ADAPTIVE FACADE DESIGN FOR THE REGULATION OF VISUAL COMFORT

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Author: Shirin Masoudi, 4621700

Delft University of Technology
MSc. Architecture, Urbanism & Building Sciences
Track: Building Technology
Sustainable Design Graduation Studio

In collaboration with Rollecate Group®

First mentor: Dr.ir T. Klein, Architectural Engineering +Technology, Building Product Innovation
Second mentor: Dr. G.J. Hordijk, Architectural Engineering +Technology, Building Physics
External examiner: Ir. J.S.J. Koolwijk, Management in the Built Environment, Design & Construction Management

6th July 2018

ACKNOWLEDGMENT

I would like to express my deep gratitude to the persons that supported me during the course of my graduation.

Firstly, I would like to thank my supervisors Dr.ir T. Klein and Dr. G.J. Hordijk that, with their experience and knowledge, guided me with constructive suggestions and excellent support during the entire process.

Thanks to Zoen and Thijn from Rollecate Group® that, with their indications, contributed to shape my project with a concrete prospective.

I want to thank my colleagues and friends of Building Technology for their help. Furthermore, I want to thank Maria in particular, because she confirmed to be a great co-worker and friend during our collaboration in the research phase.

A special thanks goes to my parents, Kasra and Nicoletta, who were constantly supporting and encouraging me, and always giving me the possibility to improve myself and to follow my dreams.

Thanks to the new family I found in Delft, composed by all those persons that, in different ways, made these two years a period that I will always remember with nostalgia.

ABSTRACT

The building sector in Europe represents 40% of the energy consumption and, of this amount, 26% is represented by office buildings that demand 44% of the energy only for lighting. Therefore, architects and engineers have a big responsibility to find design strategies and technologies that answer to this issue. In particular, a possible approach is the application of adaptive façades that respond to outdoor and indoor stimuli in order to fulfil requirements. In this research, a definition of adaptive façade will be given, and different typologies of adaptive facades will be investigated in order to understand what their future trends are. Moreover, particular attention will be given to smart windows and to daylight management strategies in order to provide a design solution that improves the visual comfort of an office space by solving glare, increasing the amount of daylight and therefore reducing the energy demand for electrical lighting. Furthermore, because of the strong correlation between visual comfort and thermal comfort - due to the fact that both of them depend on the solar radiation - the design will be further improved in order to achieve a façade that controls visible light and solar heat gain independently. This will enable to achieve the optimal configuration over the year and decrease the overall energy consumption of the building.

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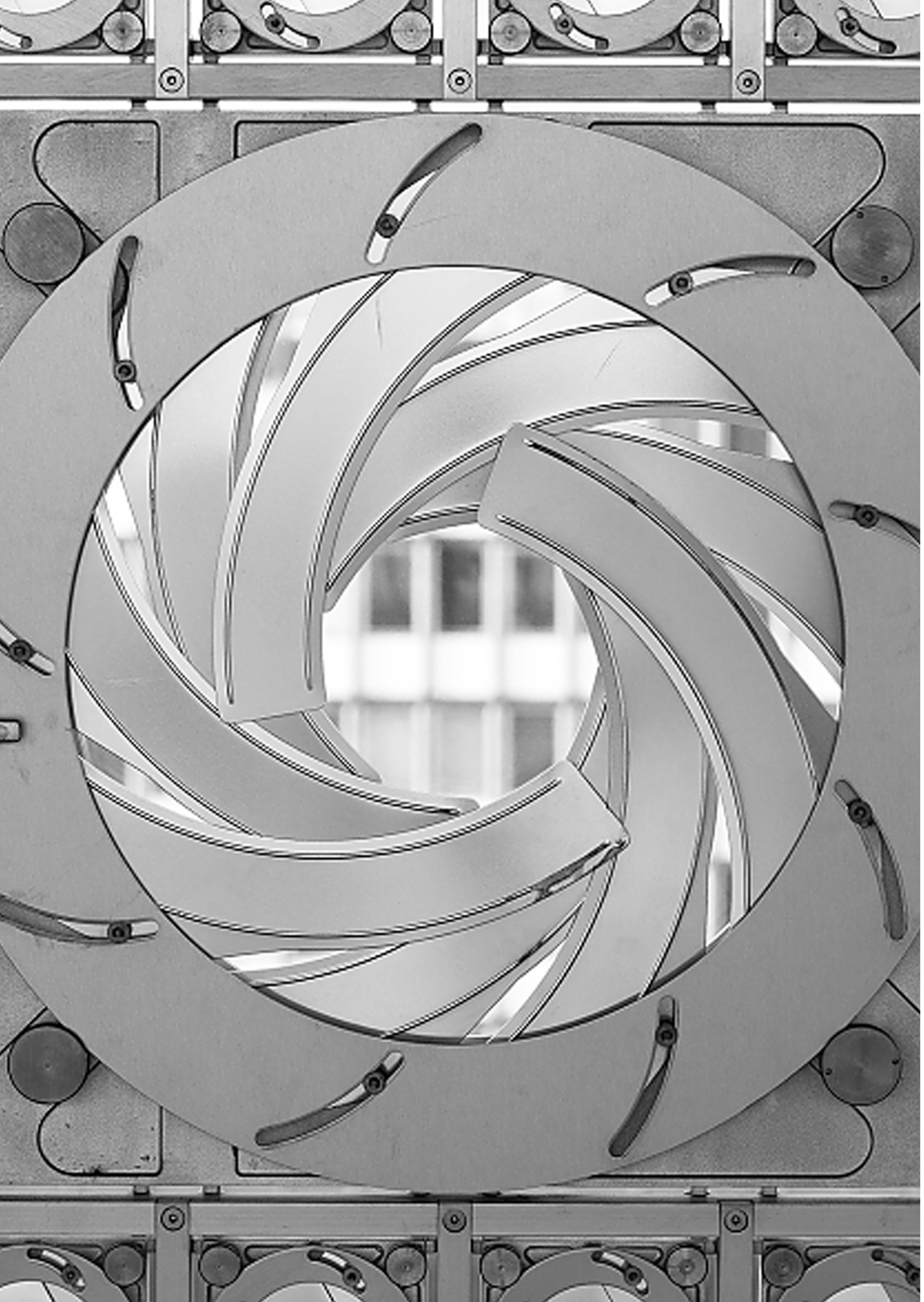

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RESEARCH FRAMEWORK

1.1 Introduction

This report illustrates the process and the results of the graduation project focused on increasing indoor well-being, particularly visual comfort, in an office environment, by applying an adaptive solution in the facade. The project started with a request from Rollecate Group® - a façade construction company in the Netherlands - to investigate the new trends of adaptive façades, with the aim of directing the company to the future development of this technology. At the same time, the interest in improving the visual comfort and decrease the energy demand of an office space has guided the decisions made during the process, as it will be described in the following paragraphs.

1.2 Background and general problem statement

Architecture has been always affected by historical, political, social and artistic influences; what is now shaping architecture is the sustainability concept (Lechner 2015). In fact, it is increased awareness on how much the human is responsible for the pollution and CO_2 emissions, in particular in the building sector. Among the aspects involved in the sustainability issue, the energy consumption covers the most relevant position: as reported by the European Commission, the building sector in Europe consumes, just for its operation, the 40% of the final energy. Of this amount, office buildings consume the 26% of energy (Eurostat 2014) and the 44% of it is used for lighting (Todd 2011). Therefore, there is a big responsibility for the architects and engineers to deal with this problem by finding solutions that decrease the energy demand and replace the fossil fuel consumption with renewable sources. From an architectural point of view, the necessity of decreasing the energy demand is significant because it requires a careful study of the environment and an integration of traditional and cutting edge design strategies that influence the building configuration. It is important to look retrospectively at our predecessors to be aware of how they adapted the building to the surroundings in order to take advantage of external conditions and improve the indoor space. Unfortunately, the technological development made possible to achieve same or better results independently from the location, but with a big energy consumption that has been neglected for decades. Therefore, it is fundamental to reapply some of the traditional techniques, but this time in combination with the advantages of the technological development.

Some design strategies are thought to have a good performance in determined situations like winter or summer, day or night, but they do not have the same good result in the opposite case. This happens because of the static configuration of the solution that does not reflect the dynamism of the outdoor environment. In particular, the façade is the element that separates indoor and outdoor space and this should have a flexible and adaptive design to better respond to indoor and outdoor stimuli and take advantage of the latters, with the final goal of reaching indoor comfort with low energy consumption.

Among all the parameters regulated by the façade, visual comfort is the most significant because it depends on the façade configuration; however, it also has a strong impact on the thermal comfort and the energy production due to the fact that all of these aspects depend on the solar radiation. Therefore, the tendency of having fully glazed facades, in particular in the office buildings, has some advantages like transparency and high amount of daylight entering the building, but also some cons like glare and solar heat gain in summer. The most common adaptive technology usually applied to solve these problems is the external shading system that, however, when in operation, has the disadvantage of reducing the view, decreasing daylight and therefore rising energy consumption for artificial lighting. At the same time, the same solution functions also as thermal regulator and therefore it can operate as a barrier for the solar radiation, but influencing the level of illuminance at the same time. Therefore, it is clear that the big disadvantage is that only one solution is usually adopted to regulate two factors that on the contrary, should be handled independently. Understood this problem, it is important to investigate the design solutions, technologies and materials that can better respond to outdoor stimuli and act independently for the satisfaction of a specific purpose. The most traditional adaptive applications will be investigated and compared with cutting edge adaptive technologies in order to offer an answer to this problem. In particular, the investigation of smart materials and, specifically smart glass, will be examined because of the potential of regulating visual and thermal comfort independently.

Considering that this research is developed in connection with a façade construction company, an additional problem addressed is that sometimes there is a gap between architects, construction companies and production companies. In fact, in some cases, the demand of the designer does not find an answer in the market and vice versa the production and construction companies offer products that, even if efficient, do not meet the architectural needs. Therefore, it is important that the final design takes into account the relationship between these three figures in order to facilitate the dialogue between them.

In sum, the main highlighted problems are the following:

- In Europe, office buildings consume the 10,4% of the final energy and specifically 4,6% for lighting;
- A static building envelope cannot optimally perform in a dynamic environment;
- The tendency to have fully glazed façade to improve transparency and amount of daylight cannot be combined with solutions that reduce these parameters. Moreover, it is important that achieving visual comfort does not influence the thermal aspect, and vice versa, but that these two parameters can be controlled independently.
- The possibility to apply new materials and techniques is usually impeded by the slow development of new technologies for architectural purposes.
- Sometimes there is a gap between architects, production and construction companies. This complicates the dialogue between the three figures and the relationship between demand and offer.

1.3 Objective

Considering the problems previously displayed, the aim of this graduation project is to investigate the current adaptive façade solutions and compare them with the new cutting edge technologies, in particular smart glass, in order to provide an overview on the possible applications and an evaluation of the optimal design solution to increase the visual comfort of an office space. The idea of applying smart materials can be challenging because introducing new technologies in architectural context is a slow process and will not end with an accurate result of the simulation. Beside the study of adaptive façades, it is important to analyse the requirements of visual comfort of an office building. Because the applications usually applied for the daylight control influence the thermal aspect, a further step is to research a solution that treats visual and thermal comfort separately in order to achieve the optimal configuration for both simultaneously and decrease the overall energy demand. The study will also consider how to relate these solutions with the products of Rollecate Group® assuring a design that reflects the future trend of adaptability and that can facilitate the dialogue between the company and the architects.

1.4 Research questions

Main question:

How can adaptive façade solutions, and specifically smart glass, improve the visual comfort and reduce the energy demand of an office building?

Sub-questions:

- What is an adaptive façade and what are the current products, state-of-the-art and future trends in terms of design, control and material application?
- Considering an office environment, what are the parameters that influence visual comfort?
- Among the adaptive façade solutions, which are the most common applications and trends for the regulation of visual comfort?
- What is a smart glass and what are its characteristics, typologies and applications?
- What are the design strategies that combined with adaptive technologies can help regulating visual comfort and reducing the energy demand of an office space?
- Considering the requirements of an office building, the typologies of smart glass, the traditional adaptive solutions and the design strategies analysed, what is the optimal façade onfiguration to achieve visual comfort and decrease energy demand of an office space?
- How can the design solution be applied to Rollecate Group®'s products?
- What are the aspects of the final product that add quality to the architectural project and increase the possibilities for success in the market?

1.5 Methodology

This graduation project is structured in mainly two phases: research and design. In particular, to understand the complexity of a problem and to analyse as many solutions as possible, it is important to have a specific knowledge about the factors that characterise the problem and to understand what has already been done by analysing the current applications and the new technologies. In this way it is possible to understand what are the potentials and the future possible developments of a specific application. In the particular case of this graduation project, the following steps have been done:

1. Research and literature review about:
   - Adaptive facades;
   - Indoor comfort and in particular visual comfort;
   - Traditional and state-of-the-art of technologies and materials for the regulation of visual comfort;
   - Different smart glass typologies;
   - Design strategies to improve visual comfort.
2. Design process
   - Elaboration of adaptive façade options;
   - Design modelling and simulation;
   - Evaluation of the results and conclusion;
   - Final solution and integration in the product of Rollecate Group® ;
   - Correlation between technology and design.

1.5.1 Research and literature review

The literature review is a fundamental step because it is the base on what the design will be developed. This graduation project started with a request from Rollecate Group® to investigate the adaptive façade technologies and to come up with a vision on their future trends. This phase has been conducted in collaboration with Maria Mourtzouchou, a fellow student also interested in the exploration of the adaptive façades. Firstly, a definition of adaptive façade has been given and afterwards many examples of buildings, products and prototypes have been considered and classified according to various parameters like the period of realization, the external triggers that influence them and the final result that they achieve. This analysis helped understanding for which intent the adaptive facades are usually applied and, thanks to an overview of the products over the time, how the different techniques evolved. This was helpful to have a general vision on the possible future trends. A similar classification has been done with the materials commonly used in adaptive products. In particular, the development of materials for architectural application is slow and some decades can pass before a new material can be applied into a project. Because of that, the level of development of materials has to be considered in order to determine if a solution is applicable in short time.

Because the office buildings represent the 10,4% of finale energy consumption in Europe, a reduction of their energy demand can have a positive impact in the sustainability goal. The requirements of this space have been investigated and a particular attention has been focused on the lighting that represents the 44% of the energy consumption. Therefore, a further research has been conducted to maximise the amount of daylight entering the building in order to decrease the energy demand for artificial lighting. Consequently, among the materials and technologies previously classified, a further research was carried out on the ones that have a highly application for the regulation of visual comfort. In addition, a further analysis has been conducted on the different typologies of smart glass, in order to evaluate the optimal option and to compare it with more traditional adaptive solutions.

Even if the visual comfort is the main interest of this project, it was useful to have a broad overview on different adaptive applications in order to find some possible solutions that could add a further function to the façade and therefore to decrease the energy demand of the building.

In the end, in order to understand what interests the construction companies to develop a specific technology, a shallow analysis on the push and pull theory has bean carried out. Furthermore, to better address the product to the necessity of the architects, a dialogue has been started with some architects in order to understand their knowledge, opinion and expectations on adaptive facades.

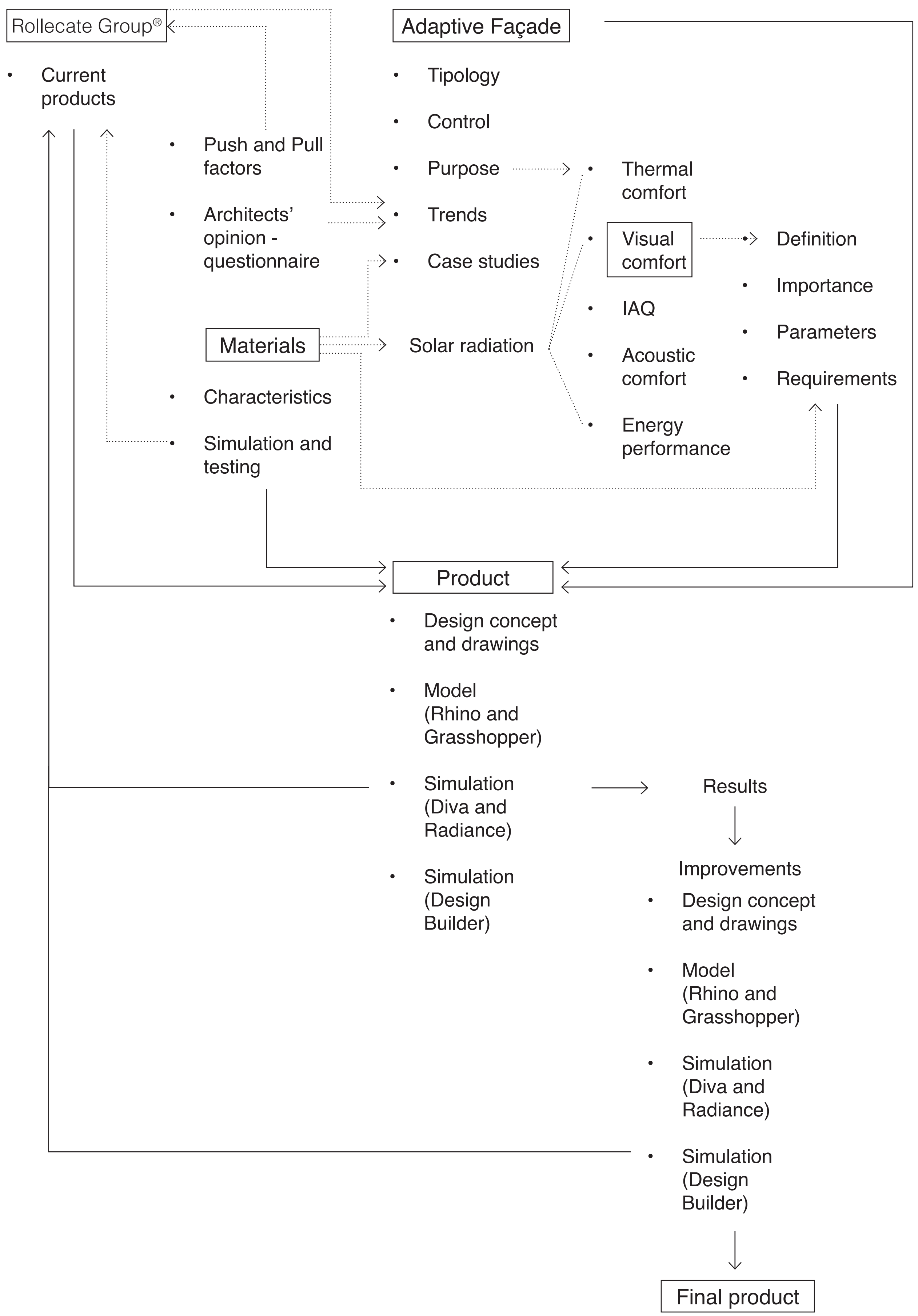
1.5.2 Design process

At the end of the first part of the thesis, an overall knowledge about existing adaptive facades and smart glass applications is reached and an idea on what are the future trends can be formulated. On the base of this knowledge, the products of Rollecate Group® can be implemented according to the adaptive strategies. Some possible designs are proposed and later a dialogue with Rollecate is needed to understand their interest in the solutions proposed and how these can be developed and eventually tested. Contemporarily, a model and a preliminary simulation are realized. The most promising solutions are chosen and developed with the realization of drawings, models and simulations. According to the design, a study of the materials and/or specific techniques is carried out. The simulation is fundamental to understand the effective contribution of the technology in the improvement of visual comfort and in the reduction of energy consumption. In particular, it is important to compare traditional technologies and new technologies in order to evaluate the new design performance. However, the results obtained with the simulation are not sufficient to validate the design and more elements have to be considered like the design value and the economical aspect.

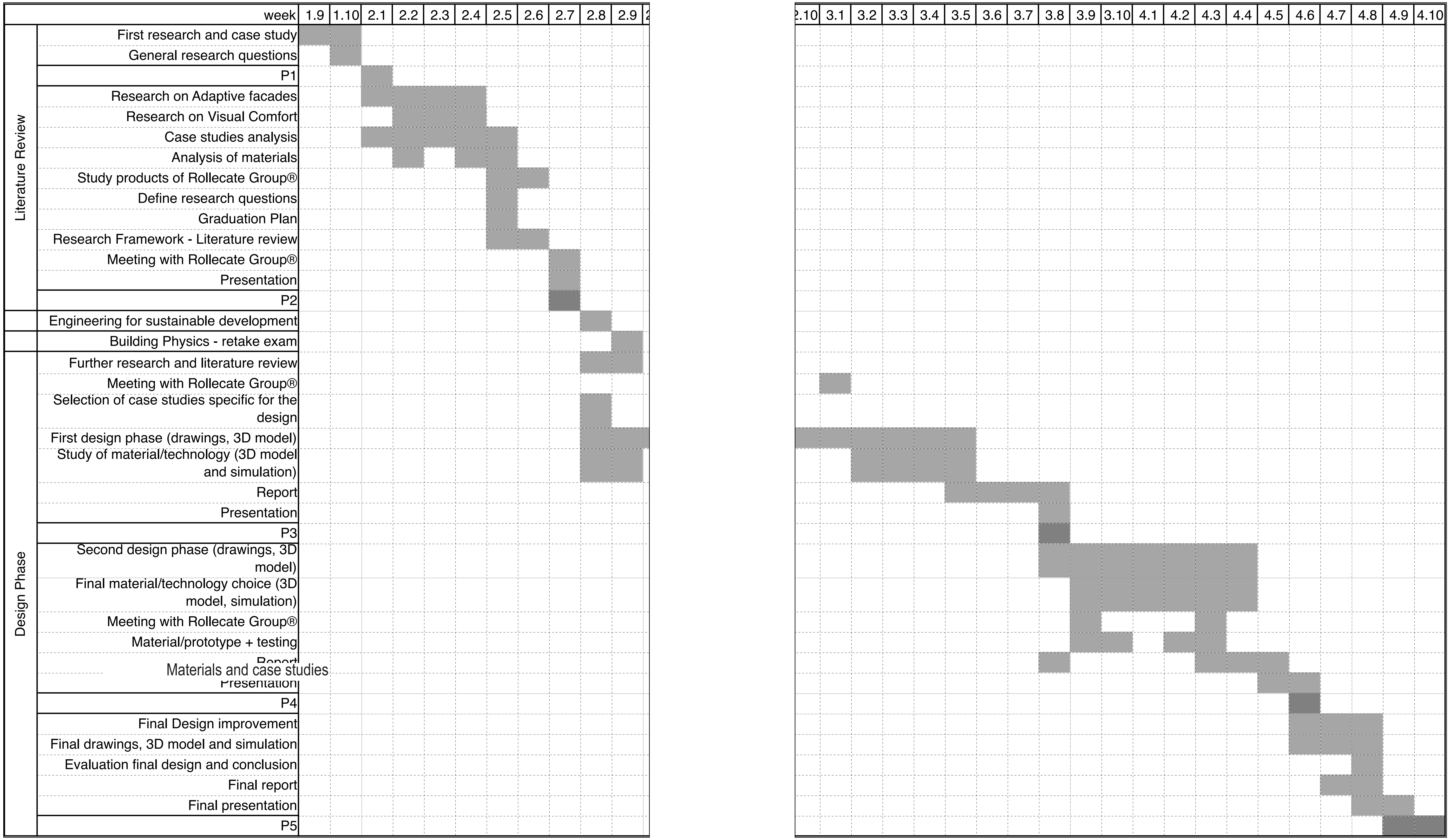
1.6 Relevance

The final product will be a possible approach of improving the visual comfort in an office building by using adaptive façade strategies. This will have a social, environmental and economical relevance because visual comfort has a big impact on the users both on their health and on their productivity. The latter has an economical benefit that is added to the more relevant reduction of energy consumption for artificial lighting. In addition, the intention of separate the regulation of visual and thermal comfort and to treat them independently, adds an innovative aspect to the design and a potential of energy saving for an office space.

1.7 Planning and organization



1.8 Timeline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Literature Review
First research and case study
General research questions
P1
Research on Adaptive facades
Research on Visual Comfort
Case studies analysis
Analysis of materials
Study products of Rollecate Group®
Define research questions
Graduation Plan
Research Framework - Literature review
Meeting with Rollecate Group®
Presentation
P2
Engineering for sustainable development
Building Physics - retake exam
Design Phase
Further research and literature review
Meeting with Rollecate Group®
Selection of case studies specific for the design
First design phase (drawings, 3D model)
Study of material/technology (3D model and simulation)
Report
Presentation
P3
Second design phase (drawings, 3D model)
Final material/technology choice (3D model, simulation)
Meeting with Rollecate Group®
Material/prototype + testing
Report
Materials and case studies
Presentation
P4
Final Design improvement
Final drawings, 3D model and simulation
Evaluation final design and conclusion
Final report
Final presentation
P5

2 LITERATURE REVIEW

This graduation project starts from the request of Rollecate Group® to investigate the adaptive façade technology and envision its future trends. Therefore, it is necessary to define what is an adaptive façade and what are the parameters that characterise it. Furthermore, it is important to analyse the development of adaptive façades over the years in order to suppose a future scenario of this technology. This first part of the research has been conducted in collaboration with Maria Mourtzouchou, a fellow student that was elaborating her graduation project on the same topic. This cooperation allowed to analyse a higher amount of case studies and to give the possibility to largely debate about the possible trends of adaptive facades.

At the same time, the elevated energy demand of an office building, in particular for electrical lighting, enlightens a problem that can find adaptive technologies as an effective solution. Therefore, a second part of the research is focused on this aspect and in particular on the requirements of an office building, specially regarding visual comfort, together with a study of the traditional and cutting edge adaptive solutions - in particular smart glass - and design strategies to achieve visual comfort and decrease the energy demand of an office building.

The aim of the research is to build the necessary knowledge on both adaptive façades and visual comfort, in order to derive an innovative design that can be proposed to Rollecate Group® as a possible direction for the development of their products.

2. Adaptive façade

The façade is a component that changes its conformation according to many diverse factors. The scheme in figure 2.2 shows an overview on the parameters and goals that influence the building envelope. The adaptive façade arises from the necessity of the building to change conformation in order to fulfil the requirements of the indoor space. In fact, the façade is an envelope that separates two environments in continuous transformation. However, it is often designed with static components that perform in the same way under different conditions. This characteristic, together with other factors, is the reason why, as reported from the European Commission, buildings represent the 40% of the energy demand (figure 2.1) (Eurostat 2014). Consequently, the necessity to reduce this percentage due to the goal of obtaining Zero Energy Buildings by 2020, evolved to a new concept of façade that can take advantage of the outdoor environment to help achieving this goal. Because buildings with adaptive envelopes are more energy efficient that static buildings, it is expected that this technology will be applied in the future constructions (Carlucci, Causone et al. 2015).

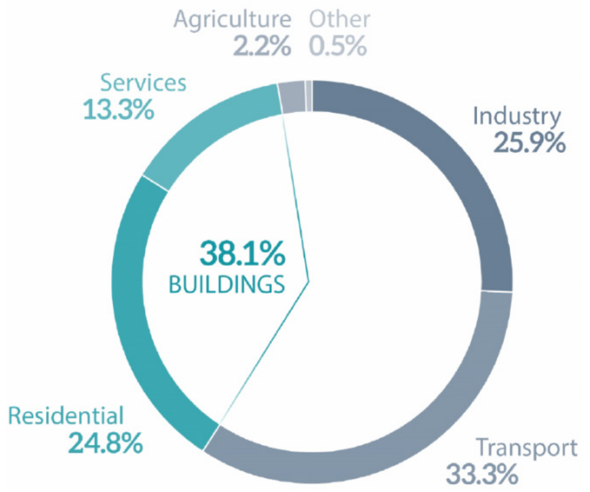


Figure 2.1: 2014 energy consumption by sector in the EU-28. Data source: Eurostat,2014

The way to apply the adaptivity concept to the envelope is different according to the specific design goal. Therefore, adaptive façade has been defined in different ways according to its predominant characteristics. Among the numerous terms, it can be described as active, advanced, dynamic, intelligent, kinetic, responsive, smart, switchable etc. (Loonen, Trčka et al. 2013).

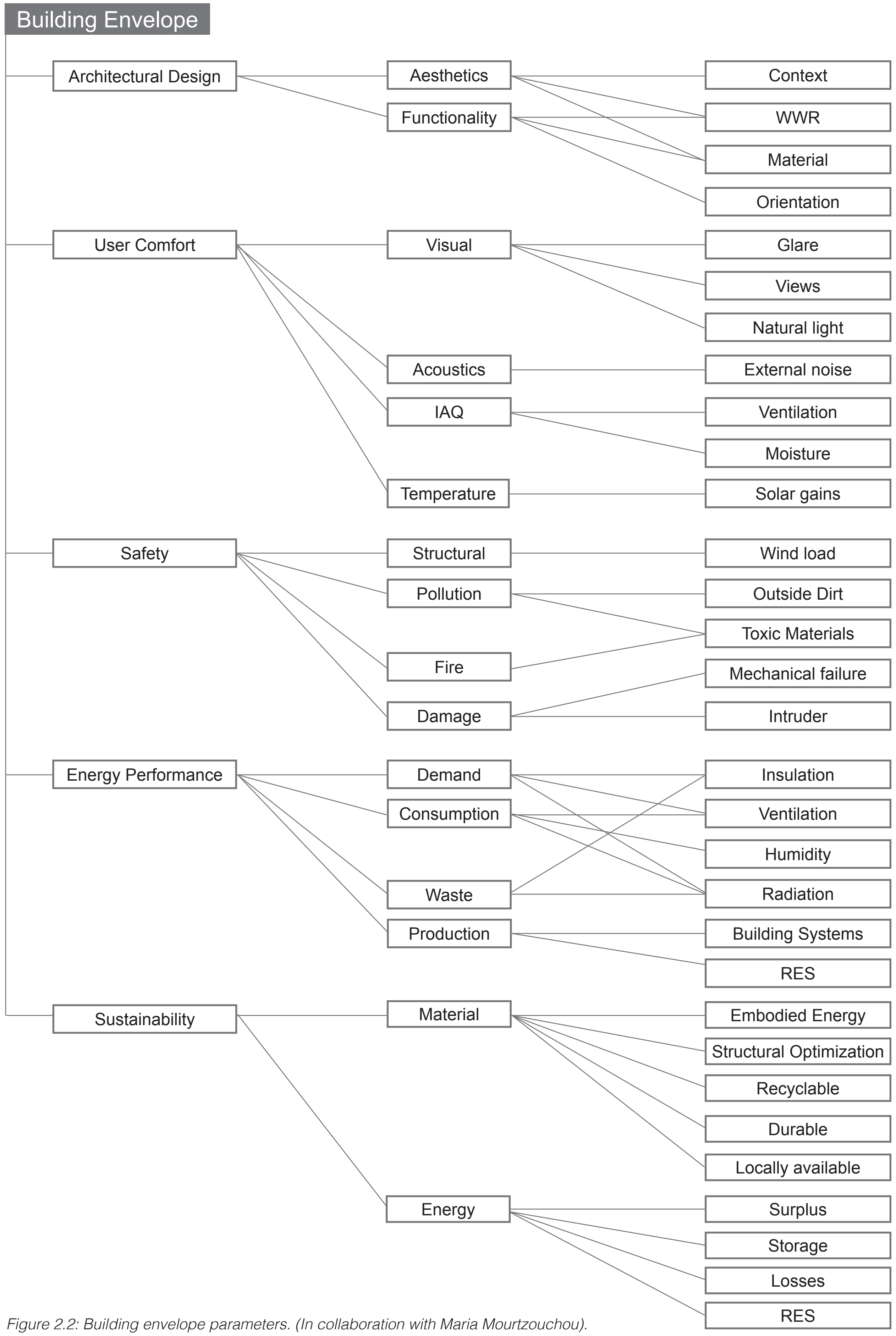


Figure 2.2: Building envelope parameters. (In collaboration with Maria Mourtzouchou).

In this report, adaptive façade is considered as an envelope that responds both to indoor and outdoor stimuli and changes conformation – both physically or chemically - to take advantage of the outdoor climate with the aim of improving the indoor environment.

This definition emphasises the relationship between the internal and external environment because, what is thought to be the most relevant breakthrough of adaptive facades, and what makes it the future of the façade technology, is that the driving force of adaptation is the capacity of interaction with the environment and the users (Gallo and Romano 2017). In particular, according to the indoor requirements, the façade changes conformation in order to take advantage of favourable outdoor conditions or to protect the building from negative impact of the outdoor environment. In the same way, the variation can happen due to an alteration of the indoor conditions that are not fulfilling anymore the indoor requirements. Therefore, it is possible to claim that the adaptive façade changes configuration in order to maintain the equilibrium imposed by the indoor settings. According to the specific design, an adaptive envelope can be chosen according to different factors: (i) type and scale of adaptation; (ii) agent of adaptability; (iii) performance; (iv) material; (v) type of control; (vi) response time; (vii) cost (figure 2.3).

Adaptive façade applications can have different goals, like thermal, visual or IAQ regulation and all of them, in different ways, contribute in the reduction of the energy demand of the building. In particular, the adaptive façade systems considered as most promising in this sense are Double Skin Façades (DSF) or Advanced Integrated Façades (AIF), smart glazing, movable solar shading, phase change materials and multifunctional facades (Favoino, Jin et al. 2014). To have an overview on the applications used until now, a study on different projects and products has been done according to the parameters that will be here described.

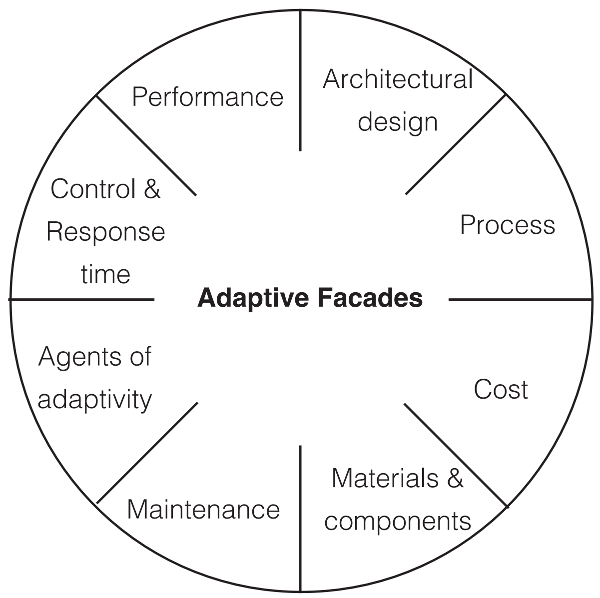


Figure 2.3: Factors that influence an adaptive facade. (In collaboration with Maria Mourtzouchou).

2.1 Behaviour

An adaptive façade can behave in a dynamic or static way according to the materials and technology used. As easily understandable by the terms, what characterizes the façade is the presence or absence of movement. Most commonly, this characteristic coincides with the scale of adaptation: a façade can respond to the stimulus in a micro or macro scale. The former is a variation of the internal structure of the material due to a variation of the chemical or physical properties. The change of condition happens due to a transformation of energy from one form to another that results in a change of performance of the material (Loonen, Trčka et al. 2013). Example of application of this technology is the switchable glazing that is able to change its optical properties due to a change of temperature, light or electricity. The study of smart materials is of relevant importance for adaptive façade application and a deeper analysis will be conducted later in the report. On the contrary, the macro scale of adaptation corresponds usually to a dynamic behaviour of the façade's components. These respond to stimulus usually coming from sensors that measure external or internal climate conditions. The most well known application is the shading system and according to the size of the kinetic component, the façade can have a significant transformation.

2.2 Agent of adaptation

The agent of adaptation is what triggers the responsive element. External agents are considered (i) solar radiation, (ii) temperature, (iii) humidity, (iv) wind, (v) precipitation and (vi) noise, while the indoor triggers are (i) temperature, (ii) humidity, (iii) light, (iv) air exchange rate and (v) sound level (Loonen, Trčka et al. 2013). The adaptive façade is most commonly triggered by an outdoors condition. However, the communication between the external internal conditions is the most efficient way to save energy. For this reason, as it will described later, a future trend has been individuated in the importance of connecting the indoor and outdoor environment.

2.3 Control of adaptivity and energy consumption

Depending on the adaptive component, the response can be intrinsic – when the change happens automatically in the material - or extrinsic – when the adaptation happens in response of a signal sent by a sensor. In the former case the system is called open loop and usually does not require any additional energy a part from the one derived by the trigger. On the contrary, the latter is called closed loop and it has three components that regulate the process: a sensor that register the specific environmental condition, a processor that interpreters the information and an actuator that transforms it into an action (figure 2.4). Because of the use of mediators, the closed loop necessitates of energy (Loonen 2010).

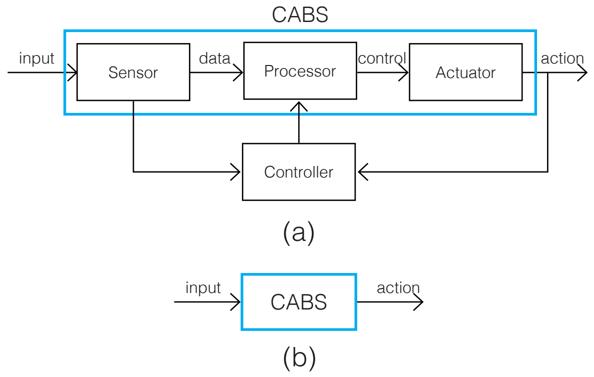


Figure 2.4: Closed-loop control (a) and open-loop control (b) (Loonen 2010)

2.4 Response time

While the indoor climate maintains almost the same requirements, the external conditions change significantly over the year. The geographic location highly determines these parameters and considering the Netherlands, temperature and amount of light can considerably vary between summer and winter, day and night. Consequently, the envelope has to change considerably to maintain the indoor comfort. According to the different parameters, the facade necessitates of different reaction times: seconds, minutes, hour, day, season (Loonen, Trčka et al. 2013). It is the type of requirement, the property of the façade and the nature of the trigger that determine the responsive time. In case of a closed loop technology, the response time can be more easily controlled.

2.5 Performance

The adaptive façade contributes to regulate requirements of thermal comfort, visual comfort, indoor air quality, energetic production and acoustic performance. Among them, some aspects are more relevant than others in the improvement of the energy performance. Moreover, some solutions are correlated to each other because they are triggered by the same agent.

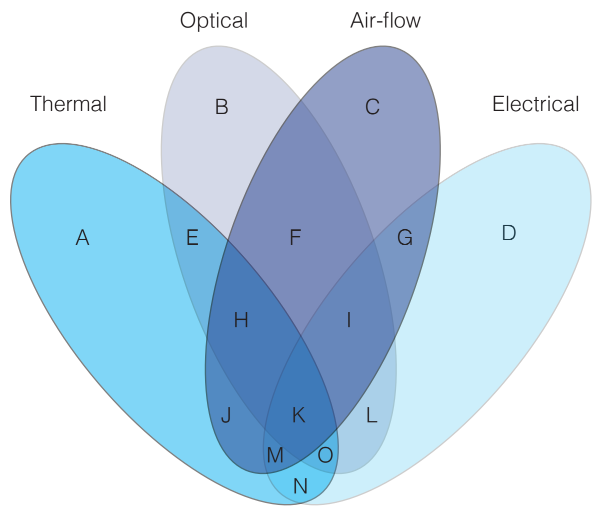


Figure 2.5: Physical domains (Loonen 2010).

A classification done by R.C.G.M. Loonen divides the adaptive technologies in four main domains and shows how adaptive facades can satisfy one or more of them obtaining 15 possible applications. This classification is explained from the Venn diagram in the figure 2.5 (Loonen, Trčka et al. 2013). Loonen uses this classification to obtain different categories that comprehend case studies analysed in his research. This classification is useful to understand the grade of completeness of a product or an envelope.

Here, the three main indoor comfort domains are briefly described.

2.5.1 Thermal comfort

The thermal comfort is determined by environmental and personal factors. The formers are (i) air temperature, (ii) radiant temperature, (iii) air velocity and (iv) humidity, while the latters are (i) clothing insulation and (ii) metabolic rate.

Every individual has a different thermal perception therefore it is impossible to satisfy all the users at the same time. For this reason, the personal factors are not taken into account, but a range of flexibility should be provided in order to adjust the indoor conditions according to the personal preferences.

A general recommendation for the indoor temperature advises a range of 23-26°C in summer and 20-23.5°C in winter with a relatively humidity of 50% (CEN/TC156 2007). Moreover, the air velocity, due to the ventilation system, can cause discomfort if it is percept in some parts of the body like shoulders, head, legs and feet (Lechner 2015). The radiant temperature includes floors and windows and therefore is the most relevant element for this research because it involves a façade component. In particular, the element that determines it is the solar radiation that can help decreasing the energy demand for heating during winter, while should be avoided during summer.

2.5.2 Visual Comfort

The visual comfort is composed of two main factors that both depend on the façade configuration: lighting and view. The former is the most studied and comprehends daylight and artificial light. As thermal comfort, also the visual comfort depends on the solar radiation. Here a general description is given while later in the report a deeper analysis will be provided where its characteristics and its correlation with the thermal comfort will be analysed. Visual comfort has a big influence on the health and productivity of the users and can have an impact on the energy saving. The main parameters that influence the visual comfort in an office space are the uniformity and amount of light, the presence of glare, the nature of the light source, the light's colour and the view.

2.5.3 Indoor Air Quality (IAQ)

The indoor air quality has a big impact on the health, comfort and productivity of the users. The presence of pollutants, particles and humidity in the air can cause tiredness and illness and therefore, an efficient ventilation system is fundamental to prevent discomfort. In office buildings, the natural ventilation is usually difficult to control and for this reason, the ventilation is usually controlled mechanically according to the amount of people and the volume of the office (Lechner 2015). The air speed has a big importance because a fast air input can cause discomfort. Even if the ventilation is mechanically controlled and works efficiently, the possibility to manually adjust the air change by operable windows is fundamental because increases the user's satisfaction. An interesting potential for the adaptive façade is to regulate the air exchange according to the percentage of CO_2 and this could be achieved locally by a façade that responds to the indoor stimulus. Furthermore, wind can be an element of adaptation that can be used to regulate the indoor air quality by allowing the outside air to enter inside the office space by a variation of the permeability of the façade.

