light on the desk enters from only one element of the array. According to the concept of Pixel strategy that element should be the only one to be turned on closed state.

Later, when the GPC control is enabled the façade presents one of its element in closed state (Figure III-23c) and the direct daylight hitting the desk is largely blocked by the DDLC glass (Figure III-23d). In Figure III-23d, the shadow of the façade array shows that one element of the DDLC array is turned in dark state (i.e. close state) to block the direct sunlight on the desk. The obstructed façade element is the only glass to be turned on close state, according to the concept of Pixel strategy for real-time solar coordinates.

This demonstration proves the effective operation of GPC control strategy 'Pixel' for protecting workstations inside and office room.

Moreover, the system worked continuously and without problems for two weeks (from May 10th to May 24th) and for one month (from June 15th to July 15th) during the time-frame of this graduation project.

Figure III-24 shows the sequence variation of DDLC façade array to protect the control volume according to Pixel strategy, in the afternoon of August 5th.

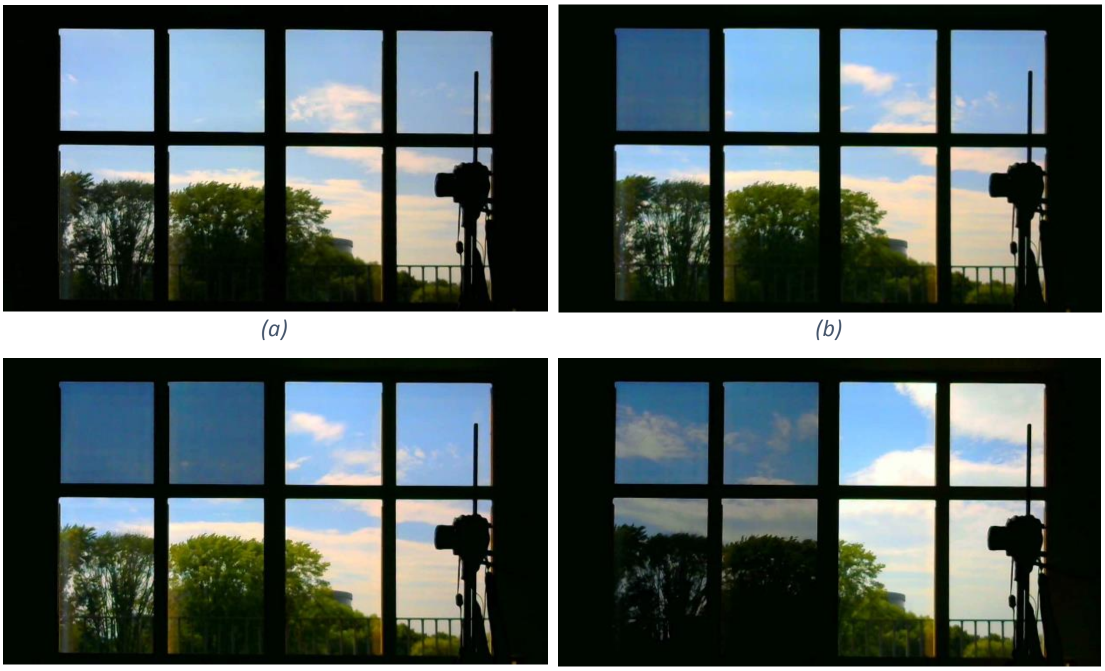

(a) *(b)* *(c)* *(d)*

Figure III-24: (a-b-c-d) Operation sequence of GPC control strategy in the pilot study, from 14:00 to 17:00 on Friday 5th of August 2016.

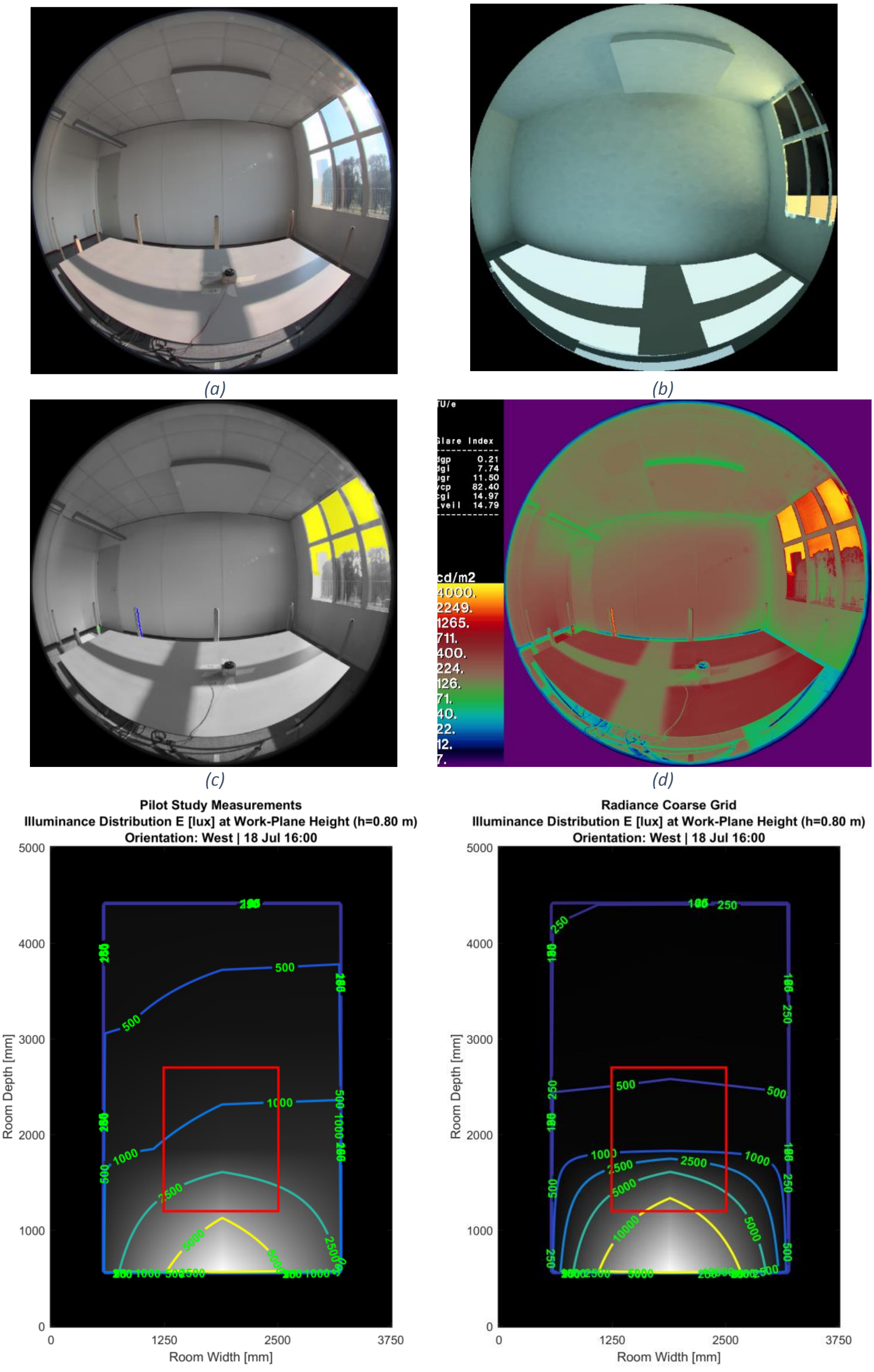
III.3.3.2 ASSESSMENT OF DAYLIGHTING PERFORMANCE

The outputs from pilot study measurements and Radiance daylighting simulations are HDR luminance pictures and arrays of room illuminance at work-plane height (h=0.80 m).

HDR luminance pictures are post-processed by *evalglare* software to identify glare sources and compute the DGP index.

Arrays of room illuminance are interpolated and post-processed by a Matlab script enabling the computation of illuminance plots at work-plane height and the performance indicators.

Figure III-25 presents the outputs for both methodologies.



(a) *(b)*

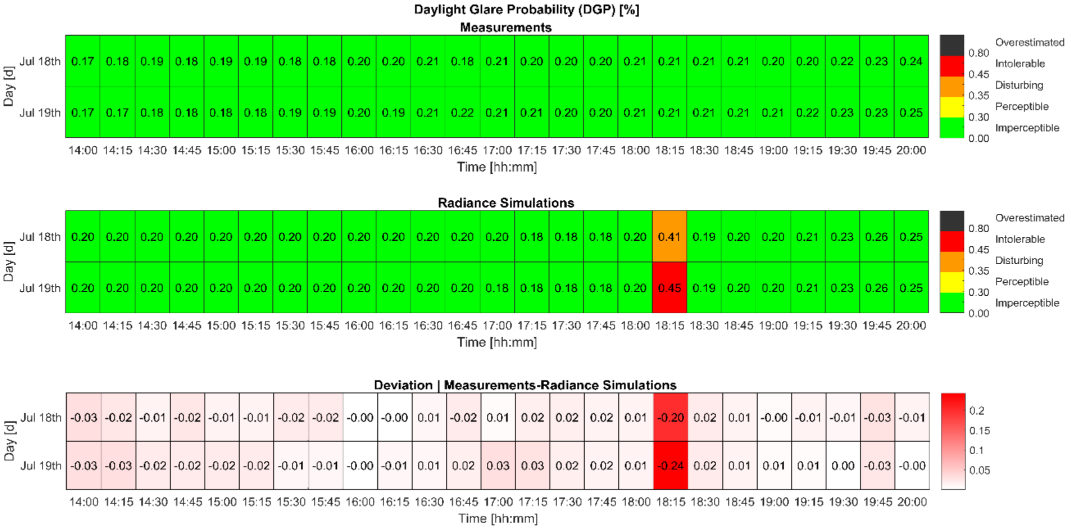
(c) *(d)*

(e) *(f)*

Figure III-25: HDR luminance picture for daylighting configuration of July 18th at 18:15; from (a) pilot study measurements and (b) daylighting simulations. Post-processing of HDR picture of July 18th at 18:30 for (c) identification of glare sources and (d) computation of DGP index. Room illuminance distribution of July 18th at 16:00 from (e) pilot study measurements and (f) daylighting simulations.

III.3.3.2.1 Discomfort Glare Assessment

Figure III-26 presents the results of discomfort glare assessment for viewpoint one; respectively for pilot study measurements, Radiance daylighting simulations and deviation between methodologies.



Measurements

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	0.17	0.18	0.19	0.18	0.19	0.19	0.18	0.18	0.20	0.20	0.21	0.18	0.21	0.20	0.20	0.20	0.21	0.21	0.21	0.21	0.20	0.20	0.22	0.23	0.24
Jul 19th	0.17	0.17	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.19	0.21	0.22	0.21	0.21	0.20	0.20	0.21	0.21	0.21	0.21	0.21	0.22	0.23	0.23	0.25

Radiance Simulations

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.18	0.18	0.18	0.20	0.41	0.19	0.20	0.20	0.21	0.23	0.26	0.25
Jul 19th	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.18	0.18	0.18	0.18	0.20	0.45	0.19	0.20	0.20	0.21	0.23	0.26	0.25

Deviation | Measurements-Radiance Simulations

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	-0.03	-0.02	-0.01	-0.02	-0.01	-0.01	-0.02	-0.02	-0.00	-0.00	0.01	-0.02	0.01	0.02	0.02	0.02	0.01	-0.20	0.02	0.01	-0.00	-0.01	-0.01	-0.03	-0.01
Jul 19th	-0.03	-0.03	-0.02	-0.02	-0.02	-0.02	-0.01	-0.01	-0.00	-0.01	0.01	0.02	0.03	0.03	0.02	0.02	0.01	-0.24	0.02	0.01	0.01	0.01	0.00	-0.03	-0.00

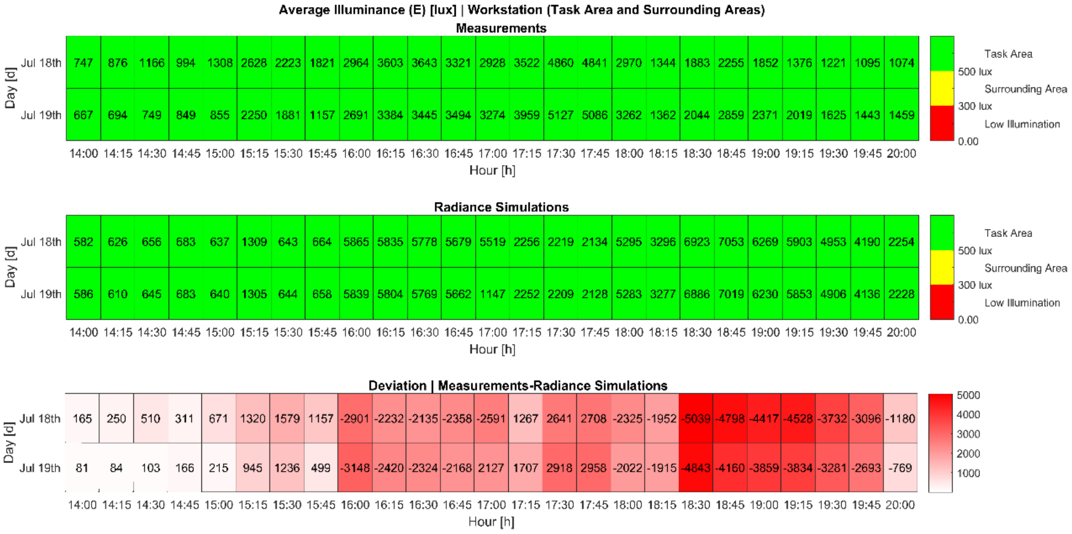
Figure III-26: DGP results, from top to bottom: pilot study measurements, Radiance daylighting simulations and deviation between methodologies.

The trend of DGP index in both methodologies shows good agreement for most of the considered time frame and the deviations stays in the order of ± 0.03. At the beginning of monitoring time, DGP stays close to 0.20 and slowly increases at the end of the day (from 19:00 to 20:00) when the sun approaches the horizon, although it is no more in the direct field of view for V1.

However, in daylighting simulations intolerable and disturbing glare is obtained at 18:15 for both days, whereas none is detected in the real testing environment and the deviation, are up to 0.24. A possible explanation might be a small difference between calculated and real solar height: the little difference in solar height can result in direct sunlight within the field of view of V1 for the simulations while not for the measurements, with real sun positions. Additional measurements appear necessary to evaluate whether the deviation is related to the cause above and validate the methodology.

III.3.3.2.2 Illumination Level and Distribution

Figure III-27 shows the results of average workstation illuminance; respectively for pilot study measurements, Radiance daylighting simulations and deviation between methodologies.



Measurements

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	747	876	1166	994	1308	2628	2223	1821	2964	3603	3643	3321	2928	3522	4860	4841	2970	1344	1883	2255	1852	1376	1221	1095	1074
Jul 19th	667	694	749	849	855	2250	1881	1157	2691	3384	3445	3494	3274	3959	5127	5086	3262	1362	2044	2859	2371	2019	1625	1443	1459

Radiance Simulations

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	582	626	656	683	637	1309	643	664	5865	5835	5778	5679	5519	2256	2219	2134	5295	3296	6923	7053	6269	5903	4953	4190	2254
Jul 19th	586	610	645	683	640	1305	644	658	5839	5804	5769	5662	1147	2252	2209	2128	5283	3277	6886	7019	6230	5853	4906	4136	2228

Deviation | Measurements-Radiance Simulations

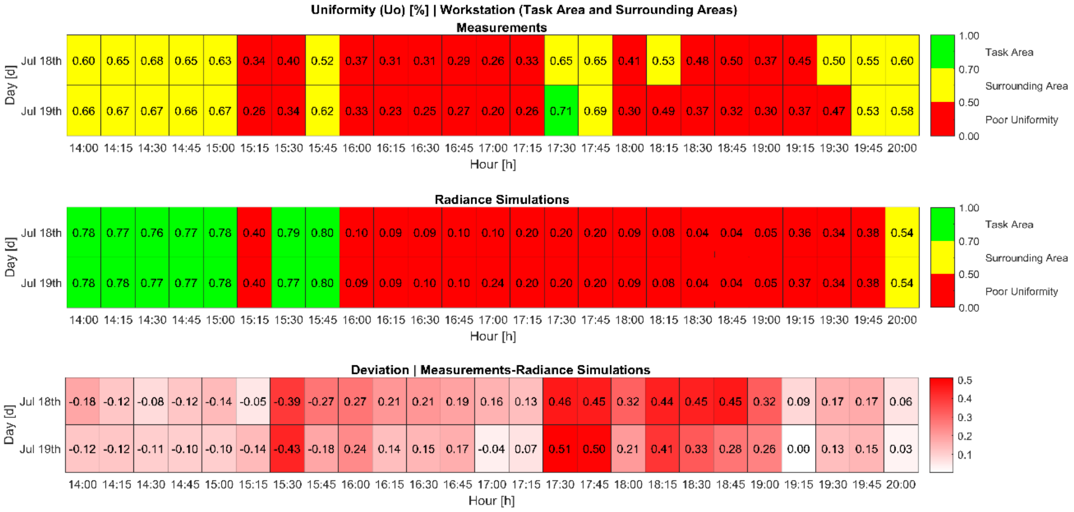
Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	165	250	510	311	671	1320	1579	1157	-2901	-2232	-2135	-2358	-2591	1267	2641	2708	-2325	-1952	-5039	-4798	-4417	-4528	-3732	-3096	-1180
Jul 19th	81	84	103	166	215	945	1236	499	-3148	-2420	-2324	-2168	2127	1707	2918	2958	-2022	-1915	-4843	-4160	-3859	-3834	-3281	-2693	-769

Figure III-27: Workstation average illuminance results, from top to bottom: pilot study measurements, Radiance daylighting simulations and deviation between methodologies.

Levels of maintained illuminance on the work-plane are obtained with both methodologies during the entire time frame considered. Although the trend is nicely similar at the beginning, with increasing variations of sun position, the deviations become larger and gets maximum between 18:30 and 19:45.

Despite the similarities in room illuminance distribution seen in Figure III-25e,f, the results for illuminance on the workstation are not reliable due to the substantial deviations between measured and simulated testing environment. The difference between the methodologies can belong to the coarse grid array, the interpolation, and the differences between real and simulated sky conditions. Interpolation of grid-point results seems not accurate enough to represent the illumination conditions on the work-plane, due to the presence of only one sensor.

Figure III-28 shows the results of average workstation uniformity; respectively for pilot study measurements, Radiance daylighting simulations and deviation between methodologies.



Measurements

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	0.60	0.65	0.68	0.65	0.63	0.34	0.40	0.52	0.37	0.31	0.31	0.29	0.26	0.33	0.65	0.65	0.41	0.53	0.48	0.50	0.37	0.45	0.50	0.55	0.60
Jul 19th	0.66	0.67	0.67	0.66	0.67	0.26	0.34	0.62	0.33	0.23	0.25	0.27	0.20	0.26	0.71	0.69	0.30	0.49	0.37	0.32	0.30	0.37	0.47	0.53	0.58

Radiance Simulations

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	0.78	0.77	0.76	0.77	0.78	0.40	0.79	0.80	0.10	0.09	0.09	0.10	0.10	0.20	0.20	0.20	0.09	0.08	0.04	0.04	0.05	0.36	0.34	0.38	0.54
Jul 19th	0.78	0.78	0.77	0.77	0.78	0.40	0.77	0.80	0.09	0.09	0.10	0.10	0.24	0.20	0.20	0.20	0.09	0.08	0.04	0.04	0.05	0.37	0.34	0.38	0.54

Deviation | Measurements-Radiance Simulations

Day [d]	14:00	14:15	14:30	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30	16:45	17:00	17:15	17:30	17:45	18:00	18:15	18:30	18:45	19:00	19:15	19:30	19:45	20:00
Jul 18th	-0.18	-0.12	-0.08	-0.12	-0.14	-0.05	-0.39	-0.27	0.27	0.21	0.21	0.19	0.16	0.13	0.46	0.45	0.32	0.44	0.45	0.45	0.32	0.09	0.17	0.17	0.06
Jul 19th	-0.12	-0.12	-0.11	-0.10	-0.10	-0.14	-0.43	-0.18	0.24	0.14	0.15	0.17	-0.04	0.07	0.51	0.50	0.21	0.41	0.33	0.28	0.26	0.00	0.13	0.15	0.03

Figure III-28: Workstation uniformity results, from top to bottom: pilot study measurements, Radiance daylighting simulations and deviation between methodologies.