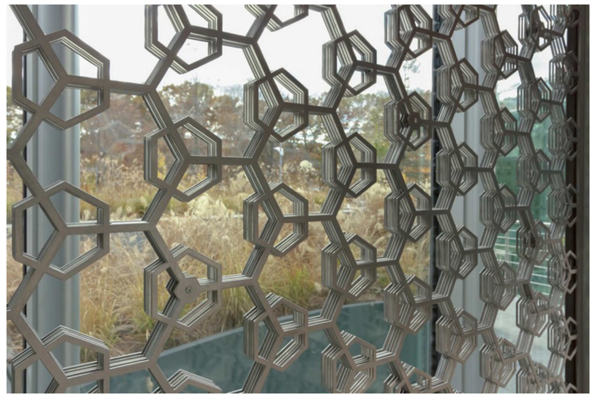
2.6 Case studies

After the definition of adaptive facades, a classification has been conducted on some buildings, products and research projects to grade their degree of complexity and to have an overview on the current applications of adaptivity in concrete situations. The characteristics previously explained are the criterions considered to classify the different adaptive façade solutions. These have been collected in a data sheet (figure 2.6) in order to easily compare the different cases. Moreover, the case studies have bee divided in the four main domains (thermal comfort, visual comfort, IAQ and energy production) and disposed in chronological order, covering the past 25 years, to understand the evolution of the adaptive envelops according to the single domain (figure 2.7). In this way, it has been possible to individuate the state-of-the-art and the future trends of adaptive facades for each category, but also if some technologies have been abandoned due to inefficiency or low technological development (EU 2017). The entire collection of sheets is reported in the Appendix A.

2.6.1 Evolution

The graphs in figure 2.8 resume the tendency of buildings (a), products (b) and research projects (c) for each parameter. In the specific, it resulted that most of the buildings have a dynamic adaptation that is triggered by the solar radiation. The interior conditions are not commonly adopted as trigger, but when they are, the air exchange rate is the one that more influences a change in the building envelope. Because of the frequent response to solar radiation, it is not surprisingly that visual & lighting and thermal comfort are the purposes of the majority adaptive façades. The use of sensors in the façade is frequent; therefore the systems are usually closed loops and require an input, and therefore energy, to respond. An approximate estimation about which phase of the life cycle of the adaptive components requires highest costs evaluates the maintenance as the most expensive phase for the buildings, due to complexity of geometry, technology and material. Among the products, the majority takes advantage of the solar radiation and the indoor temperature to achieve thermal and visual comfort. Generally, they have a static response controlled by a closed loop. However, in many cases there is a production of energy that balances this aspect. The highest costs are considered for the maintenance of the product.

The research projects are mainly focused on dynamic solutions that respond to solar radiation and temperature. On the other side, the interior agents of adaptivity are the temperature and the air exchange rate. In line with the previous categories, the most common purposes are thermal comfort, visual comfort and indoor



Simons Center

Hoberman

SUNY Stony Brook, New York, USA

2010

Response to Adaptation Agent

● Dynamic ○ Static

The installation in Simon Center shows three possible artistic patterns for a dynamic shading system. The geometry has been designed in a way that three layers with the same geometry can shift from an overlap position to three different positions that create different patterns decreasing the amount of transparency. By this way, the system regulates daylight and solar heat gain, decreasing the energy demand needed for cooling during summer.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

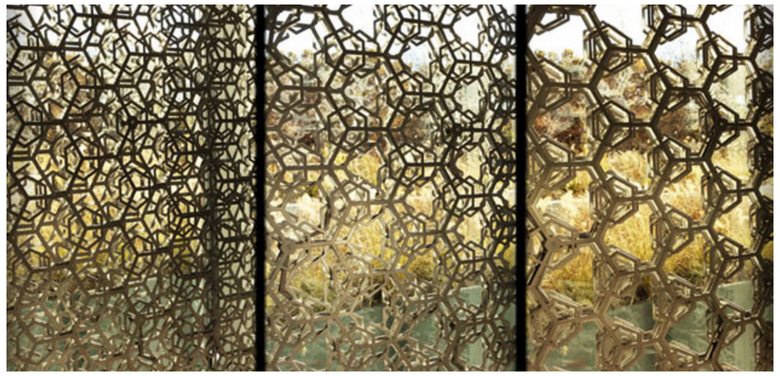
● - ○ 0 ○ +

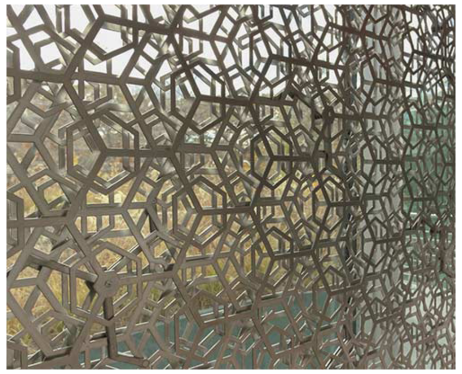
Highest cost

● Materials
● Production
○ Assembly
○ Maintenance

Architecture design freedom

● Low
○ Medium
○ High





Sources: http://www.hoberman.com/portfolio/simonscenter.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=19&category=&projectname=Simons+Center

Figure 2.6: Example of classification adaptive component. (In collaboration with Maria Mourtzouchou)

air quality. On the contrary, the application of materials with intrinsic response is increased because of the use of nanotechnologies and smart materials. The data about the costs and energy do not give useful information because these highly depend on the type of project.

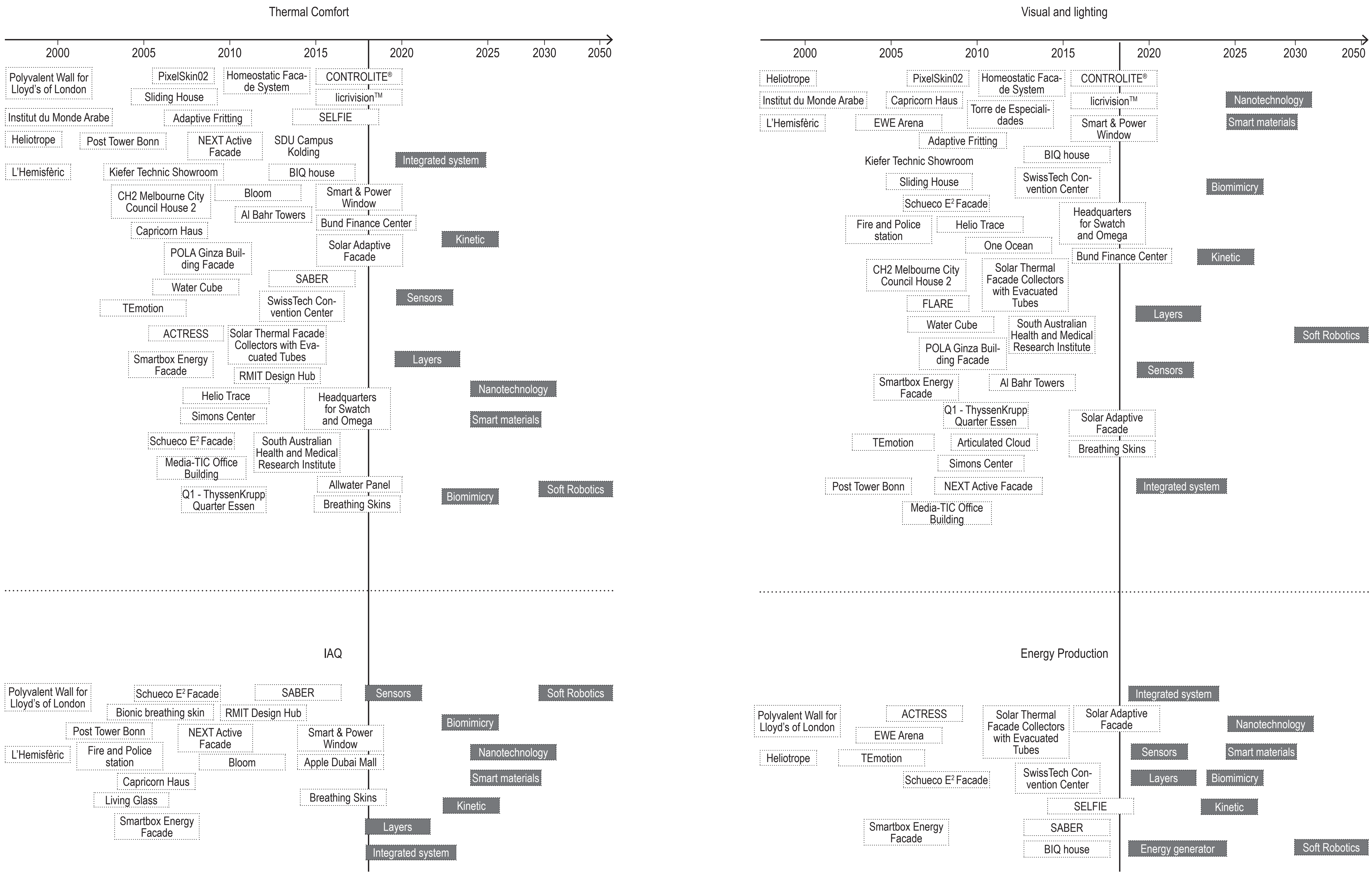
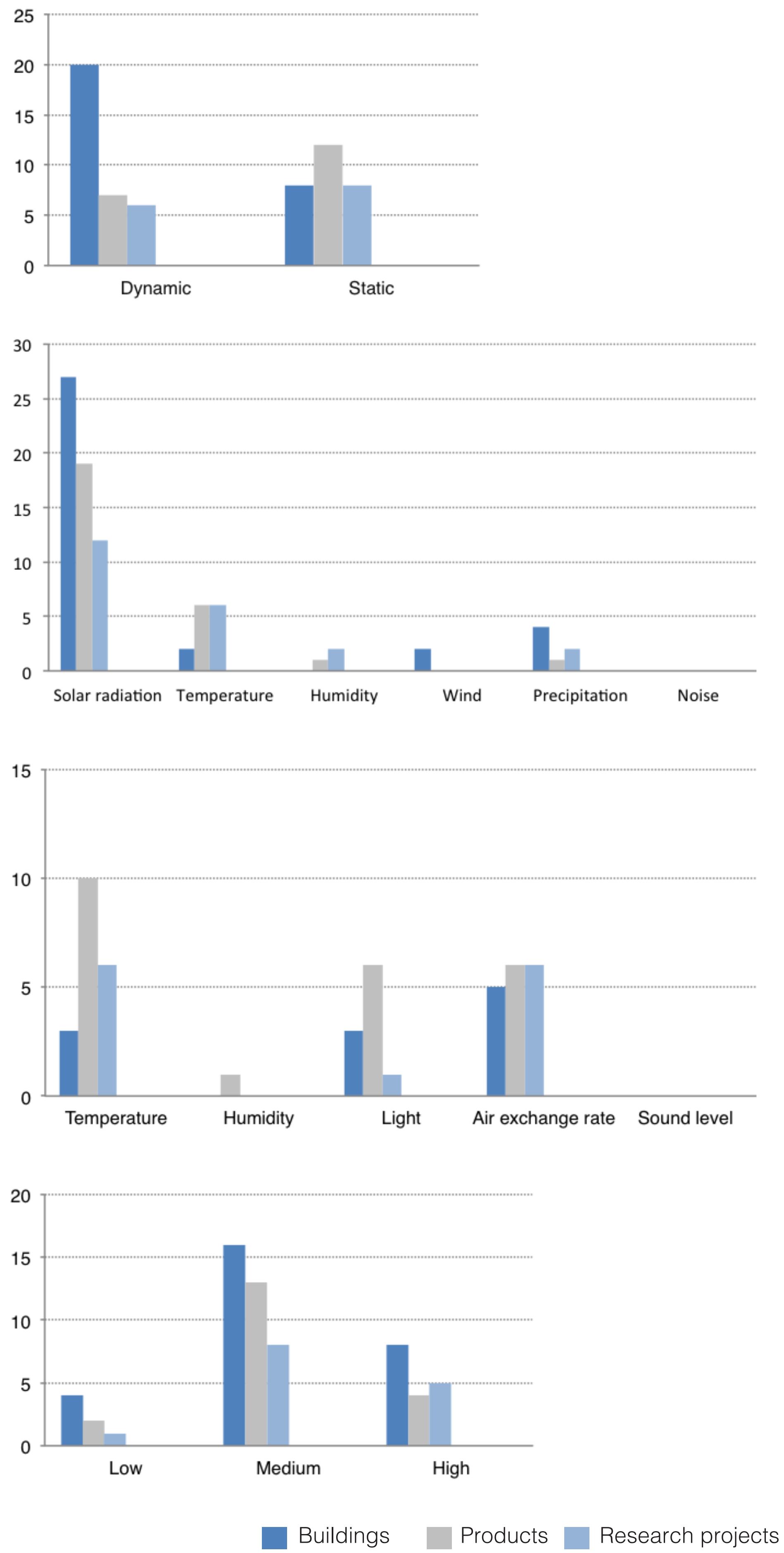


Figure 2.7: Evolution of the different daptive technologies according to their design strategies. (In collaboration with Maria Mourtzouchou).



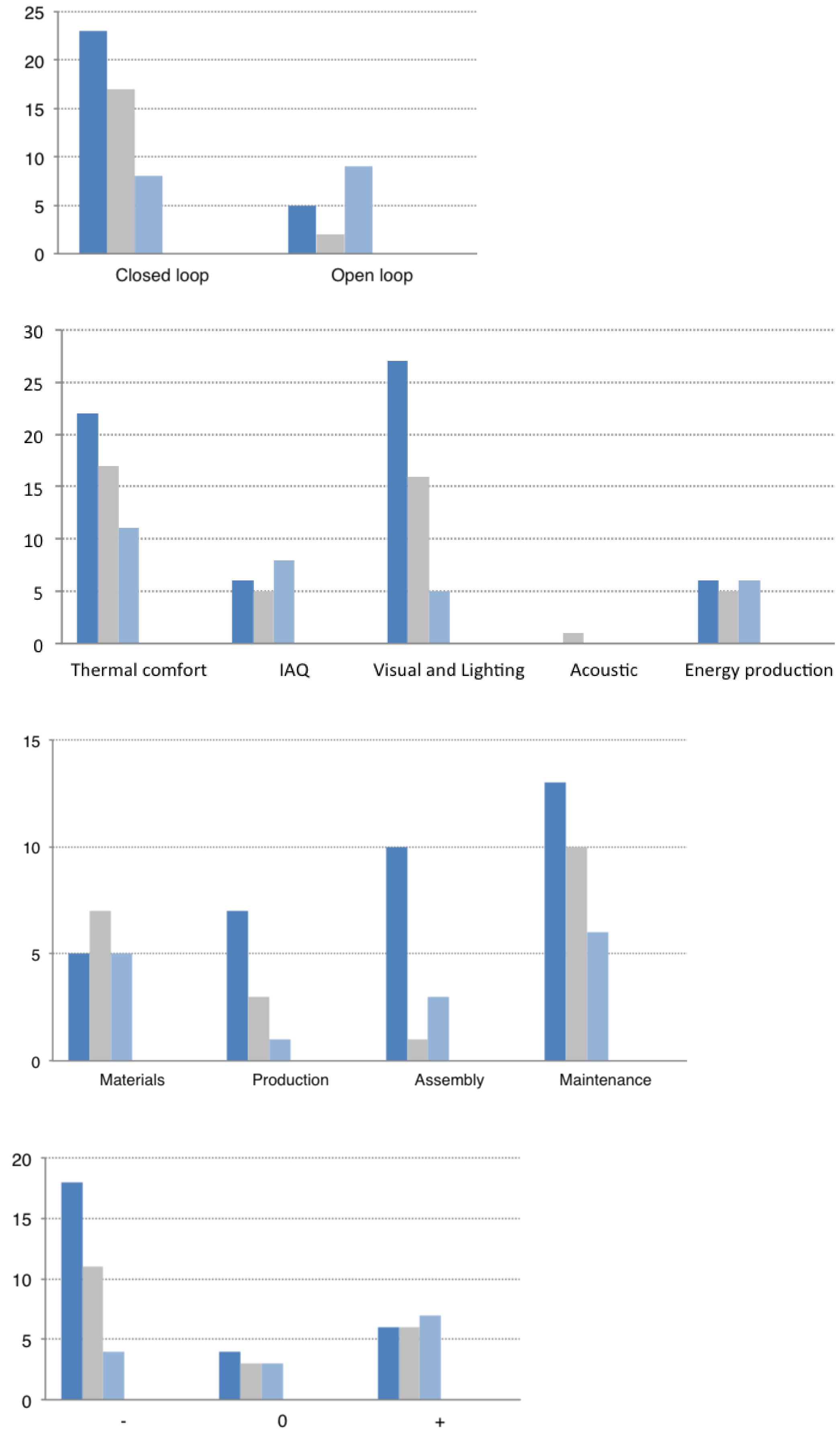


Figure 2.8: Comparison of the trends between buildings, products and research projects. (In collaboration with Maria Mourtzouchou).

2.6.2 Technology Readiness Level

The products and the research projects are in different development phases. Therefore, they have been classified according to their Technology Readiness Level (TRLs) (figure 2.10). This is a measurement of the progression of a technology addressed in the Future and Emerging Technologies section of the Horizon 2020 Work Programme 2016-2017 reported from the European Commission. It is based on 9 phases (EU 2017):

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment

As illustrated in the table n, TRL1 indicates the observation of a principle and from this point; eight steps follow until the proven of a system in the operational environment (figure 2.9).

	Reference projects	TRL
Products	Polyvalent Wall for Lloyd's of London (1981)	2
	TEmotion (2005)	9
	Smartbox Energy Façade (2006)	5
	Schueco E2 Facade (2007)	9
	Flare - Kinetic Membrane Facade (2008)	4
	PixelSkin02 (2008)	4
	NEXT Active Facade (2010)	9
	Solar Thermal Facade Collectors with Evacuated Tubes (2013)	5
	Smart Window & Power Window (2014)	8
	licrivisionTM - Liquid Crystal Window (2015)	8
	CONTROLITE® - Intelligent Daylighting System (2016)	9
Research Projects	Living Glass (2005)	3
	Bionic Breathing Skin (2007)	3
	ACTRESS (2007)	5
	Adaptive Fritting (GSD) (2009)	8
	Bloom (2011)	4
	SABER (2014)	4
	Adaptive Solar Facade (2015)	6
	Breathing Skins (2015)	4
	SELFIE (2016)	5
	Allwater Panel (2017)	5

Figure 2.10 : TRL of the products and research projects analysed. (In collaboration with Maria Mourtzouchou).

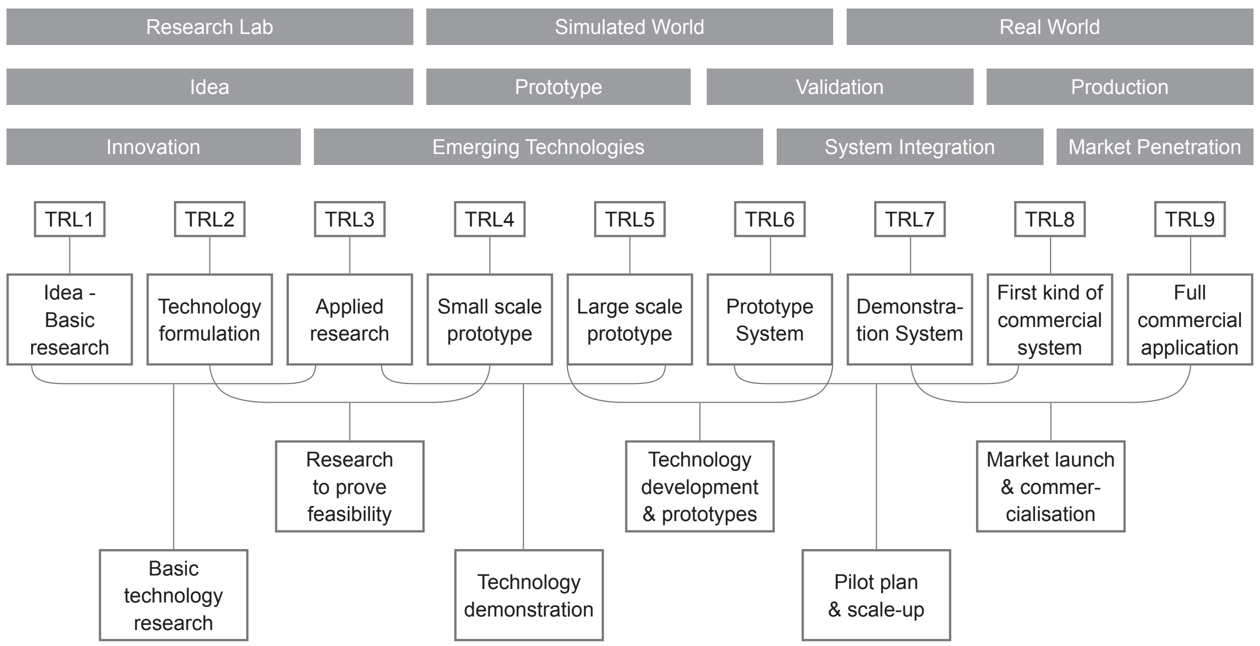


Figure 2.9 : scheme of the Technology Readiness Level (TRL) classification. (In collaboration with Maria Mourtzouchou).

2.6.3 Concept

From the observation of the different case studies and in particular to the most recent ones, it has been possible to individuate eleven main concept that are most commonly applied and that represent a trend for the future applications. These concepts are here explained, while the information about the specific project can be resumed in the table in figure 2.11.

2.6.3.1 Biomimicry

The biomimicry refers to the discipline that, inspired by the nature, takes its functionality and/or its forms and applies them in specific fields that can vary from medicine to engineering to architecture. This technique has been applied in architecture in particular to the building envelope and more recently to improve the technologies related to the building. In this context, the biomimicry takes inspiration by the mutation of the nature according to specific circumstances like humidity, wind or energy (López, Rubio et al. 2017).

2.6.3.2 Smart materials

A material is classified as smart when, without sensor, processor and actuators, can automatically respond to an environmental stimulus like light, temperature and humidity and adjust itself without the need of a further stimulus (Barozzi, Lienhard et al. 2016).

2.6.3.3 Nanotechnology

Specifically in this research, the nanotechnology refers to those solutions that adapt in a very small scale - atomic or molecular - usually due to a chemical reaction or to the application of energy. Because the response happens in a very small scale, the reaction does not usually imply movement and it can be invisible to the human eye or vary slightly, like for example changing colour (EuropeanCommission 2016).

2.6.3.4 Sensors

In the specific context of adaptive facades, the sensors are those devices that detect the indoor and/or outdoor conditions and compare them with the desired condition that has been set as comfort state. If the measured value does not fulfil the requirements, the sensor sends the information to the processor and therefore to the actuator that translates it in a variation of the façade condition with the aim of restabilising the comfort (Barozzi, Lienhard et al. 2016).

2.6.3.5 Integrated system

The integrated system is a combination of different technologies with the aim of achieving different functions together in the same product. Referring to the architectural field and in particular to the adaptive solutions, this term can refer to those adaptive technologies that are placed together to satisfy different types of comfort like thermal, visual and indoor air quality.

2.6.3.6 Layers

This term refers to the juxtaposition of different sheets with different thickness, each of them with particular qualities, with the aim to obtain a product that has several characteristics joint in the same product.

2.6.3.7 Low-tech

The term low-tech refers to innovative solutions realized applying ordinary technologies. In particular, these devices are usually low-cost and have a low energy demand, but, if applied in a specific way, can result in an improvement of the

	Reference projects	Concepts											
		Biomimicry	Smart materials	Nanotechnology	Sensors	Integrated system	Layers	Low-tech	Aesthetics	Kinetics	Soft Robotics	High Transparency	Energy generator
Buildings	Institute du Monte Arabe (1987)	x			x		x		x	x			
	Heliotrope (1994)	x			x					x		x	x
	L’Hemisfèric (1998)	x			x				x	x		x	
	Post Tower Bonn (2003)				x	x	x	x				x	
	Fire and Police station (2004)					x		x	x				
	Ewe Arena, Germany (2005)	x			x					x		x	x
	Sliding House (2005)	x			x		x	x	x	x			
	CH2 Melbourne City Council House 2 (2006)	x			x			x		x			
	Kiefer Technic Showroom (2007)	x			x					x			
	Capricorn House (2008)					x	x	x					
	Water Cube (2008)						x		x				
	Media-TIC Office Building (2009)			x	x		x						
	POLA Ginza Building Facade (2009)	x			x				x	x		x	
	Q1 - ThyssenKrupp Quarter Essen (2010)	x			x			x		x		x	
	Helio Trace (2010)	x			x		x			x		x	
	Simons Center (2010)	x			x		x		x	x			
	Articulated Cloud (2011)							x	x	x			
	Torre de Especialidades (2012)			x					x				
	One Ocean (2012)	x			x				x	x			
	Al Bahr Towers (2012)	x			x				x	x			
	RMIT Design Hub (2012)					x	x					x	x
	Homeostatic Facade System (2013)	x	x				x		x	x			
	SAHMRI (2013)	x						x	x				
	BIQ House (2013)				x		x						x
	Swiss Tech Convention Center (2014)								x			x	x
	SDU Campus Kolding (2014)	x			x					x			
	Headquarters for Swatch and Omega (2017)						x		x				
	Apple Dubai Mall (2017)	x			x			x	x	x		x	
	Bund Finance Center (2017)				x		x		x	x			
Products	Polyvalent Wall for Lloyd’s of London (1981)				x	x	x						x
	TEmotion (2005)				x	x	x						x
	Smartbox Energy Façade (2006)				x	x	x						x
	Schueco E2 Facade (2007)					x	x						x
	Flare - Kinetic Membrane Facade (2008)				x				x	x			
	PixelSkin02 (2008)		x						x	x			
	NEXT Active Facade (2010)					x	x	x					
	Solar Thermal Facade Collectors with Evacuated Tubes (2013)						x						x
	Smart Window & Power Window (2014)				x	x	x			x		x	x
	licrivisionTM - Liquid Crystal Window (2015)			x			x					x	
	CONTROLITE® - Intelligent Daylighting System (2016)				x		x			x			
Research Projects	Living Glass (2005)	x	x							x		x	
	Bionic Breathing Skin (2007)	x		x			x		x	x			
	ACTRESS (2007)		x		x	x	x						x
	Adaptive Fritting (GSD) (2009)						x		x	x			
	Bloom (2011)	x	x							x			
	SABER (2014)	x	x							x			
	Adaptive Solar Facade (2015)	x			x					x	x		x
	Breathing Skins (2015)	x					x		x	x			
	SELFIE (2016)		x	x	x	x	x						x
	Allwater Panel (2017)						x					x	

Figure 2.11 : Strategis applied in the case studies. (In collaboration with Maria Mourtzouchou)

building condition and, in the specific case of adaptive façades in creating simple responsive systems (Barozzi, Lienhard et al. 2016).

2.6.3.8 Kinetics

The kinetics is the study of the movement of a body under determined forces; in the architectural context another term used as synonymous is dynamics. In some cases it is used to indicate an adaptive façade, but its term refers only to a subcategory of responsive façades and specifically to the ones with the possibility to move. The most common example is the shading system (Barozzi, Lienhard et al. 2016).

2.6.3.9 Soft robotics

The soft robotics refers to the use of soft materials in the robotic world. In particular, soft textures are moved or deformed by a rigid structure that function as a skeleton and driving force for the movement. In the specific case of the building facade, this technology can modify the shape of the envelope according to functional or aesthetical purposes (Laschi and Cianchetti 2014).

2.2.3.10 High transparency

The high transparency indicates the tendency to choose glass or another transparent material as main component for the envelope. This allows a higher level of daylight and view to the outside, but if not designed correctly can have negative consequences like high cooling demand due to the heat solar gain. This type of façade is more frequently applied in office buildings and in high-rise buildings in general.

3.2.3.11 Energy generator

An adaptive façade can be defined as an energy generator when its main purpose is to produce energy. A further level of adaptation can consist in searching the conditions for the higher energy production, like for example a sun tracing mechanism, or the integration with a shading system. However, due to economical reasons, the energy production happens with a static configuration.

2.6.4 Materials, components and elements

The previous case studies shown the prevalent trends for the adaptive envelope. Moreover, for each case, it was possible to analyse if the response was due to the variation of the material, component or entire element. Therefore, to have an overview on the possible applications for future projects, a classification of different adaptive materials, components and elements has been done, according to the parameters considered for the classification of the case studies (figure 2.12). In this way, it is possible to know what type of materials, elements and components can be applied in a design to achieve a specific requirement. For example, it is possible to have an overview on all the solutions that have a static or dynamic behaviour, or on the solutions that respond to the outdoor temperature or to the amount of light and, among them, which one are open or closed loop. This classification has been resumed in the figure n and it includes traditional solutions such as windows and shading systems, but also more cutting edge materials like shape memory and fluorescent technologies. Unfortunately, the table contains just some examples, but the potential to formulate a complete index would represent an interesting tool that could be consulted by architects and engineers during the design phase.

Classification parameters				Components		Elements					
Product				Air cavity	Photovoltaics	Vegetation	Window	Blinds	layered ETFE	Register	Sun shading
Type of Control	Manual						x	x		x	x
	Mechanical			x			x	x		x	x
	Smart material				x	x			x		
Agent of Adaptation	Inhabitants							x		x	x
	Environment	Exterior Environment	Solar radiation	x	x	x	x	x			x
			Temperature			x					
			Humidity			x					
			Wind			x	x				
			Precipitation			x			x		
			Noise								
		Interior Environment	Temperature				x				x
			Humidity				x				
			Light								x
			Air exchange rate				x			x	
			Air velocity								
			Sound level								
	Objects										
Respond to Adaptation Agent	Static			x	x	x			x	x	
	Dynamic						x	x			x
Purpose	Thermal comfort			x		x	x				x
	IAQ			x		x	x			x	
	Visual and Lighting Performance							x	x		x
	Acoustic Performance			x		x					
	Energy Performance			x	x	x	x				x
Response time	Seconds				x		x	x		x	x
	Minutes			x					x		
	Hours			x					x		
	Days					x					
	Season					x					
Control of Adaptivity	Close Loop						x	x		x	x
	Open Loop			x	x	x			x		
Degree of Adaptability	On-off						x	x		x	x
	Gradual			x		x			x		
	Hybrid				x						

Classification parameters	Materials																	
	Bimetals	Electrochromic	Fluorescent	Hydrogel	Liquid crystal	Mechanochromic	PCM	Photocatalytics (TiO2)	Photoelectric (graphene)	Photochromic	Phosphorescent	Piezoelectric	Shape memory	Silica gel	Suspended particle	Thermochromic	Thermoluminescent	Thermotropic
Manual																		
Mechanical																		
Smart material	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
Inhabitants								x				x						
Solar radiation	x	x	x						x	x	x							
Temperature (exterior)		x					x						x			x		x
Humidity (exterior)				x										x				
Wind						x						x						
Precipitation																		
Noise																		
Temperature (interior)							x											
Humidity (interior)				x														
Light		x																
Air exchange rate																		
Air velocity																		
Sound level																		
Objects					x										x			
Static		x	x		x	x	x	x	x	x	x	x		x	x	x		x
Dynamic	x			x									x					
Thermal comfort	x	x		x	x		x			x			x			x		x
IAQ	x							x						x				
Visual and Lighting Performance		x	x		x	x				x	x				x	x		x
Acoustic Performance																		
Energy Performance	x	x	x	x			x		x	x	x	x	x					
Seconds		x	x		x				x	x		x	x	x	x	x		x
Minutes	x			x		x	x	x			x	x	x					
Hours							x											
Days																		
Season																		
Close Loop		x			x										x			
Open Loop	x		x	x		x	x	x	x	x	x	x	x	x		x		x
On-off		x			x					x					x			
Gradual	x		x	x		x	x	x			x	x	x	x		x		x
Hybrid									x									

Figure 2.12 : Classification of materials, components and elements. (In collaboration with Maria Mourtzouchou)

2.6.5 Rollecate Group® and adaptive technologies

A way to understand the trend of the adaptive technology and how this interests Rollecate Group® is to understand the position of the company in the market. Rollecate is one of the leading façade construction companies in The Netherlands. The push-and-pull force explained in the figure n guides the market.

From the scheme, it derives that the technologies applicable in the facade are fundamental to satisfy the demand of architects and designer. At the same time, the latters are fundamental to push the suppliers to invest in new technologies. Therefore, understand what the architects expect from the construction companies, particularly regarding adaptive façades, is fundamental to address the development in the right direction. To understand

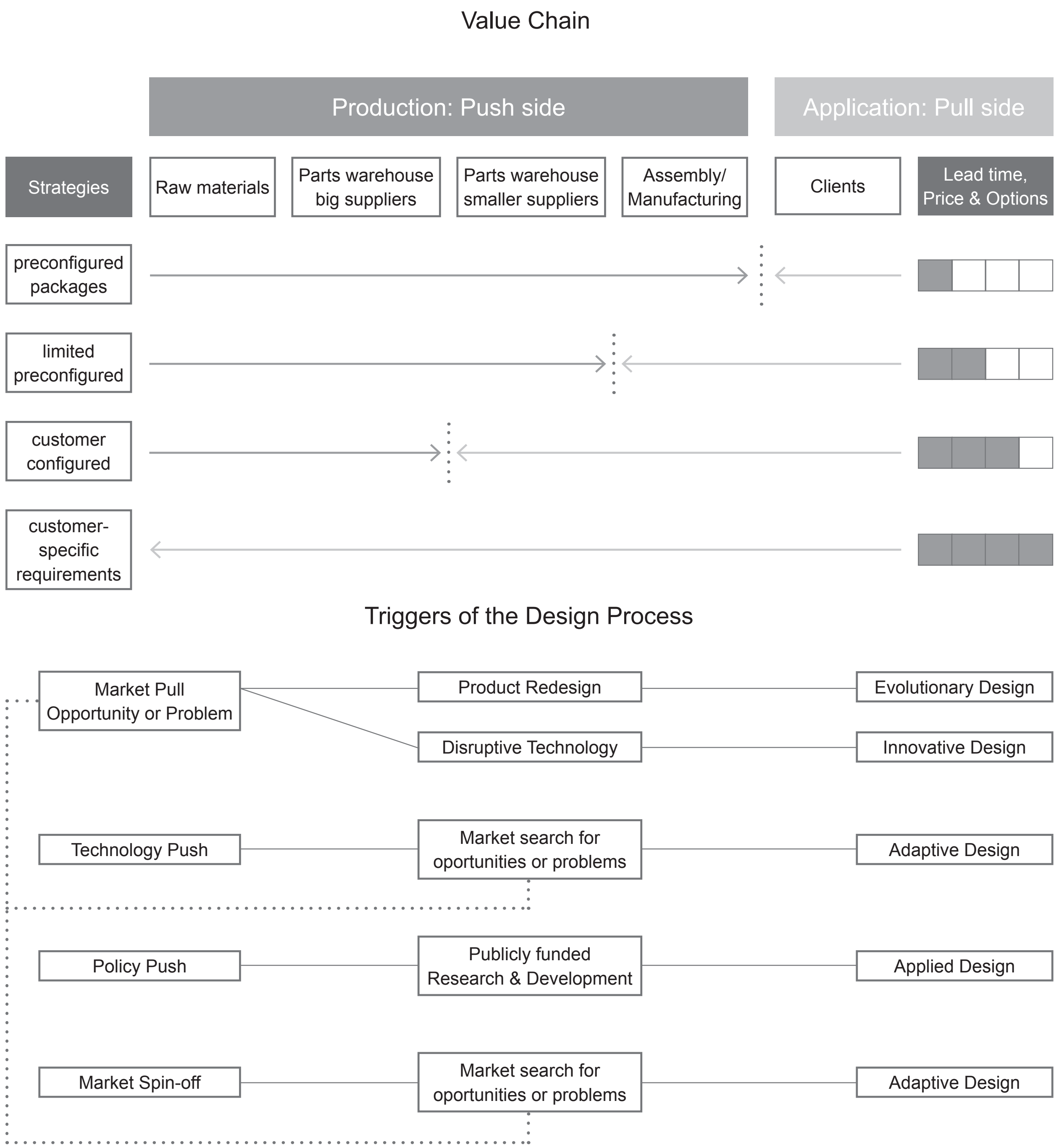


Figure 2.13 : Push and pull relationship (JDA Software Group Inc.) and Triggers of the design process (Devon 2010). (In collaboration with Maria Mourtzouchou)

the level of knowledge about adaptive facades and to learn the essential needs and expectations of the architects in relation to adaptive solutions, some questions have been asked to some architects at the Faculty of Architecture and the Built Environment of TU Delft (Full dialogue available in the appendix B). Due to the number of interviewed it was not possible to obtain a generalized information, but the dialogue showed an interest in this field and a general knowledge of the most common applications. In particular, it came out that the most common adaptive façade system applied by the interviewees is the shading, but other technologies were well known. Some useful consideration that can be taken into account for the design development is the importance of the sensors and at the same time the possibility to have a user-friendly control of the facade. Moreover the importance of modifying the functionality of the facade between day and night and summer and winter has been underlined.

2.7 Conclusion

The main goal of this research phase was to give a definition of adaptive façade that highlights the importance of using this type of technology rather than a static solution. In particular for this research, adaptive façade is considered as an envelope that responds both to indoor and outdoor stimuli and change conformation – both physically or chemically - to take advantage of the outdoor climate with the aim of improving the indoor environment.

The parameters that define this technology have been generally described and observed in the different case studies taken into account. In particular, buildings, product and research projects with adaptive characteristics have been examined with the aim of defining the state-of-the-art and the future trends of this technology. Generally, the adaptive facades are applied to respond to outdoor stimuli with the aim of improving the indoor comfort. Specifically, most of the envelopes respond to the solar radiation to influence the visual and thermal comfort of the indoor space. The need of control the indoor environment implies a preference of technologies with an extrinsic control, but self-responsive materials are also attractive especially in the research field.

A problem that has been individuated is the slow development of new technologies for architectural purposes and this factor implies a difficult prediction on the timing of application of the new technologies. Among the most applied concepts, the biggest trends have been individuated in nanotechnology and smart materials that are currently rarely applied due to their technological development, but that will appear more in the future due to their promising advantages. Another tendency is to mimic the adaptive behaviour of the nature and apply it both in a small and large scale. Furthermore, there is a tendency to combine the concepts just mentioned and other solutions in integrated products by disposing them in layers or in specific sections, in order to obtain a unique element with the ability to control different external factors at the same time. An important application that is already applied in numerous cases, but that should be expanded in more cases is the presence of sensors to measure both the external and internal environment in order to dictate the optimal response to the adaptive envelope. In conclusion, the results obtained are a broad image of the future trends and their actual application depends on the development of these technologies and on the awareness of the designer in the potential of their application.

3

VISUAL COMFORT

3 Visual Comfort

Considering the conclusions of the research obtained until here, a further analysis is conducted to understand how to achieve visual comfort by using adaptive solutions. As already mentioned, visual comfort is strongly correlated to thermal comfort because both of them dependent on solar radiation. However, the strategies usually applied to regulate these parameters do not always fulfil the requirements of both simultaneously. Therefore, firstly the solar radiation will be analysed to understand how it affects the visual and thermal comfort and how it should be regulated to control these parameters. Afterwards, a study will be conducted on the available technologies and products that can achieve this result.

3.1 Solar Radiation

The solar radiation is an electromagnetic wave that, according to the wavelength, can be divided into three main sections: UV, Visible Light (VL) and Infrared (IR) (figure 3.1). Generally, the window stops most of the UV (310-380 nm) to enter the building, while different solutions are available to control the Visible Light and the Infrared. In particular, the former represents the portion that is perceived by the human eye and covers the spectrum between 400 and 700nm. This is the area that has to be regulated according to the amount of daylight required inside the building. On the contrary, the near Infrared occupies the solar spectrum between 700 and 2500nm and it represents the portion responsible for the solar heat gain (Lechner 2015).

3.2 Visual Comfort

The visual comfort is the aspect that, more than others, is strictly dependent on the façade design. It is defined in the European standard EN 12665 as "a subjective condition of visual well-being

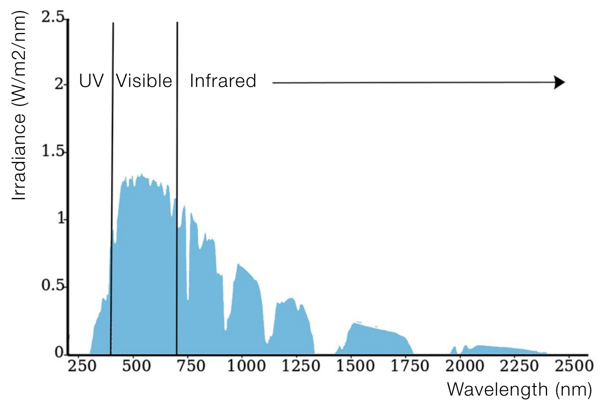


Image 3.1: Solar spectrum. Subdivision between UV, Visible Light and Infrared. (Lechner 2015)

induced by the visual environment" (EN12665 2011). The visual comfort is determined by two parameters: light and view. The former is the most studied and it comprehends both daylight and artificial light, while the latter is not always taken into account despite its relevance for the health and the productivity of the user. Concerning the light, just the daylight will be analysed because it is more dependent on the façade, helps reducing the energy demand for artificial light and has a positive influence on the user's health. Besides the aesthetical reason, the tendency to have glass as predominant element in the façade is justified as a strategy to increase daylight and

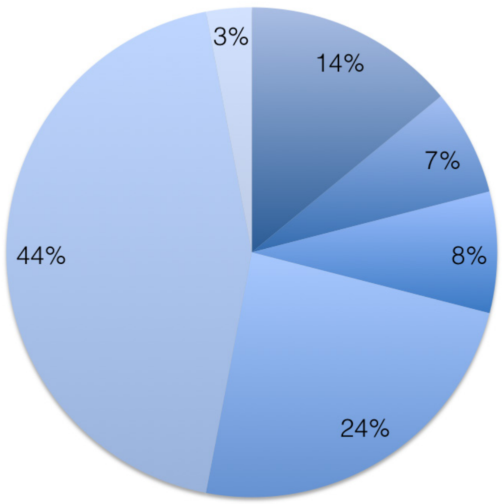


Figure 3.2 : Electricity used in office building. (Todd 2011)

view, in order to reduce stress and improve the workers' performance. However, due to the direct sunlight, these goals are usually compromised by the shading system (van Oosten and Zitto 2016). Furthermore, this element does not only reduce the visual comfort, but it also raises the energy consumption, due to the necessity of artificial light. In particular, electric lighting represents the 44% of the energy demand of an office building (figure 3.2) and this value could consistently decrease by implementing the use of daylight (Todd 2011). However, daylight is a complex factor to control because it is determined by different weather and annual conditions and it is composed by different parameters that have a particular and precise impact on the indoor environment. Therefore, an overview on the parameters that characterise the daylight is necessary to reach an efficient strategy that decreases the energy demand of an office, without compromising the quality of the space.