Results of illumination uniformity on workstation show a good agreement for large part of the measurements and the simulations. Trends of U_0 in both methods vary accordingly with sun position; when direct light reaches the workstation area, (i.e. from 16:00) U_0 decreases due to the high differences with shaded parts (i.e. façade array) and increases when the sun is uniformly in the whole room (i.e. from 19:15).

However, high deviations occur from 17:00 to 18:45 when U_0 should be at a low value. This difference seems to belong to the coarse sensor grid and interpolation of the measurements. For example, a shadow from the array falling on the only workstation sensor (Figure III-25a) or the entire central line of sensors (Figure III-25c).

III.3.4 CONCLUSIONS

The research in a real testing environment investigated the effective operation of GPC control strategies and the daylighting performance when equipped with a DDLC façade array. A pilot study of a single office fitted with a DDLC façade array and GPC control strategy ‘Pixel’ was set up for this study. Measurements and daylighting simulations in Radiance software are compared to validate the methodology developed for the virtual testing environment The final conclusions drawn from this investigation are:

- GPC control strategy ‘Pixel’ demonstrated that can be effectively operated to protect the occupants and the workstations, inside a single office room, from direct daylight. A DDLC façade array is used as a shading device by the system and provided dynamic obstruction of only those windows (for example, none, one, two or four elements; as shown in Figure III-24) allowing direct sunlight within the boundaries of the ‘control volume.' Last, the system operated without problems and continuously and for one month and a half during the time-frame of the graduation project.

- The partial agreement, between real and virtual testing environment methodologies, resulted in the daylighting performance of a single office equipped with DDLC façade array and GPC control strategies. Daylight glare assessment trends have high correspondence although a deviation emerged and seemed to occur due to the small difference between calculated and real solar coordinates. Illumination level and distribution showed a lower correlation between the two methods despite the analogies in the trends. Disagreements appear related on the coarse grid of illuminance sensors, the successive interpolation on a finer grid, and differences between real and modeled sky conditions.

In light of these conclusions and in consideration of the lacks of the employed methodology the following suggestions for future studies, with the current configuration of the pilot study, are suggested:

- Glare assessment in a different part of the year (i.e. with lower solar height) and from a different point of view, either in position and view direction (e.g. one rotate toward the façade and then toward room interior). Such variations can provide information about either the validity of the employed methodology (DGP as an index) but also on the effect on daylighting performance of the system.
- Implementation of same grid of sensors in real and virtual testing environment and comparison of the resulting illuminance values without interpolation of the data; last, the measurements should be done with finer time step (i.e. t < 15 minutes).

IV CONCLUSION AND RECOMMENDATIONS

IV.1 CONCLUSIONS

The first goal of this study was the definition of research methodologies for the development and evaluation of control strategies in combination with an SG technology, DDLC glass. Three methodologies are used in this research: analytical, virtual, and real testing environment. This combination of the methods appears to be suitable for providing qualitative and quantitative proof about the potential of automatic daylighting systems and/or SG technologies.

The primary objective of this study was the application of the methodologies for the development and the assessment of a combined application of DDLC façade array and control strategies. Different types of investigations were carried out to fulfill this objective, resulting in the following conclusions:

- An innovative approach for automatic daylighting systems, the GPC control strategies, is developed with the aim to provide protection against direct glare while maximizing daylight admittance and view to the outside. GPC strategies control individually the elements of façade arrays to protect 'control volume(s)', enclosing user(s) and workstation(s), from direct sunlight but also to avoid unnecessary blockage of daylight. In consideration of solar position and space configuration, the system obscures only those elements of the façade array that allow direct sunlight (i.e. potential glare source) within the 'control volume(s)'. Four strategies, based on different geometrical constraints, were developed: 'Pixel', 'Column', 'Row', and 'Homogeneous'.

- Among the developed control strategies, 'Pixel' approach allows the greatest daylight admittance in a standard single office for all the considered location, orientation a façade grid refinement. Orientation and location influence importantly the effectiveness of the control strategies, showing clear guidelines for each parameter such as the greatest performance benefits of 'Pixel' are achieved for South orientation. However, the most influential parameter is the dimension of control volumes, able to impact positively also the performance for façade array refinement; these parameters seems promising for improvements with multiple control volumes and constraints. Last, daylight access about window position in a façade array depends on orientation and control volume's height; defining possible advantages in the design of transparent facades.

- Obscuring daylight with the entire façade array seems to not provide effective benefits for user's glare protection, so the advantages in terms of greater daylight admittance and view to the outside make 'Pixel' prevailing on the other approaches. DDLC windows seem to provide not enough protection against glare from sunlight; for both 'Pixel' and 'Homogeneous' approaches the DGP index reaches the level of intolerable disturbance when the sun is low and hitting the user directly. 'Pixel' and 'Homogeneous' strategies allow a considerable amount of daylight into space that also meets requirements for illumination level and distribution on the workstation. More satisfying luminous conditions are provided by 'Pixel' that also allows a larger amount of savings from the electrical lighting, required to support daylighting and its correct distribution.

- 'Pixel' control strategy is implemented in the pilot study and effective protection from direct daylight, on occupants and workstations inside a single office room, is demonstrated. A DDLC façade array is controlled as a shading device by the GPC system and operated smoothly and continuously for one month and a half. The device provided dynamic obstruction of only the window array elements allowing direct sunlight within the boundaries of the 'control volume'. A partial agreement in daylighting performance resulted from the comparison between real and virtual testing methodologies. Correspondence of results and trends is stronger for daylight glare assessment compared to illumination distribution. Disagreement and differences seem due to the coarse grid of illuminance sensors and differences, between real and virtual, in solar coordinates and sky model.

IV.2 RECOMMENDATIONS

In light of the conclusions, the following recommendations for future studies are suggested:

- Extended and upgraded testing activity, both in real and virtual environments, to obtain stronger insights on daylighting performance of the system. Different daylighting conditions (i.e. part of the year) and viewpoints are suggested to either assess daylighting glare, correct the algorithm for solar coordinates, and provide more definite information about the efficacy of DDLC as a shading device. Modeling of different sky conditions (e.g. mixed sky) in Radiance can be done *gendaylit* light source that simulates the luminous conditions with irradiance inputs, for example from real-time weather data. Last, a finer grid of illuminance sensors in the pilot study (i.e. on the workstations or in the room) is advised to allow a higher precision for the validation of illumination level and distribution.

- A Human-technology interaction study is necessary to evaluate the acceptance and the effect on the users by the GPC control system but also the DDLC windows. The pilot study can host up to two users and their workstation for such investigation. In the framework of such research upgrade of the system with manual override and sensors' feedbacks from occupancy and luminous exterior conditions are advised. Moreover, an investigation on the physiological (e.g. health and circadian rhythm) and psychological (e.g. view to the outside) effect is suggested due to the lack of knowledge regarding the impact of DDLC façade system.

- Building simulations are not only the traditional tool used as an aid for the design but are also useful in product research and development. In our case, Radiance software showed the capability to model the luminous properties of DDLC glass accurately; therefore, it can be used to investigate which modifications to these properties can provide benefits for glare protection. Two possible adjustments to DDLC properties should be researched: a further reduction of luminous transmittance (reducing the intensity of light), and the application of an additional layer with scattering properties (increases luminous source size and balances the luminous field). This methodology might offer some useful guidelines to the developer of DDLC technology to improve the performance of the device.

- GPC control strategies are currently focused only on the improvement of the visual environment but lacking on attention for thermal balance and energy. Effect on heat gains by GPC strategies can be estimated in the analytical study with an additional loop considering the amount of irradiance, from meteorological data (i.e. IWEC weather file), transmitted in the room. Also, a new modality 'Energy Saving', aiming at the reduction of energy demand and control of heat gains, should be designed. Optimal control of the daylighting systems can be obtained by coupling of both the visual and the thermal control approach.

Also, some suggestions for the application of GPC and DDLC are provided:

- Implementation of sensors to the GPC control algorithm for occupancy and luminous exterior conditions. Detection of sky luminance would be the most suitable in consideration of glare strategy (i.e. strong correlation); however, devices enabling this measurement (e.g. sky scanner) are either too expensive or too slow for feedbacks to the algorithm.

- Integration of GPC control system with the electrical lighting.

- Creation of graphical user interfaces for the GPC control strategies.

- DDLC façade might be employed during nighttime for architectural lighting exhibitions. The technology can provide a visual connection from the exterior to building interior when the electrical lighting is kept on. In combination with an appropriate control any dark/bright patterns can be obtained with the façade, allowing entertainment and providing additional value to the technology and the building employing the system.

V REFERENCES

Aldawoud A.; Conventional fixed shading devices in comparison to an electrochromic glazing system in hot, dry climate. Energy and Buildings (2013). 59: 104–110.

Aries M.B.C., Aarts M.P.J., van Hoof J.; Daylight and health: a review of the evidence and consequences for the built environment. Light Res Technol 2015; 47:6–27.

Assimakopoulos M.N., Tsangrassoulis A., Santamouris M., Guarracino G.; Comparing the energy performance of an electrochromic window under various control strategies. Building and Environment 2007; 42:2829–2834.

Baetens R., Jelle B.P., Gustavsen A.; Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: a state-of-the-art review. Solar Energy Materials and Solar Cells 2010; 94 (2): 87–105.

Bakker L.G., Hoes - van Oeffelen E.C.M., Loonen R.C.G.M., Hensen J.L.M.; User satisfaction and interaction with automated dynamic facades: a pilot study. Building and Environment 2014; 78: 44–52.

Beck W., Dolman D., Dutoo G., Hall A., Seppanen O.; Solar shading - How to integrate solar shading in sustainable buildings. REHVA Guidebook 12, 2010.