3.2.1 Daylight

Daylight is being experienced as more comfortable and attractive than artificial lighting (Hellinga and Hordijk 2014) for the following reasons:

- It increases the satisfaction and therefore the productivity of the workers;
- It improves the visual quality in terms of colour rendering properties;
- It shows the time is passing thanks to the changing of intensity, direction and colour during the day;
- It reduces the need of artificial lighting and therefore of electricity (Rea and America 2000).

The architect has the important task to give quality to the indoor space by regulating the amount of light and its distribution in the space. In particular, there are some parameters that have to be taken into account during the design process.

3.2.1.1 Illuminance

The illuminance is the amount of light that falls on a surface and it is measured in lux in the SI. According to the indoor environment, the requirements for the illuminance change in order to set the standard of comfort (Lechner 2015). Among the parameters that should be considered, a relevant one for the office space is the horizontal illuminance that represents the amount of light that is distributed on a horizontal area. In the particular case of an office space this is usually measured on the desks and should have a minimum value of 300-500 lux (figure 3.3). According to the European standard the requirement for the horizontal illuminance is of 300 lux on at least half of a plane at a height of 0.85 m, during half of the year (EN 2011). Moreover, the area where the users work during the day should have a uniform spread of light to avoid visual stress due to over-lit and under-lit areas (Group 1994).

Typeof interior, task or activity	lux
Filling, copying, etc.	300
Writing, typing, reading, data processing	500
Technical drawing	750
CAD work station	500
Conference and meeting rooms	500
Reception desk	300
Archives	200

Figure 3.3 : Lighting requirements for an office building. (Lechner 2015)

3.2.1.2 Luminance

The luminance is the amount of light that is reflected by a surface and reaches the eye of an observer. It is measured in candle per square meter (cd/m^2) and it depends on the object that reflects the light and, in particular, to its geometry, material, colour and on the user's position respect to the object. To assure visual comfort, it is recommended that this value does not exceed 3000 cd/m^2 (Lechner 2015).

3.2.1.3 Daylight Autonomy

The Daylight Autonomy (DA) represents the percentage of the annual daylight time during which a space reaches an illumination level higher than a specific illumination value. When related to a space, it is named Spatial Daylight Autonomy (sDA) and describes the amount of the space that receives sufficient daylight for at least 50% of the annual occupied hours. As previously mentioned, for an office space, the amount of illuminance that should be reached is 300-500 lux, depending on the task. The daylight autonomy is significant to understand the energy consumption for electrical lighting because when the daylight illuminance is not sufficient, the electric light has to compensate this value causing a consumption of energy. Therefore, from a higher Daylight Autonomy derives a lower energy consumption for electrical lighting (C. F. Reinhart 2006).

3.2.1.4 Glare

Glare is a light phenomenon that is caused by a bright artificial or natural light that interferes with the visual field of the user causing difficulties in seeing and discomfort including eyestrain and headaches (Winterbottom 2009). Focusing on the façade, glare is dependent on the luminance of the window and it can occur when the amount of light reaching the observer's eyes is excessive or when the visual field contains a too wide range of luminance values (Lechner 2015). In many situations, glare is a consequence of the objects' material inside the room and on how these reflect the light. Some examples are the luminance peaks caused by particular shading systems like venetian blinds, the glare spot caused by the whiteboard or metal surfaces, striped patterns and reflection on the desk or on the display screen (Wienold and Christoffersen 2006, Weinold 2014). In order to evaluate the glare perception, glare is described as "imperceptible", "perceptible", "disturbing" and "intolerable" according to the Daylight Glare Probability (DGP) used to predict the glare over the day. In particular, contrarily to other indices, the DGP derives from experiments done under real daylight conditions and considers the probability of disturbed people, instead of the glare magnitude considered by other indices (Wienold and Christoffersen 2006), by taking into account the vertical eye illuminance, the glare source luminance and its position index (BArch 2002). To reach the best performance, the DGP should not exceed a value of 0.35 that indicates that in 95% of the office time, glare is weaker than imperceptible (Weinold 2014). The luminance contrast ratio should be lower than 1:30 in the wide visual field (panorama), 1:10 in the narrow visual field (ergorama) and 1:3 on a task.

Different solutions are commonly adopted to solve the glare and some examples are external shading systems, internal blinds or venetian blinds. However, the negative aspect is that these solutions reduce the amount of light and the view to the outside. Moreover, in the particular case of the venetian blinds, the occupants regulate them infrequently (Rea and America 2000). As it will be explained later, the view is a very important aspect for the visual comfort; solving glare should not reduce the possibility to have a view, but on the contrary, the view can help in a reduction of the glare perception. A solution that helps solving

the direct sunlight without highly reducing the amount of daylight is the light-shelf. This element is usually positioned on the upper fraction of the window without interfering with the view. The light-shelf should be design correctly to increase the amount of daylight inside the space, avoiding glare caused by the reflection. Moreover, in case of diffuse skylight, the risk of glare caused by the upper portion of the window can be solved by screening only the upper part of the window (Rea and America 2000).

3.2.1.5 Daylight Factor (DF)

The daylight factor (DF) is the ratio between the illumination measured indoor and the one measured outdoor during an overcast day. This parameter indicates the amount of light that enters the room: the smaller the number, the lower the amount of light that enters through the window. This parameter can be influenced by the dimension of the openings, the typology of the window, the position of the window, the geometry of the indoor space, the presence of a shading systems and the sky condition (Lechner 2015). Furthermore, it is obvious that the daylight factor is higher in the space close to the window and lower in the area far from the window.

3.2.1.6 Colour rendering and colour appearance of the light

The colour appearance refers to the colour of the light emitted from a light source. Its unit is the colour temperature (K) that can vary from warm (< 3000 K), intermediate (between 3300 and 5300 K) and cool (> 5300 K). The colour rendering is very important for the visual comfort because it indicates how much the colour of the light renders the object naturally (Lechner 2015).

3.2.2 View

The biophilia hypothesis claims that humans have a benefit from the connection with living things and therefore, the interaction with the nature is something fundamental for the human's health (Lechner 2015). Consequently, it is essential to always provide view from the indoor space to preserve the connection with the outside environment and with the circadian rhythm. Moreover, the view can have disparate impacts on the user's perception: a green space, for example, has a completely different effect than a congested street. Therefore, a method has been established to assess the quality of the view according to the object visible from the indoor (Hellinga and Hordijk 2014). However, assessing the view would go beyond the goal of this research, but what is important instead is guaranteeing the possibility to look outside the window under every climatic condition.

3.3 Thermal Comfort

The thermal comfort has been briefly explained in the previous section and is here re-examined because it can be altered by the solar radiation. In particular, the solar heat comes mainly from the nearly infrared light that has a wavelength between 700 nm and 2500 nm, it is invisible to the human eye and it represents almost half of the total solar energy (Khandelwal 2017). In winter, the required indoor temperature should be around 21°C, while in the summer it should not exceed 26°C (CEN/TC156 2007). According to the season, the infrared should be transmitted or reflected to help reducing the energy consumption for heating and cooling. Furthermore, the amount of visible light that enters the building has also an influence on the thermal balance because it determines the consumption of electric light and therefore of the heat production. This is more relevant in the summer when the daylight is desired to turn off the electric lights that otherwise would increase the amount of cooling: for the same light level, incandescent lamps and fluorescent lamps produce respectively 6 and 1,5 times more heat than daylight (Lechner 2015).

3.4 Goals, requirements and problem statement

To summarize, visible light and Infrared have to be controlled with the intent of increasing daylight, assuring outside view, preventing glare, regulating the temperature and therefore improving the energy efficiency of the building (Loonen, Trčka et al. 2013). Therefore, the following requirement should be satisfied to achieve indoor comfort:

Illuminance	300-500 lux
Light distribution	difference between two sensors < 30%
Daylight Glare Probability (DGP)	< 0,35
Ergorama Luminance contrast ratio	1:10
Panorama Luminance contrast ratio	1:30
Task Luminance contrast ratio	1:3
Colour Rendering Index	> 80%
View	Assure the view to the external environment
Temperature winter	20-24 °C
Temperature summer	23-26 °C

Figure 3.4 : Table of requirements

To reach these requirements, it is important to consider the relationship between indoor and outdoor space. In particular, the indoor space can be divided in two areas: the occupied space, where the user is positioned, and the surrounding area. On the other side, the solar radiation represents the external factor. Analysing a period of one year, there are four main indoor situations that require different portions of the spectrum:

- Occupied area in summer: both visible light and infrared need to be reflected to avoid direct sunlight, glare and solar heat gain (figure 3.5);
- Unoccupied area in summer: the direct daylight can be transmitted if it does not cause glare, and this can help increasing the amount of daylight in the whole space (indirect daylight for the user), while the infrared has to be reflected to avoid the solar heat gain (figure 3.6);
- Occupied area in winter: the visible light has to be reflected to avoid direct sunlight and glare, while the infrared can be transmitted because the solar heat gain can help decreasing the energy demand for heating (figure 3.7);
- Unoccupied area in winter: both visible light and infrared can be transmitted into the indoor space (figure 3.8).

Moreover, in every period of the year, the visible spectrum should be reflected, very time the DGP exceeds imperceptible values.

The graphs in the figure n are translated in schemes that show the façade behaviour in relationship to the outdoor environment and according to the different indoor requirement over the year (figure 3.9). The problem identified is that the solutions usually applied to the façade do not cover these four cases because they treat the whole spectrum in the same way. Therefore, to provide a new approach for the control of the solar radiation, different technologies, materials and design strategies are here examined.

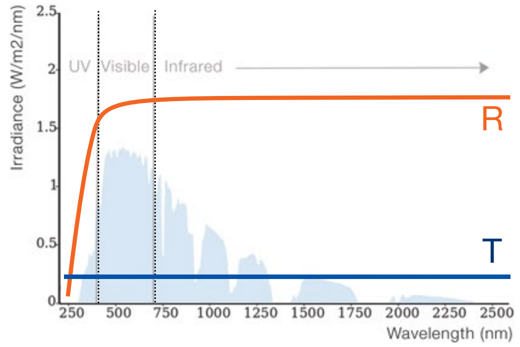


Figure 3.5: Occupied area in summer

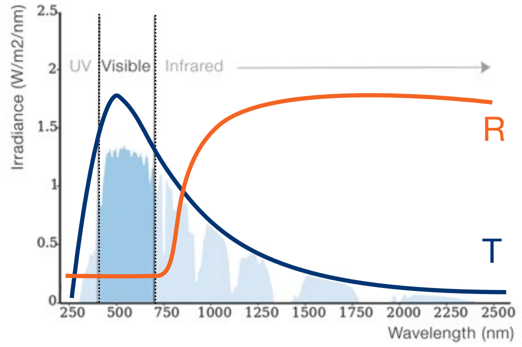


Figure 3.6: Unoccupied area in summer

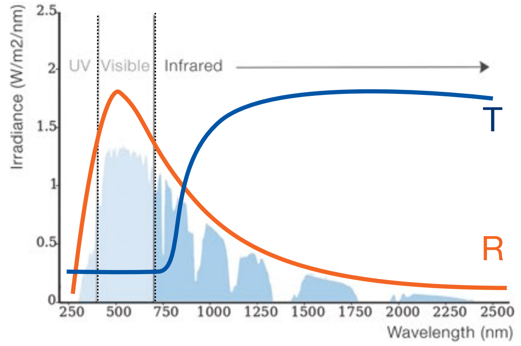


Figure 3.7: Occupied area in winter

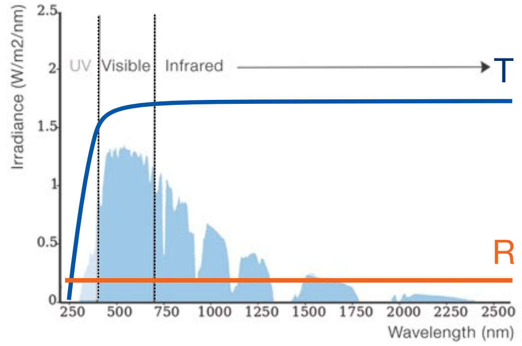


Figure 3.8: Unoccupied area in winter

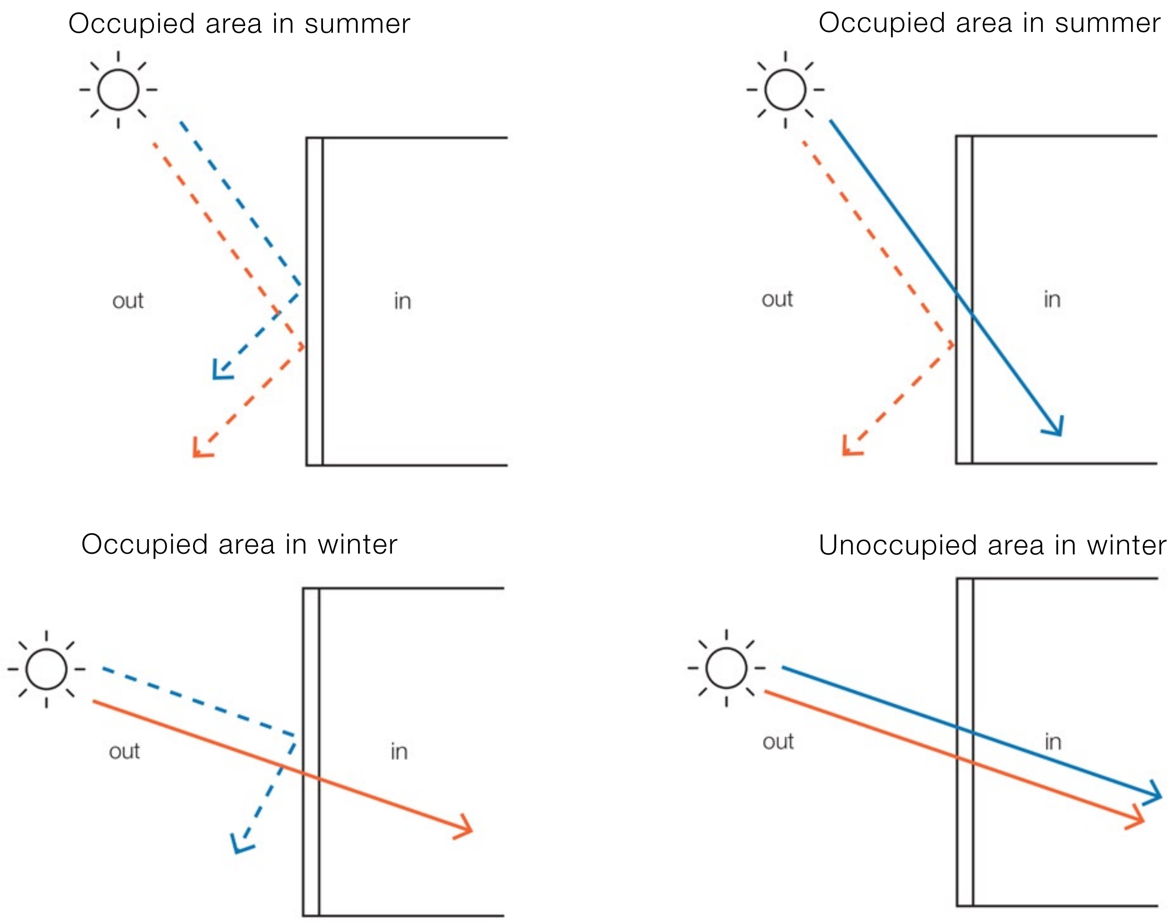


Figure 3.9: Facade behaviour in function of the solar radiation

3.5 Design Strategies

Different technologies and design strategies are usually applied to regulate the solar radiation. In this analysis, special attention has been given to the visual comfort and on the current approaches of daylight management. In particular, daylight management refers to the design and products used to control the daylight penetration into the building with the aim of improving the quality of the indoor space (Papamichael 2017).

Regarding this discipline, a possible solution for daylight control has been proposed by K. Papamichael, Professor of the Department of Design and Co-Director of California Lighting Technology Centre at the University of California. This strategy consists in dividing the window in different areas and treat them differently according to the annual situations (Rea and America 2000). In particular, K. Papamichael claims that there should be two horizontal subdivisions: a lower area that satisfies the view and a higher section that provides daylight. Moreover, the advantage of using automated operations for the daylight management has been underlined as a way to increase efficiency and performance (Papamichael 2017). An example of a project that applies this concept is the Frederiksbjerg School designed by Henning Larsen Architects, where the façade has an interesting windows composition. In particular, the openings are divided into three typologies: larger windows are placed in the middle to maximize the view and the amount of daylight; smaller windows are placed on the top to maximize the daylight and the smallest at the bottom to invite the children to sit and read with good light quality (figure 3.10). This pattern assures a natural daylight dynamism that provides different spaces for the users and consequently a rising of attention for longer time during the day. The disposition of these windows is fixed, but the result is a high dynamism, in particular regarding the relationship between

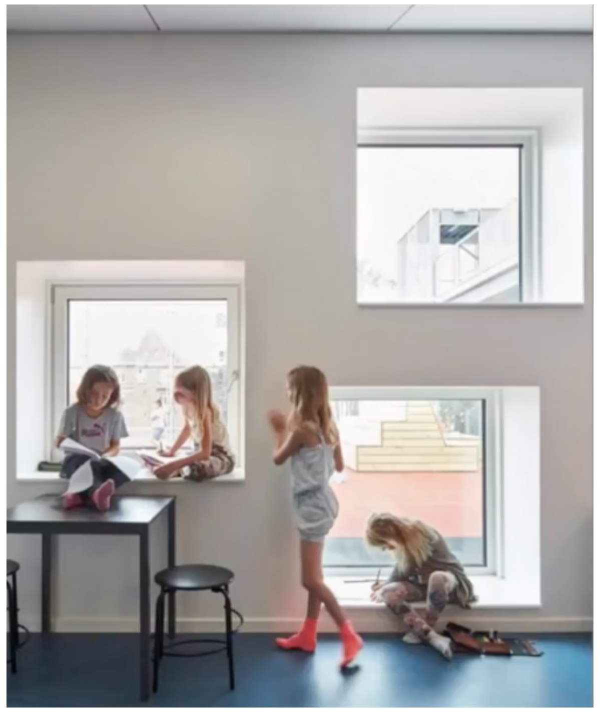


Figure 3.10: three windows typologies in Frederiksbjerg School, Henning Larsen Architects. (www.archdaily.com)

user, light and view that creates a real spatial experience (Architonic 2016).

The concept of spatial experience can be achieved in different ways like using different materials or different furniture, but also by treating the light in different ways. In particular, this concept is very present today because the office environment is radically changed compared to the past and it requires more flexibility and dynamism due to the constant movement of the employees that are used to change location over the day. Specifically, if this is applied to an office, the daylight can add quality to the indoor space to improve the productivity and the life quality of the employees (Strømann-Andersen 2017).

3.5.1 Conclusion

The division of the façade in two sections has been taken into account as principle, but has been modified according to the relationship between interior space and user. In the case of a fully transparent envelope, the areas that can be individuated are three: top, middle and bottom (figure 3.11). The height of the division is related to the user and in particular the lowest part coincides with the height of the desks and the middle section with the height of a standing person. These areas play a role in providing daylight and view, but not all of them have the same influence on these two parameters: the upper and lower areas are considered secondary than the middle in providing view, while they can be significant for the implementation of the daylight. A second aspect that will be considered is the communication between the indoor and outdoor space. In many cases, the shading system answers to the amount of solar radiation or according to a schedule of occupancy over the year. However, this solution cannot be optimal if compared with the possibility to answer to indoor illuminance levels or to DGP. Therefore, the façade needs to communicate between outdoor and indoor space by the use of sensors in order to optimize its adaptive response.

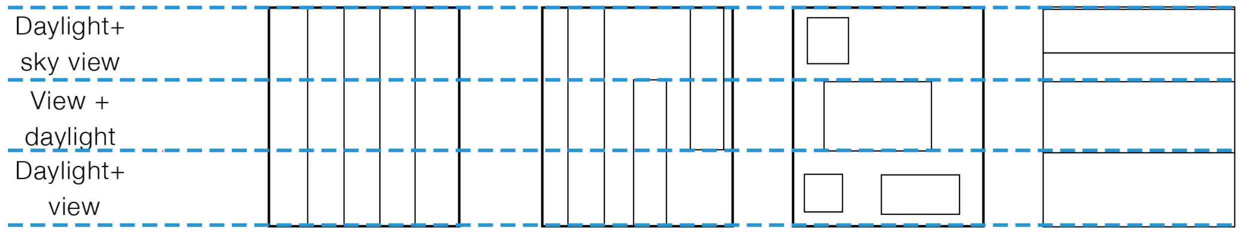


Figure 3.11: Scheme of the facade division into three areas

3.6 Technologies and Products

The next step is to study the possible applications for every portion of the facade by analysing external, integrated and internal solutions for daylight control. For this analysis the static solutions are neglected and just the adaptive technologies are taken into account. The aim is to discover the trends and the challenges of the daylight management in terms of adaptive solutions. Moreover, it will be investigated if these solutions leave freedom to the architect in terms of geometry, materials and aesthetic. In particular, the aim is to find adaptive technologies that allow daylight control and at the same time maximise the view to the outside. The category of products that more than others satisfies these requirements is the switchable glazing. However, more traditional options are also considered and integrated with other solutions to achieve better performances. Because of the high amount of typologies of switchable glazing, different options will be analysed according to the material used and an explanation about the different possibilities will be provided. Moreover, some commercial products with the application of smart glass have been considered to find out the level of development available on the market. Furthermore, another strategy that has been considered is to combine static and adaptive solutions to achieve a more flexible and integrated product.

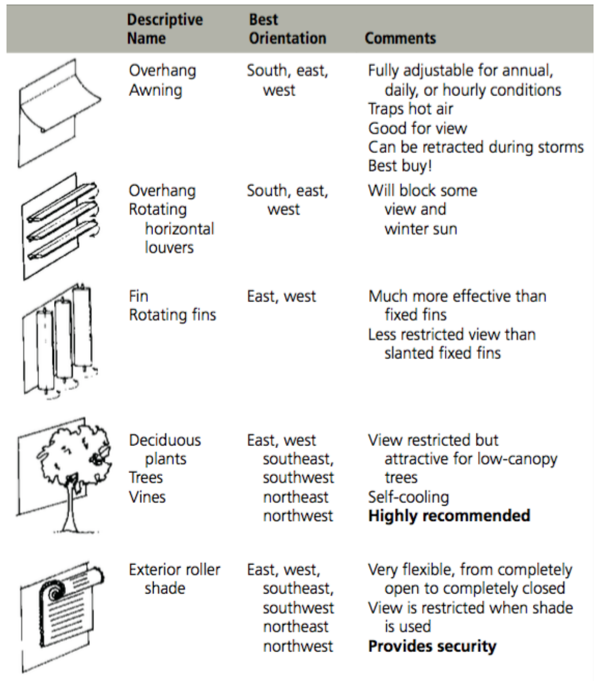
3.6.1 Internal solutions

Indoor shadings are the solutions that are usually used to control light, privacy and glare. They might have different geometries, materials, textures and colours and these influence their impact and perception of the indoor space. The most common solutions are roller blinds, curtains and venetian blinds. In particular, the latters are the option that provides more flexibility thanks to the rotation of the lovers, however, the users do not take advantage of this aspect very frequently (Lechner 2015). A disadvantage of the indoor applications is the poor influence on the thermal aspect because the solar radiation is stopped when it has already entered inside the building. Because of this, the colour and the material can significantly improve the performance: a strategy that helps reducing the heat gain is to use a reflective material facing the window so that part of the solar radiation is reflected back to the glass.

3.6.2 External solutions

The external shadings can be fixed or movable. The latters have a better performance because respond to the dynamism of the external environment with a better impact on the lighting and thermal conditions. Examples of movable external shadings are overhang awning, overhang rotating horizontal louvers, rotating fins, deciduous plants and exterior roller shades (figure 3.12) (Lechner 2015). As reported by N. Lechner, the best shading device is the deciduous plant because it responds to the thermal changes, it is low cost, improves the view quality assuring privacy, reduces glare and decrease the air temperature in summer. The disadvantage, however, is a reduction of daylight during the winter, due to the obstruction of the plant in front of the window. Because different orientations require different types of shading, provide a single solution can be a challenge and would require a high level of adaptability. At the same time, it is not necessary to achieve all the visual comfort requirements with the same solution, but different strategies can be combined. Some examples of external shading solutions are here shortly described.

3.6.2.1 Overhang: this solution is designed thinking about the different position of the sun between winter and summer. A drawback is that the upper view and the amount of light are reduced due to the depth of the overhang. A development



	Descriptive Name	Best Orientation	Comments
	Overhang Awning	South, east, west	Fully adjustable for annual, daily, or hourly conditions Traps hot air Good for view Can be retracted during storms Best buy!
	Overhang Rotating horizontal louvers	South, east, west	Will block some view and winter sun
	Fin Rotating fins	East, west	Much more effective than fixed fins Less restricted view than slanted fixed fins
	Deciduous plants Trees Vines	East, west southeast, southwest northeast northwest	View restricted but attractive for low-canopy trees Self-cooling **Highly recommended**
	Exterior roller shade	East, west, southeast, southwest northeast northwest	Very flexible, from completely open to completely closed View is restricted when shade is used **Provides security**

Figure 3.12: Examples of movable shading devices (Lechner 2015)

of this product from an adaptive point of view can have and interesting application.

3.6.2.2 Venetian blinds: this is an effective control system that adjusts the amount of sunlight and reduces glare. In this sense, the type of material, the colour and the depth of the louvers play an important role. Even if the possibility to control the rotation of the louvers is high and versatile, the users do not adjust it frequently, resulting not effective if manually controlled.

3.6.2.3 Vertical and horizontal louvers: these elements are designed to exclude and redirect the direct sunlight and the use of horizontal or vertical lovers depends on the exposition of the façade. Because of the variation of the sun position during the year, movable solutions are preferable because they can be designed to track the sun, resulting always perpendicular to the sunrays in every moment of the year.

3.6.3 Integrated solutions

3.6.3.1 Venetian blinds: the system is located in the air cavity between two layers of glass. Because of its position, it is not subjected to the atmospheric agents, dust and direct contact with the users. Therefore, the system remains clean and is not damaged, reducing the costs of maintenance. As mentioned already for the external and internal typologies, the amount of light that is reflected or transmitted and the DGP are influenced by the material and colour of the louvers.

3.6.3.2 Light shelf: this element interrupts the window on the upper side, with the goal of reflecting the daylight deeper into the space. This solution has the additional advantage of reducing glare because it operates on the upper area of the window, however, it has the disadvantage of obstructing the view to the sky. The reflectance of the light to the inside is influenced by the material, colour and the depth of the light-shelf.

3.6.3.3 Smart windows: this category of windows are composed by glass that changes its visible light transmission due to a change of conditions like amount of light, temperature or voltage application. There are different categories of switchable glazing according to the material that is applied and the trigger that causes the variation.

This technology has been taken into consideration because it seems a promising option that can regulate the amount of light and reduce glare without obstructing the view. Because of the wide variety of switchable glass, a deeper analysis and comparison of the possibilities is done. Specifically, the comparison has been done by taking into account light transmittance and general colour rendering among the optical properties and solar heat gain coefficient for thermal aspect. What is also important to take into account is how these technologies are applied in the building, if they leave design freedom to the architect, if they influence the aesthetic of the façade composition, if they can be applied in different shapes and dimension and if their application is affordable in terms of cost.

Smart windows are divided into different categories according to the material and the stimulus that triggers them. There are two main groups of responsive glazing: passive (open loop), like photochromic and thermochromic glazing, that automatically respond to the variation of the environmental conditions, and active (closed loop), like electrochromig and gasochromic, that can be controlled according to desired requirements (Lechner 2015).

a. Photochromic material

The material adjusts the amount of daylight entering the building by changing transparency in response to the outdoor light intensity. In this way, the quantity of light that passes through the gazing is the same in every moment (Lechner 2015). The advantage of this product is that it does not require electricity. However, because this is a passive solution, it automatically responses to external stimuli and therefore, its behaviour cannot be regulated by the user and this can possibly imply discomfort. Photochromic materials are not largely applied for architectural purposes and they are usually used for small design products like sunglasses (figure 3.13).

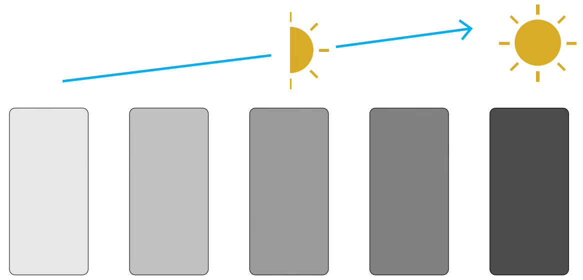


Figure 3.13: Examples of photochromic material

b. Thermochromic material

The thermochromic materials change their optical properties in response to a variation of temperature. In this way, they help regulating heat gain and therefore indoor temperature. The advantage of this technology is that it does not require energy, but at the same time, the impossibility for the user to have control on it represents a disadvantage (Lechner 2015). Moreover, the material changes optical properties according to climate thermal condition without a constant correlation between the two parameters (figure 3.14) .

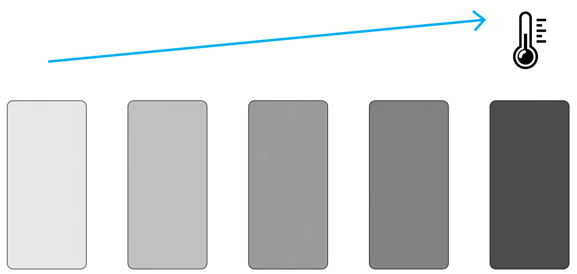


Figure 3.14: Examples of thermochromic material

c. Electrochromic materials

The electrochromic materials are coatings that change their optical properties when electricity is applied. According to the material of the coating, the electrochromic windows are subdivided in different typologies. The advantage of this technology is that it can be directly adjusted.

Liquid-Crystal Glazing

A Liquid Crystal window is composed by glass panes that include a layer of liquid crystals between them. The most diffuse function is to provide privacy changing from clear to opaque state, but some products have been developed that can change from clear to dark, maintaining the transparency and therefore the possibility to see through the glass. In both cases, the variation of light transmittance happens due to the application of a low voltage through conductive coatings that cause a rearrangement of the orientation of the crystals dispersed in the liquid. In particular, when the electricity is not applied, the crystals are disposed in a random order that blocks the light. On the contrary, when a voltage is applied, the crystals rearrange parallel to each other and in the same direction of the light, allowing it to pass trough the layer. The change happens instantaneously and, according to the voltage, it is possible to have intermediate situations that allow regulating the amount of light. The system can be switched on and off manually by the users or automatically according to the outdoor and indoor conditions (van Oosten and Zitto 2016). A drawback is that a continuous voltage is needed to maintain the clear state. The material can switch with different colours and the advantage is the possibility to have a grey scale that does not highly influence the perception of the indoor space. The possibility to apply the material in different shapes and sizes allow having a flexible design and therefore a more architectural freedom (figure 3.15).

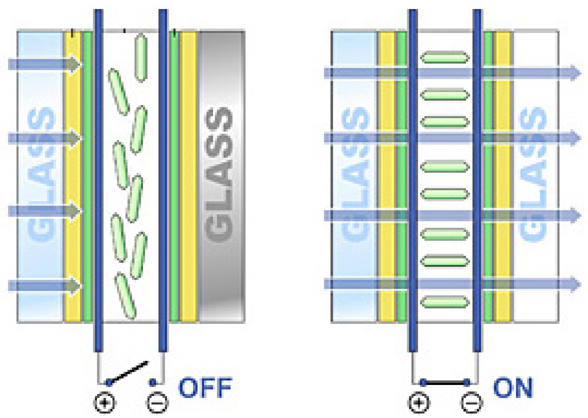


Figure 3.15: Liquid Crystals. (s.hswstatic.com)

Suspended-Particle Device (SPDs)

The system works as the liquid-crystal glass, but it can change transmittance in a wider range of shades that provide solar control and preserve the view (Lechner 2015). In this type of glazing, two panes of glass or plastic contain a liquid in which nanoscale particles, that absorb the light, are suspended in a random order. When the voltage is applied, the particles reorient with an angle that depends on the voltage. This can happen with a fast speed of around 2 seconds. Different orientations allow having a different amount of light that can be transmitted through the glazing. The visible light transmission at the darkest state is 0,5% and it does not provide complete privacy because of the material's transparency. A negative aspect is that the colour of the tint is blue and this can have a negative contribute for the perception of the indoor environment (figure 3.16).

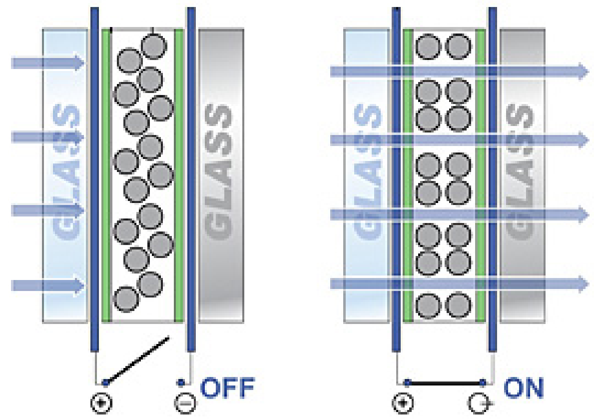


Figure 3.16: Suspended-Particle Device. (s.hswstatic.com)

Electrochromic Polymer Glazing

The material works similarly to the Liquid Crystals and the Suspended Particles Devices. The switchable layer changes from clear to dark by applying a low voltage. However, contrarily to the previous cases, the advantage is that the electricity is needed only to change state and it is not required during the whole operation. The control can be both manual and automatic (Lechner 2015). The dark colour is usually blue even if there are some products that switch with a grey shade. A problem that can occur is that, depending on the size of the window, the colour is not uniform, but darker at the edges, creating the so called "iris effect". A significant problem for this technology is the switching speed that is very slow, reaching several minutes according to the panel size. This factor can be neglected in environments where the weather is stable for long time, while is not preferable in locations where there is fast weather variability, like in The Netherlands (figure 3.17).

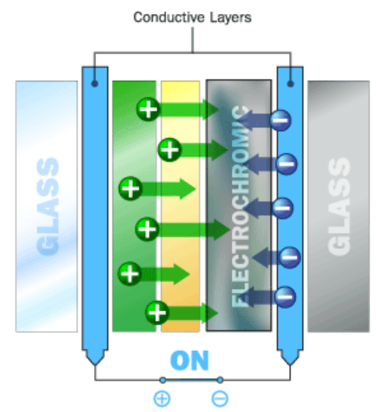


Figure 3.16: Electrochromic Polymer Glazing. (openaccessjournals.siftdesk.org)

Cholesteric Liquid Crystals (Ch-LC)

Cholesteric Liquid Crystal is an organic material and therefore it does not interfere with the electromagnetic waves. This solution can be applied to regulate the solar radiation of the whole spectrum, but particular attention has been focused to regulate the infrared part of the solar radiation. The system is composed by layers of nematic liquid crystals doped with chiral molecules (figure 3.17). Because of the chiral geometry, every layer of nematic liquid crystals has a small-rotated orientation respect the previous and the successive layer and twisting the chiral determines a different orientation of the layers between each other. In particular, the rotation can be right-handed or left-handed depending on the typology of the chiral dopant molecule. According to the rotation, the layers are overlapping with different angles that cause the reflection of different parts of the spectrum (Khandelwal, Schenning et al. 2017). When the Ch-LC is applied as a reflective layer, this can reflect only half of the incident sunlight and this depends on the polarization of its helix: a right-handed Ch-LC reflects the right circularly polarized light and vice versa for the left-handed. Therefore, two layers with different polarizations are always needed to completely reflect a specific bandwidth. Moreover, theoretically, this solution provides a control of the solar heat gain without influencing the visible spectrum. However, because this technology is still in a development phase, there can be an influence on the visual spectrum according to the observer's position. This is due to the helical geometry that causes a different perception of the layer from different inclinations: if looked perpendicularly, the layer influences only the infrared, but observed from an inclined position, the range moves to the last portion of the visible spectrum causing a slightly perception of pink.

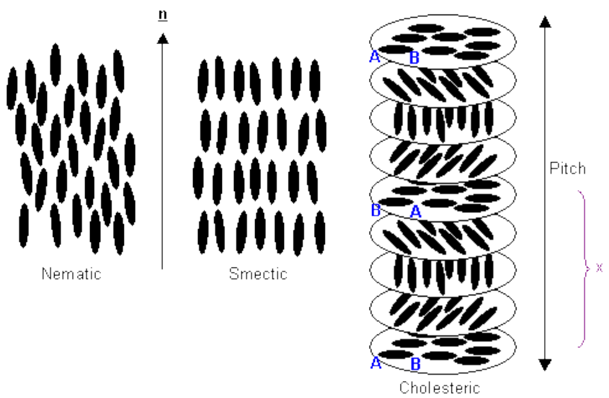


Figure 3.17: Cholesteric Liquid Crystals. (www.doitpoms.ac.uk)

d. Gasochromic Windows

The gasochromic windows work similarly to the electrochromic windows, but the trigger that changes their optical properties is diluted hydrogen instead of electricity. The presence of hydrogen switches the colour of the glass while reintroducing oxygen turns the window transparent again. According to the thickness of the air gap and to the hydrogen concentration, the shades vary intensity and the switching time varies between 20 second and one minute. A disadvantage is that the material has a blue tint that influences the perception of the indoor space (Collaborative 2018) (figure 3.18).

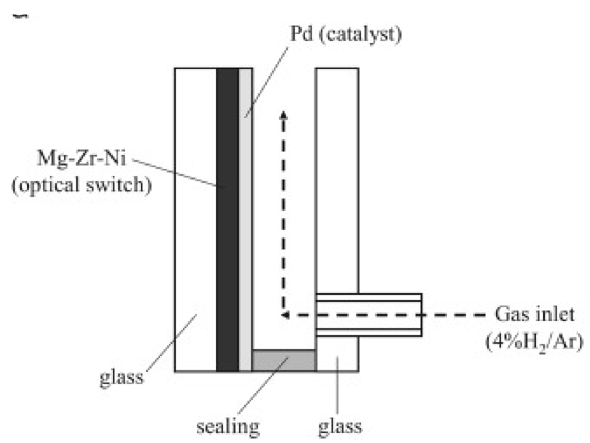


Figure 3.18: Gasochromic Window. (Collaborative 2018)

3.6.4 Conclusion

Generally, smart windows have the advantage to control the amount of light without obstructing the view. Contrarily to other solutions, they can be adjusted according to the users' needs maintaining a neat composition of the façade. In addition, they can be applied in panels of every geometry and size, maintaining a high level of freedom for the architects.

Among the different typologies of smart windows (figure 3.19), the passive solutions are discarded because of the inability of directly control them. Among the different active solutions, the electrochromic polymer glazing is eliminated, even if it has the advantage of consuming electricity only during the switching time, because it has a blue tint and a long switching time that does not reflect the fast Dutch weather variability. In the same way, the Suspended Particle Devices and the Gasochromic windows are discarded because of the blue tint that modifies the perception of the indoor space. On the contrary, the Liquid Crystal is considered as an option because it has a fast switching time and it changes light transmittance with a grey scale. Finally, the Ch-LC is considered for the possibility to control the solar heat gain maintaining a clear state. Among the more traditional options, the venetian blinds are considered due to the high level of flexibility. However, the option to implement this product with other technologies will be considered with the aim of increasing its visual and thermal properties.

	Passive		Active				
				Electrochromic			
	Photochromics	Thermochromics	Gasochromic	Liquid Crystal Device (LCD)	Suspended Particle Device (SPD)	Cholesteric Liquid Crystals (Ch-LC)	Electrochromic polymers (EC)
Activation	light	temperature	diluted hydrogen	voltage	voltage	voltage	voltage
Transparency	yes	yes	no	yes/no	yes	yes	yes
Colour	variable	variable	blue	variable	cobalt blue state	-	blue
Time	sec-min	sec-min	20 sec - 1 min	1-2 sec	<1sec	1-2 sec	5-10 min
Electricity	no	no	no	switching and mantaining	switching and mantaining	yes	just switching
Cost	-	low	-	high	high	high	high

Figure 3.19: Overview of the different smart technologies

3.7 Case studies

After the analysis of smart materials and adaptive technologies, some case studies have been taken into account to understand how these solutions are applied in existing products and which are their performances. The comparison between them will help coming up with a solution that takes into account and combines the advantages of every aspect. Every case study is described and their characteristics are resumed in a table to have a clearer overview of the current available solutions. For each product pro and cons are mentioned, as well as the potential improvements, to explain why one solution is preferable to another.

3.7.1 licrivision™, Merck

licrivision™ (Appendix A, Products) is a product developed by Merck that applies a layer of dyes and liquid crystals between two panes of glass to control the amount of solar radiation passing trough the window. The layer switches from a clear to a darker state when a voltage is applied and therefore it is a closed-loop system. Centrally to the common applications of liquid crystals that offer an opaque state with the aim of providing privacy, Merck provides an interesting variation with the possibility to switch the tint of the glass from clear to dark, maintaining the transparency. The latter is not an unique quality if compared with Electrochromic or Suspended Particles products, but what is relevant is the colour of the tint that varies in shades of grey, instead of blue, representing a big advantage in terms of quality of the colour. Another advantage of this solution is the switching speed that is less than a second, assuring a fast response, particularly useful in the Dutch weather conditions. Both an automatic and manual control is possible and this allows customising the façade according to the user's needs. Currently, the product is not available on

Figure 3.20: Application of licrivision™ in Innovation Center in Darmstadt, Germany. *(www.merckgroup.com)*

the market, but it has been applied in the Modular Innovation Center in Darmstadt, Germany. The disadvantage of this solution is the cost that starts from around 800 euros/m^2 with the prediction to decrease to around 300 euros/m^2. (Further info: www.merckgroup.com).

3.7.2 SageGlass, Saint-Gobain

SageGlass (Appendix A, Products) is a smart window developed by Saint-Gobain that uses electrochromic glass as smart technology to maximize the solar energy and minimize glare and solar heat gain. This product is a closed-loop system that changes its tint according to the amount of voltage that is applied, varying its visibility from 60% to 1% and reducing the solar heat gain coefficient from 0.41 to 0.09. A negative aspect is that the glass changes with a blue tint that has an impact on the colour-rendering index. The application of the voltage can be automated thanks to light sensors, motion sensor, lighting control and thermostat or by the users' control. An advantage of this solution is the multi-zone tinting that is the possibility to colour portions of the same glass independently from each other, without the necessity to divide the glass with a frame. A disadvantage is that the switching time is between 7 and 12 minutes and therefore this solution is not the most appropriate for the Dutch weather conditions. (Further info: www.sageglass.com)

Figure 3.21: Example of application of SageGlass. (www.sageglass.com)

3.7.3 ECONTROL®, EControl-Glas

ECONTROL® (Appendix A, Products) is a dimmable solar control glass developed by EControl-Glas that uses electrochromic glass to vary the tint of the glass and therefore its light transmittance and solar factor. According to the shade of the glass, the light can be transmitted from 10% to 56%, maintaining a level of brightness even in its darkest state. As all the smart glazing, this solution protects the indoor climate during summer and reduces glare maintaining the view to the outside. Disadvantages of this product are the colour, that transmits a blue light inside the building, and the dimming time that takes 20-25 minutes. The control can be automated or by the users. (Further info: www.econtrol-glas.de/en)

Figure 3.22: Example of application of Econtrol®. (www.econtrol-glas.de/en)

3.7.4 CONTROLITE®, Danpal®

The system developed by Danpal® is a translucent glazing panel with integrated louvers that rotate according to the amount of solar radiation with the goal of optimizing the daylight transmission and the solar heat gain and reducing the energy consumption due to heating, cooling and artificial lighting (Appendix A, Products). The rotation of the louvers regulates the amount of daylight, but also provides an extra layer that reduces the SHGC and decreases the U-value of the façade. The system is a closed-loop because the adaptation is a consequence of the information detected by external and internal sensors, assuring a balance of the light levels and solar heat gain. A manual control by the user is also possible. Because of the translucent material that composes both the louvers and the panels that contain them, the result is a very diffuse light that enters the building, but a big disadvantage is that the opacity of the surface does not allow the view to the outside. (Further info: www.danpal.com)

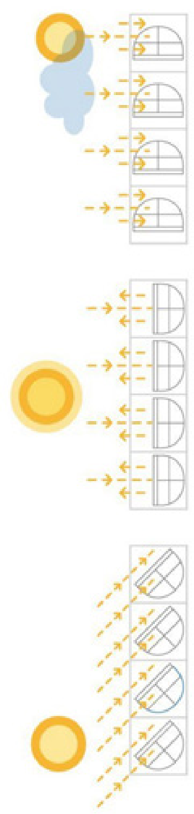


Figure 3.23: Scheme of the mechanism of Controlite®. (www.danpal.com)

3.7.5 Polyarch, TU Delft and TU/e

Polyarch (Appendix A, Research projects) is a project developed by TU Delft in collaboration with the Department of Functional Organic Materials and Devices at the TU/e. The goal is the production of a responsive coating of Cholesteric Liquid Crystals. Differently from the coatings analysed before, this technology operates on the infrared spectrum, resulting invisible to the human eye. The result is an adaptive coating that controls the amount of solar heat gain entering the building, working as a thermal regulator and reducing the energy required for heating and cooling. By extending the domain to the visual spectrum, this technology has the potential of regulating also glare and transmittance of visible light. The product has still to be further developed to eliminate some drawback like the dependency on the light angle that can cause a colour disturbance at some incident light angles. In addition, to reflect the infrared spectrum (750-1100 nm) three right-handed and three layers of left-handed CH-LC layers are necessary, for a total of six layers. Therefore, further developments are necessary to reduce the number of layers needed to cover the IR bandwidth. Compared with a static coating, this technology can reduce the energy demand for cooling by about 15% on a south facing office (Khandelwal 2017). (Further info: https://www.4tu.nl/bouw/en/LHP2015/Polyarch/)

Figure 3.24: Scheme of the Polyarch concept. (https://www.4tu.nl/bouw/en/LHP2015/Polyarch/))

3.7.6 Kindow Binds, Kindow

Kindow Blinds (Appendix A, Products) are an indoor solution for daylight control that are composed by vertical slats made of two different materials: on one face a highly reflective material reflects the solar radiation back to the window in summer and on the other side a dark absorbing material gains heat during winter. The face exposed to the sunlight depends on the season. Every blind can rotate thanks to a sun-tracking device that optimizes the angle of the blinds in relationship to the angle of incidence of the sun. The result is 25% of saved energy on lighting, heating and cooling. As consequence, also the amount of view and the portion of the outside environment change over the day. Because the blinds are positioned on a rail and change position automatically, the result is a very uniform façade. When there is no sun, the blinds automatically go back to a fixed position that optimizes the amount of daylight. Even if the sun tracking technology allows having the optimal rotation angle, the users can customize the position of the blinds according to their preferences. (Further info: www.kindowblinds.com).

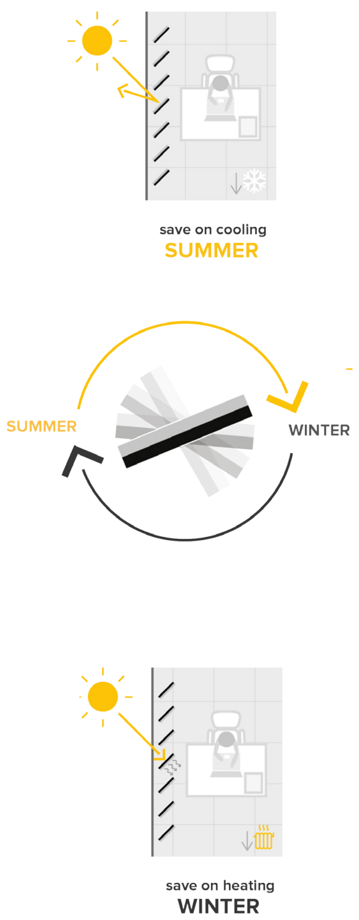


Figure 3.25: Scheme of the mechanism of Kindow. (www.kindowblinds.com)

3.7.7 PowerWindow, Physee

PowerWindow (Appendix A, Products) is a transparent double-paned window that converts light into electricity. It functions thanks to a transparent coating that redirects the light to the edges where PV cells are located to convert this light into electricity. A positive result is that the light is not reflected from the window to the outside and this helps decreasing the heat island effect in the city. Currently, the window can have integrated venetian blinds for the daylight control, but this window is here taken into account for the possibility to integrate smart glass that locally produces the energy needed to function. (Further info: www.physee.eu).

Figure 3.26: PowerWindow (www.physee.eu)

3.7.8 iSolar Blinds, LCG

iSolar Blinds (Appendix A, Products) are a transparent window insulator that allows natural daylight and control the solar heat gain. This is possible tanks to the design of this product that is made of a aluminium coated polyethylene sheet laminated to a sheet of carbon graphite later perforated and laminated to a sheet of clear polyester. Each side of the material has a different benefit on the indoor climate: the aluminium side reflects the solar radiation and it is displaced to the outside during summer and to the indoor space during winter to maintain the heat into the building. The carbon graphite is a dark non-reflective layer that faces outward during winter, absorbing the heat and releasing it into the indoor space. This solar control technique allows saving up to 40% of energy costs. (Further info: www.lcgenergy.co.uk).

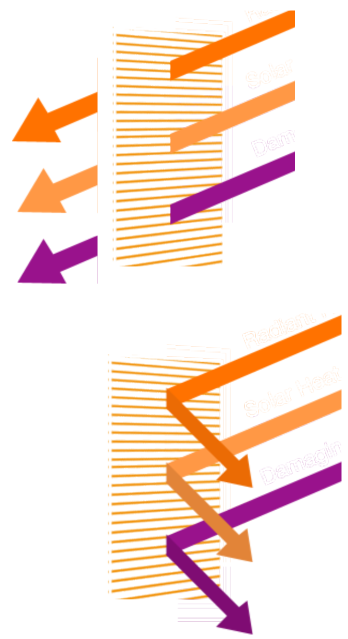


Figure 3.27: Scheme of the mechanism of iSolar Blinds. (www.lcgenergy.co.uk)

3.7.9 LCG® Films, Gauzy

Gauzy uses Polymer Dispersed Liquid Crystals Films for lighting control (Appendix A, Products). The company has developed different solutions that change transparency when a voltage is applied. The film can have a white or dark dimming option that can be atomized or controlled by the users. An interesting possibility offered by this product is the chance to project on the glass to have the additional functions of advertisement. The complete opacity condition allows having HD images, but the disadvantage is that it obstructs the view to the outside. (Further info: www.gauzy.com)

Figure 3.28: Image of the projection on a facade with the LCG® system. (www.gauzy.com)

PRODUCT	TECHNOLOGY	PROS	CONS	IMPROVEMENTS	COMBINATION WITH OTHER TECHNOLOGIES	COMBINATION WITH OTHER PRODUCTS
licrivisionTM Merck	Liquid Crystals	– Transparency – Fast switching time – Neutral tint – Design freedom – Low maintainance	– High cost – Energy consumption during the operation time	– Production of energy to reach an energy neutral system – Energy production	– Switchable coatings – PV cells	– Kindow – PolyArch – iSOLAR Blinds – PowerWindow
ECONTROL® GmbH & Co.	Electrochromic glazing	– Transparency – Design freedom – Energy consumption just during the switching time – Low maintainance	– Blue tint – Long switching time	– Grey tint – Faster switching time – Seprate thermal control from lighting control	– PV cells	– Kindow – PolyArch – iSOLAR Blinds – PowerWindow
SageGlass Saint-Gobain	Electrochromic glazing	– Transparency – Design freedom – Energy consumption just during the switching time – Shading zones – Low maintainance	– Blue tint – Long switching time	– Grey tint – Faster switching time – Seprate thermal control from lighting control	– PV cells	– Kindow – PolyArch – iSOLAR Blinds – PowerWindow
Controlite® Danpal®	Vertical louvers	– Solar heat gain control – Reduction of energy for heating and cooling – Easy asembling – Easy maintenance	– Translucent surface	– Transparency surfce – Daylight control – Thermal control	– Switchable coatings – Smart glass	– licrivisionTM – ECONTROL® – SageGlass – PolyArch – iSOLAR Blinds – Kindow – LC Films - Gauzy
Kindow Binds Kindow	Vertical indoor movable solar blinds	– Allows daylight – Thermal control	– Partially obstruction of the view	– Transparency – Daylight control	– Smart glass	– licrivisionTM – ECONTROL® – SageGlass – PolyArch – LC Films
Integrated venetian blinds	Horizontal integrated solar blinds	– Redirection of the light – High adaptivity – View to the outside – Low maintenance	– Possible glare effect caused by the material – View obstruction in determined positions	–Transaprecy/ translucency of the louvers	– Switchable coatings – Sun tracker – Smart glass	– licrivision – ECONTROL® – SageGlass – Kindow – PolyArch – iSOLAR Blinds – LC Films - Gauzy
External venetian blinds	Horizontal external solar blinds	– Redirection of the light – High adaptivity – View to the outside	– Possible glare effect caused by the material – View obstruction in determined positions – High maintenance	– Transaprecy/ translucency of the louvers	– Switchable coatings – Sun tracker – Smart glass	– licrivisionTM – ECONTROL® – SageGlass – Kindpw – PolyArch – iSOLAR Blinds – LC Films - Gauzy
PolyArch	Cholesteric Liquid Crystal	– Transparency during every stage – Design freedom – Invisible to the human eye	– Highly dependent on the light's angle of incidence – Necessity of at least two layers because of the structure of Ch-LC – No daylight control	– Reduction of layers – Daylight control	– Smart glass – Turning louvers	– licrivisionTM – ECONTROL® – SageGlass – Controlite® – Kindow – LC Films
iSOLAR Blinds LCG	Aluminum coated Polyethylene, carbon graphite, clear polyester	– Seasonal adaptation – Transaprency	– No daylight control	– Daylight control	– Smart glass	– licrivisionTM – ECONTROL® – SageGlass – LC Films
LC Films Gauzy	Liquid Crystals	– Fast switching time – Neutral tint – Design freedom – Low maintainance – Possible media purpose	– Transluent	– Transparency – Energy production	– Switchable coatings – PV cells	– Controlite® – Kindow – PolyArch – iSOLAR Blinds – PowerWindow
PowerWindow Physee	PV cells	– Transparency – Energy production	– No thermal control – Daylight control that obstructs the view	– Daylight conrol – Thermal control	– Smart glass – Switchable coatings	– licrivisionTM – ECONTROL® – SageGlass – PolyArch – LC Films - Gauzy

Figure 3.29: Table of the quality and possible improvements of each analysed product

3.7.10 Conclusions

The case studies just mentioned represent an overview of the products currently available on the market that have an innovative aspect compared with the traditional solutions. All of them have positive qualities that can be combined together with a new product to achieve a unique solution that satisfies visual and thermal comfort (figure 3.29). In particular, among the solutions that apply smart glass, the most interesting ones are licrivision™ by Merck and LCG Film by Gauzy because they use Liquid Crystals that have a fast switching time and a grey tint. The advantage of Merck is its transparent quality, while Gauzy has the possibility to project images on the dimmed surface. These are two strong aspects and a decision can be made according to the single specific building. In terms of costs, the possibility to project on the façade has a big advantage because it would add quality to a very expensive product. Polyarch is a very interesting application for the control of solar heat gain and it can be applied in combination with other solutions that control the visual comfort. The same consideration can be done for iSolar Blinds and Kindow Blinds that show how a traditional adaptive technology, as the rotating slats, can be combined with a static solution, as a coating, to obtain a more efficient product.

However, these products use technologies that are still under development and they will increase their performance in the upcoming period. In particular, the layer of LC has been taken as example from the product licrivion™ by Merck that will be lately described. This solution has the smart window that consists of four glass panels of 4mm each that enclose the LC film. It is expected that in the future the amount of glass will be reduced to two panes that enclose one film. The same consideration is necessary for the Ch-LC window that, because of its geometry, needs two films of Ch-LC to cover a portion of the spectrum. In conclusion, the new project can be design theoretically, assuming a development of the smart glass in the near future.

4 DESIGN

The design phase was guided by the environmental conditions of the location and the indoor requirements of an office space, in order to provide a façade solution that responds to indoor and outdoor stimuli to provide visual comfort and decrease the energy demand of the building. The final design strategies, the technologies and the materials applied are the result of the research phase previously described, a dialogue with Rollecate Group® and the outcome of the simulation phase.

4.1 Environmental conditions

The office building considered is located in the Netherlands and the climate data refer to the area of Amsterdam. In particular, what is relevant for this research is the data regarding the amount of solar radiation and the temperature over the year.

As shown by the graph in figure 4.1, the average maximum temperature is 12°C and the warmest month is August with an average maximum temperature of 20°C. On the other side, the average annual minimum temperature is 5°C and the coolest month is January with an average minimum temperature of 0°C (Information 2018).

However, the data about the temperature trends shows that the temperature is increasing in the last decades, in particular during spring and autumn (figure 4.2) (CBS 2018). Moreover, in the Netherlands, the weather conditions vary continuously and with a high speed during the day and over the month. Therefore, what can be concluded from this data is that the high climate variation and the future scenario require

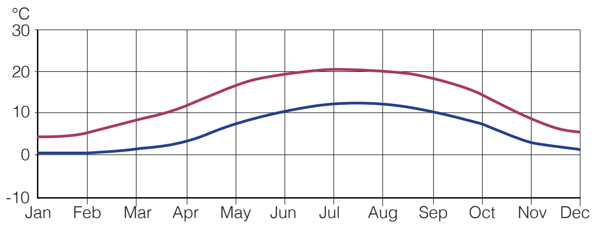


Figure 4.1: Average max (red) and min (blue) temperature in Amsterdam, Netherlands. (www.weather-and-climate.com)

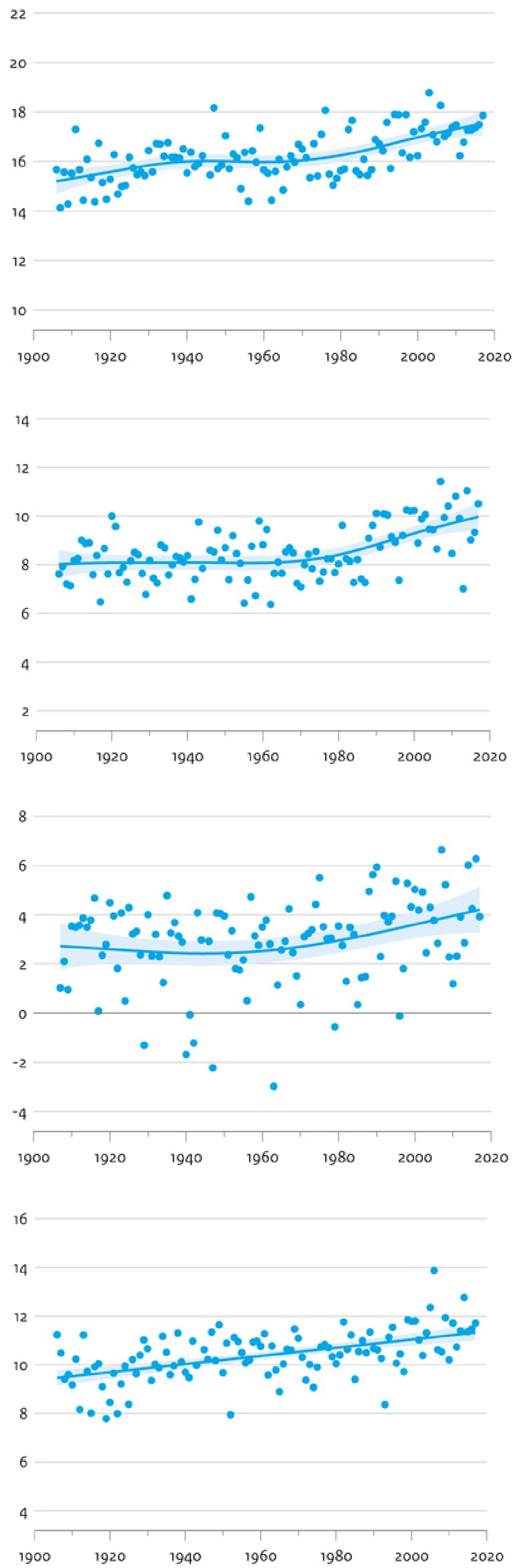


Figure 4.2: Trend of summer, spring, autumn and winter temperature. (www.clo.nl/nl022613)

a building with adaptive conditions in particular of the envelope, to maintain stable indoor comfort.

Because the design is focused on the visual comfort and the regulation of the solar radiation, the monthly sun hours and the average percentage of sunshine in Amsterdam have been considered (figure 4.3-4). Moreover, the relationship between office building and solar radiation can be seen in the sun path diagram shown in figure 4.5, that gives information about 21st March, 21st June and 23rd December at 10:00, 13:00 and 16:00.

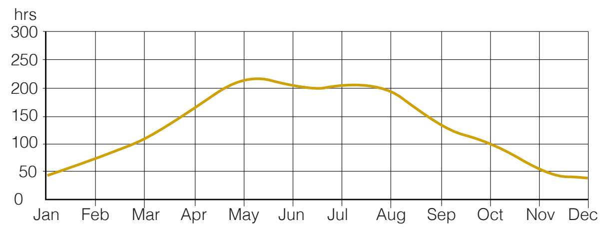


Figure 4.3: Average monthly sunhours in Amsterdam. (www.clo.nl/nl022613)

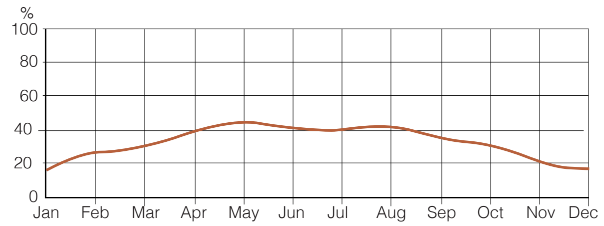


Figure 4.4: Average percent of sunshine in Amsterdam. (www.clo.nl/nl022613)

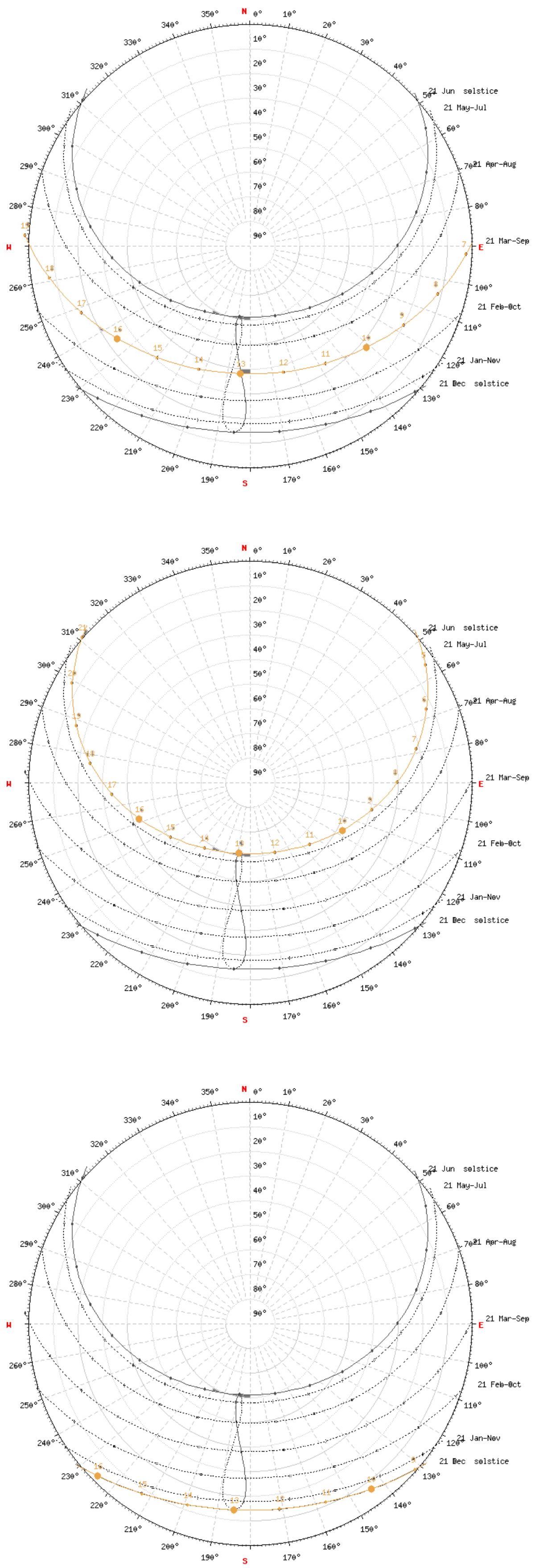


Figure 4.5: Solarpath of March, June and December in the three hours considered (10:00, 13:00 and 16:00). (www.sunearthtool.it)

4.2 Façade composition

The composition of the façade takes into account the previous observations about the daylight management. Moreover, the relationship between user and façade has been considered, in particular regarding the aspects related to the visual comfort. Therefore, the façade has been divided horizontally into three parts at a height of 0.8m and 2.2m. This decision has been made in relationship to the user: these measures correspond respectively to the height of the office desk and the visual field of a standing person. In particular, these three areas have three different functions in relation to the user's comfort and specifically, the upper part increases the amount of daylight into the indoor space; the middle area offers view and daylight and the lower side provides the connection to the outside (figure 4.6). These three sections can be treated differently to control the solar radiation and therefore the impact on the visual and thermal comfort. Furthermore, the façade is divided vertically with a rhythm of 0.9 m that, together with the horizontal division, provides a grid that allows a higher freedom for the independent control of each portion of the façade. The construction typology has been discussed with Rollecate that stabilized one possible product for three possible construction typologies:

- Window: RT 72 Reflex Aluminium Windows, Kawneer;
- Curtain Wall System Construction: AA 100 Q Aluminium Curtain Walls, Kawneer
- Unitized System Construction: Schüco Façade USC 65

Among these, the unitized system has been chosen because of the advantage of having a more controlled environment during construction and assembly and because this system reduces the construction time on-site. However, this system is more advantageous for multi-store buildings and therefore, the construction typology can vary according to the project. More detailed information about the façade composition will be provided in the section related to the technical drawings.

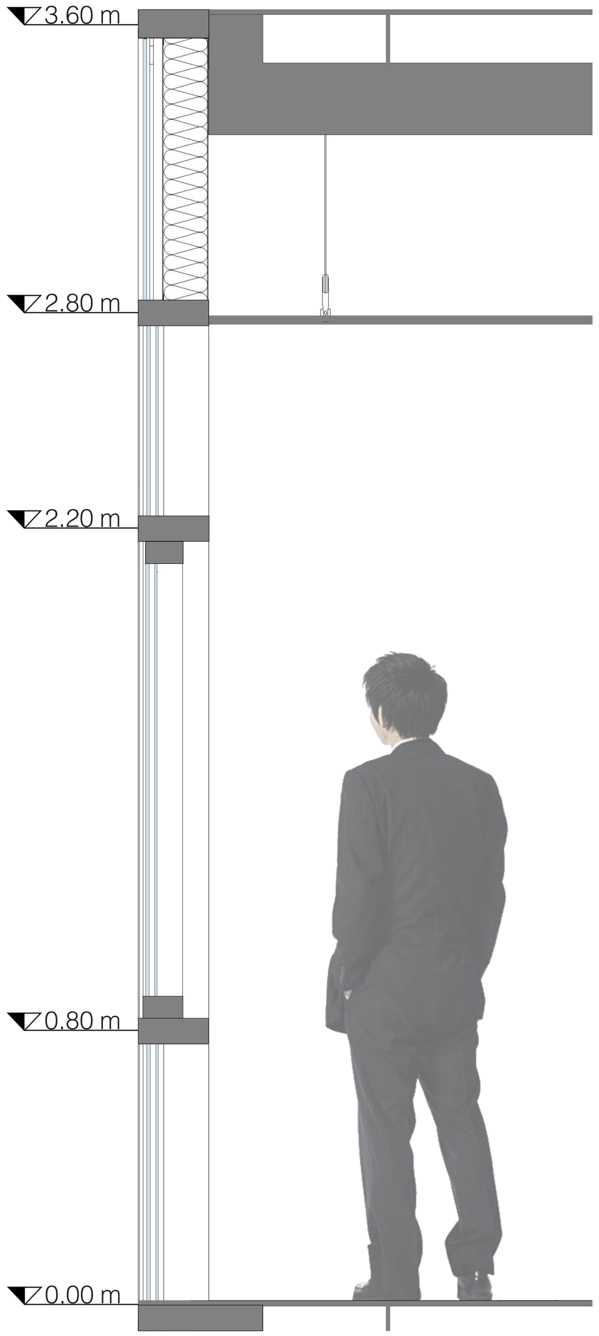


Figure 4.6: Relationship between facade division and user

4.3 Window technology

The façade of this design is fully glazed due to the trend, analysed before, of increasing the transparency of the envelope in order to increase the amount of daylight and view to the outside. However, the design has to deal with the disadvantages that this aspect brings, like glare and overheating. Therefore, the aim of this research is to find a shading option that controls the solar radiation for optical and thermal purposes in order to decrease the energy consumption for lighting, heating and cooling. To do that, as previously explained in the problem statement, the visible light and the infrared should be regulated separately and the conclusions deduced by the analysis on the different materials and technologies are here applied to achieve this type of control.

In particular, the strategy chosen to control the visible light is a smart window with a layer of liquid crystals that can change shade according to the user's preferences and it can be automatically controlled according to specific requirements of comfort. In particular, a special relevance was given to the glare perception because this is a significant source of discomfort and regulating it can highly increase the working conditions of the users. In particular, one of the aim is to understand how the different subdivisions of the façade can change tint according to the glare perceived by the user and how this influences the illuminance level into the indoor space and therefore the consumption of energy for lighting.

At the same time, according to the indoor temperature, the infrared hitting the façade should be transmitted during the heating season and reflected during the cooling season helping decreasing the energy consumption for heating and cooling. To achieve this goal, two main solutions have been individuated. The first one is to add a second transparent coating of Cholesteric Liquid Crystal (Ch-LC) that, as previously described, can reflect different percentages of infrared when electricity is applied. To help maintaining the indoor climate to a comfort level, this layer should be triggered by the indoor temperature. The advantage is that the Ch-LC film does not influence the visual spectrum resulting completing transparent to the user.

The second possibility has been inspired from iSolar LCG® and Kindow Blinds and consists in perforated venetian blinds, coated with a reflective material on one face and an absorptive material on the other. However, as it can be shown in the figure 4.7, the reflectance of the element is not due to a chemical variation of the material, but depends on the density of the perforation of the venetian blind and therefore the transparency of the material is inversely proportional to the infrared reflection. Consequently, to increase the reflectance of the infrared, the visibility and the

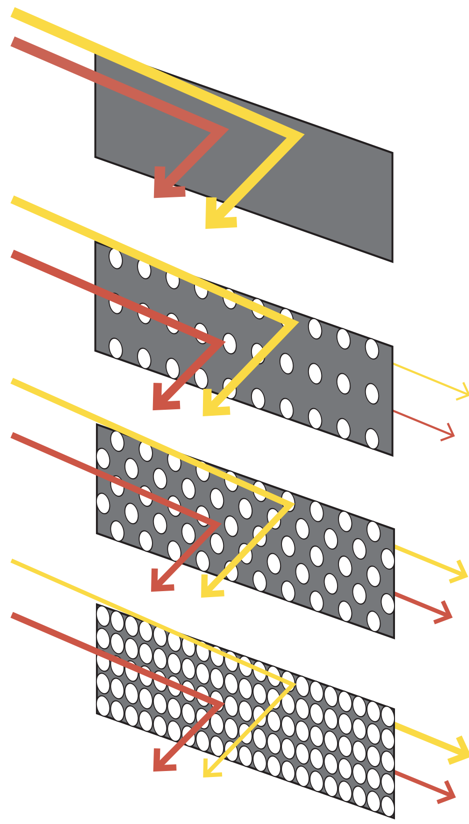


Figure 4.7: Scheme on the relationship between perforation percentage and solar transmittance

amount of daylight would be also compromised. Therefore, between the two options, the layer of Ch-LC will be take into account for the further analysis and simulation.

In conclusion, the design is a unitized system that combines a layer of Ch-LC to control the infrared and a layer of liquid crystals to control the visible light (figure 4.11). The differentiation between the panels is a further level of adaptivity of the design because, according to the user's comfort, the panels can be adjusted separately. For example, in case of glare, just the panels that include the glare source will become darker while the rest of the façade will maintain transparency and therefore will transmit daylight into the indoor space (figure 4.9-10). In the same way, the layer of Ch-LC can influence the indoor climate only in certain spaces like for example in the area under the desk or, if desired, directly

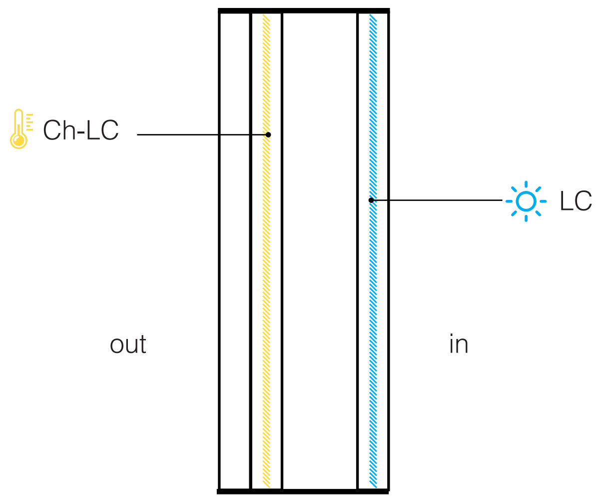


Figure 4.8: Combination of one layer of Ch-LC for the control of infrared and one layer of LC for the control of visible light

in the space occupied by the user. The two layers are positioned as shown in the figure 4.8 and their performance will be tested, evaluated and eventually illustrated in detail in the further sections.

The new design option will be compared with other two more traditional adaptive solutions:

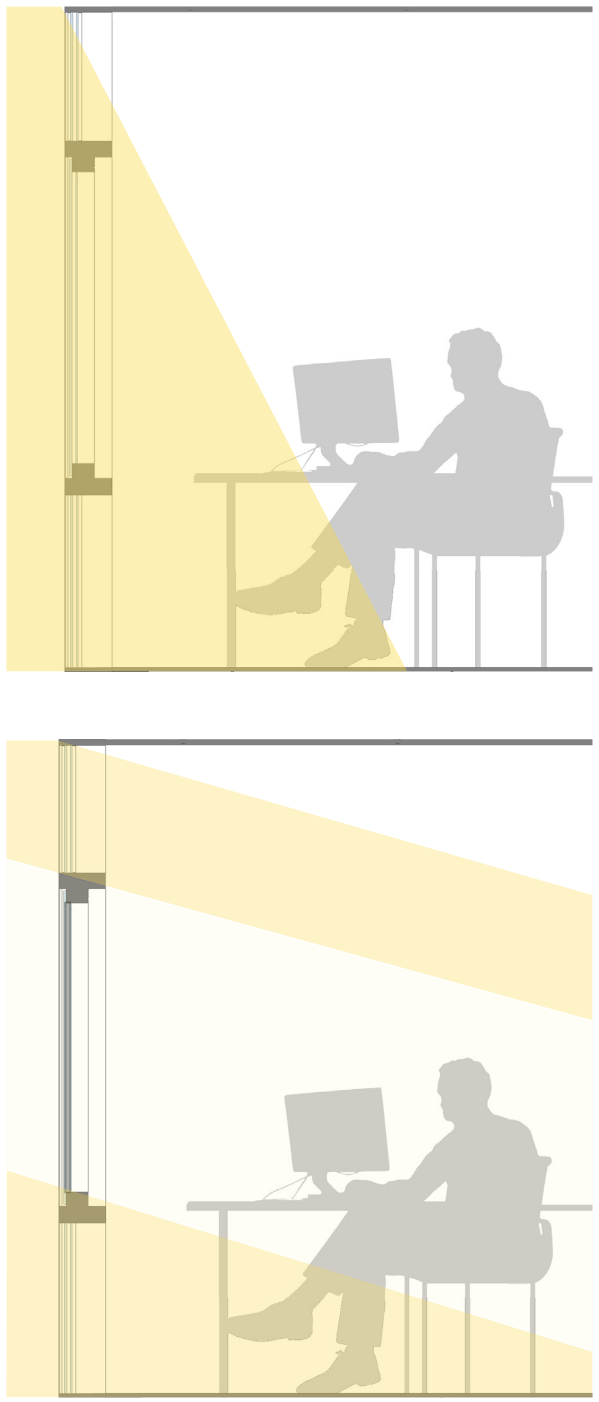


Figure 4.9-10: Regulation of the solar radiation according to the different position of the sun

external roller shading and integrated venetian blinds. These two products are effective mainly for daylight control, but they also work as a thermal barrier. However, the negative aspect is that they do not differentiate the control of visual light from infrared and therefore, in some cases, they do not perform in the optimal way for one of the two aspects.

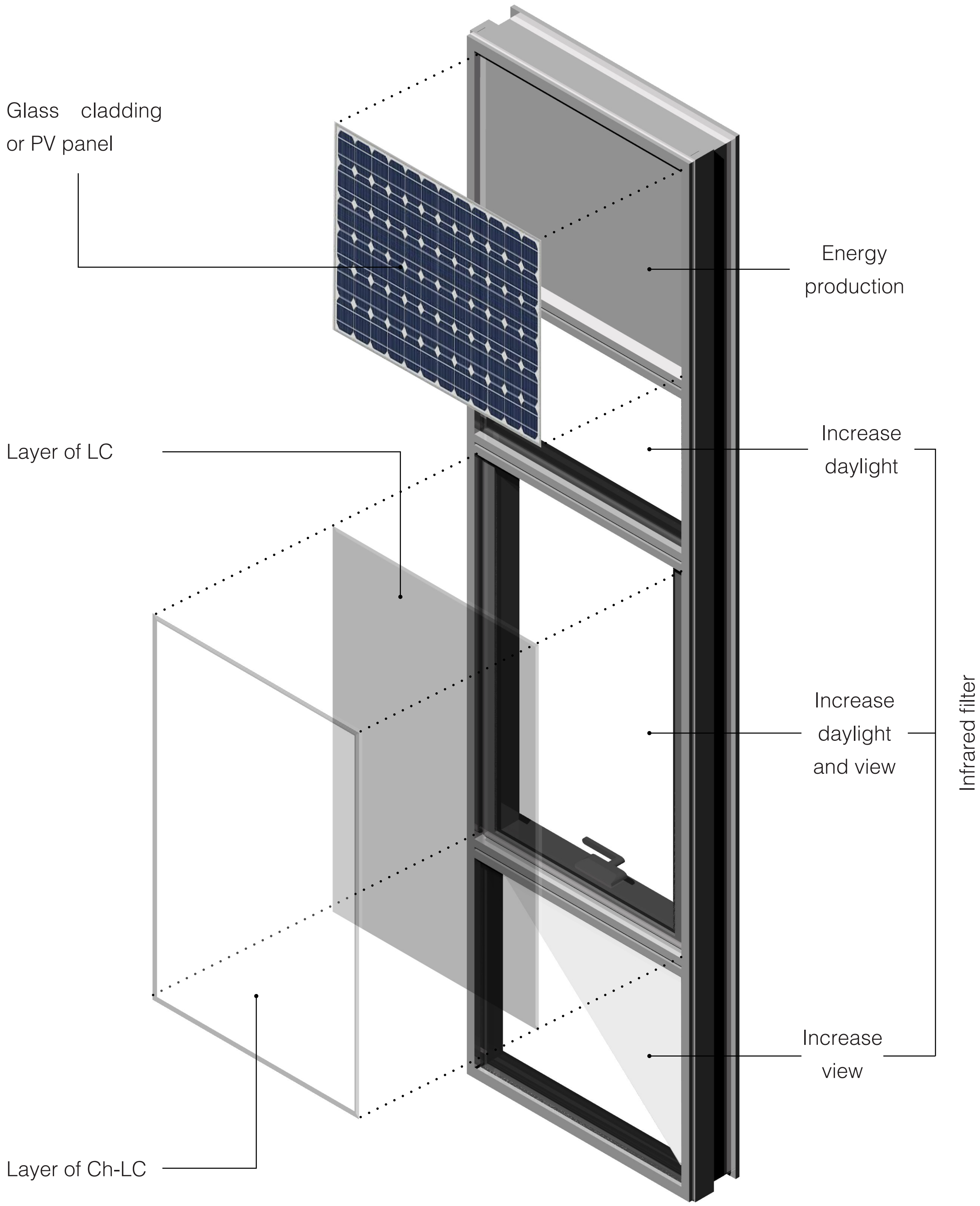


Figure 4.11: unitised system with the application of the new design.

Some additional functions like the energy production and the media purpose can be added to the new design option (figure 4.12). In particular, the production of energy could be integrated in the frame of the glass panel to produce the energy needed to operate and become an energy neutral product. However, both switchable windows and integrated PV cells in the frame are expensive solutions that therefore can hardly be combined. Moreover, the Liquid Crystal needs energy to maintain its clear state and therefore the hours when the PV cells produce energy are the hours when the Liquid Crystal does not require an electric field and therefore the direct connection between solar radiation, energy production and switchable glazing is missing. For these reasons, the energy needed to operate the glass can easily come from a different green energy source like a PV panel positioned in the upper portion of the unitized system (figure 4.11).

On the other side, the media purpose is an interesting application to combine with the switchable glazing because it extends the function of the façade after the office time, thanks to the possibility to project advertisement or videos on the dimmed glass. However, because of the typology of liquid crystal chosen for this design, the projection does not have the highest result because the glass maintains the transparency during its tinted state. However, according to the project, the type of smart glass can be substituted with a liquid crystal that changes its transparency. This additional function of the façade might be interesting for architectural reasons and could compensate the high cost of the switchable glazing.