Bellia L, De Falco F., Minichiello F.; Effects of solar shading devices on energy requirements of standalone office buildings for Italian climates. Applied Thermal Engineering 2013; 54: 190-201.

Beute F.; Powered by nature: the psychological benefits of natural views and daylight. PhD Thesis 2014. Technische Universiteit Eindhoven.

Bülow-Hübe H.; Solar Shading and daylight redirection. Demonstration project for a system of motorized daylight redirecting venetian blinds and light controlled luminaire. Energy and Building Design, Lund University; 2007.

Capperucci R.; Influence of DDLC window (dye-doped liquid crystal) adaptive façade system and control strategies on visual environment and performance. Graduation Project M3 Report. Eindhoven University of Technology; 2016.

Carlucci S., Causone F., De Rosa F., Pagliano L.; A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Ren Sus Energy Rev 2015; 47: 1016-33.

Chaiwiwatworakul P., Chirarattananon S., Rakkwamsuk P.; Application of automated blind for daylighting in tropical region. EnergyConversManag 2009; 50:2927–43.

Chauvel P., Collins J.B., Dogniaux R., Longmore J.; Glare from windows: current views of the problem. Light Res Technol 1982;14(1):31–46.

Clear R.D., Inkarojrit V., Lee E.S.; Subject responses to electrochromic windows. Energy and Buildings 2006. 38 :758–779.

Colaco S.G., Kurian C.P., George V.I., Colaco A.M.; Prospective Techniques of Effective Daylight Harvesting in Commercial Buildings by Employing Window Glazing, Dynamic Shading Devices and Dimming Control—A Literature Review. Build Simul 2008; 1: 279–289.

Cuce E., Riffat S.B.; A state-of-the-art review on innovative glazing technologies. Renewable and Sustainable Energy Reviews 2015; 41:695–714.

Cupelli D., Nicoletta F.P., Manfredi S., Vivacqua M., Formoso P., De Filpo G., Chidichimo G.; Self-adjusting smart windows based on polymer-dispersed liquid crystals. Solar Energy Materials & Solar Cells 2009; 93:2008–2012.

de Wilde P.; Design analysis integration: supporting the selection of energy saving building components. Building and Environment 2002;37(8-9): 807–16.

Debije M.G.; Solar energy collectors with tunable transmission. Advanced Functional Materials 2010, 20 (9): 1498-1502.

DIN 5034-3:2007-02. Daylight in interiors - Part 3: Calculation, 2007.

Dussault J.M., Gosselin L., Galstian T.; Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads. Solar Energy 2012; 86: 3405–3416.

EN12464-1. Light and lighting - Lighting of work places - Part 1: Indoor work places, 2009.

Favoino F., Overend M., Jin Q.; The optimal thermo-optical properties and energy saving potential of adaptive glazing technologies. Applied Energy 2015. 156: 1–15.

Fernandes L.L., Lee E.S., Ward G.; Lighting energy savings potential of split-pane electrochromic windows controlled for daylighting with visual comfort. Energy Build 2013; 61:8–20.

Galasiu A.D., Veitch J.A.; Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energy and Buildings 20006; 38 (7) 728–742.

Galasiu A.D., Veitch J.A.; Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. Energy and Buildings 2006; 38 (7):728–742.

Gardiner D.J., Morris S.M., Coles H.J.; High-efficiency multistable switchable glazing using smectic A liquid crystals. Solar Energy Materials & Solar Cells 2009; 93:301–306.

Ghosh A., Norton B., Duffy A.; Daylighting performance and glare calculation of a suspended particle device switchable glazing. Solar Energy 2016; 132: 114–128.

Ghosh A., Norton B., Duffy A.; Measured thermal performance of a combined suspended particle switchable device evacuated glazing. Applied Energy 2016; 169: 469–480.

Gustavsen A., Jelle B.P., Arasteh D., Kohler C.; State-of-the-art highly insulating window frames – Research and market review. Project Report 6, SINTEF Building and Infrastructure, 2007.

Hee W.J., Alghoul M.A., Bakhtyar B., Elayeb O, Shameri M.A., Alrubaih M.S., Sopian K.; The role of window glazing on daylighting and energy saving in buildings. Renewable and Sustainable Energy Reviews 2015; 42:323–343.

Hellinga H.; Daylight and View: The influence of windows on the visual quality of indoor spaces. PhD thesis 2013. Delft University of Technology.

Huang Y., Niu J., Chung T.; Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates. Applied Energy 2014; 134: 215–228.

Hviid C., Nielsen T., Svendsen S.; Simple tool to evaluate the impact of daylight on building energy consumption. Sol Energy 2008; 82(9):787–98.

IESNA; The lighting handbook. Ninth ed. New York(USA): Illuminating Engineering Society of North America; 2000.

Jakubiec J, Reinhart C.; The ‘adaptive zone’ – a concept for assessing discomfort glare throughout daylit spaces. Light Res Technol 2012;44 (2):149–70.

Jelle B.P., Hynd A., Gustavsen A., Arasteh D., Goudey H,. Hart R.; Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Solar Energy Material and Solar Cells 2012; 96:1–28.

Jelle B.P., Hynd A., Gustavsen A., Arasteh D., Goudey H., Hart R.; Fenestration of today and tomorrow: a state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells 2012; 96 (7465): 1–28.

Kirimtat A., Koyunbaba B.K., Chatzikonstantinou I., Sariyildiz S.; Review of simulation modeling for shading devices in buildings. Renew Susta in Energy Rev 2016; 53:23–49.

Kleindienst S., Andersen M.; Comprehensive annual daylight design through a goal-based approach. Building Research & Information 2012; 40(2): 154–173.

Konstantoglou M., Tsangrassoulis A.; Dynamic building envelope system: a control strategy for enhancing daylighting quality and reducing energy consumption. Energy Forum 2012:6–7.

Konstantoglou M., Tsangrassoulis A.; Dynamic operation of daylighting and shading systems: A literature review. Renewable and Sustainable Energy Reviews 2016; 60: 268–283.

Koo S.Y., Yeo M.S., Kim K.W.; Automated blind control to maximize the benefits of daylight in buildings. Building and Environment 2010; 45:1508–1520.

Lee E.S., Claybaugh E.S., LaFrance M.; End user impacts of automated electrochromic windows in a pilot retrofit application. Energy and Buildings 2012; 47: 267–284.

Lee E.S., Claybaugh E.S., LaFrance M.; End user impacts of automated electrochromic windows in a pilot retrofit application. Energy and Buildings 47 (2012) 267–284

Lee E.S., DiBartolomeo D.L., Selkowitz S.E.; Thermal and daylighting performance of an automated Venetian blind and lighting system in a full-scale private office. Energy and Buildings 1998; 29: 47-63.

Lee E.S., DiBartolomeo D.L.; Application issues for large-area electrochromic windows in commercial buildings. Solar Energy Materials & Solar Cells 2002. 71: 465–491

Loonen R.C.G.M., Singaravel S., Costola D., Hensen J.L.M.; Simulation-based support for product development of innovative building envelope components, Automation in Construction 2014; 45: 86–95.

Loonen R.C.G.M., Trcka M., Costola D., Hensen J.L.M.; Climate adaptive building shells: State-of-the-art and future challenges. Renewable and Sustainable Energy Reviews 2013; 25: 483–493.

Mardaljevic J., Kelly R., Painter B.; Electrochromic glazing: avoiding the blues. In Proceedings of the CIBSE-ASHRAE Technical Symposium 2014. 2014: Dublin, Ireland.

Nazzal A.; A new evaluation method for daylight discomfort glare. IntJ Indus Ergon 2005; 35(4):295–306.

Nielsen M.V., Svendsen S., Jensen L.B.; Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight. SolEnergy 2011; 85:757–68.

O'Brien W., Kapsis K., Athienitis A.K.; Manually-operated window shade patterns in office buildings: A critical review. Building and Environment 2013. 60: 319-338.

Ochoa C.E., Aries M.B.C., van Loenen E.J., Hensen J.L.M.; Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Applied Energy 2012. 95: 238–45.

Osterhaus W.K.E.; Design guidelines for glare-free daylit work environments, In: Proceedings of the 11th European conference on lighting – Lux Europe. 2009: Istanbul(TR).

Osterhaus W.K.E.; Discomfort glare assessment and prevention for daylight applications in office environments. Sol Energy 2005; 79(2):140–58.

Osterhaus, W.K.E., Recommended luminance ratios and their application in the design of daylighting systems for offices, In: Proceedings of the 35th Annual Conference of the Australia and New Zealand Architectural Science Association (ANZAScA). 2002: Geelong(AU).

Papaefthimiou, S., Leftheriotis, G., Yianoulis, P., Hyde, T.J., Eames, P.C.,Fang, Y., Pennarun, P.Y., Jannasch, P., 2006. Development of electrochromic evacuated advanced glazing. Energy Building 2006; 38, 1455–1467.

Piccolo A., Pennisi A., Simone F.; Daylighting performance of an electrochromic window in a small scale test-cell. Solar Energy 2009. 83(6): 832–844.

Piccolo A., Simone F.; Effect of switchable glazing on discomfort glare from windows. Building and Environment 2009; 44: 1171–1180.

Rosemann A.; Lighting Technology - Reader fot hte Master Course 7S880. Not Published 2015.

Sbar N.L., Podbelski L., Yang H.M., Pease B.; Electrochromic dynamic windows for office buildings. Int. J. Sustainable Built Environ 2012. 1:125–139

Singh R., Lazarus I.J., Kishore V.V.N.; Effect of internal woven roller shade and glazing on the energy and daylighting performances of an office building in the cold climate of Shillong. Applied Energy 2015; 159: 317–333.

Suk J.Y., Schiler M.; Investigation of evalglare software, daylight glare probability and high dynamic range imaging for daylight glare analysis. Light Res Tec 2013; 45: 450-63.

Van den Wymelenberg K., Inanici M.; A critical investigation of common lighting design metrics for predicting human visual comfort in offices with daylight. LEUKOS 2014; 10(3): 145-64.

Wienold J., Christoffersen J.; Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy Build 2006;38(7):743–57.