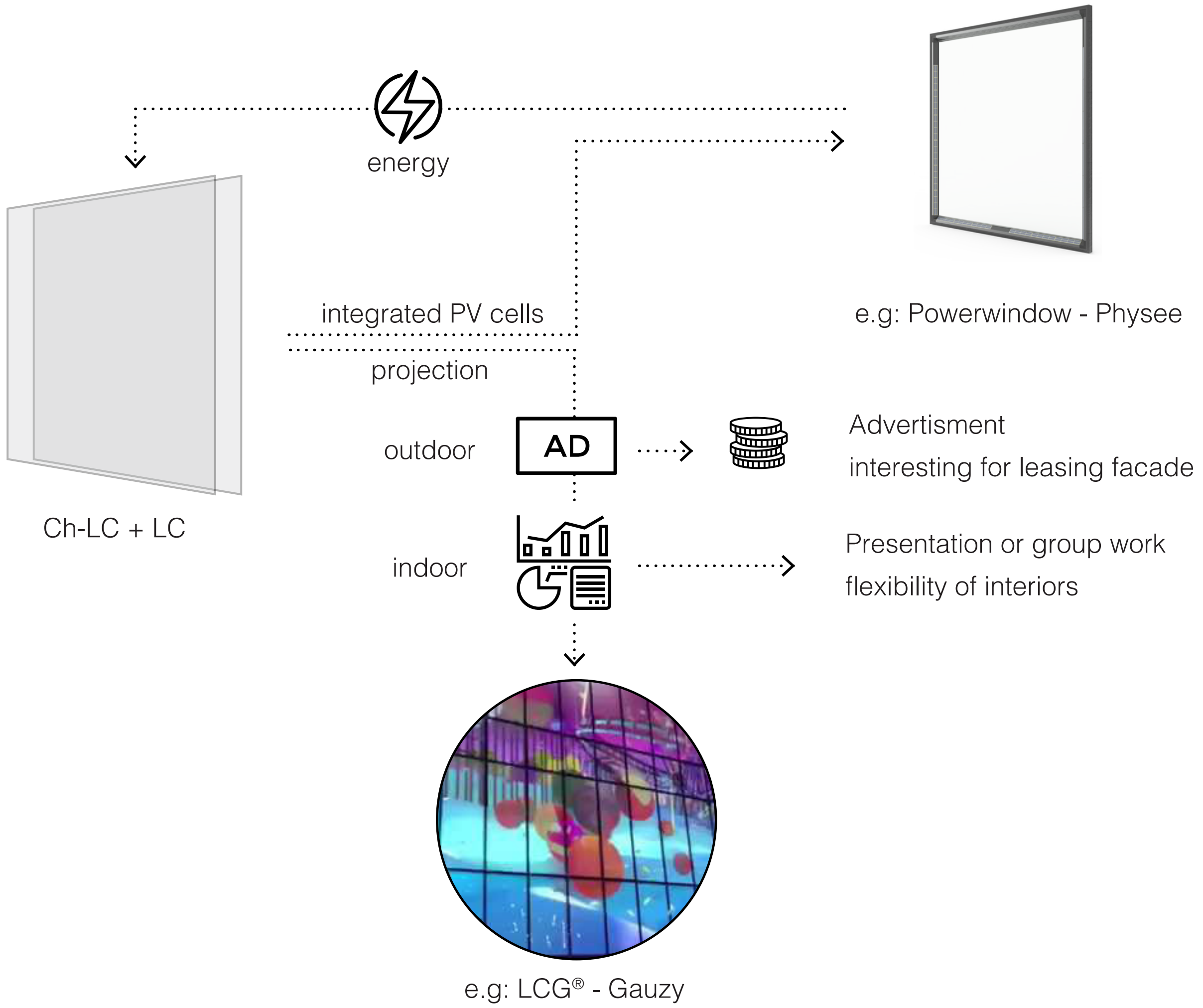


Figure 4.12: Scheme of the pssible additional functions

4.4 Simulation

The simulation takes into account an office space of 20 m² with a south facing façade of 3,9x3,6 m² (figure 4.14). In particular, the façade is divided with the grid mentioned in the previous paragraph and the three different design solutions are applied to each portion with an independent control between the different areas. The simulation of a three models with the three different façade typologies will help to evaluate the performances of the new design in comparison with the two traditional options. The simulation has been structured in two sections: firstly the visual comfort and the energy performances for lighting have been analysed by using the software DIVA for Rhinoceros and Grasshopper; secondly the thermal comfort and the energy performance for heating and cooling have been considered by using the software DesignBuilder.

Here the general logic behind the simulation is illustrated and later each simulation will be described separately (figure 4.13).

The office space is occupied by two users that require the specific levels of comfort mentioned in the chapter 3. Among them, the first goal is to increase the level of visual comfort by decreasing the glare perception. Therefore, the façade has been modelled with the three different shading systems regulated by the Daylight Glare Probability (DGP) for the users. To assess the performance of the new design option, the results have been compared with the two reference shading systems: roller shading and venetian blinds. The shading schedule determined by the DGP influences the amount of daylight and therefore the level of illuminance into the indoor space. In particular, the lowest the level of illuminance, the higher is the energy consumption

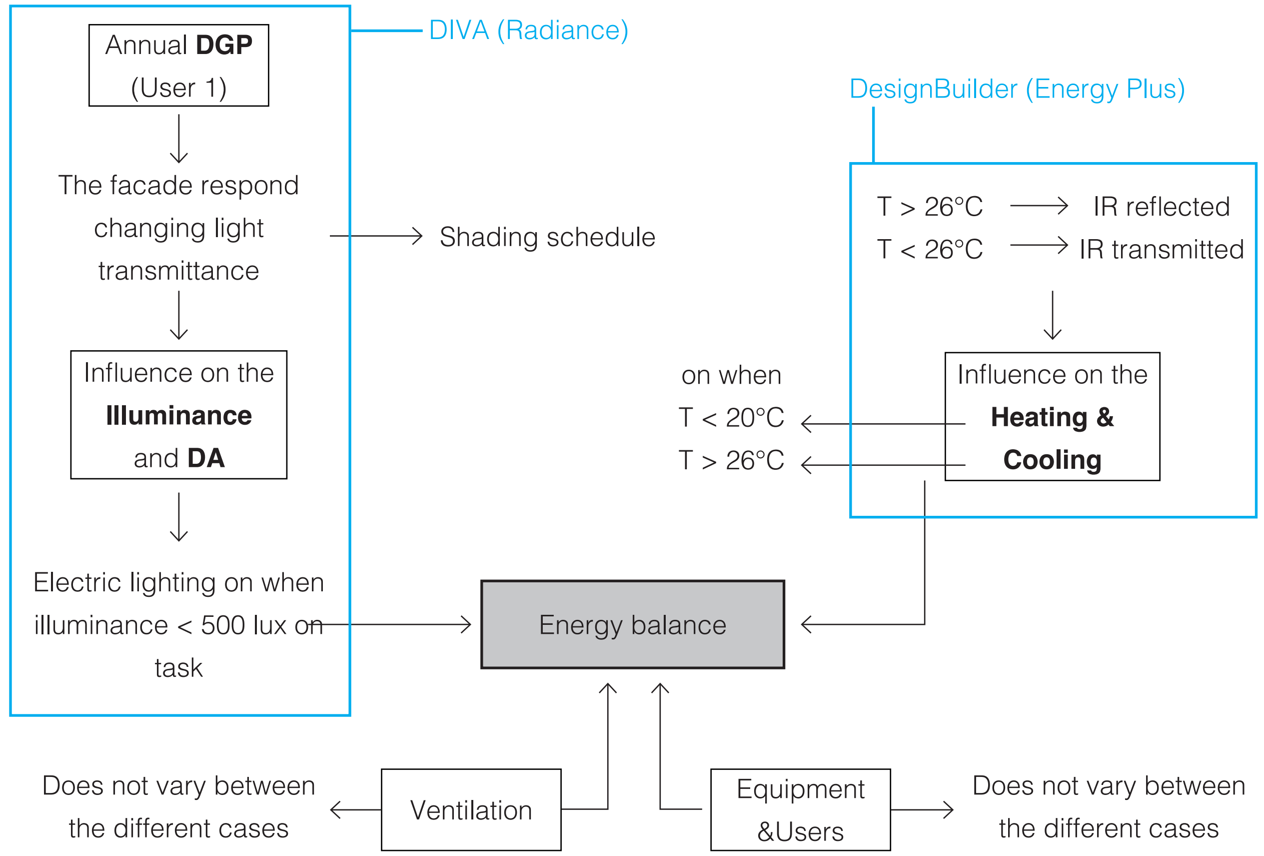


Figure 4.13: Scheme of the simulation's logic

for lighting needed to satisfy the illuminance requirements. At the same time, the influence that the different shading solutions have on the thermal comfort is considered to assess if these help in reducing the energy demand for heating and cooling. The energy demandààm for lighting, heating and cooling could be eventually added to the energy required for ventilation, equipment and users, to represent the entire energy balance of the building. However, this research does not take into account the last two parameters as design variables and therefore they are considered as constants in each simulation.

4.4.1 Visual comfort

The simulation software used for the daylight analysis is DIVA, a highly optimized daylight and energy modelling plug-in for Rhinoceros and Grasshopper. The office environment has been modelled in Rhinoceros and the simulation was obtained with DIVA that uses Radiance as its rendering tool. Radiance is a software that exclusively uses the raytracing technique for its calculation. In particular, this type of calculation follows the rays that hit the surfaces and takes in consideration how they are reflected back into more rays by the different materials. Because the software takes into account all types of surfaces, it was possible to obtain photorealistic images, false-colour maps and information on the illuminance levels and to have a prediction on the possible discomfort thanks to the Daylight Glare Probability (DGP) measurement. DIVA can also be used as a plug-in for Grasshopper, giving the possibility to create animations, allowing to see how a user perceives the indoor space during the day and therefore to assess the design according to the user prospective. In this simulation only the visual comfort and the energy used for lighting have been calculated.

4.4.1.1 Geometry and general settings

The office has an area of 3.6x5.4 m^2, a height of 2.8 m and is occupied by two users sitting in front of each other; in this way, it is possible to simulate the visual comfort for two opposite orientations. The desks are positioned in the middle of the room because in this way the area of the façade that influences the visual comfort is bigger and it is possible to observe how its subdivisions can behave differently to prevent glare. As previously explained in the design, the façade is divided horizontally in three areas at a height of 0,9m, and 2,2m and the vertically with a rhythm of 0.9m (figure 4.14-15).

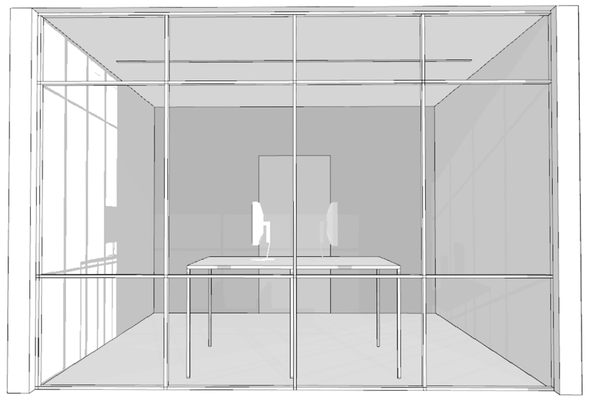


Figure 4.14: Image of the office model from outside

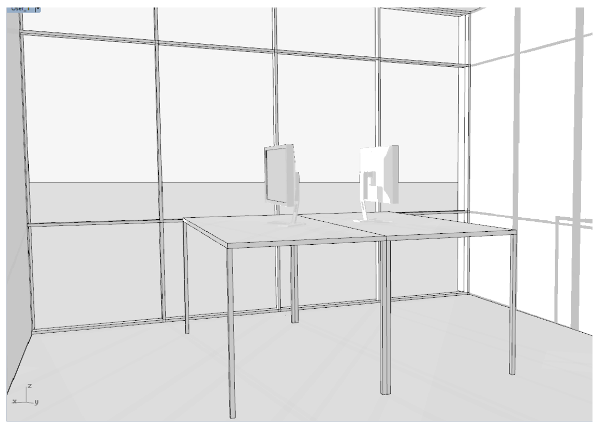


Figure 4.15: Image of the office model from inside

The office is located in the Netherlands and therefore the weather data of Amsterdam have been considered. The occupancy period has been calculated for an office with the working schedule from 9.00 to 18:00 from Monday to Friday. The DGP and the Daylight Autonomy have been calculated for the entire year, while the visualization of the indoor space has been considered for three days of the year: 21st March, 21st June and 23rd December. The level of horizontal illuminance has been measured at 10:00, 13:00 and 16:00 of the same days (figure 4.16).

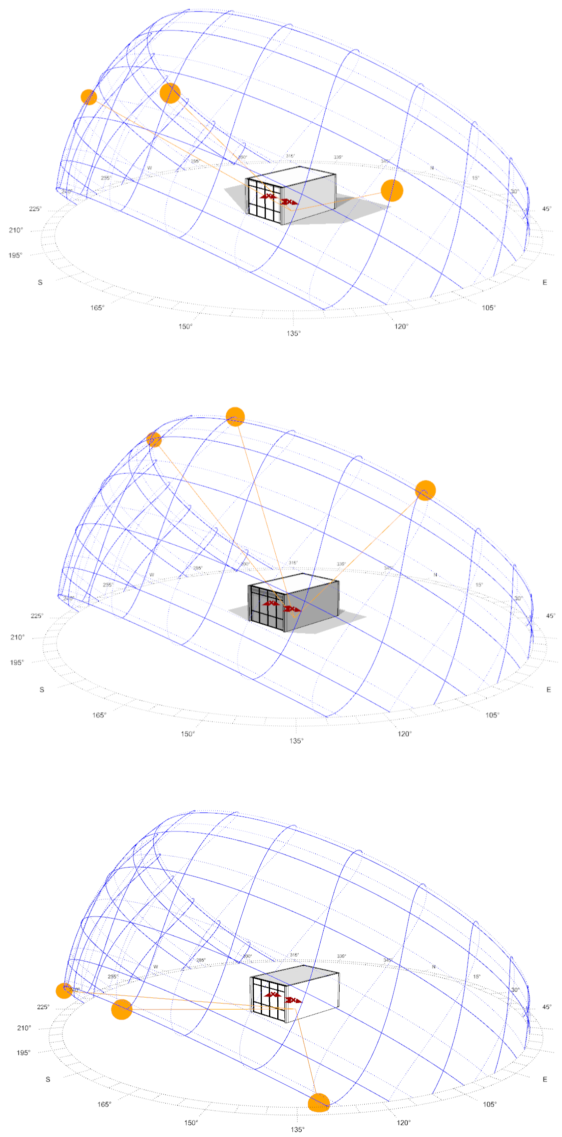


Figure 4.16: Sunpath on 21st March, 21st June, 23rd December at 10:00, 13:00 and 16:00

To measure the DGP and the level of illuminance, it was necessary to place sensor that detect these two parameters. In particular, the DGP is evaluated according to the users, while the horizontal illuminance along the office area. Therefore, in the first case, four cameras have been set: two for each user and specifically one that faces the computer and the other that faces the window. However, for simplification, the annual DGP has been measure only in relation to the User 1. Because of the orientation, it is predictable that the User 2 has similar conditions during the middle of the day and opposite conditions during the early morning and late afternoon compared to the User 1. The amount of illuminance that is relevant to detect is the one on top of the desks. Therefore, the sensors have been positioned on a grid of 0.9x0.9 m^2, at a height of 0.85 m (figure 4.17).

Electric lighting control

To provide enough illuminance, a light with a power of 250 W has been positioned on top of the two desks. Sensors for the electric lighting control have been positioned on top of the desks to determine the operation of the light that works with a dimming control to cover the level of illuminance required.

Materials

In every simulation, the materials that have been assigned to the geometry are the same for every part of the construction, except for the façade that changes condition according to the typology of glass and the shading system. The materials influence the light perception of the space due to the different levels of reflectance and absorbance of each material. However, because the office space took into account is a generic example, the materials that have been selected are generic:

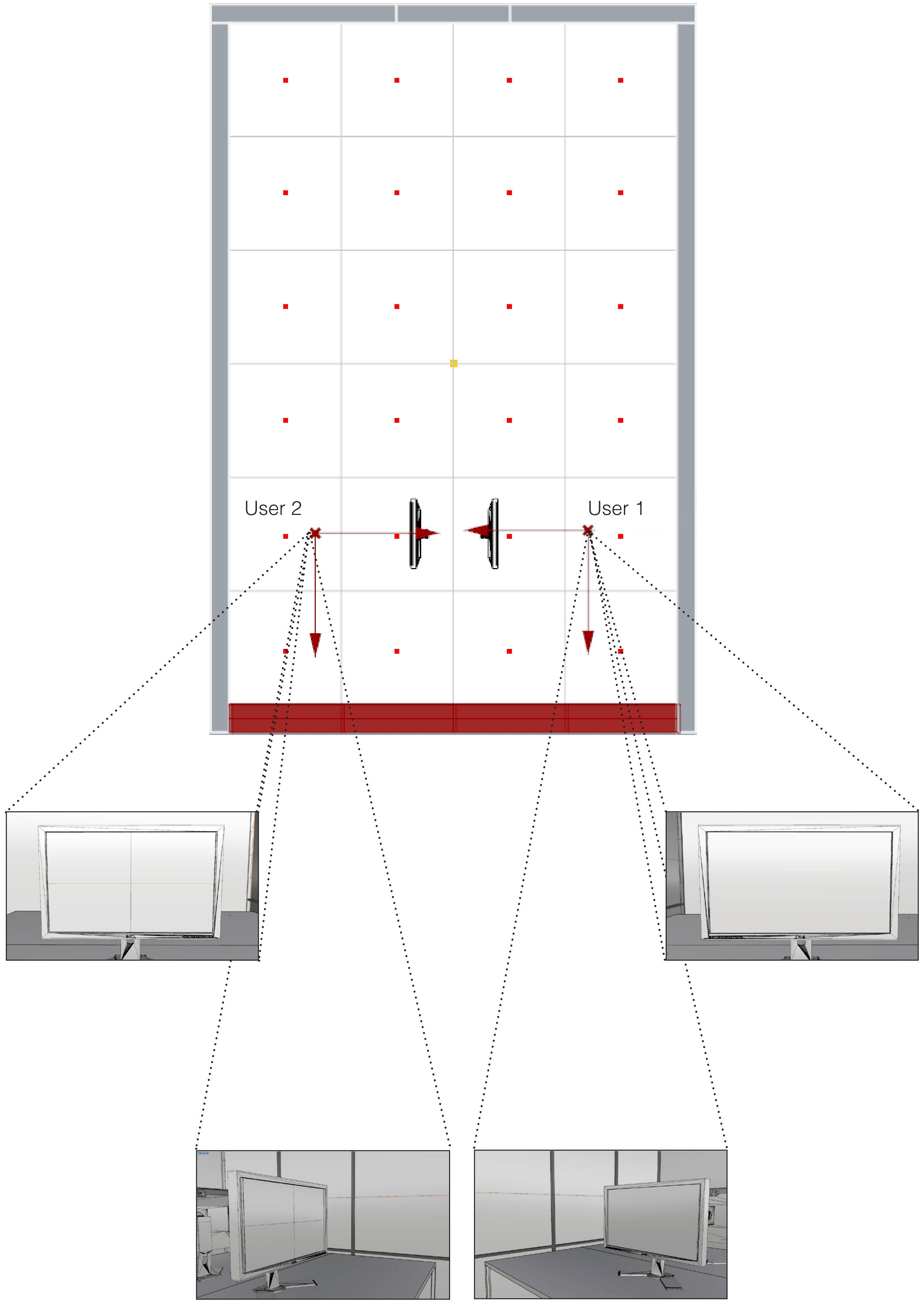


Figure 4.17: Position of the sensors in the horizontal grid and visualizations of the four views used to assess the DGP

Geometry	Material
Floor	GenericFloor_20
Walls	WhiteInteriorWall_70
Roof	GenericCeiling_70
Ground plane	OutsideGround_20
Furnishing	GenericFurniture_50
Mullions	SheetMetal
Monitor Screen	250cdm²_screen

On the contrary, the façade can vary according to the different options. A comparison between a reference model and the new design options has to be done to check the validity of the new design. In particular, the models are:

- Reference Project 1: Roller shading (figure 4.18)
- Reference Project 2: Venetian blinds (figure 4.19)
- New Design: Smart glazing (figure 4.20)

The materials and the shading control are here explained separately.

The shading thresholds are the values of illuminance that control the switching state of a shading element. When the amount of illuminance detected by the sensors, exceeds 3000lux, the shading system is positioned in its first state. If the level of illuminance falls into the requirements, the shading remains in this position until the amount of illuminance is too low and therefore the window returns unshaded. If the shading state was not enough to solve the discomfort, the shading system turns to the next shading position until the comfort is reached.

4.4.1.2 Reference project 1

Parameter	Setting
Glazing material	Glazing_DoublePane_ LowE_65
Shading typology	Roller shading

Figure 4.18: Reference project 1 - roller shading

Shading Control	
Shading material	RollerShade
Shading type	Mechanical
Operation	Automated glare control with occupancy
Base geometry layer	window
State 1 (off 600lux; on 3000lux)	Shading on top
State 2 (off 1000lux; on 3000lux)	Shading in the middle
State 3 (off 1000lux; on 3000lux)	Shading in both the areas

4.4.1.3 Reference project 2

Parameter	Setting
Glazing material	Glazing_DoublePane_ LowE_65
Shading typology	Venetian blinds

Figure 4.19: Reference project 2 - venetian blinds

Shading Control	
Shading material	SheetMetal
Shading type	Mechanical
Operation	Automated glare control with occupancy
Base geometry layer	window
Shading Group 1 - on top	
State 1 (off 600lux; on 3000lux)	Slats at 0°
State 2 (off 1000lux; on 3000lux)	Slats at 45°
State 3 (off 1000lux; on 3000lux)	Slats at 90°
Shading Group 1 - in the middle	
State 1 (off 600lux; on 3000lux)	Slats at 0°
State 2 (off 1000lux; on 3000lux)	Slats at 45°
State 3 (off 1000lux; on 3000lux)	Slats at 90°

4.4.1.4 New Design

One of the goals of this research is to understand if different parts of the façade can respond independently to each other to avoid discomfort. However, the software offers only two independent shading controls and therefore different configurations had to be tested analytically. However, a first simulation has been done automatically by the software in order to have a general idea on the variation of the shading state. The switchable technology used in the design project, is Liquid Crystal film, however, it is simplified in this simulation with the application of a generic electrochromic glazing already existing among the material database of DIVA. The material can change visible transmittance as follows:

Shading Control	
Glazing material	Glazing_Electrochromic_Clear_60
Shading type	Switchable
Operation	Automated glare control with occupancy
Base Glazing Material	Glazing_Electrochromic_Clear_60 (60% transmittance)
Shading Group 1 - on top	
State 1 (off 600lux; on 3000lux)	EC_Tinted_30 (30% transmittance)
State 2 (off 1000lux; on 3000lux)	EC_Tinted_02 (2% transmittance)
Shading Group 2 - in the middle	
State 1 (off 600lux; on 3000lux)	EC_Tinted_30
State 2 (off 1000lux; on 3000lux)	EC_Tinted_02

Figure 4.20: New design - switchable glazing

When the shading is automatically controlled, just the areas on top and middle vary the visible light transmittance in response to the amount of glare. On the other hand, in the analytical method, different portions with different shades have been tested as shown in the figure 4.21. The colour of each part of the façade indicates at which switchable state the glass has been set:

- White: Electrochromic glazing 60
- Light grey: Electrochromic glazing 30
- Dark grey: Electrochromic glazing 02

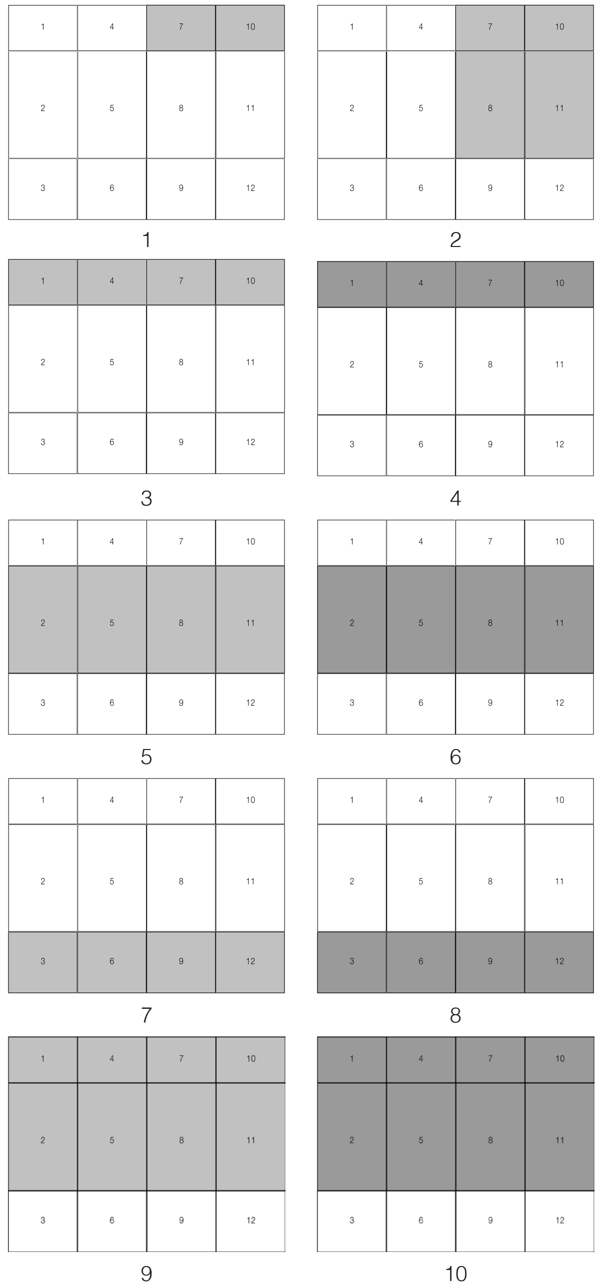


Figure 4.21: Different switchable states used in the analytical method

The annual DGP has been measured for each shading state and later the daily and annual shading schedule has been calculated by choosing, for each hour, the shading state that solved the glare perception with the lowest intervention. The comparison between the automatic and the manual results is fundamental to understand if there is an effective difference between the two control methods.

The simulation will determine:

- Annual DGP for User 1. This parameter will give the overview on the level of comfort perceived by the user over the year. The result is a schedule that indicated a range of DGP: intolerable (DGP > 0.45), disturbing (0.45 > DGP > 0.4), perceptible (0.4 > DGP > 0.35) and imperceptible (0.35 > DGP) (figure 4.29).

- The shading system works in function of glare and therefore the shading schedule obtained is the one that shows when the shading is operating over the year in order to maintain the DGP lower than 0.35 (figure 4.30).

- Annual Daylight Autonomy (DA) that indicates the percentage of the space that receives a level of illuminance above 300 lux over the daylight hours. This value is indicated in percentage and it can be represented in plan, giving information about every portion of the space. When the level of illuminance is below the requirements, the electrical light turns on with the intensity necessary to reach the comfort level. Therefore, the amount of electricity for lighting and the lighting schedule can be provided.

- Measuring the Illuminance in the room during specific moments can provide more specific information about the illuminance level during the day. The results have been collected at

10:00, 13:00 and 16:00 on 21st March, 21st June and 23rd December. The weather data of an average year in Amsterdam have been considered and therefore the results can highly differ between two consecutive days. However, what is relevant for this simulation is to compare the level of illuminance at the same hour on the same day under different shading solutions and therefore these nine simulations are sufficient because they cover the three azimuths with three different elevations of the sun.

- DGP for User 1-2 for both the views during the working time on 21st March, 21st June and 23rd December. This simulation offers wide prospective of the office thanks to the fisheye camera and it gives information about the illuminance level and the DGP in the space. With these visualizations is possible to obtain a time-lapse showing the variation of the façade during the day.

- Total energy demand for lighting. This value will be added to the other energy consumptions to obtain overall information on the energy balance of the office space.

4.4.2 Thermal comfort

DIVA for Rhino offers the possibility to simulate the energy performance for the thermal comfort by using Archsim Energy Modelling that uses EnergyPlus as simulation engine. However, this simulation tool has some limitations regarding the control of switchable gazing for thermal purposes because the control is focused on the lighting performance. Therefore DesignBuilder, that also uses EnergyPlus, has been used as simulation software. EnergyPlus is a building energy simulation program, developed by the US Department of Energy, that offers the possibility to simulate heating, cooling, lighting and ventilation and that uses other software, like DesignBuilder, as interface. In this research, it has been used only regarding the energy consumption for thermal purposes and to measure the level of comfort over the year.

4.4.2.1 Geometry and general settings

The models that have been simulated are:

- Reference project 1: Roller shading
- Reference project 2: Integrated venetian blinds
- New design: Liquid Crystals
- New design: Cholesteric Liquid Crystal
- New design: Liquid Crystals and Cholesteric Liquid Crystals combined

For all the simulations, the model and the general settings remain constant, while the only variation is the façade composition. Therefore, the model and the general settings are firstly explained and later the specific characteristics of the façade are described for each case. The general settings are reported in figure 4.23 and the information that is missing indicates that no variation has been done compared to the DesignBuilder template. The model is the same office space that has been considered in the DIVA simulation. The dimensions are therefore 3.6x5.4x2.8 m^3. The glazing façade has an area of 3.6x2.8m^2 and is south oriented (figure 4.22). The climate data and the environmental conditions refer to the location Amsterdam AP Schipol, in the Netherlands region.

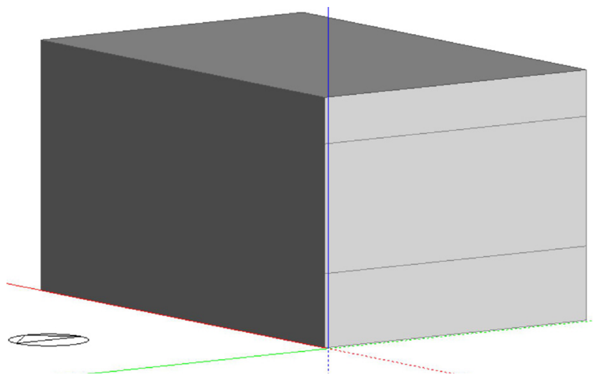


Figure 4.22: Office model in Design Builder

LOCATION		
Amsterdam AP Schipol		
REGION		
Netherlands		
ACTIVITY		
Activity template	Template	Template: Office Buildings – Office-Open Plan
Occupancy	Occupancy	floor area per person: 10 m2/person
	Schedule	9:00 - 18:00, Monday-Friday
Metabolic	Activity	Typing
Environmental Control	Heating	21°C
	Heating set back	18°C
	Cooling	24.5 °C
	Cooling set back	26°C
Minimum fresh air	Fresh air	7 l/s-person
	Mechanical vent per area	0.3 l/s-m^2
Lighting	Target illuminance	500 lux
Computers	Power density	5 W/m^2
	Schedule	9:00 - 18:00, Monday-Friday
	Radiation fraction	0.2
LIGHTING		
Lighting Template	Template	Common Space Types, Office - Open Plan, 12.0 W/m^2
General Lighting	Power density	2W/m^2
	Schedule	9:00 - 18:00, Monday-Friday
	Luminaire type	1-Suspended
Lighting control	Working plane height	0.8 m
	Control type	Linear
HVAC		
HVAC Template	Template	Fan Coil Unit (4-Pipe), Air cooled Chiller
Mechanical Ventilation	Outside air definition method	2-Min fresh air per person
	Schedule	9:00 - 18:00, Monday-Friday
Heating	Fuel	Electricity from the grid
	Heating seasonal CoP	0.85
Cooling	Fuel	Electricity from the grid
	Cooling seasonal CoP	1.8

Figure 4.23: Table with the general settings of the model of DesignBuilder

4.4.2.2 Reference project 1

The first reference project is the facade with a roller shadying system. The properties of this model are contained in the following table:

OPENINGS	
Template	Double glazing, LoE, argon-filled
External Windows	
Glazing type	Dbl LoE (e3=.1) Clr 6mm/13mm Arg
U-value [W/m²K]	1.493
SHGC	0.603
Visible Transmittance	0.745
Shading	
Type	Shade roll – medium opaque
Position	3 - Outside
Control type	Glare

4.4.2.3 Reference project 2

The second reference project is the facade with integrated venetian blinds. The properties of this model are contained in the following table:

OPENINGS	
Template	Double glazing, LoE, argon-filled
External Windows	
Glazing type	Dbl LoE (e3=.1) Clr 6mm/13mm Arg
U-value [W/m²K]	1.314
SHGC	0.538
Visible Transmittance	0.664
Shading	
Type	Mid-pane blind with medium reflectivity slats
Position	2 - Mid pane
Control type	Glare

4.4.2.4 New Design

The layers of Ch-LC and LC could not be simulated respecting the design properties and some simplifications had to be done. In particular, the liquid crystal has been approximated with a layer of electrochromic glazing that switches visible transmittance according to the glare perception. At the same time, the layer of Ch-LC has been approximated with a transparent insulation that varies its solar transmittance according to the indoor temperature. The switching behaviour could not be realized directly by the software and this is the reason why three different models with different solar transmittance have been simulated. In particular, the first has an infrared reflection of 0%, the second of 50% and the third of 100%. The properties of the Ch-LC have been determined according to the amount of solar radiation that is transmitted into the building. As assumed in the design process, this layer is transparent and therefore it completely transmits the visible light, while it has the function of regulating the amount of infrared; and therefore this is the fraction of the solar spectrum that is allowed with different percentages. The settings of the different models are provided in the following tables.

Firstly four simulations have been done: one with the LC and one for each state of Ch-LC in order to measure the effect of the two layers independently. Later the two layers had to be put together to simulate their combined effect, but a further simplification had to be done because of the impossibility to insert two different shading controls simultaneously. Therefore six other simulations were done by combining a clear state of LC to the three different states of Ch-LC and then again the same three simulations, but with the LC in the tinted state (figure 4.24-28).

OPENINGS	
Template	Double glazing, electrochromic (reflective) switchable
External Windows	
Glazing type	Dbl Elec Ref Bleached 6mm/13mm Arg
U-value [W/m²K]	1.314
SHGC	0.538
Visible Transmittance	0.664
Shading	
Type	Elec Ref Coloured
Position	4 - Switchable
Control type	Glare

Figure 4.24: Characteristics of the model with only LC

Parameter	0%	50%	100%
Solar transmittance	0.95	0.60	0.22
Visible transmittance	0.9	0.9	0.9
Long-wave emissivity	0.9	0.9	0.9
Shading to glass distance	0.01	0.01	0.01

Figure 4.25: Table with the variables of the transparent insulation

OPENINGS			
Template	Double glazing, LoE, argon-filled		
External Windows			
Glazing type	Dbl LoE (e3=.1) Clr 6mm/13mm Arg		
U-value [W/m²K]	1.493		
SHGC	0.603		
Visible Transmittance	0.745		
Shading			
Type	Transparent insulation 0%	Transparent insulation 50%	Transparent insulation 100%
Position	3 - Outside		
Control type	7 - Inside Air Temperature		

Figure 4.26: Settings of the three models with double glazing + Ch-LC

OPENINGS			
Template	Double glazing, electrochromic (reflective) switchable		
External Windows			
Glazing type	Dbl Elec Ref Bleached 6mm/13mm Arg		
U-value [W/m²K]	1.493		
SHGC	0.603		
Visible Transmittance	0.745		
Shading			
Type	Transparent insulation 0%	Transparent insulation 50%	Transparent insulation 100%
Position	3 - Outside		
Control type	7 - Inside Air Temperature		

Figure 4.27: Settings of the model with LC clear + Ch-LC

OPENINGS			
Template	Double glazing, electrochromic (reflective) switchable		
External Windows			
Glazing type	Dbl Elec Ref Coloured 6mm/13mm Arg		
U-value [W/m²K]	1.231		
SHGC	0.399		
Visible Transmittance	0.591		
Shading			
Type	Transparent insulation 0%	Transparent insulation 50%	Transparent insulation 100%
Position	3 - Outside		
Control type	7 - Inside Air Temperature		

Figure 4.28: Settings of the model with LC tinted + Ch-LC

4.5 Results

In this section, the results obtained from the simulation are collected and discussed and the new design option is evaluated in comparison with the two reference projects. As previously explained and represented in the figure 4.13, the simulation was based on a specific logic.

4.5.1 Visual comfort

The first parameter that has been analysed is the annual Daylight Glare Probability perceived by the User 1 facing the monitor. The first DGP scheme is equal for each simulation because it has been calculated when the shading system is not applied (figure 4.29).

Figure 4.29: annual DGP without shading

According to the design option, the DGP is reduced in stages that can be found in the Appendix C. Because of the same environmental conditions, the shading systems are activated on the same hours and almost in the same areas of the façade. The roller shading does not have much flexibility while the venetian blinds and the smart glass have an additional adaptive quality that is respectively the variation of the slats angle and the percentage of tint of the glass. The schedule of the smart glass has been calculated analytically by measuring the DGP for the User 1 after the application of shading in different positions of the façade and with different shades. As visible from the images in the Appendix C, each portion separately cannot solve the DGP for the entire year, but the different stages can be combined in order to find the shading schedule that reduces glare with the minimum intervention (figure 4.30).

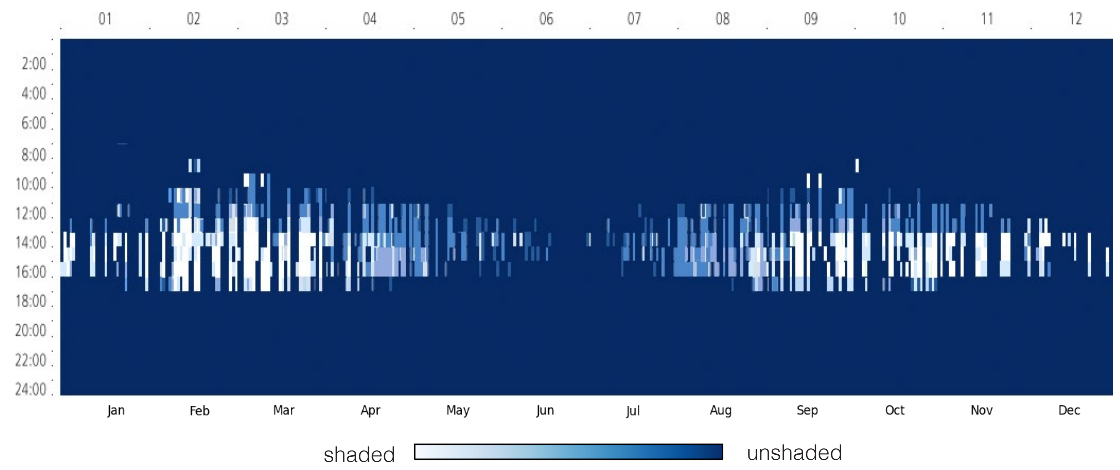


Figure 4.30: Shading schedule obtained by the analytical method

From the manual simulation, it was possible to conclude that the lower portion of the façade does not have an impact on the glare perception because the main light source is outside this area and therefore, this part of the facade can always remain unshaded and maintain the connection between user and outside environment. Moreover, a similar conclusion can be obtained observing the effect of the shading on the upper area. The impact is more significant between May and August because of the sun position that can be obstructed just from the upper side. However, if the size of the top portion were bigger, it would effect more hours during spring and autumn.

A further conclusion is that screening just half portion of the façade has positive effects for the User 1, but it is possible only when it does not influence the User 2. However, the DGP for User 2 has not been measured, but it can be assumed that shading just half part of the façade would work in the early morning and late afternoon because these are the hours when the sun is opposite to one user and behind the other. Furthermore, the shaded area would also solve the reflection of the sun on the computer screen of the user that has the sun behind. The expectation about the results of the complete shading state is the absence of glare perception because the complete obscuration of the middle and upper part of the façade. However, the DGP has been reduced to 4.9% with the roller shading, 0% with the venetian blinds and 26.1% with the automated smart glazing control. However, from the analytical calculation, the latter percentage is lower and reaches around 4.5%. The reason why the venetian blinds achieve the absence of glare is probably related to the material that completely reflects the visible light. In the other cases, the glare detected in the last stage occurs in the middle of the day, mainly during spring and autumn and therefore it can be related to the position of the sun in relation to the user.

To visualize the impact of the shading system and the difference between the design options, the visualization of the room under each shading typology are available during the 21st March, 21st June and 23rd December in the Appendix C.

A result of the DGP is the shading schedule. As before, the shading schedule of the reference projects have been automatically calculated by the software, while the shading schedule of the new design has been analytically obtained by reporting the portions of the façade that activate to solve the DGP (figure 4.30). The annual shading schedule of the analytical calculation has been represented with the same graphics of the other simulations to have a better comparison (Appendix C).

In the tables in figure 4.31, a further analysis of the variation of the shading schedule over the day has been reported. This has been done by observing the false-colour images on the 21st March, 21st June and 23rd December by all four points of view. In particular, it is interesting to observe the difference between the roller shading that has a low flexibility and the other two shading typologies that compare with a higher amount of conditions. Specifically, for each system, the 0 indicates an unshaded state, while the other numbers refer to:

Roller shading:
1= shading on the top
2 = shading on the top and middle

Venetian blinds:
slats' angle on top | slats angle in middle

Smart glazing:
façade state according to the configuration shown in the previous chapter.

Roller Shading Schedule												
	March				June				December			
	User 1		User 2		User 1		User 2		User 1		User 2	
h	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen
9	0	0	0	0	2	0	2	1	0	0	0	0
10	2	0	2	2	2	0	2	1	0	0	0	0
11	0	0	0	0	2	0	2	1	0	0	0	0
12	2	1	2	2	2	0	2	1	2	0	2	0
13	2	1	2	0	2	1	2	1	2	0	2	0
14	2	1	2	0	2	0	2	0	2	0	2	0
15	0	0	0	0	2	2	2	0	0	0	0	0
16	2	1	2	1	2	1	2	0	0	0	0	0
17	0	0	0	0	2	0	2	0	0	0	0	0
18	0	0	0	0	2	0	1	0	0	0	0	0

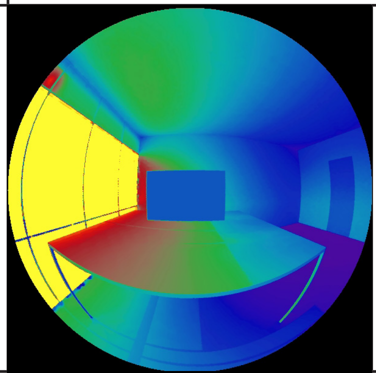
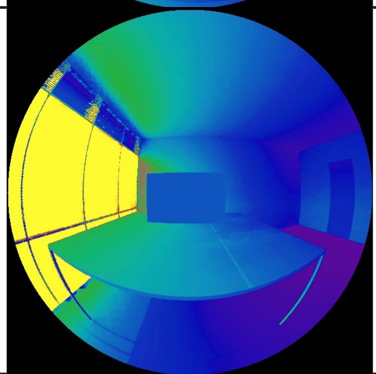
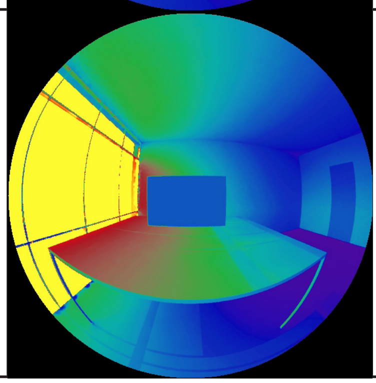
Venetian Blinds												
	March				June				December			
	User 1		User 2		User 1		User 2		User 1		User 2	
h	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen
9	0	0	0	0	45l90	0	0	45l90	0	0	0	0
10	90l90	0	90l45	90l90	45l90	0	0l0	45l90	0	0	0	0
11	0	0	0	0	45l90	0	0l0	45l90	0	0	0	0
12	90l90	0	90l45	90l90	45l90	0		45l90	0l90	0	0	0l90
13	90l90!	90l45	0	90l90	45l90	0	0l0	45l90	90l90	0	0	0l90
14	90l90	90l45	0	90l90	45l45	0	0	45l45	0l90	0	0	0l90
15	0	0	0	0	45l90	45l45	0	45l90	0	0	0	0
16	90!45	90l45	90l90	90l45	45l90	0l0	0	45l90	0l45	0	0	0l45
17	0	0	0	0	45l45	0	0	45l45	0	0	0	0
18	0	0	0	0	0l0	0	0	0l0	0	0	0	0

Switchable Glazing Manual												
	March				June				December			
	User 1		User 2		User 1		User 2		User 1		User 2	
h	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen	Window	Screen
9	0	0	0	0	4	0	0	6	0	0	0	0
10	4	0	5	8	6	0	1	6	0	0	0	0
11	0	0	0	0	6	0	0	6	0	0	0	0
12	8	0	8	8	6	0	0	6	4	0	0	2
13	8	3	0	8	6	0	0	6	6	0	0	6
14	8	3	0	8	4	0	0	2	4	0	0	2
15	0	0	0	0	6	2	0	6	0	0	0	0
16	6	1	5	2	6	1	0	2	0	0	0	0
17	0	0	0	0	4	0	0	2	0	0	0	0
18	0	0	0	0	2	0	0	0	0	0	0	0

Figure 4.31: Hourly shading schedule of the three typologies of shading in the three days of the year considered

The shading schedule is important not only because it influences the amount of light that enters into the office during the day, but also because it determines the possibility to have a view to the outside. This parameter can be deducted by analysing the indoor visualizations. Here an analysis is provided to show the correlation between DGP, shading system, amount of light and view. As mentioned before, 21st of March, 21st June and 23rd December have been considered as reference days to compare the different comfort for the User 1. Some examples are provided while in the Appendix C it is possible to have information about the whole working schedule from 9:00 to 18:00 of the three days, from the prospective of both User 1 and 2 each of them looking to the window and to the computer screen. The results are related to the specific view and they are not combined to reach the comfort for both the users and both the views simultaneously because the aim is to prove the possibility to adjust the façade according to the user's need and therefore a fixed composition is not necessary and researched in this design.

The table below (figure 4.32) compares the three shading options on 21st March at 13:00. The roller shading and the layer of LC are applied only in the upper part of the façade, while the venetian blinds are closed (90°) on top and turned with an angle of 45° in the middle. From the fisheye image, the Illuminance on the task is between 300 and 1000 lux in the former cases and between 200 and 400 lux in the latter. Therefore, the venetian blinds are not considered the best option in this moment of the day. A similar result has been obtained on 21st June at 13:00 when the roller shading covers the top row of windows, the venetian blinds are positioned with an angle of 0° both in the top and middle area and the switchable glazing is active on half of windows on the top (state 1) (figure 4.33). It is possible to notice that the amount of illuminance is sufficient in all three options and that it is more uniform when the venetian blinds

21st March 13:00				
Case	Shading typology	DGP		Illuminance level on the desk
Reference project 1	Roller shading		32%	300-1000 lux
Reference project 2	Venetian blinds		29%	200-400 lux
New design	Switchable glazing		35%	400-1000 lux

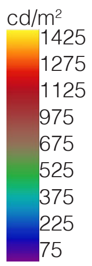
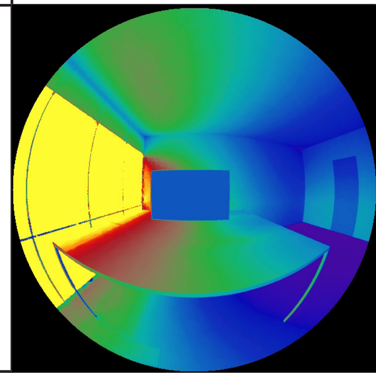
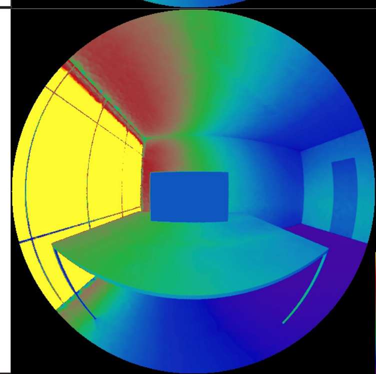
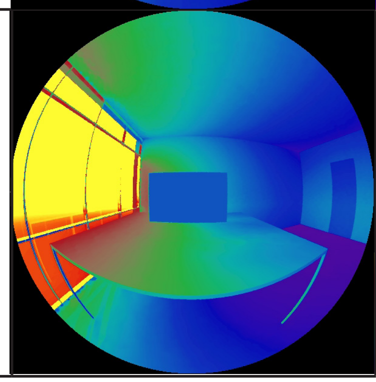


Figure 4.32: Comparison between the three shading typologies on 21st March at 13:00.

are applied, with a value between 300 and 500 lux. On the contrary, even if the level of illuminance is satisfied for the other two options, this is not uniform on the desk and it varies from around 300 and 1000 lux.

Another way to use these images is to assess the view to the outside. In particular, in this situation the upper area is shaded in all three cases, but the view is obstructed only in the reference projects, while it remains clear by using the switchable glazing. This aspect is not highly relevant in the examples just taken into account because the remaining part of the façade remains clear and therefore the view to the outside is provided. However, the condition could highly change between two consecutive hours because the weather conditions considered are specific of the climate data. For example, selecting the visualizations on 21st June at 16:00, it is visible that the shading is required also in the middle area (figure 4.34). In particular, the switchable glazing covers just half of the facade because this is sufficient to avoid glare. Applying roller

21st June 13:00				
Case	Shading typology	DGP		Illuminance level on the desk
Reference project 1	Roller shading		34%	500-1000 lux
Reference project 2	Venetian blinds		35%	300-500 lux
New design	Switchable glazing		32%	300-700 lux

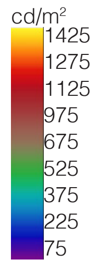
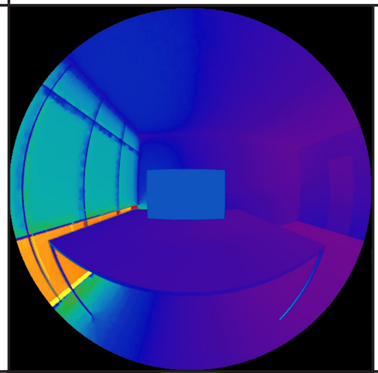
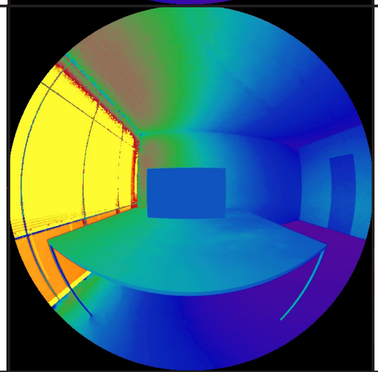
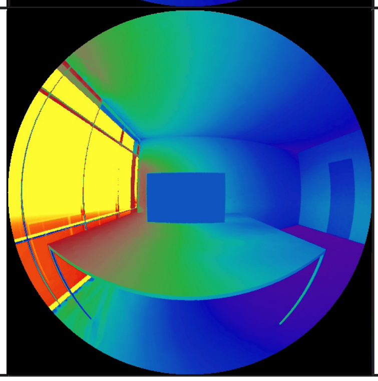


Figure 4.33: Comparison between the three shading typologies on 21st June at 13:00.

shadings and venetian blinds, the amount of illuminance decreases under the comfort level and therefore electrical lighting is necessary. On the contrary, the illuminance measured with the switchable glazing is around 300 and 1000 lux. Moreover, contrarily to the reference projects, a further advantage is that the view to the outside is completely clear.

These examples considered the glare perceived by the User 1. However, focusing on the images of the other three views provided in the Appendix C, it is possible to observe how the façade responds according to the glare that is perceived from that precise point of view. A useful information is how important is the relationship between user and façade and in this specific case, how advantageous is to place the desks perpendicularly to the window, with the light source coming from the side. On the contrary, the opposite disposition would imply a high amount of glare and therefore a higher amount of shaded hours. In particular, observing the images, the illuminance level on the desks when the user is

21st June 16:00				
Case	Shading typology	DGP		Illuminance level on the desk
Reference project 1	Roller shading		20%	75 lux
Reference project 2	Venetian blinds		32%	200-300 lux
New design	Switchable glazing		35%	300-1000 lux

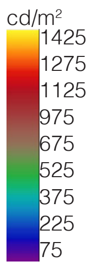


Figure 4.34: Comparison between the three shading typologies on 21st June at 16:00.

facing the window and the shading is operating, are in many cases lower than the requirements for the reference projects, while it reaches 300 lux in most of the cases when the smart glazing is applied.

To understand which option is better to provide daylight, other two important aspects to consider are the daylight autonomy and the energy consumption for the electrical lighting. In particular, these two values are strongly correlated because when the daylight does not provide enough illuminance, the electrical lighting has to compensate the amount of light to reach the comfort level (figure 4.35). In particular, the roller shading has mean daylight autonomy of 83% of the occupied hours and has an energy consumption of 45.5 kWh for electrical lighting. The venetian blinds have mean daylight autonomy of 86% and an energy consumption of 37.5 kWh for electrical lighting. Regarding the switchable glazing, these values are available only for the automatic calculation because the composition of the different shading configurations could not be simulated for the entire year. The values obtained by the automatic calculation are 85% of daylight autonomy and 38.2 kWh of energy consumption for lighting. However, because the analytical model can shade smaller portion of the facade compared with the automated one, it can be assumed that the DA is higher and therefore the energy consumption for lighting is lower. Moreover, in the simulation, the smart glazing changes only with three different shades, while in reality the light transmittance changes according to the voltage that is applied and to the amount of glare that has to solve.

In conclusion, the amount of daylight and the energy consumption are very similar between venetian blinds and switchable glazing, but it can be assumed that the switchable glazing has better performances in reality because of the higher level of adaptation. Moreover, in this condition, the view to the outside is always provided and this can increase the visual comfort of the user that maintains the connection with the outdoor environment.

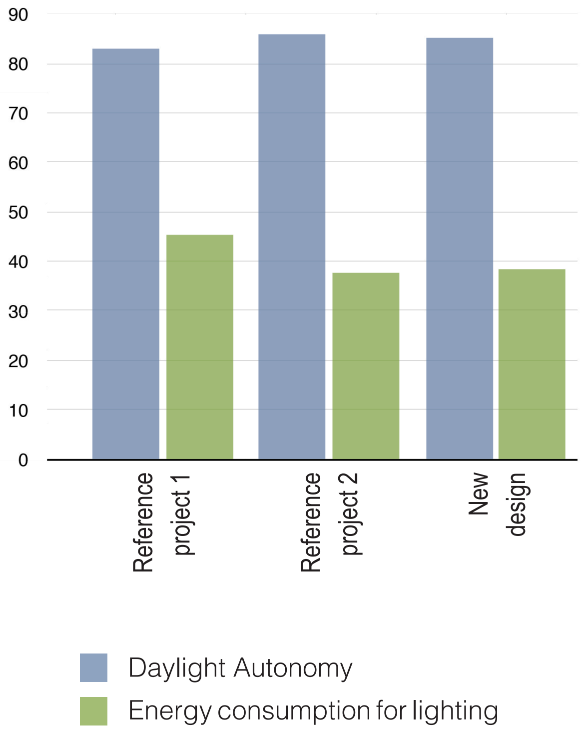


Figure 4.35: Comparison between DA and energy consumption of the three shading systems

4.5.2 Thermal comfort

Design Builder has been used to evaluate the design in terms of energy consumption for heating and cooling. In particular, the values have been considered monthly, yearly and hourly on the 21st March, 21st June and 23rd December. The aim of this simulation is to observe the influence of a switchable layer of Ch-LC that regulates the infrared without influencing the visual spectrum and independently from the shading layer.

As explained in the previous chapter, some simplifications had to be done for the switching behaviour and for the combination of layers of Ch-LC and LC. Therefore, different models of the new design had to be simulated and the results were analysed and combined to obtain the situation that more reflects the design project. Consequently a comparison between the new project and the reference projects was done to evaluate the design. All the results obtained can be found in the Appendix C, while here the discussion on the main results are provided.

Starting from the analysis of the new design project, the simplifications done during the simulation have to be considered to correctly read the data. In particular, the material that simulates the liquid crystals is an electrochromic glazing with a higher influence on the infrared than the liquid crystal considered in the design. Therefore, in the model that simulates the LC, the switching behaviour changes the demand of heating and cooling because the coloured state has a significant lower solar transmission than the clear state. Moreover, the shading control in this model is related to the amount of glare and not to the indoor temperature. On the contrary, in all the other models that have a layer of Ch-LC as transparent insulation, the switching behaviour is in function of the indoor temperature. Because of the influence of the tinted LC on the solar transmission, the combination of Ch-LC and LC in a tinted state has better results for cooling and worse results for heating compared to the ideal projects. In conclusion, the results of the LC model can be compared with the Ch-LC with the 50% of solar transmission applied to a glass of LC in a clear state. The reason is that the influence of the Ch-LC with the 50% of solar transmittance is comparable with the influence that the tinted LC has on a glazing of LC in the clear state. The Ch-LC changes transmittance according to the amount of solar heat gain that is desired inside the building. Because the aim of the research is to reduce the energy consumption for heating and cooling, the model that has the lowest energy consumption of heating and cooling together has been chosen: this corresponds to a layer of Ch-LC with 100% of infrared reflectance applied to a glazing of clear LC (figure 4.36). What is surprising is the fact that the best energy performance is always reached by a layer that always reflects the infrared, while the expectation was that the Ch-LC reflected the solar spectrum in summer and transmitted it in winter. The reason of this result can be due to both indoor and outdoor environments. In particular, the office space has

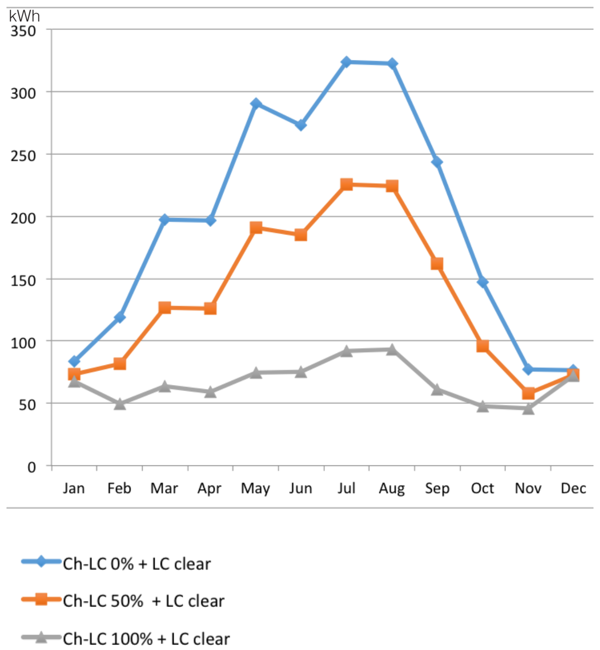


Figure 4.36: Comparison of the energy consumption in the three states of Ch-LC

an internal heat production that can be sufficient for a small and very well insulated volume with a south facing façade. In addition, the weather conditions determine the amount of solar heat gain. Therefore, an interesting and possible further development could be to simulate the design with different climate conditions, particularly in a region with big climate differences between winter and summer.

The result does not reflect the real adaptive behaviour of the coating and therefore its result is considered as an approximation. To have an overview on the possible adaptive behaviour of this layer, three days are analysed (figure 4.37-38).

The biggest variation of the facade is individuated on the 23rd December, but this composition can highly vary between the days according to the climate conditions. Moreover, the percentage of transmittance has been chosen according to the energy consumption, but in some cases this does not highly vary between the different states of Ch-LC. Moreover, the value of each hour is a consequence of the thermal condition of the previous hour and depends on the amount of solar heat gain that has been previously transmitted. Consequently, these results are an approximation of the possible switching behaviour and the comfort conditions of the Ch-LC coating.

	9	10	11	12	13	14	15	16	17	18
21st March	100	100	100	100	100	100	100	100	100	100
21st June	100	100	100	100	100	100	100	100	100	50
23rd Decen	0	0	0	0	50	100	100	100	100	50

Figure 4.37: Table with the switching behaviour of the Ch-LC in the three days tconsidered

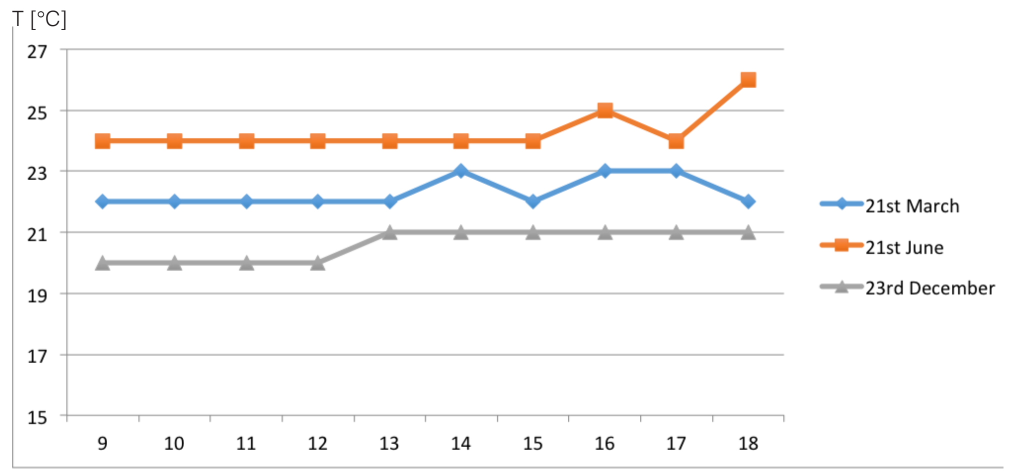


Figure 4.38: Average hourly temperature of the Ch-LC 100% reflectance in the three days of the year considered

The results of the new model are now compared with the reference projects. In particular the sum of the monthly energy consumption for heating and cooling is compared for each option (figure 4.39-40). While the energy consumption of the new design remains almost stable during the whole year, the energy demand of the reference projects increases during the summer and in some cases reaches three times the energy needed by the new design model. Therefore, the layer of Ch-LC has a big contribution on the reduction of energy consumption that can reach around 65% compared to both the reference projects. This percentage is taken ad a general indication of the possible reduction of the energy demand for heating and cooling due the fact that eventually the coating does not take into account its adaptive quality.

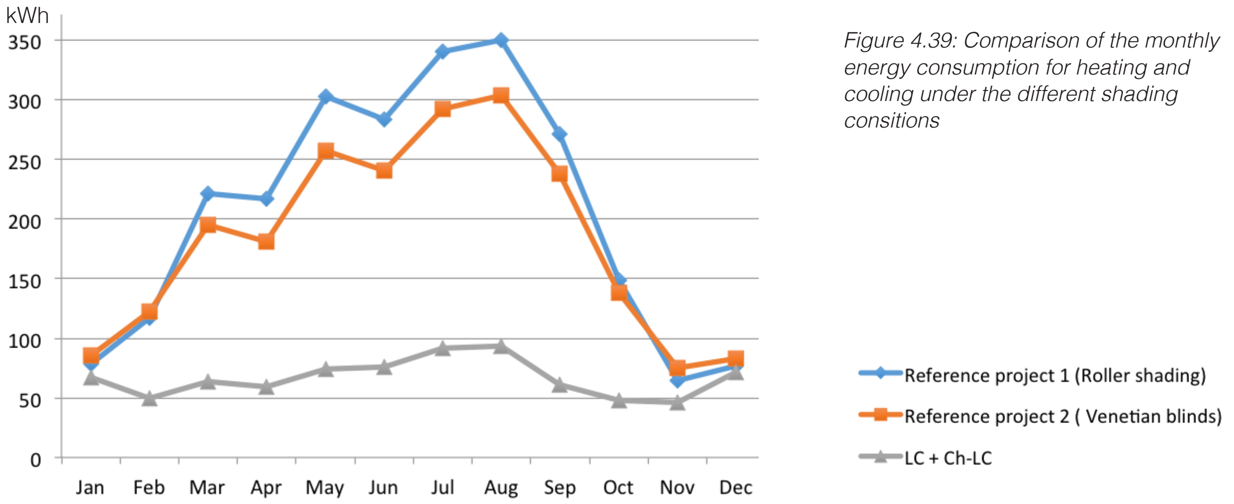


Figure 4.39: Comparison of the monthly energy consumption for heating and cooling under the different shading consitions

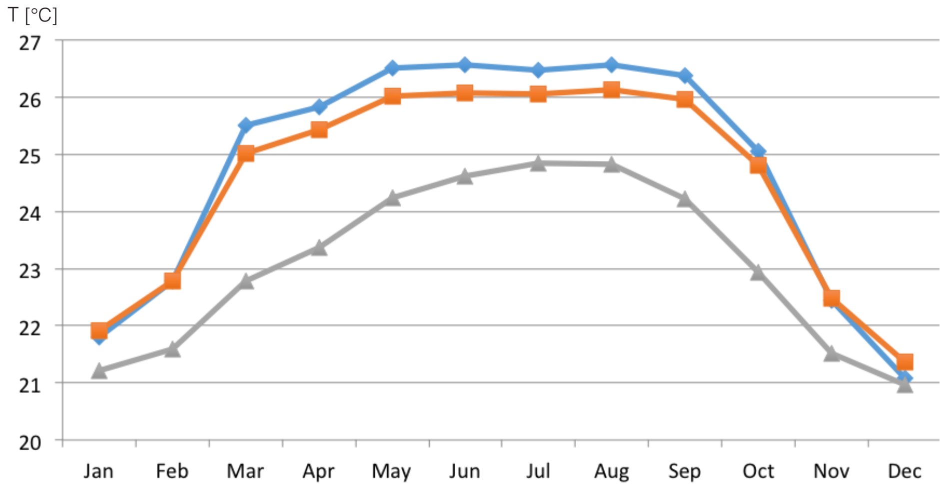


Figure 4.40: Comparison of the monthly temperature under the different shading consitions

4.6 Conclusions

In the following tables (figure 4.41) it is possible to have an overview on the results of each shading typology, in the three days took into exam, and to compare their effect on the illuminance, temperature and energy demand for heating and cooling.

21st March

	Shading schedule				Illuminance [lux]			Temperature [°C]		Energy demand [kWh]		
9:00	-			100%	200			24,5	21,5	0,33	0,32	0,14
10:00	-			100%	450			24,5	21,5	0,32	0,31	0,22
11:00	-			100%	200			24,5	21,5	0,51	0,49	0,19
12:00	top	-	-	100%	900	500	700	25	21	0,34	0,35	0,27
13:00	top	90°|45°	half-top	100%	600	200	600	25,5	22,5	0,40	0,40	0,27
14:00	top	90°|45°	half-top	100%	600	200	600	25,5	22,5	0,42	0,41	0,27
15:00	-			100%	200			25,5	22,5	0,38	0,31	0,26
16:00	full	90°|45°	half-top	100%	200	100	400	25,5	22,5	0,40	0,34	0,26
17:00	-			100%	300			25,5	22,5	0,38	0,31	0,26
18:00	-			50%	100			25	22	0,32	0,30	0,26

21st June

	Shading schedule				Illuminance [lux]			Temperature [°C]		Energy demand [kWh]		
9:00	-			100%	500			25,5	24	0,41	0,41	0,19
10:00	-			100%	600			25,5	24	0,44	0,40	0,19
11:00	-			100%	600			25,5	24	0,51	0,49	0,19
12:00	-			100%	500			26	24	0,62	0,63	0,19
13:00	top	-	-	100%	600	700	700	26	24	0,65	0,58	0,19
14:00	-			100%	200			26	24	0,61	0,52	0,19
15:00	full	45°|45°	half-full	100%	100	200	500	26	24,5	0,7	0,66	0,20
16:00	top	0°| 0°	half-top	100%	300	400	400	26	24,5	0,71	0,64	0,19
17:00	-			100%	200			26	24,5	0,65	0,53	0,19
18:00	-			50%	200			26	25,5	0,14	0,05	-

23rd December

	Shading schedule				Illuminance [lux]			Temperature [°C]	Energy demand [kWh]		
9:00	-			0%	100			20	0,23	0,18	0,16
10:00	-			0%	100			20	0,19	0,15	0,12
11:00	-			0%	100			20	0,15	0,1	0,09
12:00	-			0%	200			20,5	0,07	0,02	0,03
13:00	-			50%	300			20,5	0,01	0,04	0,01
14:00	-			100%	300			20,5	0,02	0,07	0,01
15:00	-			100%	200			20,5	0,03	0,04	0,01
16:00	-			100%	100			20,5	0,03	0,01	-
17:00	-			100%	100			20,5	0,03	-	-
18:00	-			50%	100			20,5	0,03	-	0,01

Figure 4.41: Comparison between the results of the three shading typologies on 21st March, 21st June and 23rd December.

The aim of the simulation was to evaluate the design strategies and specifically the façade division, the presence of sensors and the different typologies of adaptive shading. In particular, it was visible that the subdivision of the façade plays an important role in the visual comfort and each subdivision can be effectively treated individually. Specifically, the lower area does not influence the glare perception and is not source of discomfort and for this reason it can remain unshaded providing view to the outside. Therefore, because the LC has been applied only for optical reasons, it can be applied only to the middle and upper areas unless the necessity to completely darken the room. On the contrary, in case of roller shading and venetian blinds, that also play a role in the thermal regulation, this area can be shaded, but the main purpose would be for the thermal regulation and not for the visual comfort. In this case, even if not simulated, a warning has to be given for the venetian blinds that, when applied in the lower area can cause glare due to the high reflectance of the material.

measured and represents the trigger for the shading system. This is fundamental because the goal is the indoor comfort and therefore the adaptation can happen in response of the user's needs. Moreover, in this way, only the effective occupancy hours and space would be considered.

Among the solutions analysed, the roller shading has the lowest level of adaptation in comparison to the other two solutions because the only response is its application on the façade. On the contrary, the venetian blinds have the additional advantage to vary the rotation of the slats while the smart glazing can vary the colour percentage of the glass (figure 4.41). Having a second level of adaptation is important because the discomfort can be solved by a smaller intervention that can maintain higher levels of illuminance and view to the outside. The result is a reduction of energy consumption that for both cases has been measured around 16% respect to the roller shading and that, in the case of the switchable glazing can reach higher levels (figure 4.42).

A significant aspect of the new design is that visual comfort and thermal comfort are controlled separately (figure 4.41). In fact, because the main goal of this research is the achievement of visual comfort, the shading systems are regulated in order to satisfy only this parameter. However, as previously mentioned in the problem statement, even if in some situations this control coincides with the thermal control, it does not represent all the cases. This is one of the reason why the performances of the new design are better than the performances of the reference projects where the thermal analysis has been done with shading systems that where used only to achieve visual comfort. Moreover, in the case of Ch-LC, the fact that this layer is transparent means that it does not have an influence on the transmittance of visible light and therefore on the energy consumption for lighting. Considering the design project that

The top and middle areas are more relevant in terms of daylight regulation and their subdivision is important because, according to the sun position and the glare source, just a portion of the façade can be activated to solve the discomfort, while the rest can remain unshaded providing daylight and view. This has been proved during the simulation and it is applicable mainly in extreme positions of elevation and azimuth of the sun in relationship to the façade.

The division of the shading system does not mean always a visible division of the façade. For example, in the case of the smart glazing, the zoning technique allows to divide the façade in areas that have an invisible separation between each other, allowing a differentiation of colour between two adjacent zones. What is fundamental is that top and middle areas are independent from each other because in some cases just one of them is sufficient to achieve visual comfort.

What has been observed about the vertical subdivision is that half of the façade can solve the glare perception and therefore the vertical subdivision is also relevant. However, a general rule about the rhythm division has not been found because of the small portion of the façade. What can be concluded is that the smaller the division, the smaller is the area that is shaded because just the portions of the façade that contain the source of glare will be shaded. This solution would not be pleasant for the application of roller shading and venetian blinds because it would imply a high percentage of window frames in the façade. On the contrary, considering the smart glazing and again the zoning method, it would be interesting to obtain a pixelated façade that responds according to the glare perception with the minimum amount of coloured portions.

A second important aspect is the typology of control. Both for the visual and thermal comfort, it is fundamental that the internal conditions are

applies a Ch-LC and a LC layers, the energy reduction that can be achieved is of 16% for lighting compared to a roller shading system and around 65% of energy for heating and cooling compared to both the systems (figure 4.42a).

	Reference project 1 Roller shading	Reference project 2 Venetian blinds	Design option Ch-LC + LC
Daylight Autonomy	83%	86%	85%
View availability	low	medium	high
Energy consumption lighting	45,5 kWh/y	37,5 kWh/y	38,2 kWh/y
Energy heating & cooling	127,1 kWh/y	113,7 kWh/y	41,3 kWh/y

Figure 4.42a: Comparison between the results of the three shading typologies

4.6.1 Further developments

The results obtained by the simulation are related to the climate zone considered. Because of the strong correlation between the technology chosen and the solar radiation, an interesting further development would be to observe the adaptive behaviour of this technology under different climate conditions. Moreover, the model considered has a south facing façade that reduces the value of the results just to projects with this orientation. Therefore, an interesting analysis would be to simulate different models with different facades orientations. Because this graduation project was more focused on the evaluation of the visual comfort, the layer of Ch-LC has been positioned in the whole façade with a uniform behaviour over the whole surface. However, it would be interesting to apply the same logic applied for the visual comfort, also to this layer to understand if this can respond with different percentage of transmittance in different areas of the façade. To do that, the better type of control would be the indoor temperature combined to the amount of solar heat gain, to optimize the response of the layer of Ch-LC in relationship to both indoor and outdoor environment. In the end, simulating both the visual and thermal comfort by using the same software would be preferable to achieve a more accurate energy balance and therefore a more realistic evaluation of the design.

4.7 Design

The results of the simulation in the figure 4.42a validated the design from a comfort and energetic point of view. In the figure 4.42b, the three design options are compared according to other parameters more related to the desig.



	Reference project 1 Roller shading	Reference project 2 Venetian blinds	Design option Ch-LC + LC
Level of adaptation	1 - on/off	2 - on/off + angle of the slats	2 - on/off + shade variation
Transparency	Low, dependent on the material	Dependent on the angle of the louvers. If the shading is completely closed, the facade is opaque	Always
Design freedom	Medium	Low	High
Layers	Additional visible layer in the facade	Additional visible layer in the facade	No additional layer in the facade
Maintainance	Depends on the position of the shading: external shadings are more efficient for the thermal control, however, the level of maintainance in higher because the system is subjected to environmental agents	Depends on the position of the shading. Usually the venetian blinds are applied indoor, however, the direct contact with the user can cause damage. Peferable to integrate the venetian blinds between two window panes	Low mainatinance due to the fact that the LC and the Ch-LC are laminated in the glass panes
Energy consumption	Only when it changes position	Only when it changes position	During the clear state
Cost	Depends on the material and the type of control	Depends on the type of control, material and integration with other technologies	High cost due to the innovative material and the low applications
Independent visual & thermal control	no	no	yes
Level of development	Traditional technology. Possible development on different use of materials and control	Traditional technology. Possible development on materials, control and integration with other technologies such as pv cells	The technology development has not reached the final stage. Long process necessary to increase the technology

Figure 4.42b: Comparison between the characteristics of the three shading typologies

The following drawings show how the technology is applied in the facade and specifically in a unitized system that allows obtaining one single pane subdivided in the four areas as established in the design (figure 4.43). As previously explained, the smart glass can be applied is every façade system, but the unitized system has been chosen because of its fast assembling, particularly in the tall buildings, and because of the constant condition maintained during the construction phase.

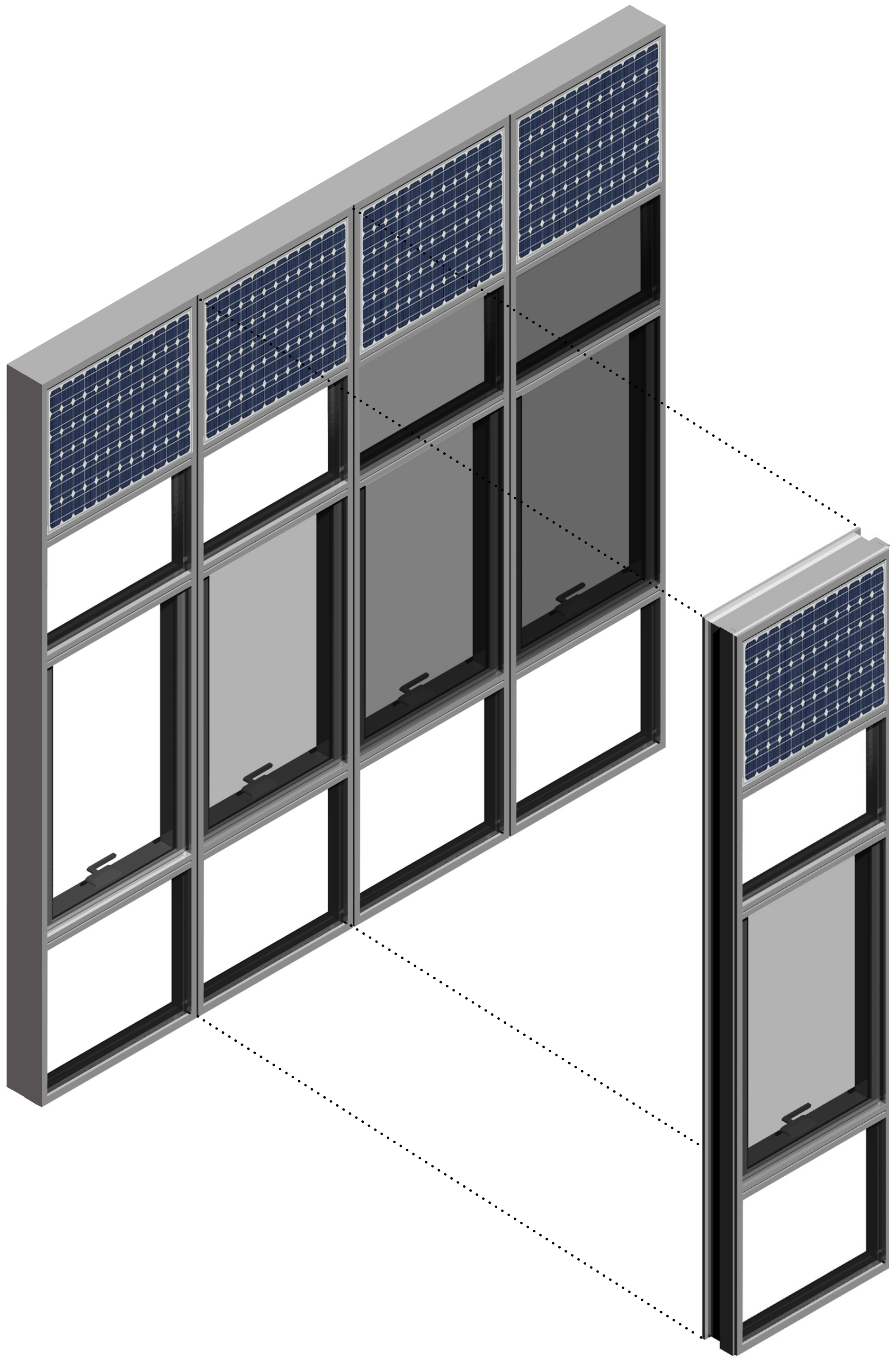


Figure 4.43: Unitized system facade with the single unit divided in four independent areas.

Figure 4.44: Elevation, scale 1:20

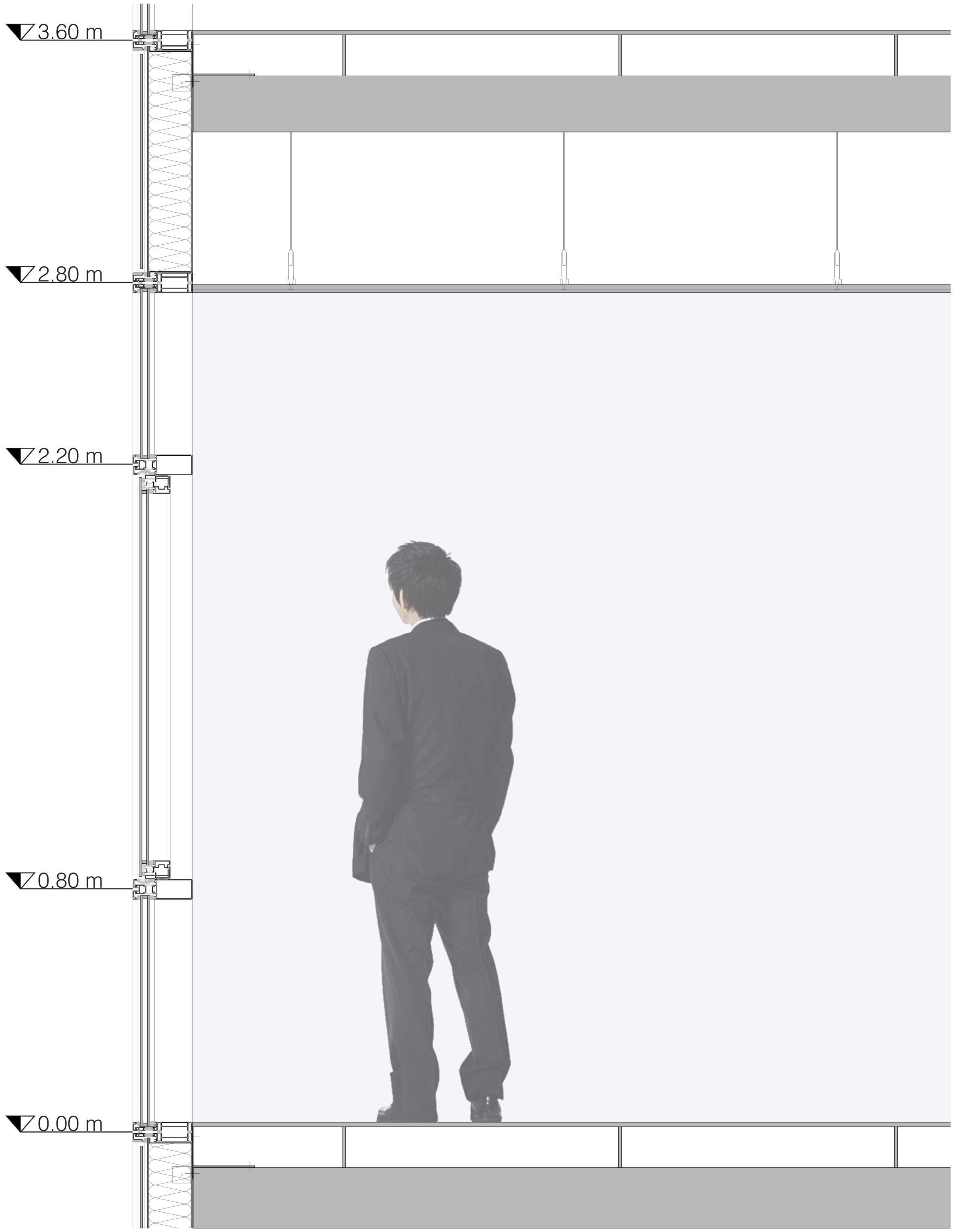
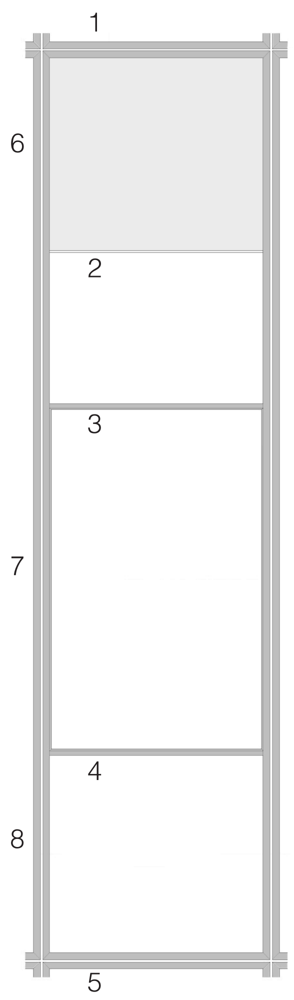


Figure 4.45: Section, scale 1:20

The product shown on the drawings (figure 4.43-44-45-46) can be realized in different variation with the prerequisite of maintaining the combination of the two switchable layers. Moreover, the importance of subdividing the façade in areas can be reached in different ways than the one proposed. In fact, this composition was chosen because represents a more standard version of a fully glazed façade and because its standard condition allows to apply it in different projects. Therefore it could potentially become a product designed by Rollecate Group® and proposed to the architects as a solution that assures high energy performances and high design freedom at the same time. Furthermore, the main product is not the unitized panel, but the combination of LC and Ch-LC, or better, the independent control of visual and thermal comfort with the same architectural element.