Wienold J., Dynamic daylight glare evaluation, In: Proceedings of the11th International IBPSA Conference, BuildingSimulation.2009: Glasgow, Scotland (UK). p.944–51.

Wienold J.; Dynamic daylight glare evaluation, In: Proceedings of the11th International IBPSA Conference, BuildingSimulation.2009: Glasgow, Scotland (UK). p.944–51.

Wienold J.; Dynamic simulation of blind control strategies for visual comfort and energy balance analysis, In: Proceedings of the Building Simulation 2007. 2007: Bejing, China.1197–1204.

Wienold, J.; Evalglare: a new RADIANCE-based tool to evaluate glare in office spaces. 3rd Internatiol Radiance Workshop 2004., Fribourg, CH.

Wyckmans A.; Intelligent building envelopes—architectural concept & applications for daylighting quality. PhD thesis. Norwegian University of Science and Technology; 2005.

Zinzi M.; Office worker preferences of electrochromic windows: a pilot study. Building and Environment 2006. 41: 1262–1273.

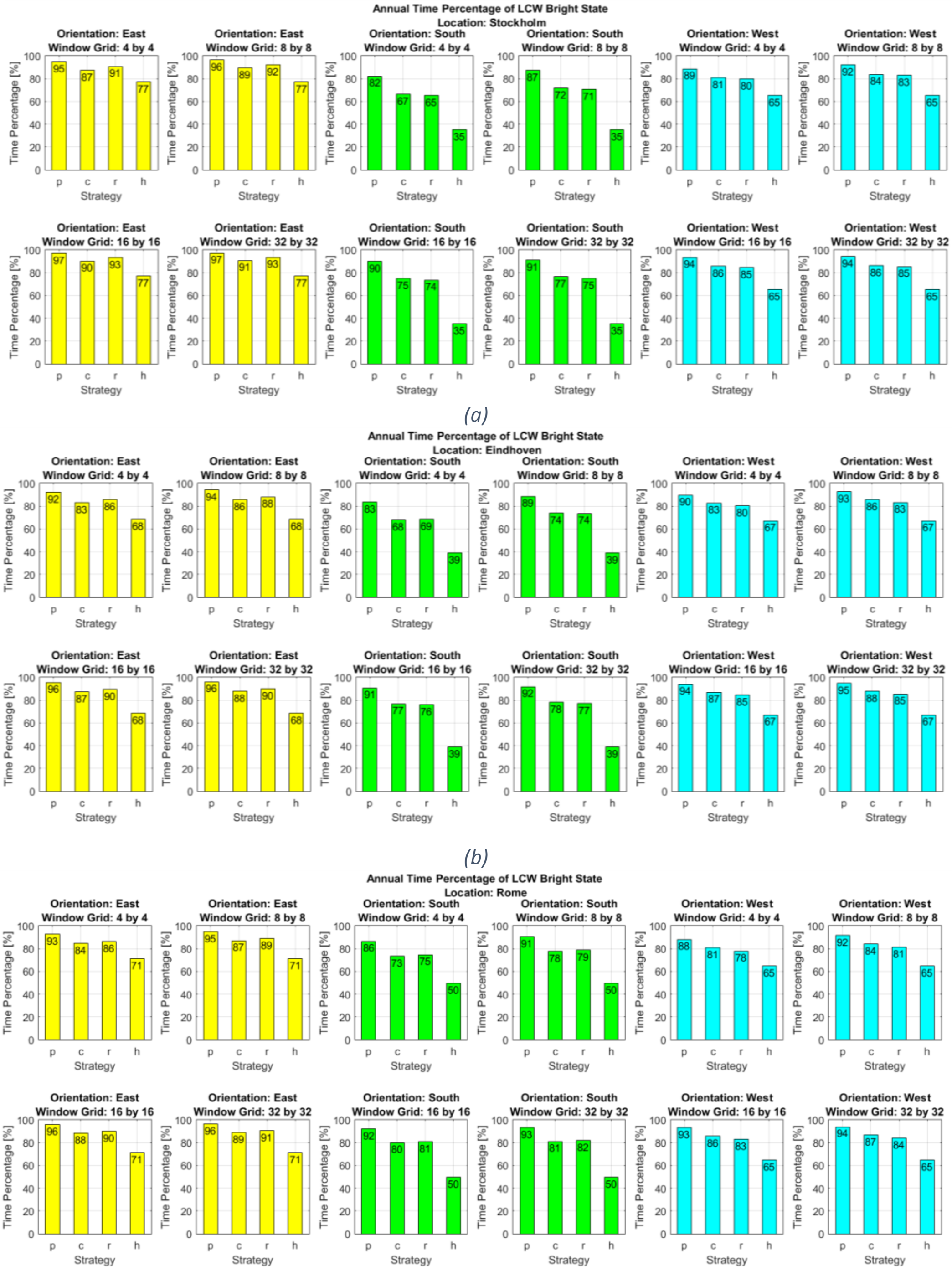
VI APPENDIX

VI.1 PARAMETRIC STUDIES OF GPC CONTROL STRATEGIES

VI.1.1 RESULTS

VI.1.1.1 SET I | DAYLIGHT ADMITTANCE POTENTIAL OF CONTROL STRATEGIES

Results of the set I for control volume on user and workstation are presented in Figure VI.1.



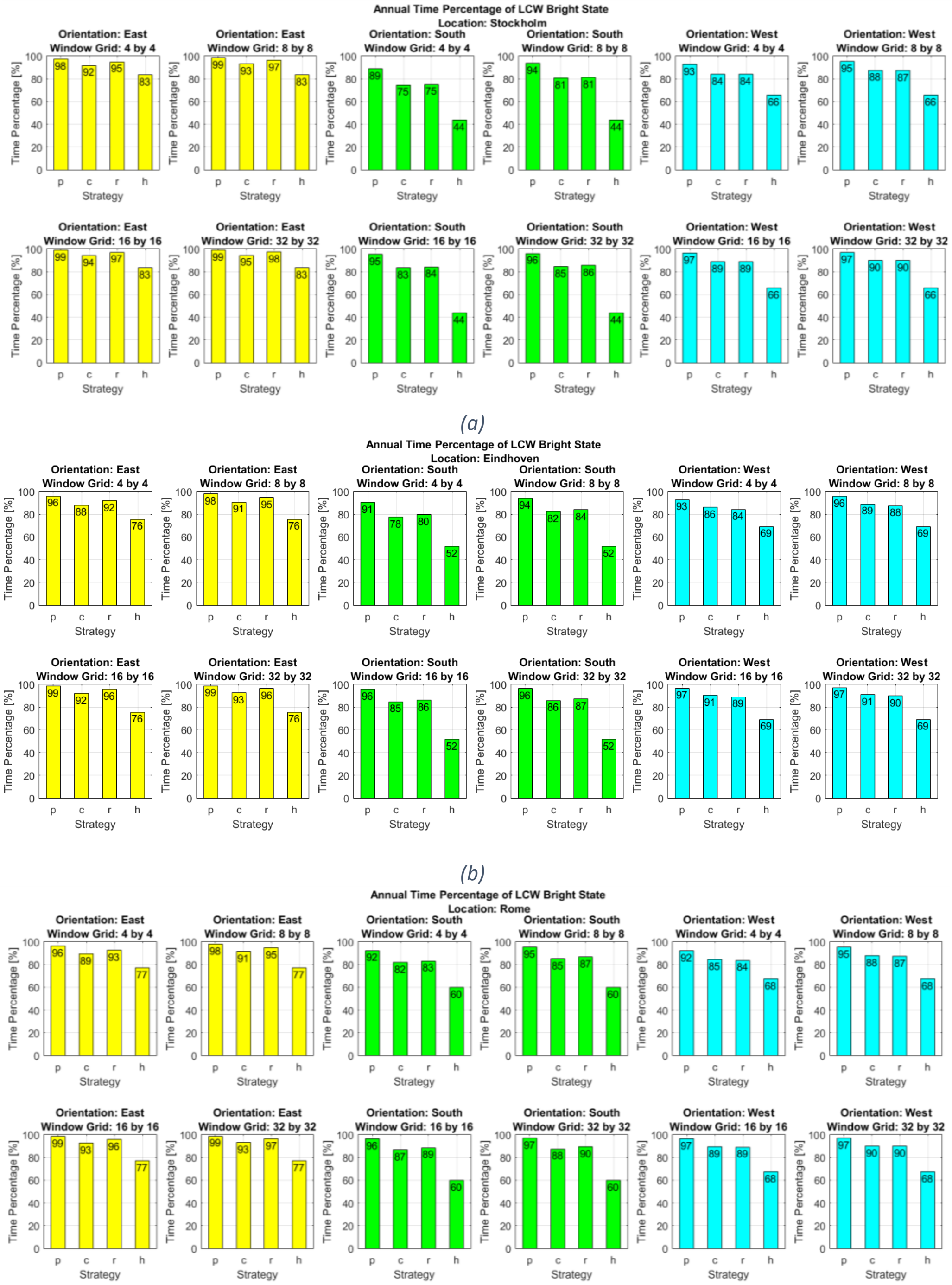
(a)

(b)

(c)

Figure VI-1: Annual time percentage of open state for control volume on user and workstation. Results for each control strategy, window grid, and orientation Respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

Results of the set I for control volume only to the user are presented in Figure VI-2.