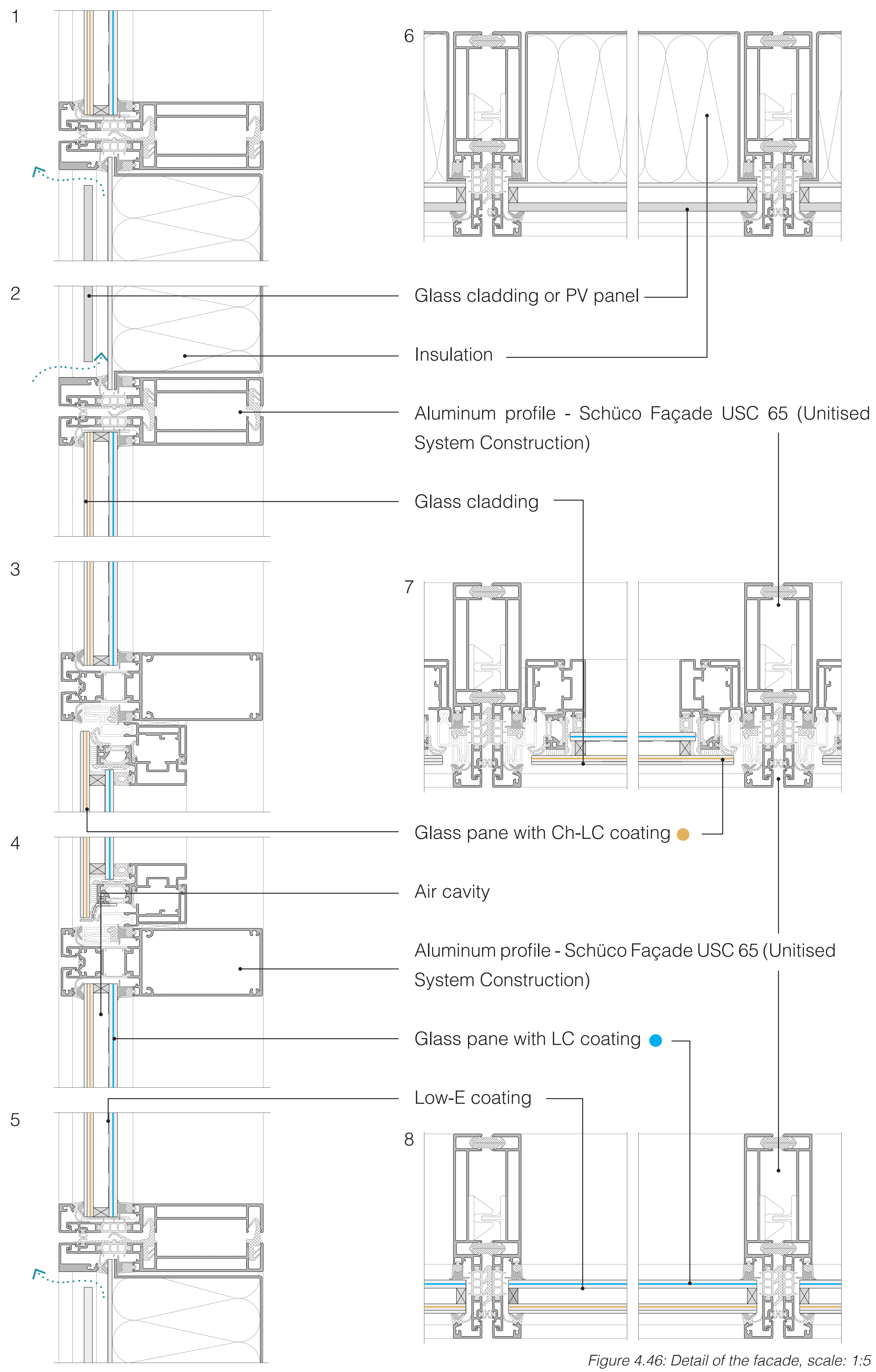


Figure 4.46: Detail of the facade, scale: 1:5

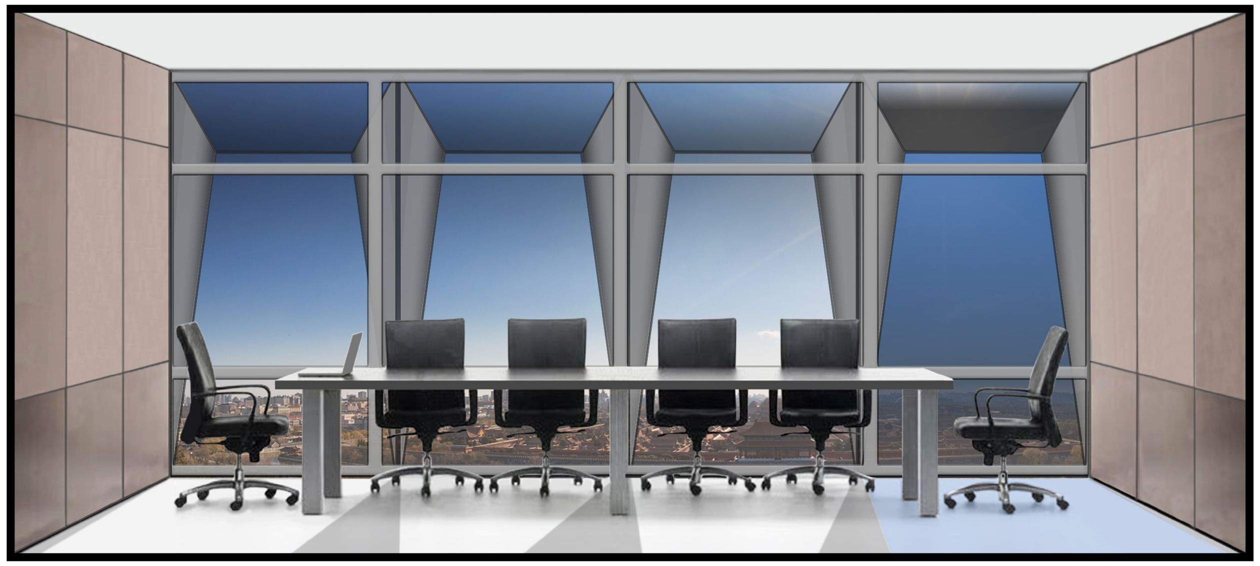
The images below show the discomfort situation caused by direct sunlight, and how it is solved by applying roller shading (figure 49-50), venetian blinds (figure 51-52) and the new design option of LC (figure 4.53-54).

Figure 4.47-48: Situation of discomfort from inside and outside.

Figure 4.53-54: Application of the new design option of LC

The product can be applied with different shapes, size and colours according to the architect's preferences, but with the awareness of the importance of the façade subdivision and the façade control. Here some examples of possible applications are provided.



4.8 Conclusion

This graduation project started with the request from Rollecate Group® to provide an overview on adaptive façade technologies and their future trends with the aim to possibly apply this concept to their products. Because of the wide application of the adaptivity concept, a definition of adaptive facades has been developed to clarify how this would be considered in the research. In particular, the adaptive façade is described as an envelope that responds both to indoor and outdoor stimuli and changes conformation – both physically or chemically - to take advantage of the outdoor climate with the aim of improving the indoor environment.

At the same time, due to the high energy demand of office buildings and particularly for lighting, a personal and more specific interest was on how adaptive façades, and specifically smart glass, in comparison with more traditional adaptive solutions, can improve the visual comfort and reduce the energy demand of an office environment. The interest on the application of smart glass derives from the big potential of this technology and from the possibility to achieve many of the trends identified for the future of adaptive facades. In particular, they consist in applying smart materials and nanotechnologies, integrating different layers and functions in the same product, maintaining the transparency of the façade and regulating the façade behaviour by the use of sensors.

Furthermore, it was observed that the control of visual and thermal comfort by regulating the solar radiation happens usually by applying a single solution that controls both the parameters at the same time without reaching the optimal performance for both the aspects. A fundamental step was therefore to study the composition of solar radiation and to formulate an ideal façade that selected just the desired portions of it according to the indoor requirements. This is a further reason why smart windows were taken into account and more specifically because of their potential of separately control visible light and infrared. Moreover, fundamental was to understand the strategies of daylight management to combine them with the adaptive techniques. In addition, the goal that wanted to be reached with the design was to increment the daylight into the indoor space and decreasing the energy demand without compromising the view to the outside environment. After the study of different adaptive solutions, smart glass confirmed to be the most promising technology and therefore a further study was carried on together with a comparison between more traditional products like roller shading and venetian blinds, in order to individuate the best façade application.

The result of the combination between daylight management and adaptive technologies consists in some guidelines that, according to the research developed, appear as the most logical approach to improve visual comfort. Specifically, the façade should be divided in areas with different functions in terms of daylight and view availability and these should have the ability to be treated independently from each other. A second important consideration is the communication between outdoor and indoor environment by the use of sensors. In particular, detecting the indoor conditions is fundamental to provide an effective response of the façade. These first two guidelines can be applied to different design solutions and do not require an adaptive envelope per se. In this research they have been combined with the smart window because this has the potential of regulating daylight and solar heat gain reducing the energy demand of the office building. In particular, to control the two parameters separately, two independent coatings have been applied to the different façade subdivisions; the first of Liquid Crystals is triggered by the glare perception and the second, of Cholesteric Liquid Crystal, is triggered by the indoor air temperature. In this way, both the layers can work to optimise the specific requirement. Because of the adaptive behaviour and the independency of the two layers, it is possible to achieve the optimal configuration during the day and over the year.

As concluded from the research, the combination of these strategies decreases the energy consumption for lighting, heating and cooling with the big positive aspect of having a small impact on the façade. The advantage is not only related to the energy consumption, but the main goal of the research was to achieve a high level of visual comfort inside the office space increasing the amount of daylight and offering the possibility to maintain the contact with the outdoor environment. Therefore, the design has also a social value focused on improving the space quality of the user and his productivity.

Because the research was finalized to the evaluation of visual comfort, the material chosen for the switchable glass was the Liquid Crystal mainly because of its fast switching speed and because of the possibility to have a colour-rendering index in natural grey. However, the same technology is available in different colours and this can add flexibility to the design. Furthermore, the façade subdivision is an indicative guideline that can be achieved with different geometries and sizes and therefore this additionally increases the design freedom of the architects. These two aspects represent an advantage for the façade construction company because it can both realize a standard product applicable in different buildings, like the one obtained at the end of this project, and, at the same time, customized solutions that meet the needs of the architect. The substitution of the traditional shading system with smart glazing, does not only mean a simplification of the façade, but also a reduction of materials and maintenance for the shading system. In particular, this aspect has also to be taken into account when thinking about the high cost of the switchable glazing. In fact, their application, not only helps reducing the cost for the energy consumption, but also eliminates the costs related to the shading system. Furthermore, the possibility use the façade outside the office hours as advertisement area or projection panel, adds an economic and aesthetical value that increases the level of adaptivity of this solution and represents an interesting advantage for the potential application of leasing façades.

The disadvantage of the smart glazing is the slow development of the technology for architectural purposes. Even if the switchable glazing is already available in the market, there is a big range of improvement in terms of performances and how these are achieved. However, this research was mainly focused on finding the optimal solution for the requirements of comfort, being aware of the current technology development and at the same time being confident in the achievement of a more complex and affordable technology in a short term.

The following scheme summarizes the conclusions obtained at the end of the research, how they can be applied in a general situation and how they have been considered in the specific design.

Trends of Adaptive Facades

Smart Materials and Nanotechnologies	Use of Sensors	Integrated system and Layers	Energy Reduction/ Generation
Big potential, but long development time. Maintain flexibility in order to adapt to technological improvement.	Communication between facade and indoor space for an optimization of the facade performance.	Include as many functions as possible in the same product with the combination of different layers or the subdivision of the facade in different areas.	Integration of systems for the energy redution and generation. (PV panel, solar collector, heat exchanger, evaporative cooling etc.)

How they are applied in the design

Application of LC and Ch-LC. Currently, different layers are needed to control the entire spectrum. It is necessary to take into account the possibility of an improvement of the performance that can end to a reduction of layers.	The facade is triggered by indoor conditions. Specifically, the layer of LC is activated by the presence of glare, while the Ch-LC is activated by the indoor temperature.	The combination of two layers allows to control daylight and solar heat gain separately.	The design allows to save energy for lighting, heating and cooling. It is possible to integrate the system in a window frame with integrated PV cells or to substitute the cladding glass on the top with a PV panel.

Design variables

Subdivision of the facade in different areas: According to the project, the facade is subdivided horizontally into three areas and it has a vertical rhythm of 0.9m. However, accordign to the design requirements, the visual comfort can be reached with a subdivision with different shape and size.

Location (climate zone): The office space in the research is located in the Netherlands and the surroundings are not taken into account. However, it is important to be aware of the climatic conditions and the influence of other buildings on the design in order to apply the technology only when effective.

Orientation: The results obtained in the research are related to a south facing facade. To apply the solution to different orientations it is fundamental to calculate its effective advantages in those orientations.

Function (office, residential, commecial etc.): According to the function, the indoor requirements, in particular for the visual comfort, can vary. The reduction of glare in a residential space is not as importan as in an office building, while the privacy has more relevance. Moreover, in a dwelling, traditional solutions that apply particular materials, textures and colours are usually preferable.

Design requirements: The choices made in this graduation project are highly related to the visual and thermal comfort. The liquid crystal has been chosen due to its neutral colour and its fast switching time. However, different colours and switching times are possible and therefore other smart materials can be applied according to the architectural preferences.

Budget: The application of smart materials in the facade has a high cost that reduces its applications. Combining the shading function with the media purpose can add quality to the envelope and an additional advantage for the product.

REFLECTION

The conclusion of this graduation project results in a product, but also more generally it can serve as guideline on how to reduce the energy demand of an office building and at the same time increase the level of visual comfort, by applying specific design strategies and adaptive technologies. In particular, the research is the answer to multiple questions and problems that have been observed before and during the research process. Specifically, it started with the aim for searching the future trends of the adaptive envelopes under the request of the façade construction company Rollecate Group® and, consequently, to integrate this concept in their product with the aim for improving their technological innovation and to connect the company with potential architects' demand.

Researching adaptive facades, made clear that this concept has the benefit of taking advantage of the outdoor conditions with a bigger potential compared with static solutions. Therefore, the adaptive solution was the first requirement for the final design. Moreover, during the research phase, it was clear that these solutions have a big potential in the improvement of the visual comfort because they can relate with the daylight that is the most variable external condition that influences the visual comfort. Regulating this parameter could imply a higher level of comfort into the indoor space and at the same time a reduction of energy for electrical lighting. Furthermore, during the research process it was clear that the solar control that influences the daylight management has also an influence on the thermal balance of the indoor space. In particular, the problem that was observed is that in many cases the adaptive (and static) solutions that regulate these two parameters usually coincide without optimizing both the factors at the same time. Therefore, the next important step, that represents the innovative aspect of the design, was to decide to obtain a unique product with the ability of regulating the solar radiation with two independent layers, each of them with a different purpose: visual and thermal control. In particular, the former aspect has a higher relevance on the project because one of the further purposes was to achieve the visual comfort of an indoor office environment by increasing the amount of daylight, reducing discomfort and maintaining the view to the outside. Moreover, a research on the façade composition and control of the adaptivity has been done to reach the optimal solution with the conclusion that the other two important strategies are to divide the façade in areas with different visual comfort goals, and to control the indoor environment with the use of sensors.

The result obtained at the end of this process is a fully glazed façade subdivided in areas, each of them composed by two layers of smart glass and precisely one of Liquid Crystal that controls the visual comfort and a layer of Cholesteric Liquid Crystal that regulates the solar heat gain. The two layers work independently from each other and from the adjacent panels and respond to the input received from the outdoor conditions and respectively from the daylight glare perception ad the indoor air temperature. The design has been validated by the simulation with a result that meets the expectations. However, the method has some limitations due to the fact that the smart glazing is a technology that has a limited flexibility in the simulation software and its properties and control strategies are not easy to manipulate. Because of this reason, two different simulations had to be done, each of them for a different type of comfort and therefore a unique and more precise result could not be achieved. Unfortunately, the result obtained in the research is mainly theoretical. It is founded on research and studies of existing products, but also on techniques that are still under development. The concept that has been followed is an idealized product that meets some challenges in practice, like the precise control of the different portions of the solar spectrum, the realization of the concept with a small amount of layers of glass and the high cost. These aspects are obstacles in the present because of the technology development level. However, it is solvable in the future and therefore the application of it is a matter of time. This can be compared with the development of the PV panels that, as other products, were not an affordable technology at the beginning, but are currently common applications.

The improvement of daylight into the indoor space and the reduction of energy demand both for lighting and cooling have an economical, environmental and social impact. Apart from reducing the energy demand, further aspects that contribute in the environmental and economic sustainability are the systems that take advantage of the outdoor environmental conditions to increment the indoor comfort and that the product demands a low amount of electrical energy that can eventually be taken from a green source. The product would have the potential to be autonomous by the integration of PV cells in the window frame. However, this system would be more expensive than connect the façade to a separate PV panel. Furthermore, because the system requires just the application of two coatings, a further consequence is the reduction of materials and maintenance of a traditional shading system. Because of the simplicity of the technology, it is possible to apply the system as a retrofitting solution, applying the coating to existing windows, reducing the waste of the old windows. From the social point of view, the product offers the possibility to increase the level of daylight maintaining transparency and therefore connection to the outside. The quality of daylight and the view are two elements that have a big impact on the users both from a physical and psychological point of view and they help creating a pleasant work environment that reduces the stress and increases the productivity.

The advantage of this solution is the high technological performances with a little impact on the facade and almost no restrictions for the architect. Moreover, the standard solution offered to Rollecate, can become a standard product of the company, but according to the architect's requirement it can be customized with different sizes, shapes and colours, increasing the design freedom of the architect.

In conclusion, the goal of applying the future trends of adaptive technologies to improve the visual comfort and decrease the energy consumption for lighting, heating and cooling has been achieved with the realization of a product that improves the environmental, economic and social impact of a building and covers the responsibility of building technology, in connecting a construction companies with architectural needs, technology with comfort, and, functionality with aesthetics.

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Figure 3.27: www.lcgenergy.co.uk

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Figure 4.3: www.clo.nl/nl022613

Figure 4.4: www.clo.nl/nl022613

Figure 4.5: www.sunearthtool.it

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APPENDIX

In collaboration with Maria Mourtzouchou

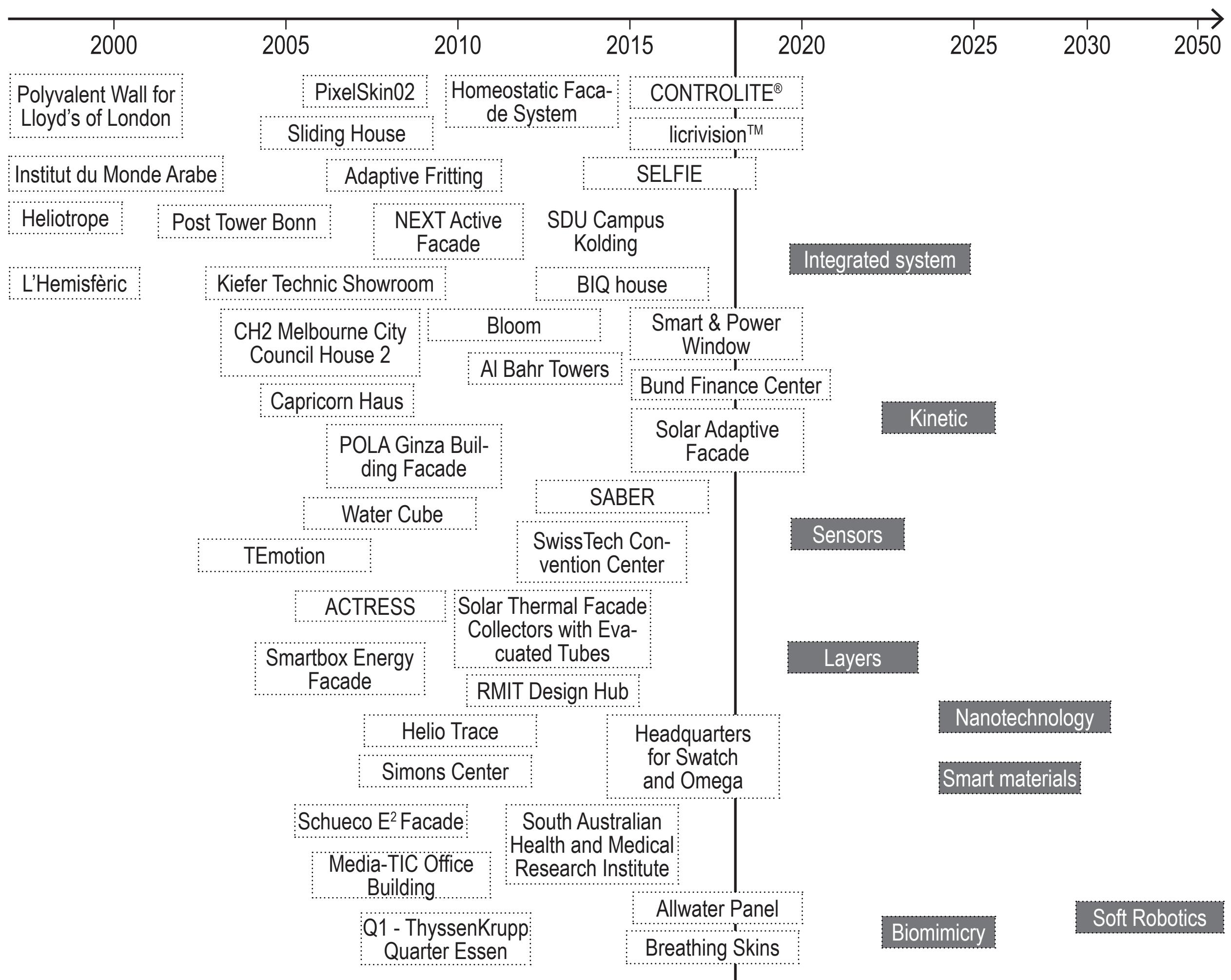
Index

Buildings

Products

Research projects

Thermal Comfort



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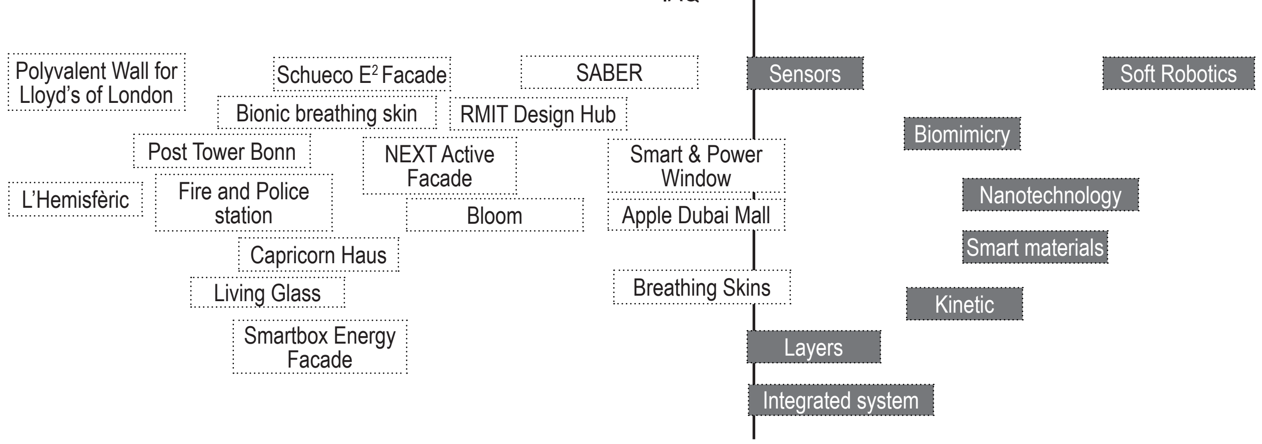

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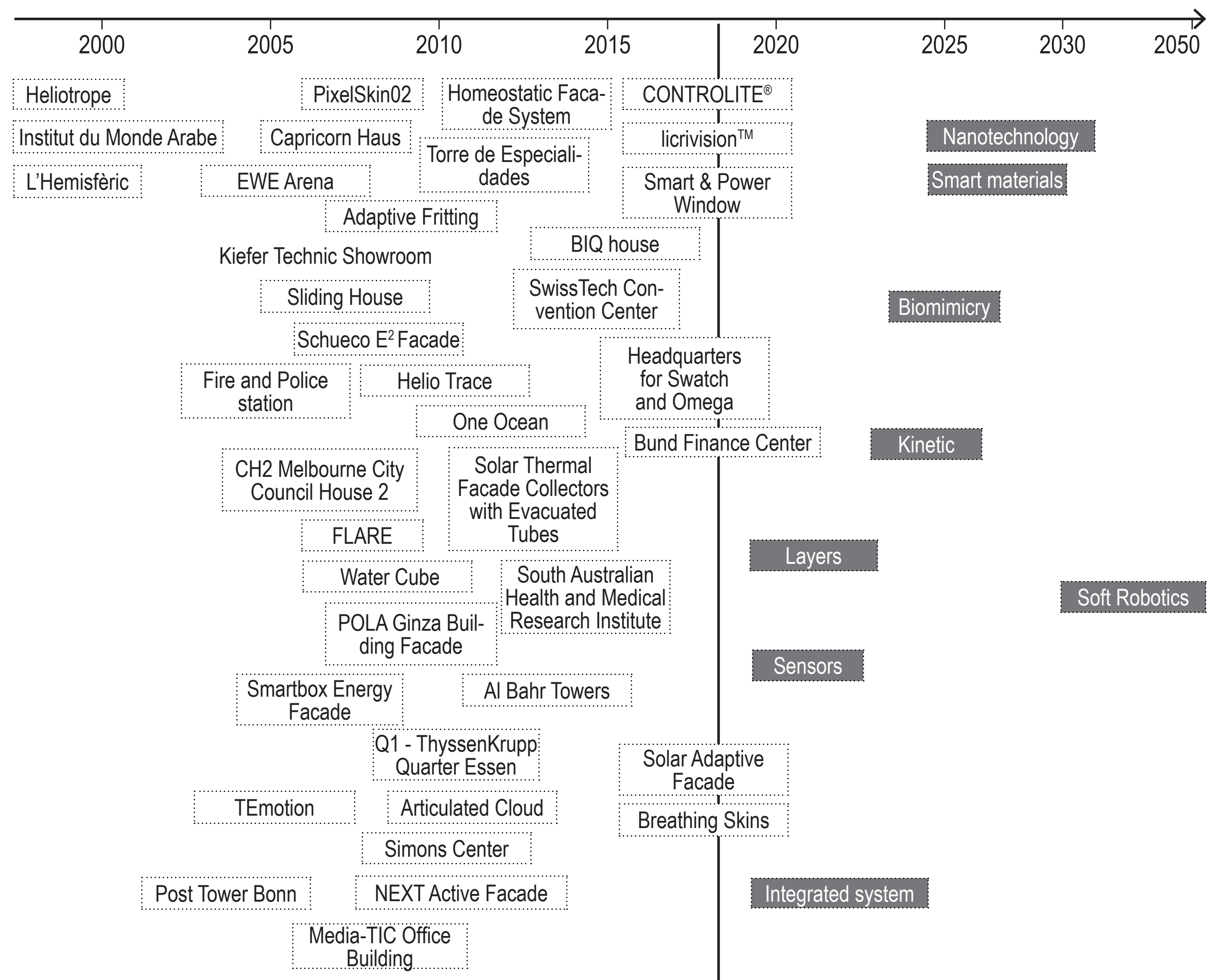
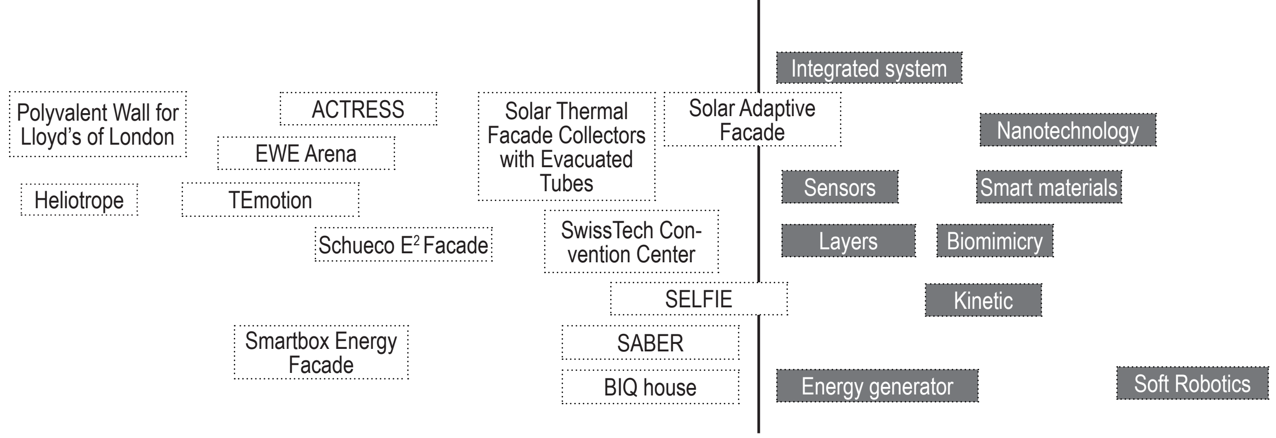


Energy Production



Response to adaptation agent	
Dynamic	20
Static	9

External Agent of Adaptivity	
Solar radiation	28
Temperature	2
Humidity	0
Wind	2
Precipitation	4
Noise	0

Interior Agent of Adaptivity	
Temperature	3
Humidity	0
Light	3
Air exchange rate	5
Sound level	0

Purpose	
Thermal comfort	23
IAQ	6
Visual and Lighting	28
Acoustic	0
Energy production	6

Control od Adaptivity	
Closed loop	24
Open loop	5

Highest Cost	
Materials	5
Production	8
Assembly	11
Maitenance	13

Architectural Design Freedom	
Low	4
Medium	17
High	8

Energy	
-	18
0	5
+	6

Figure 6 a : Results about the common trends of buildings

Response to adaptation agent	
Dynamic	4
Static	7

External Agent of Adaptivity	
Solar radiation	11
Temperature	6
Humidity	1
Wind	0
Precipitation	0
Noise	0

Interior Agent of Adaptivity	
Temperature	6
Humidity	1
Light	3
Air exchange rate	6
Sound level	0

Purpose	
Thermal comfort	10
IAQ	5
Visual and Lighting	10
Acoustic	0
Energy production	5

Control od Adaptivity	
Closed loop	10
Open loop	1

Highest Cost	
Materials	2
Production	2
Assembly	1
Maitenance	8

Architectural Design Freedom	
Low	2
Medium	8
High	1

Energy	
-	4
0	2
+	6

Figure 6 b : Results about the common trends of products

Response to adaptation agent	
Dynamic	7
Static	3

External Agent of Adaptivity	
Solar radiation	8
Temperature	6
Humidity	2
Wind	0
Precipitation	1
Noise	0

Interior Agent of Adaptivity	
Temperature	4
Humidity	0
Light	0
Air exchange rate	6
Sound level	0

Purpose	
Thermal comfort	8
IAQ	5
Visual and Lighting	4
Acoustic	0
Energy production	2

Control od Adaptivity	
Closed loop	5
Open loop	5

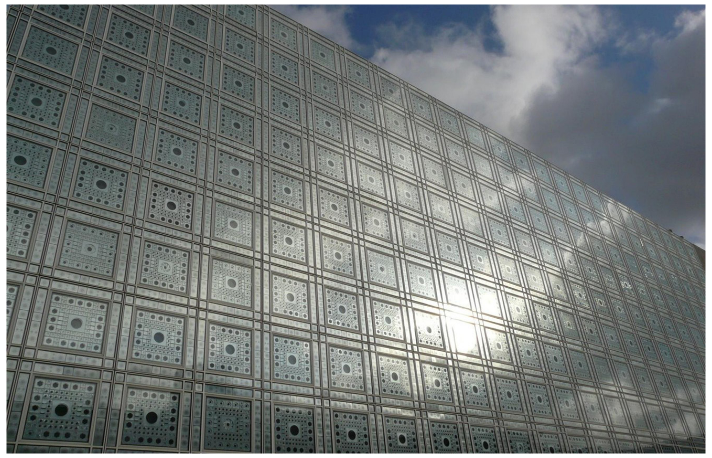
Highest Cost	
Materials	3
Production	2
Assembly	3
Maitenance	3

Architectural Design Freedom	
Low	1
Medium	6
High	3

Energy	
-	4
0	3
+	3

Figure 6 c : Results about the common trends of research projects

BUILDINGS



Institut du Monde Arabe

Jean Nouvel, Architecture-Studio, Pierre Soria and Gilbert Lezenes

Paris, France

1987

Response to Adaptation Agent

● Dynamic ○ Static

The south facade of The Institut du Monde Arabe is composed by advanced responsive metallic brise soleil that have been inspired by the mashrabiyya, an archetypal element of Arabic architecture. The system has been used for centuries in the Middle East to protect the indoor environment from the sun radiation and to provide privacy. The amount of light that enters into the building is regulated by light sensitive diaphragms that shifting geometric pattern, regulate the dimension of transparency and opaque surface.The panels are composed by squares, circles and octagonal shapes that vary in their dimension and change configuration in a fluid motion.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

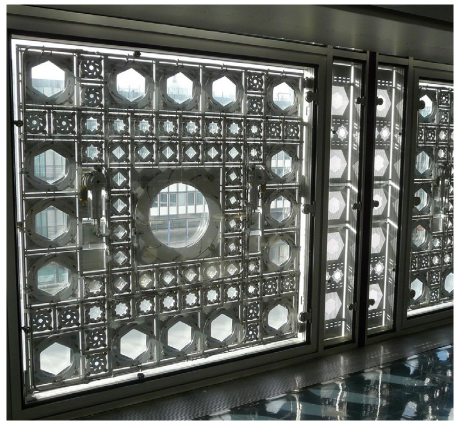
● - ○ 0 ○ +

Highest cost

○ Materials
● Production
● Assembly
○ Maintenance

Architecture design freedom

● Low
○ Medium
○ High



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Heliotrope

Ralph Disch

Freiburg, Germany

1994

Response to Adaptation Agent

● Dynamic ○ Static

Heliotrope is one of the first zero-energy houses in the world. It is mounted on a pole that allows it to rotare of 180 degrees during the day, taking advantage of the sun radiation, increasing the amount of daylight into the indoor space and assuring heat gain thanks to the solar thermal pipes on the facade. The PV panels and the solar thermal tubing provide both electricity and heating, transforming the project in a perfect example of sustainability.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

● Low
○ Medium
○ High

Sources: https://inhabitat.com/heliotrope-the-worlds-first-energy-positive-solar-home/

L'Hemisfèric

Santiago Calatrava

Valencia, Spain

1998

Response to Adaptation Agent

● Dynamic ○ Static

The building is composed by an IMAX theatre, a planetarium and a laserium. The design reminds to a human eye with the pupil, that hosts the planetarium, and the eyelid. The latter is the dynamic component of the building and it can open and close thanks to hydraulic lifts that move the shutters. The result is similar to an eye that coloses and opens. These are made out of steel and glass that provide daylight in the building and work as a glasshouse.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
● Light
● Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

● Low
○ Medium
○ High

Sources: http://www.idesignarch.com/lhemisferic-an-eye-catching-architectural-masterpiece-in-valencia/

Post Tower Bonn

Murphy/Jahn

Bonn, Germany

2003

Response to Adaptation Agent

○ Dynamic ● Static

Post Tower Bonn has a twin-shell facade with the outer shell being completely out of glass. The sytem used is a unitised curtain wall with custom designed exterior layer. The double-glazed facade compensates for heat gain, providing ventilation without a central mechanical system. The shades and operable windows facilitate climate control, while daylight sensors automatically adjust office light levels reducing energy costs. Post Tower offers to its occupants enormous control over their environments, being able to adjust both the shading system sandwiched between the two-layered curtain wall and the operable windows. The aim of the design is to integrate as essential component the idea that the skin of the building modulates its own climate and therefore decentralised installation units are located on the floor slab directly behind the facade layer.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
● Light
● Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

○ - ● 0 ○ +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://www.archlighting.com/projects/a-facade-for-the-future_o
https://www.archdaily.com/231521/flashback-post-tower-murphyjahn

Fire and Police Station

Sauerbruch Hutton

Berlin, Germany

2004

Response to Adaptation Agent

● Dynamic ○ Static

The Fire and Police Station in Berlin is an extension to a now free-standing 19th-century structure and its facade is built up from large-scale, red and green glass shingles. When closed, the glass shingles are slightly tilted, which causes the creation of sky reflections on the building volume. The ones that are placed in front of windows can be opened individually in order to provide sunshading and protect from glare. These movable glass louvres create variations of colors according to whether they are open or closed. The aim of the design was to decrease the reliance on mechanical systems and allow the building and its users to interact with the exterior environment by maximising natural ventilation and daylighting.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
● Light
● Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

○ - ● 0 ○ +

Highest cost

○ Materials
○ Production
● Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://architectuul.com/architecture/fire-and-police-station
http://www.talkitect.com/2008/11/fire-and-police-station-elizabeth-abegg.html

EWE Arena

asp Architekten Stuttgart

Oldenburg, Germany

2005

Response to Adaptation Agent

● Dynamic ○ Static

The facade of EWE Arena consists of a fully-glazed facade, in front of which a large mobile sunscreen is mounted. This mobile solar shade continuously tracks the sun at half-hour intervals, in 7,5° steps with the aim of generating green power, while reducing the amount of solar insolation and significantly reducing the costs of air conditioning. The approximately 240 m² brise soleil consists of 70 frameless monocrystalline PV modules, which generate 27200kWh of energy per year and can travel 200° around the perimeter of the building.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://www.solarfassade.info/en/project_examples/de/ewe_arena_oldenburg.php
Vogt, M. et al. (2010). MOVE: Architecture in Motion - Dynamic Components and Elements

Sliding House

dRMM Architects

Suffolk, East Anglia, GB

2005

Response to Adaptation Agent

● Dynamic ○ Static

The Sliding House has a part of glass and aluminium construction while the rest is timber-frame with larch timber boarding. It consists of a second, sliding sleeve that envelopes the whole ensemble and therefore can be arranged in many different positions. In summer, the sliding roof shades against the sun while in winter it functions in reversed way, allowing passive solar gains during the day and shielding against heat losses during the night. The movable second-skin consists of a steel frame construction with an insulated and moisture-proofed timber infill. Railway tracks assist the sliding movement which is powered by four electric motors.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

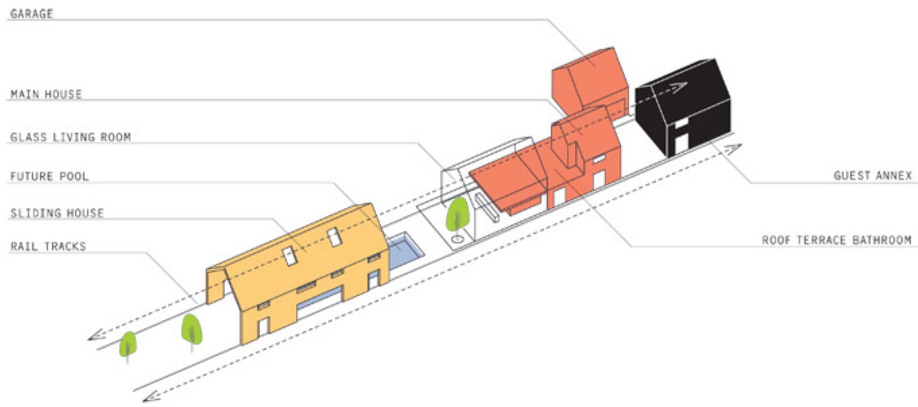
● - ○ 0 ○ +

Highest cost

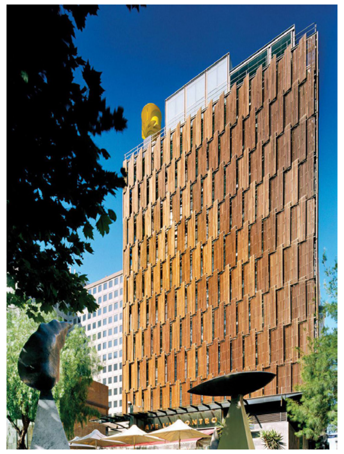
○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High



Sources: https://www.dezeen.com/2009/01/19/sliding-house-by-drmm-2/
Vogt, M. et al. (2010). MOVE: Architecture in Motion - Dynamic Components and Elements



CH2 Melbourne City Council House 2

DesignInc

Melbourne VIC, Australia

2006

Response to Adaptation Agent

● Dynamic ○ Static

The building is a high example of sustainability. it responds to sun and wind to optimize natural light and ventilation. Among the sustainable techniques applied in the design, just the adaptive facade strategies are considered. In particular, the western facade is protected by the sun thanks to a shading system made of recycled timber screens. Moreover, the daylight is integrated by tapered ventilaton ducts. Because of the orientation of the facade, the shading system rotates horizontally according to the position of the sun. The view is never completely obstructed because the panels do not close completely.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

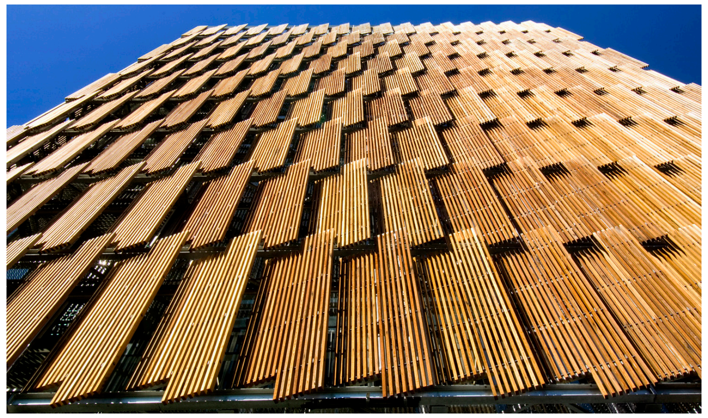
● - ○ 0 ○ +

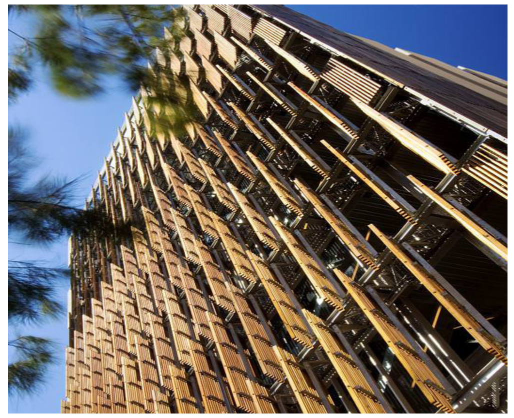
Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High





Sources: https://www.designinc.com.au/portfolio/commercial-workplace/ch2-melbourne-city-council-house-2

Kiefer Technic Showroom

Ernst Giselbrecht and Partner

Bad Gleichenberg, Austria

2007

Response to Adaptation Agent

- ● Dynamic
- ○ Static

The facade of Kiefer Technic Showroom consists of sun screen electronic shutters of preformed aluminum. These can be regulated automatically to optimize the indoor climate, or they can be personalized by the users according to their preferences. The facade changes during the day according to the sun location that determines the position of the shading system. Therefore, the building can change from a completely closed configuration, to an open transparent glazing facade.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