(a)

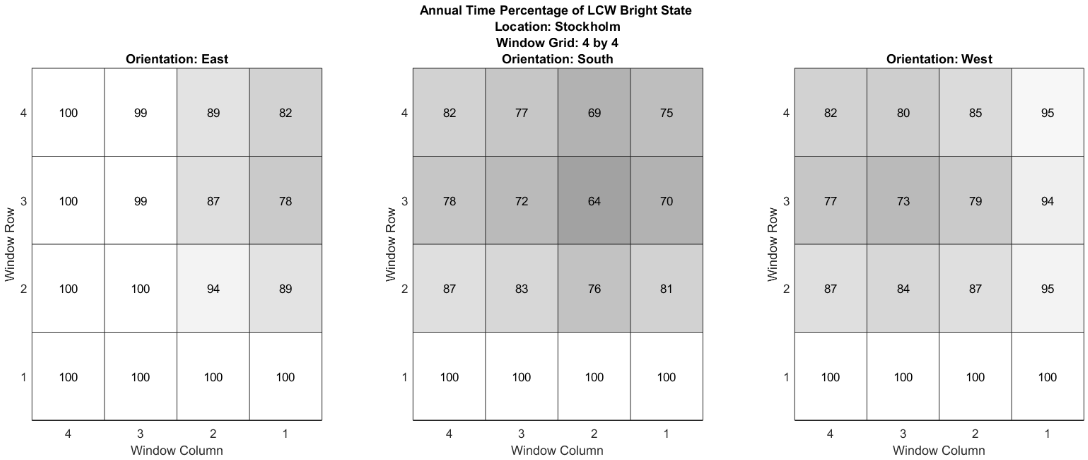
(b)

(c)

Figure VI-2: Annual time percentage of open state for control volume on the user. Results for each control strategy, window grid, and orientation are shown respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

VI.1.1.2 Set II | Daylight Admittance Potential of Window Position in Façade Array

Results of set II for control volume on user and workstation, for grid refinement equal to 4 are presented in Figure VI-3.



Orientation: East

Window Row	4	3	2	1
4	100	99	89	82
3	100	99	87	78
2	100	100	94	89
1	100	100	100	100

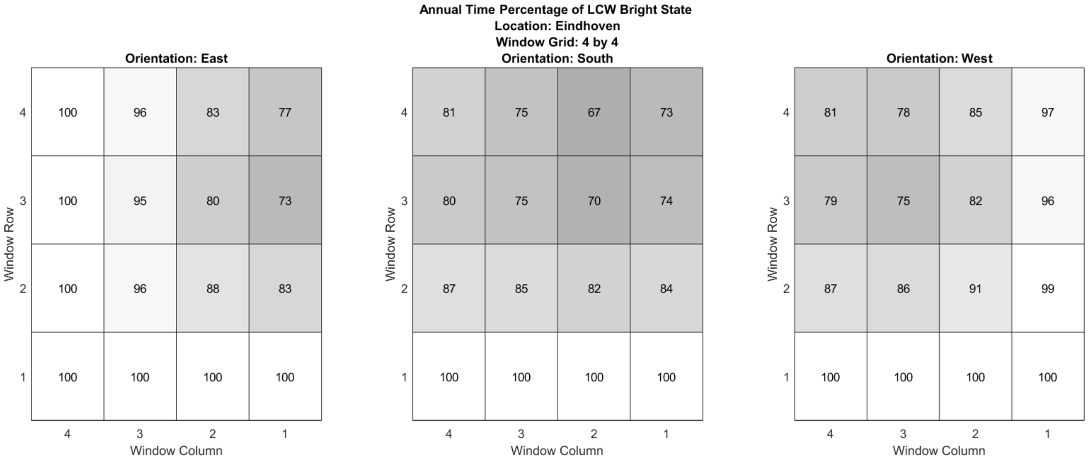
Orientation: South

Window Row	4	3	2	1
4	82	77	69	75
3	78	72	64	70
2	87	83	76	81
1	100	100	100	100

Orientation: West

Window Row	4	3	2	1
4	82	80	85	95
3	77	73	79	94
2	87	84	87	95
1	100	100	100	100

(a)



Orientation: East

Window Row	4	3	2	1
4	100	96	83	77
3	100	95	80	73
2	100	96	88	83
1	100	100	100	100

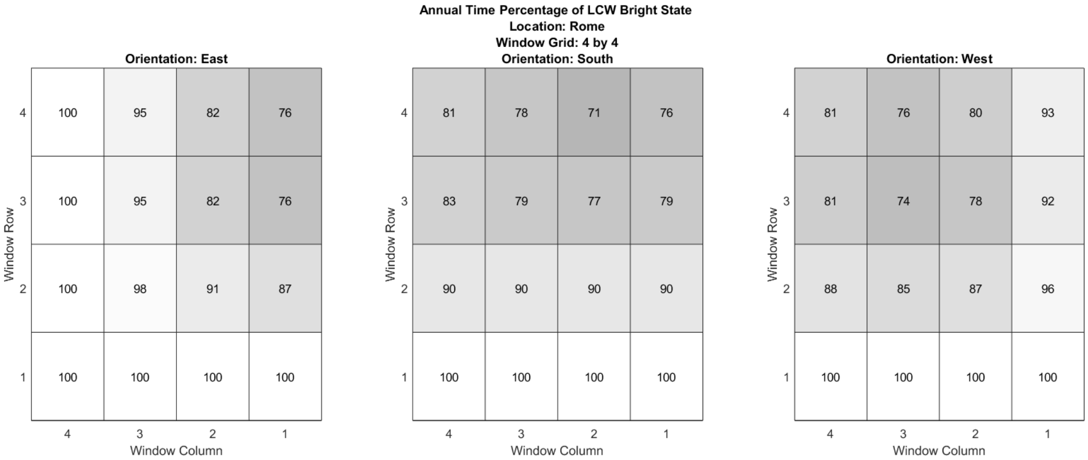
Orientation: South

Window Row	4	3	2	1
4	81	75	67	73
3	80	75	70	74
2	87	85	82	84
1	100	100	100	100

Orientation: West

Window Row	4	3	2	1
4	81	78	85	97
3	79	75	82	96
2	87	86	91	99
1	100	100	100	100

(b)



Orientation: East

Window Row	4	3	2	1
4	100	95	82	76
3	100	95	82	76
2	100	98	91	87
1	100	100	100	100

Orientation: South

Window Row	4	3	2	1
4	81	78	71	76
3	83	79	77	79
2	90	90	90	90
1	100	100	100	100

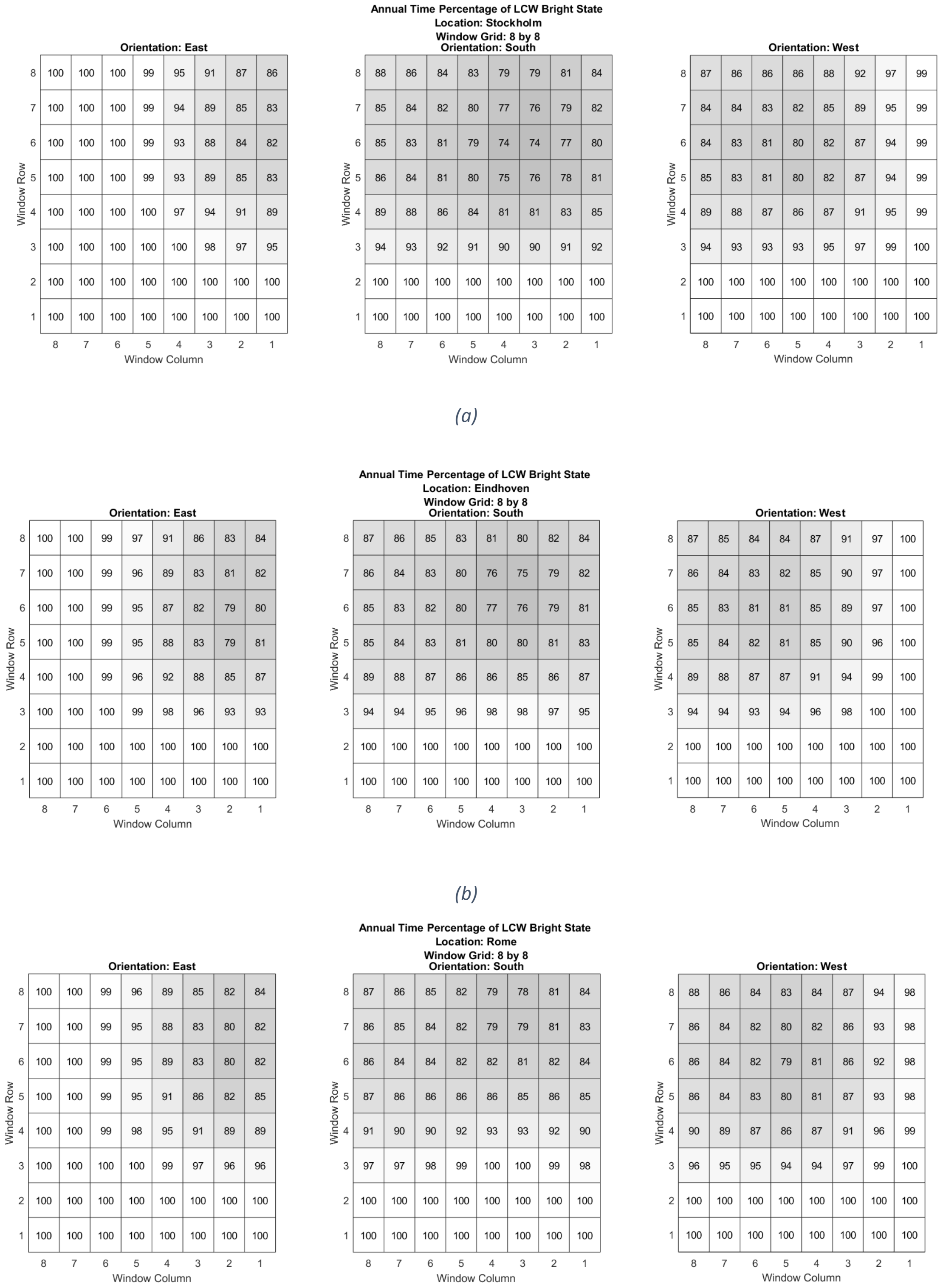
Orientation: West

Window Row	4	3	2	1
4	81	76	80	93
3	81	74	78	92
2	88	85	87	96
1	100	100	100	100

(c)

Figure VI-3: Annual time percentage of open state for control volume on user and workstation. Results for each window and orientation with grid refinement equal to 4 are shown respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

Results of set II for control volume on user and workstation, for grid refinement equal to 8 are presented in Figure VI-4.



Orientation: East

Window Row	8	7	6	5	4	3	2	1
8	100	100	100	99	95	91	87	86
7	100	100	100	99	94	89	85	83
6	100	100	100	99	93	88	84	82
5	100	100	100	99	93	89	85	83
4	100	100	100	100	97	94	91	89
3	100	100	100	100	100	98	97	95
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row	8	7	6	5	4	3	2	1
8	88	86	84	83	79	79	81	84
7	85	84	82	80	77	76	79	82
6	85	83	81	79	74	74	77	80
5	86	84	81	80	75	76	78	81
4	89	88	86	84	81	81	83	85
3	94	93	92	91	90	90	91	92
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

Window Row	8	7	6	5	4	3	2	1
8	87	86	86	86	88	92	97	99
7	84	84	83	82	85	89	95	99
6	84	83	81	80	82	87	94	99
5	85	83	81	80	82	87	94	99
4	89	88	87	86	87	91	95	99
3	94	93	93	93	95	97	99	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Window Column

(a)

Orientation: East

Window Row	8	7	6	5	4	3	2	1
8	100	100	99	97	91	86	83	84
7	100	100	99	96	89	83	81	82
6	100	100	99	95	87	82	79	80
5	100	100	99	95	88	83	79	81
4	100	100	99	96	92	88	85	87
3	100	100	100	99	98	96	93	93
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row	8	7	6	5	4	3	2	1
8	87	86	85	83	81	80	82	84
7	86	84	83	80	76	75	79	82
6	85	83	82	80	77	76	79	81
5	85	84	83	81	80	80	81	83
4	89	88	87	86	86	85	86	87
3	94	94	95	96	98	98	97	95
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

Window Row	8	7	6	5	4	3	2	1
8	87	85	84	84	87	91	97	100
7	86	84	83	82	85	90	97	100
6	85	83	81	81	85	89	97	100
5	85	84	82	81	85	90	96	100
4	89	88	87	87	91	94	99	100
3	94	94	93	94	96	98	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Window Column

(b)

Orientation: East

Window Row	8	7	6	5	4	3	2	1
8	100	100	99	96	89	85	82	84
7	100	100	99	95	88	83	80	82
6	100	100	99	95	89	83	80	82
5	100	100	99	95	91	86	82	85
4	100	100	99	98	95	91	89	89
3	100	100	100	100	99	97	96	96
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row	8	7	6	5	4	3	2	1
8	87	86	85	82	79	78	81	84
7	86	85	84	82	79	79	81	83
6	86	84	84	82	82	81	82	84
5	87	86	86	86	86	85	86	85
4	91	90	90	92	93	93	92	90
3	97	97	98	99	100	100	99	98
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

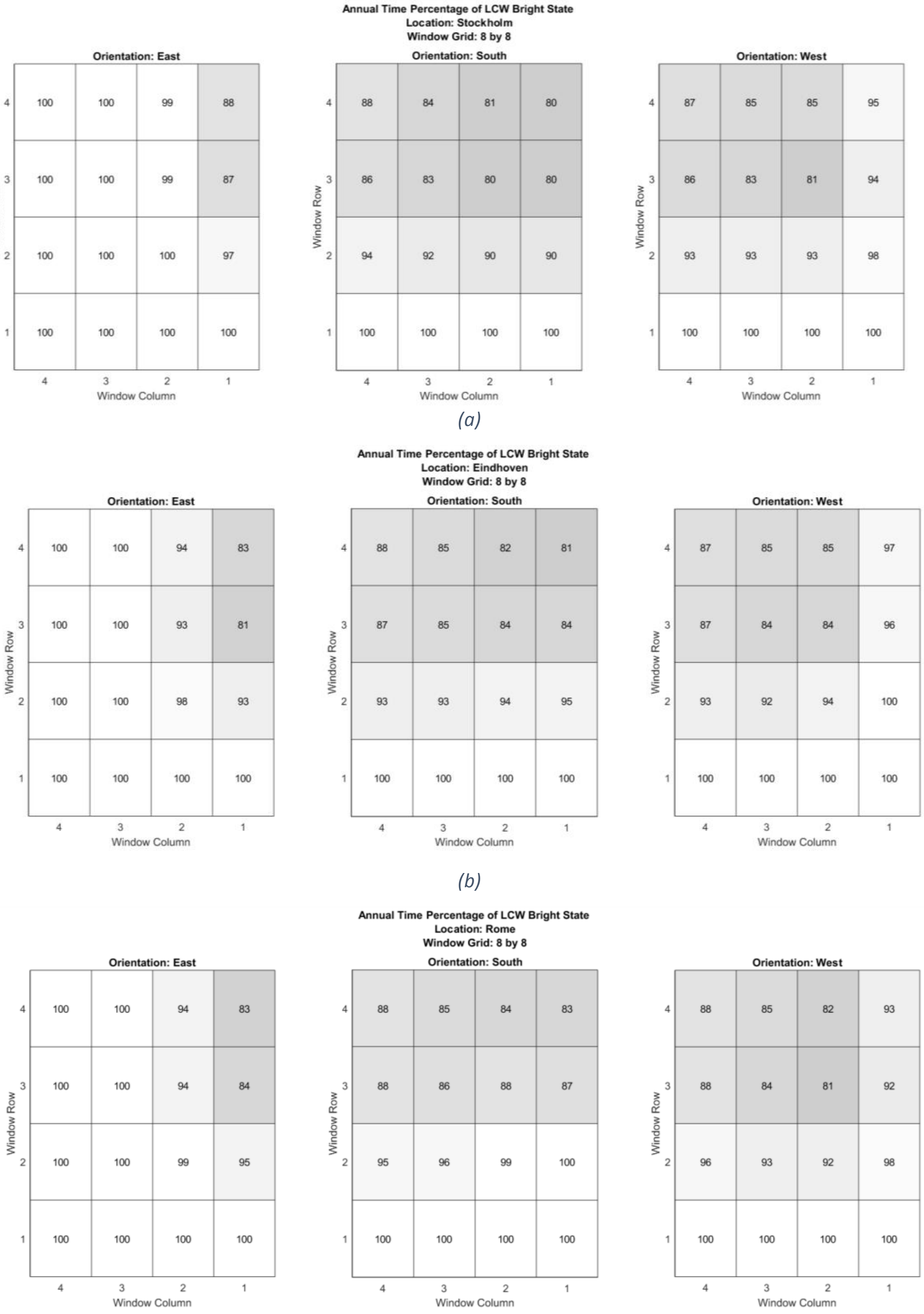
Window Row	8	7	6	5	4	3	2	1
8	88	86	84	83	84	87	94	98
7	86	84	82	80	82	86	93	98
6	86	84	82	79	81	86	92	98
5	86	84	83	80	81	87	93	98
4	90	89	87	86	87	91	96	99
3	96	95	95	94	94	97	99	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Window Column

(c)

Figure VI-4: Annual time percentage of open state for control volume on user and workstation. Results for each window and orientation with grid refinement equal to 8 are shown respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

Results of set II for control volume on user and workstation, for grid refinement equal to 4 are presented in Figure VI-5.



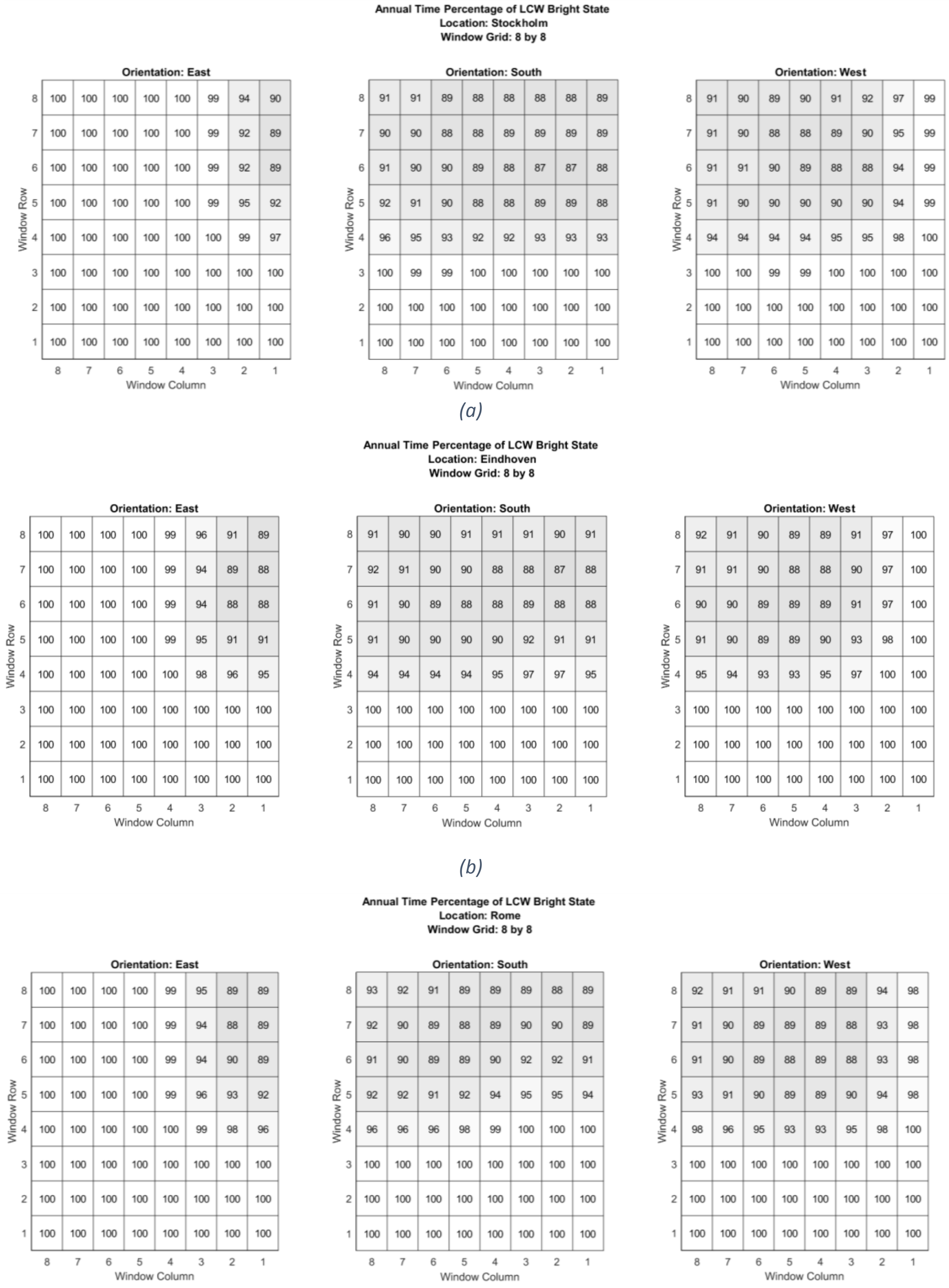
(a)

(b)

(c)

Figure VI-5: Annual time percentage of open state for control volume on the user. Results for each window and orientation with grid refinement equal to 4 are shown respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

Results of set II for control volume on user and workstation, for grid refinement equal to 8 are presented in Figure VI-6.



Annual Time Percentage of LCW Bright State
Location: Stockholm
Window Grid: 8 by 8

Orientation: East

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	100	100	100	100	100	99	94	90
7	100	100	100	100	100	99	92	89
6	100	100	100	100	100	99	92	89
5	100	100	100	100	100	99	95	92
4	100	100	100	100	100	100	99	97
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	91	91	89	88	88	88	88	89
7	90	90	88	88	89	89	89	89
6	91	90	90	89	88	87	87	88
5	92	91	90	88	88	89	89	88
4	96	95	93	92	92	93	93	93
3	100	99	99	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	91	90	89	90	91	92	97	99
7	91	90	88	88	89	90	95	99
6	91	91	90	89	88	88	94	99
5	91	90	90	90	90	90	94	99
4	94	94	94	94	95	95	98	100
3	100	100	99	99	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

(a)

Annual Time Percentage of LCW Bright State
Location: Eindhoven
Window Grid: 8 by 8

Orientation: East

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	100	100	100	100	99	96	91	89
7	100	100	100	100	99	94	89	88
6	100	100	100	100	99	94	88	88
5	100	100	100	100	99	95	91	91
4	100	100	100	100	100	98	96	95
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	91	90	90	91	91	91	90	91
7	92	91	90	90	88	88	87	88
6	91	90	89	88	88	89	88	88
5	91	90	90	90	90	92	91	91
4	94	94	94	94	95	97	97	95
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	92	91	90	89	89	91	97	100
7	91	91	90	88	88	90	97	100
6	90	90	89	89	89	91	97	100
5	91	90	89	89	90	93	98	100
4	95	94	93	93	95	97	100	100
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

(b)

Annual Time Percentage of LCW Bright State
Location: Rome
Window Grid: 8 by 8

Orientation: East

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	100	100	100	100	99	95	89	89
7	100	100	100	100	99	94	88	89
6	100	100	100	100	99	94	90	89
5	100	100	100	100	99	96	93	92
4	100	100	100	100	100	99	98	96
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: South

Window Row \ Window Column	8	7	6	5	4	3	2	1
8	93	92	91	89	89	89	88	89
7	92	90	89	88	89	90	90	89
6	91	90	89	89	90	92	92	91
5	92	92	91	92	94	95	95	94
4	96	96	96	98	99	100	100	100
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

Orientation: West

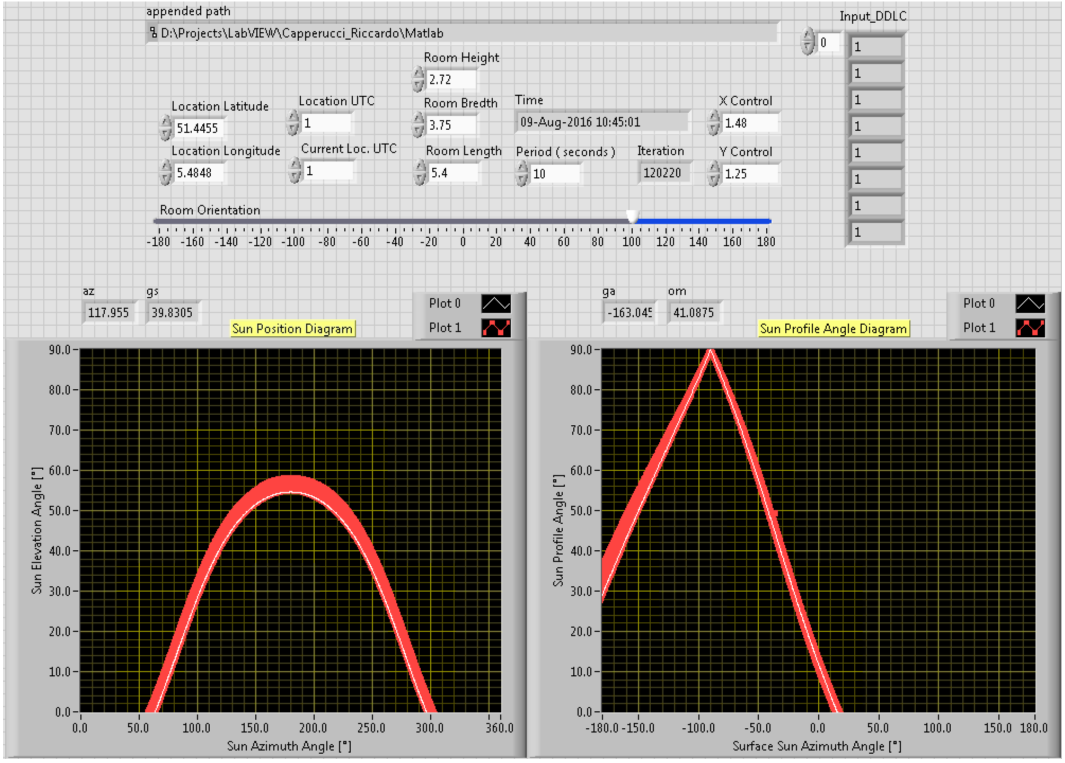
Window Row \ Window Column	8	7	6	5	4	3	2	1
8	92	91	91	90	89	89	94	98
7	91	90	89	89	89	88	93	98
6	91	90	89	88	89	88	93	98
5	93	91	90	89	89	90	94	98
4	98	96	95	93	93	95	98	100
3	100	100	100	100	100	100	100	100
2	100	100	100	100	100	100	100	100
1	100	100	100	100	100	100	100	100

(c)

Figure VI-6: Annual time percentage of open state for control volume on the user. Results for each window and orientation with grid refinement equal to 8 are shown respectively for (a) Stockholm, (b) Eindhoven and (c) Rome.

VI.2 PILOT STUDY ASSESSMENT OF DDLC FAÇADE AND GPC CONTROL STRATEGIES

VI.2.1 LABVIEW GRAPHICAL USER INTERFACE



appended path: D:\Projects\LabVIEW\Capperucci_Riccardo\Matlab

Room Height: 2.72

Location Latitude: 51.4455

Location UTC: 1

Room Bredth: 3.75

Time: 09-Aug-2016 10:45:01

X Control: 1.48

Location Longitude: 5.4848

Current Loc. UTC: 1

Room Length: 5.4

Period (seconds): 10

Iteration: 120220

Y Control: 1.25

Input_DDLC: 0; 1, 1, 1, 1, 1, 1, 1, 1

az: 117.955

gs: 39.8305

ga: -163.045

om: 41.0875

Figure VI-7: Graphical user interface (GUI) designed in the LabVIEW program to control the flow of information between softwarea and hardware composing the set-up application in the pilot study.

VI.2.2 DDLC FAÇADE ARRAY DESIGN

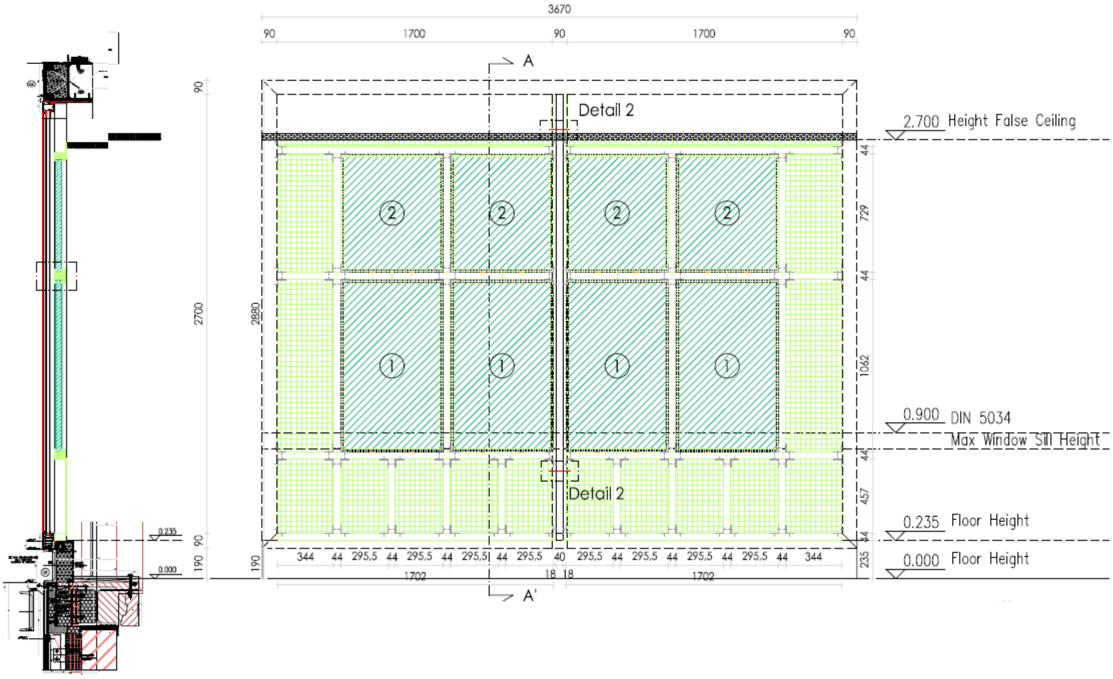


Figure VI-8: Façade array design for pilot study office. The wooden structure is fastened to the structure of the existing façade. The gaps between the wooden structure hosts DDLC glasses (dark green hatches) whereas and opaque white surfaces (light green hatches), probably white wooden boards similar to the walls.