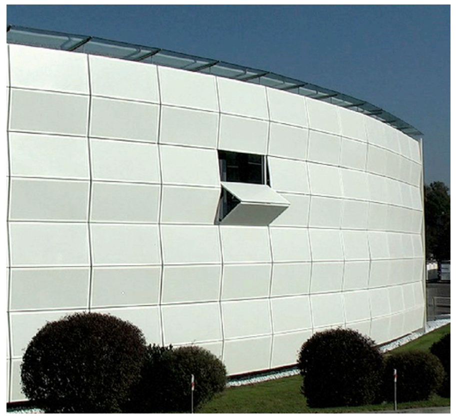
● - ○ 0 ○ +

Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High



Sources: https://www.archdaily.com/89270/kiefer-technic-showroom-ernst-giselbrecht-partner

Capricorn Haus

Gatermann + Schossig

Dussldorf, Germany

2008

Response to Adaptation Agent

- ○ Dynamic
- ● Static

Capricorn Haus is built up from a multi-functional facade module which incorporates all the technology and equipment to regulate the indoor climate through a specially designed closed panel containing a decentralised service module. This unit provides heating, cooling, ventilation and heat exchange and requires an external power source and cold and hot water supply. The system can be controlled by each user individually. The façade is based on a unitised curtain wall system and each unit has a floor-high glazed part in form of a boxed window. Venetian blinds are used for sun-shading in the cavity of the boxed windows, while a light shelf is also used for light direction.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

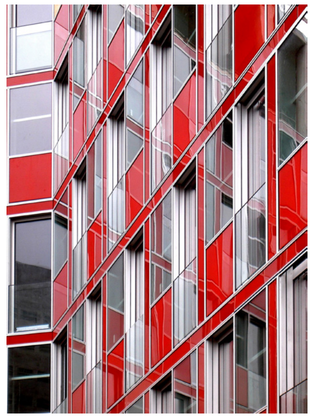
● - ○ 0 ○ +

Highest cost

- ○ Materials
- ● Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High



Sources: https://www.schneiderelectric.es/documents/buildings/capricorn_haus.pdf
http://www.gatermann-schossig.de/pages/de/alle_projekte/office/30.capricornhaus_duesseldorf.htm

National Aquatics Center / Water Cube

PTW Architects, Arup

Beijing, China

2008

Response to Adaptation Agent

○ Dynamic ● Static

The organic form of the "Water Cube" is inspired by the natural formation of soap bubbles. On the one hand, it is a very simple regular building form with highly repetitive geometry but on the other hand the facade has a very unique complex geometry which appears random and organic. The facade consists of translucent ETFE (ethylene tetrafluoroethylene) bubble cladding, which allows high levels of natural daylight to into the building. The project has managed to achieve a reduction of in total 30% energy consumption, savings of 55% lighting energy and a capture of 20% solar energy, which is used for heating the interior space and the swimming pools.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

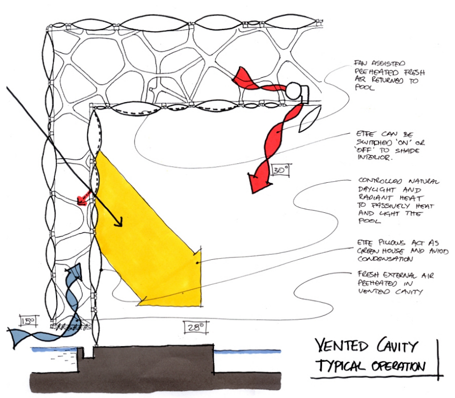
○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High



Sources: https://www.arup.com/projects/chinese-national-aquatics-center
https://www.dezeen.com/2008/02/06/watercube-by-chris-bosse/

Media-TIC Office Building

Enric Ruiz Geli

Barcelona, Spain

2009

Response to Adaptation Agent

○ Dynamic ● Static

This digital technology hub uses distributed sensors to control solar shading by ETFE (ethylene tetrafluoroethylene) cladding. The ETFE cladding surface has two different configurations to match the building's orientation to the sun. The south-west facade filters solar radiation through a screen of vertical cushioned panels filled with nitrogen, which resembles a 'cloud' sunscreen. The south-east facade is arranged in convex and concave triangles, whereby three inflatable chambers within each triangular frame provide both shade and thermal insulation. In total, the Media-TIC technology hub achieves 20% of energy savings by using 2500m^2 of ETFE cladding.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

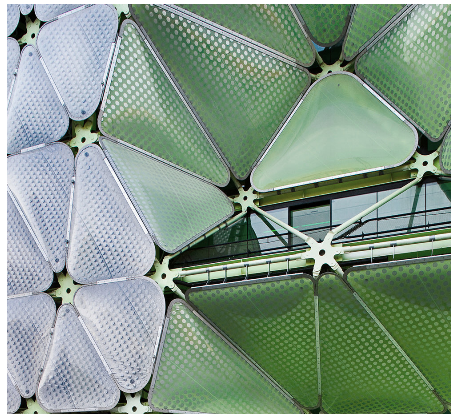
● - ○ 0 ○ +

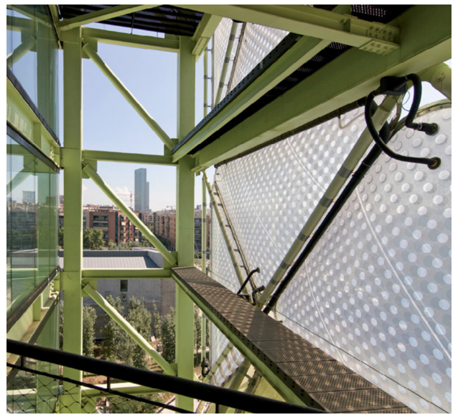
Highest cost

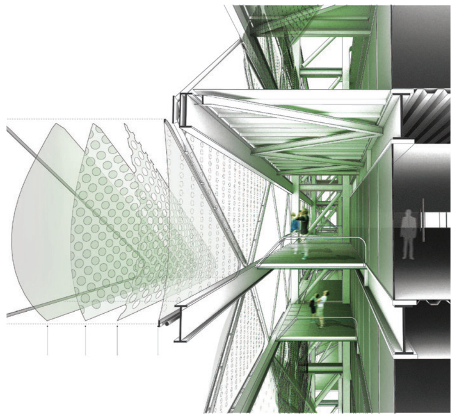
○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

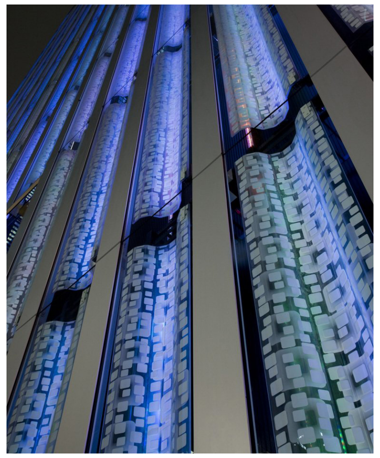
○ Low
○ Medium
● High







Sources: http://www.ruiz-geli.com/projects/built/media-tic
https://www.designbuild-network.com/projects/media-tic/



POLA Ginza Building Facade

Hoberman, Yasuda Atelier and Nikken Sekkei

Ginza District, Tokyo, Japan

2009

Response to Adaptation Agent

● Dynamic ○ Static

The facade of the building is characterized by around 185 shutters positioned between the double skin facade. Each shutter can be individually controlled and has a dimension of one by three meters. The shutters are made of an acrylic sheet that has bee formed into a curved surface and provide shading. During the night, the shading system is illuminated with different colours transforming the aspect of the building.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

- ○ Materials
- ● Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High

Sources: http://www.hoberman.com/portfolio/pola.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=17&category=&projectname=POLA+Ginza+Bu-ilding+Facade

Q1 - ThyssenKrupp Quarter Essen

JSWD Architekten, Chaix & Morel et Associés

Essen, Germany

2010

Response to Adaptation Agent

● Dynamic ○ Static

The building has two facade typologies: two fully transparent that act as gigantic windows and the rest that is covered by triangulr panels made of stainless steel lamellas. The latters, change orientation by rotating horizontally according to the sun position and, thanks to the lamellas, they redirect the light without blocking the view. When the triangular panels are perpendicular to the facade, the orthogonal view is completely free from obstructios.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
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Highest cost

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Architecture design freedom

- ○ Low
- ● Medium
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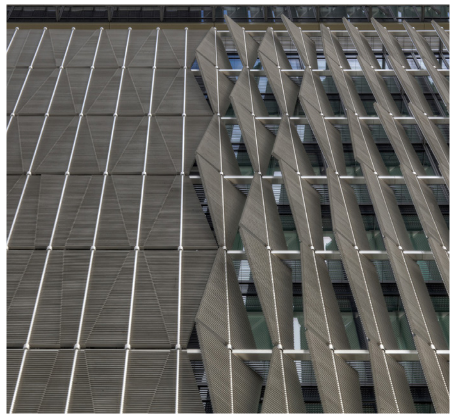
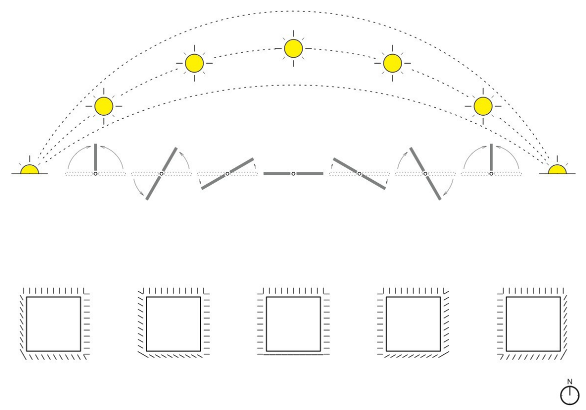
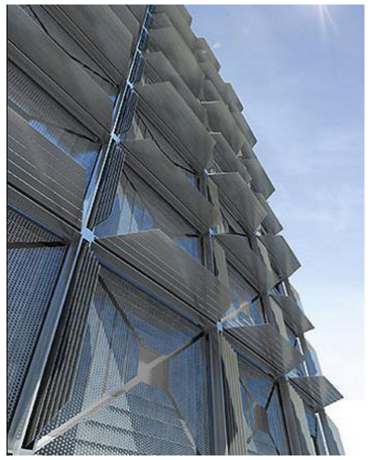




Sources: https://www.archdaily.com/326747/q1-thyssenkrupp-quarter-essen-jswd-architekten-chaix-morel-et-associes



Helio Trace

Skidmore, Owings, Merill, Permasteelisa Group, Hoberman

Center of Architecture, New York, USA

2010

Response to Adaptation Agent

● Dynamic ○ Static

The shading system is a prototype that responds to the solar radiation, by adjusting its position, regulating glare and amount of daylight. From the thermal poin of view, it decreases the solar heat gain by the 81%, decreasing the cooling demand and therefore the energy consumption. During the day, the building gradually transforms from completely transparent to opaque, according to the incident solar radiation.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
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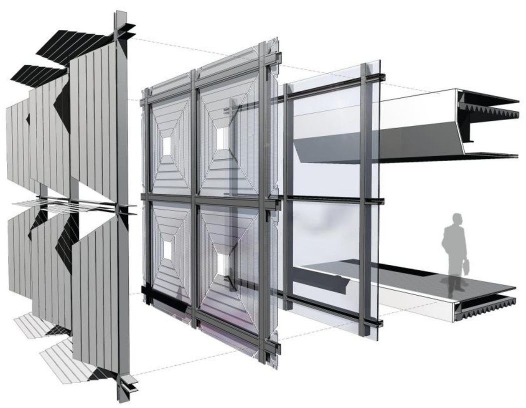
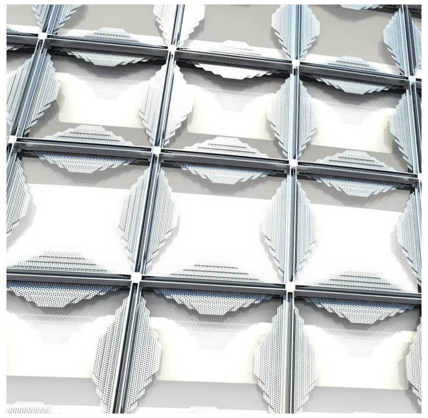
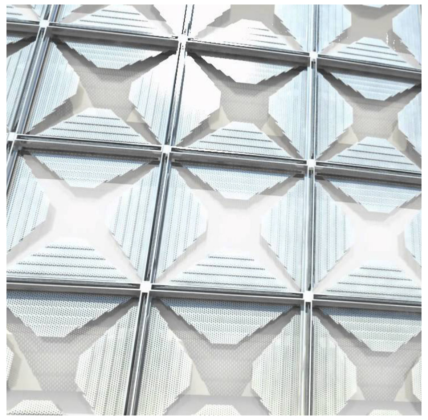
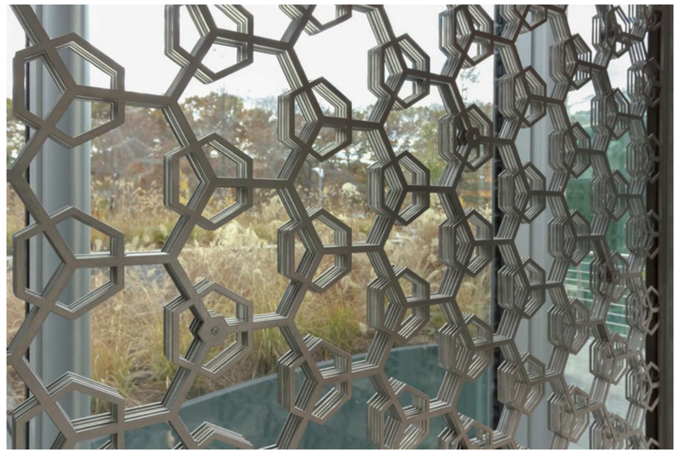






Sources: http://www.hoberman.com/portfolio/heliotrace.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=11&category=&projectname=HelioTrace



Simons Center

Hoberman

SUNY Stony Brook, New York, USA

2010

Response to Adaptation Agent

● Dynamic ○ Static

The installation in Simon Center shows three possible artistic patterns for a dynamic shading system. The geometry has been designed in a way that three layers with the same geometry can shift from an overlap position to three different positions that create different patterns decreasing the amount of transparency. By this way, the system regulates daylight and solar heat gain, decreasing the energy demand needed for cooling during summer.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
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Control of Adaptivity

● Closed loop
○ Open loop

Energy

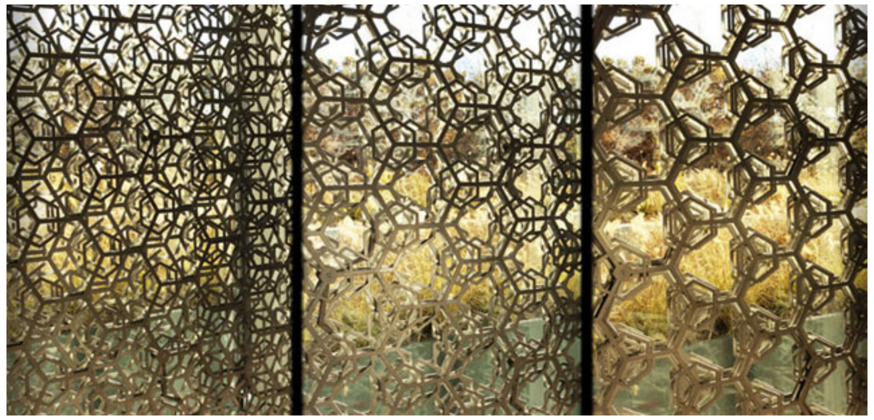
● - ○ 0 ○ +

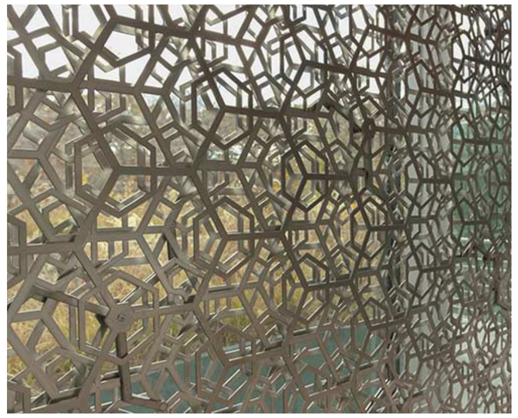
Highest cost

● Materials
● Production
○ Assembly
○ Maintenance

Architecture design freedom

● Low
○ Medium
○ High





Sources: http://www.hoberman.com/portfolio/simonscenter.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=19&category=&projectname=Simon-s+Center

Articulated Cloud

Ned Kahn

Children's museum of Pittsburgh, Pennsylvania

2011

Response to Adaptation Agent

● Dynamic ○ Static

Articulated Cloud is both a façade and an art installation, composed of thousands of translucent, white plastic squares that move in the wind. Natural conditions, such as shifting light and weather, change the optical qualities of the skin in unique and unpredictable ways. The articulated skin is supported by an aluminum space frame so it appears to float in front of the building. It modulates light reaching the main enclosure behind and produces visual and audio outputs according to the wind and light available.

Exterior Agent of Adaptation

○ Solar radiation
○ Temperature
○ Humidity
● Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

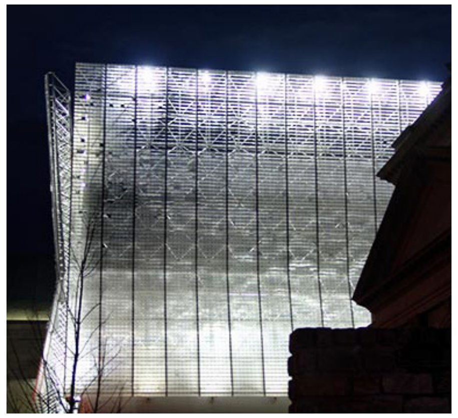
○ - ● 0 ○ +

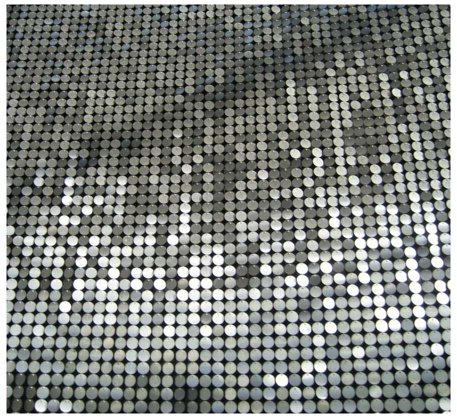
Highest cost

○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High





Sources: http://nedkahn.com/portfolio/articulated-cloud/
http://ming3d.com/DAAP/ARCH713fall11/?tag=ned-kahn

Torre de Especialidades, Hospital Manuel Gea Gonzales

Elegant Embellishments

Mexico City, Mexico

2012

Response to Adaptation Agent

○ Dynamic ● Static

A hive-like double skinned facade is made of decorative architectural module that can effectively reduce air pollution. The facade is made up from Prosolve370e, a new type of ceramic developed by the office Elegant Embellishments. The specialized material is covered with superfine titanium dioxide (TiO_2), a technology that neutralizes contamination when in contact with daylight and which is known for its self-cleaning, anti-microbial and de-polluting properties. The design is also important for this effect since it increases the capacity to receive and disperse ultraviolet light. The wind speed through the façade creates turbulence, causing a better distribution of the contaminants across the active surfaces. In addition, the facade skin acts as a natural light filtration system and solar gain blocker for the interior.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
● Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

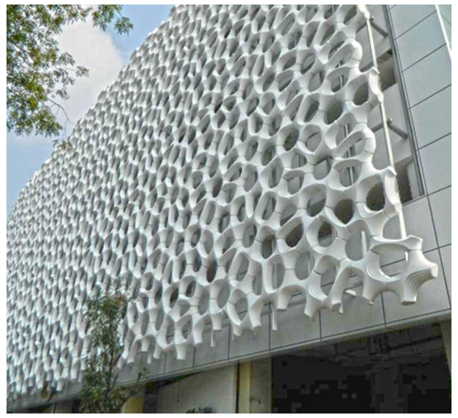
○ - ● 0 ○ +

Highest cost

● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High



Sources: https://inhabitat.com/mexico-citys-manuel-gea-gonzalez-hospital-has-an-ornate-double-skin-that-filters-air-pollution/
https://www.centreforpublicimpact.org/case-study/mexico-citys-manuel-gea-gonzalez-hospital-facade/

One Ocean, Thematic Pavilion Expo 2012

Soma ZT GmbH

Yeosu, South Korea

2012

Response to Adaptation Agent

● Dynamic ○ Static

The Thematic Pevilion is fully integrated into its urban context and natural environment and has become an iconic landmark for the area.The kinetic facade consists of glass fiber reinforced polymers (GFRP) creating various animated patterns in order to control the interior light conditions. The effect is achieved by continuous surfaces which twist from vertical to horizontal orientation creating a connection of interior and exterior space. The longer a lamella is, the wider the opening angle can become and the bigger the area affected by light that enters the building. After sunset, the visual effect of the moving lamellas is enhanced by LEDs.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ○ Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

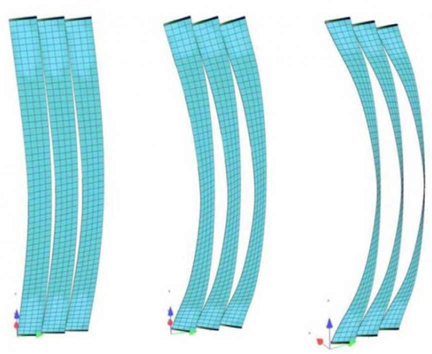
● - ○ 0 ○ +

Highest cost

- ○ Materials
- ○ Production
- ● Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High



Sources: http://www.soma-architecture.com/index.php?page=theme_pavilion&parent=2
http://compositesandarchitecture.com/?p=68

Al Bahr Towers

Aedas Architects

Abu Dhabi, United Arab Emirates

2012

Response to Adaptation Agent

● Dynamic ○ Static

Al Bahr Towers incorporate a “mashrabiya” inspired shading system, which operates as a curtain wall. The facade which is suspended on an independent frame consists of triangles. Each triangle is coated with fiberglass and is programmed to respond to the movement of the sun with the aim to reduce solar gain and glare. The screen was simulated by the computational team of the architectural office to test its response to sun exposure and the changing incidence angles throughout the year. In addition, it allowed the architects to use more naturally tinted glass which not only provides better views but also allows more light to enter the interior space thus leading to less need for artificial light.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
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- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

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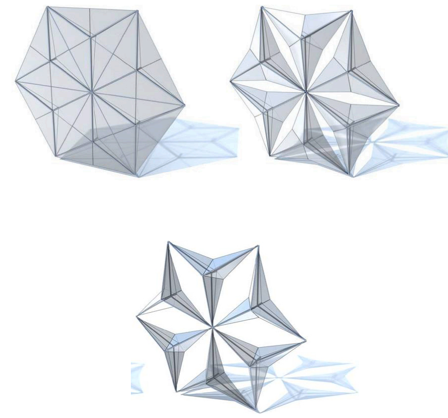
● - ○ 0 ○ +

Highest cost

- ○ Materials
- ○ Production
- ● Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High



Sources: https://www.arch2o.com/al-bahr-towers-aedas/
http://www.ahr-global.com/Al-Bahr-Towers

RMIT Design Hub

Sean Godsell

RMIT University, Melbourne, Australia

2012

Response to Adaptation Agent

● Dynamic ○ Static

RMIT Hub incorporates strategies of water, waste and recycling management. In particular, it consists of an automated operable second-skin sunshading system which includes photovoltaic cells, evaporative cooling and fresh air intakes with the aim of improving the indoor air quality and lowering running costs. The second skin is made up of sandblasted glass disks, which are fixed to either a horizontal or vertical aluminium axel. Every 21 disks, 12 operable and 9 fixed, compose one panel of the curtain wall face of the building. The entire facade is designed in such a way that can be easily replaced so that it can be upgraded as solar technology evolves witht the possibility of being able one day to produce enough electricity to run the entire building.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
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○ Precipitation
○ Noise

Interior Agent of Adaptation

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● IAQ
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Control of Adaptivity

● Closed loop
○ Open loop

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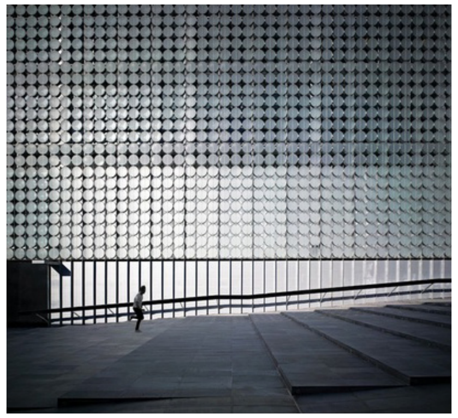
Highest cost

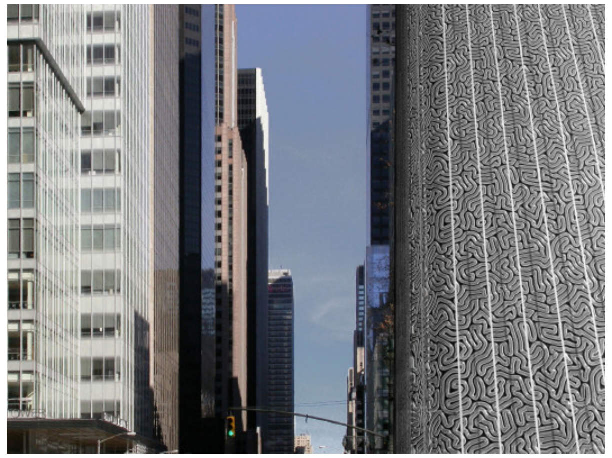
○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
○ Medium
● High



Sources: http://www.seangodsell.com/rmit-design-hub
https://www.archdaily.com/335620/rmit-design-hub-sean-godsell



Homeostatic Facade System

Decker & Yeadon

New York, USA

2013

Response to Adaptation Agent

● Dynamic ○ Static

Homeostatic Facade is a prototype system that regulates the solar radiation by changing shape. It is composed of ribbons made of dielectric elastomers, a polymer material, that polarizes when an electrical current is applied. It works as a muscle and consumes a little amount of energy. The ribbons are coated with silver electrodes that reflect light and distribute the electricity through the material. The ribbons expand or contract according to the environmental conditions, regulating both the solar heat gains and the amoutn of light.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
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○ Sound level

Purpose

● Thermal comfort
○ IAQ
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○ Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

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Highest cost

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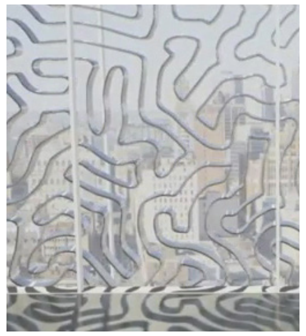
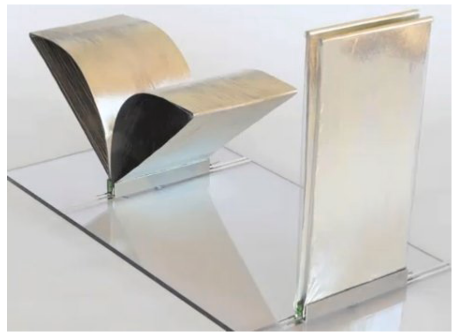
● Production
○ Assembly
○ Maintenance

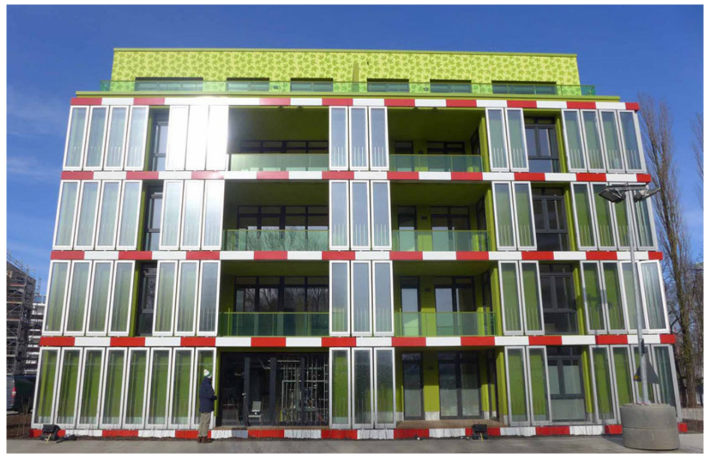
Architecture design freedom

○ Low
● Medium
○ High





Sources: https://materia.nl/article/homeostatic-facade-system/
https://www.archdaily.com/101578/moving-homeostatic-facade-preventing-solar-heat-gain



BIQ house

Splitterwerk Architects & Arup

Hamburg, Germany

2013

Response to Adaptation Agent

○ Dynamic ● Static

The “bio-adaptive” facade consists of live microalgae which are used as bio-reactors and are growing in glass louvres that clad the southeast and southwest facades of the building in order to generate renewable energy and provide shade at the same time. The algae are continuously supplied with liquid nutrients and carbon dioxide via a water circuit running through the facade. The sun encourages the algae’s growth to provide more shade, while at the same time heat is absorbed to warm the building’s hot water tank. By growing, the algae are able to produce biomass, which is then converted into biofuel and consequently the process of photosynthesis is responsible for a dynamic response to the required solar shading. At the same time the algae creates harvestable energy, the excess of which can be stored in buffers or sold back to the local grid.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: https://www.arup.com/en/projects/s/SolarLeaf
http://www.iba-hamburg.de/en/themes-projects/the-building-exhibition-within-the-building-exhibition/smart-material-houses/biq/projekt/biq.html

SwissTech Convention Center

Richter Dahl Rocha & Associés

University of Lausanne, Switzerland

2014

Response to Adaptation Agent

○ Dynamic ● Static

The SwissTech Convention Center is the first large-scale convention hall to use EPFL’s dye-sensitized solar cells. These are integrated in panels that constitute the building envelope. The EPFL’s dye-sensitized solar cells have been invented by Michael Grätzel and, differently from the common solar cells, have the same performance independetly from the angle of incidence of the light. A second advantage is that these solar cells are translucent and therefore they protect the building from solar radiation, allowing the passage of daylight, but reducing the solar gain and therefore the energy demand for cooling during summer.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

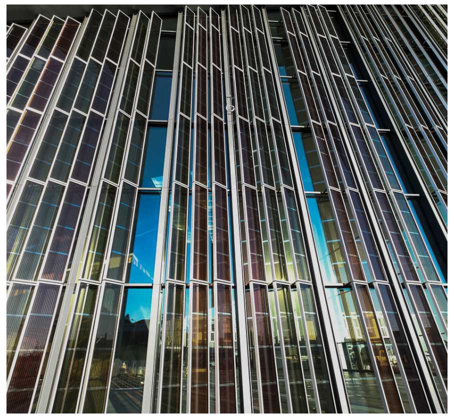
○ - ○ 0 ● +

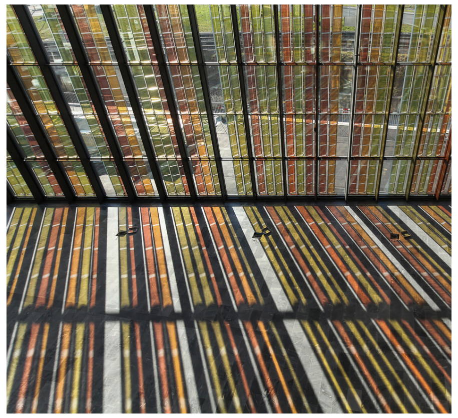
Highest cost

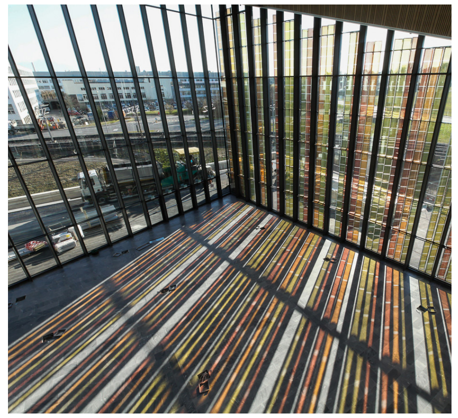
● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

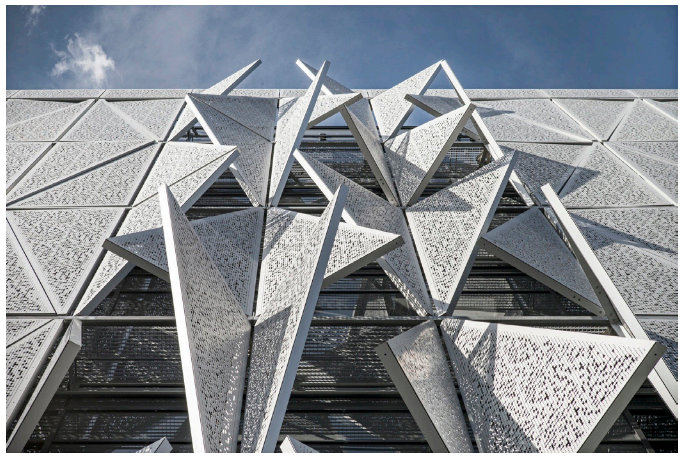
○ Low
○ Medium
● High







Sources: https://www.archdaily.com/491135/richter-dahl-rocha-develop-innovative-facade-for-swisstech-convention-center



SDU Campus Kolding

Henning Larsen Architects

Kolding Campus, Denmark

2014

Response to Adaptation Agent

● Dynamic ○ Static

The facade modifies its composition according to the solar radiation, to adjust daylight and thermal comfort. The facade is made up 1600 triangular shape panels of perforated steel that change their position according to the amount of daylight. The latter is measured by some sensors that detect the light and the heat and modify the shutters position from flat along the facade, to open and perpendicular to the facade, providing daylight. In this way, the aspect of the building changes continuosly.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

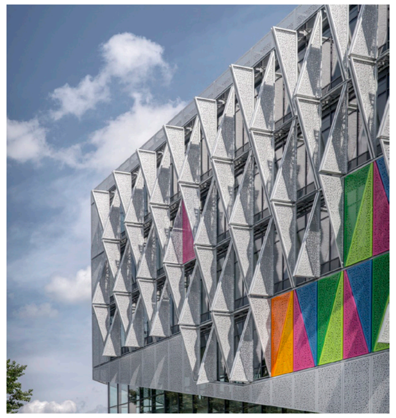
● - ○ 0 ○ +

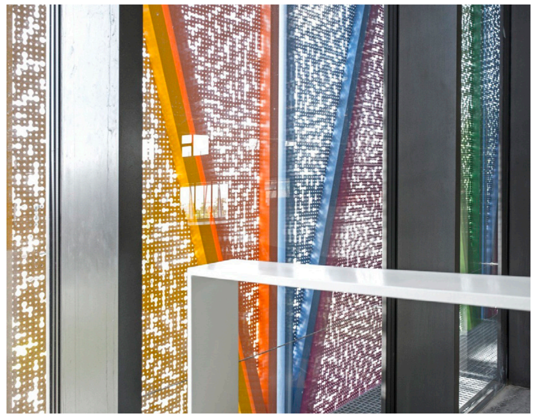
Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High





Sources: https://www.archdaily.com/590576/sdu-campus-kolding-henning-larsen-architects

Headquarters for Swatch and Omega

Shigeru Ban Architects

Biel, Switzerland

2017

Response to Adaptation Agent

○ Dynamic ● Static

The Headquarters for Swatch and Omega consist of three buildings and the facade is a free form shell built with semi-circular timber frame structure. This shell is composed of different types of elements out of glass, ETFE and polycarbonate or timber. At the same time, all the elements are quadrangular whichs means that they follow the doubly curved shape of the building. The glass used is cold and warm bended, which works as a sun shading device. The polycarbonate is cold bended and is used as an internal layer of the ETFE cushions.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

- ○ Materials
- ○ Production
- ● Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High

Sources: http://www.leichtonline.com/uploads/files/Swatch_eng_web(1).pdf
https://www.designboom.com/architecture/shigeru-ban-headquarters-for-swatch-production-buildings-for-omega/

Apple Dubai Mall

Foster + Partners

Dubai, United Arab Emirates

2017

Response to Adaptation Agent

● Dynamic ○ Static

The daylight is a significant element of this building.The amount of daylight is regulated by a shading system that has been reinterpreted by the traditional Arabic Mashrabiya. The shading system is called Solar Wings because it resembles wings that open and close according to the amount of light. These are made of multiple layers of tubes of lightweight carbon fibre that are more concentrated where the solar radiation is more intense. The dimension of the net allows to have a clear view to the outside environment.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
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Purpose

○ Thermal comfort
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Control of Adaptivity

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Energy

● - ○ 0 ○ +

Highest cost

● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: https://www.archdaily.com/870357/apple-dubai-mall-foster-plus-partners

Bund Finance Center

Foster + Partners and Heatherwick Studio

Shanghai

2017

Response to Adaptation Agent

● Dynamic ○ Static

The building has been inspired by the traditional Chinese theatres. Its envelope is made by three layers of bronze tubes that work as shading system all around the building. According to the direction and amount of daylight, the three layers adjust their position changin the level of transa-prency of the facade. The effect is a dynamic envelope that seems to rotate around the building is a very fluid effect.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
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Architecture design freedom

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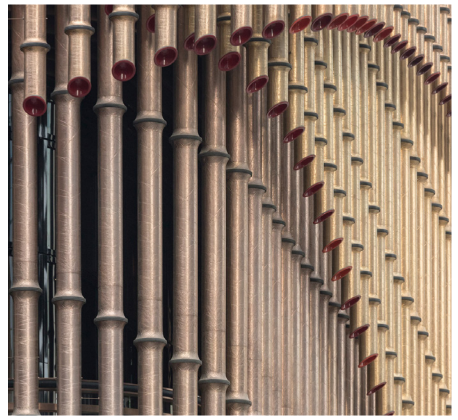
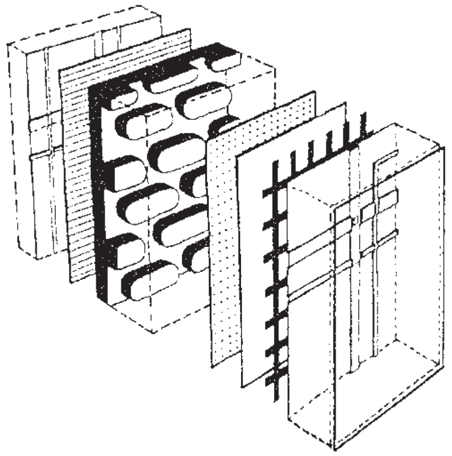


Sources: https://www.dezeen.com/2017/06/09/foster-heatherwick-complete-shanghai-arts-centre-curtain-like-facade-fosun-foundation-theatre-architecture/

PRODUCTS



Polyvalent Wall for Lloyd's of London

Mick Davies

London, UK

1981

Response to Adaptation Agent

○ Dynamic ● Static

The Polyvalent Wall is a layered, multifunctional and highly integral construction. The concept was to integrate all façade functions in one layer while incorporating energy collection and ventilation. The polyvalent wall would consist from different layers on top of a glass layer which would act as absorber, radiator, reflector, filter and transfer device at the same time. The necessary energy needed to be gained by the façade itself. In order for the façade to respond automatically to both the outer circumstances and the inside users, it needs to have sensors which contain information on usage schedules, habits and environmental performance data from the users of the building.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
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Purpose

- ● Thermal comfort
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Control of Adaptivity

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- ○ Open loop

Energy

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Highest cost

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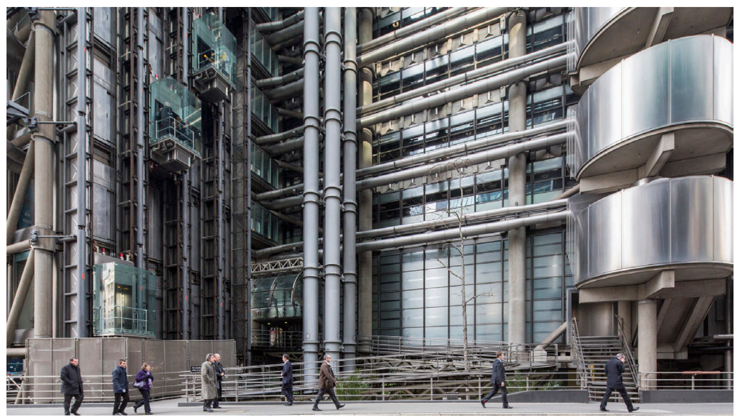
- ○ Assembly
- ● Maintenance

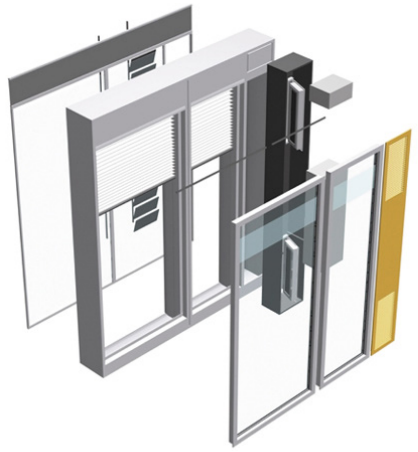
Architecture design freedom

- ○ Low
- ● Medium
- ○ High



Sources: https://books.bk.tudelft.nl/index.php/press/catalog/download/600/693/499-1?inline=1

Klein, T. (2013). Integral Facade Construction: Towards a new product for curtain walls.



TEmotion

Hydro Building Systems

WICONA global company & Univercity of Dortmund

2005

Response to Adaptation Agent

○ Dynamic ● Static

TEmotion is a synthesis of technology and emotion and it is actually a facade that responds to changes in outdoor and indoor conditions, such as light or temperature by incorporating technical components, sensors and control systems. The intelligent façade controls the integrated ventilation, air-conditioning and heating technology, adjusts the sun protection and prevents the interior from overheating. In addition, PV cells are used for generating energy in order to supply the building installations with electric current. All components of building services which are integrated in the functional element can be controlled through a central building services management system or by the user with the aim to achieve energy savings and a high level of well being for the users.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

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- ○ Open loop

Energy

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Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High

Sources: https://www.wicona.com/en/se/Aluminium/Sustainability/TEmotion/

ECONTROL®

EControl-Glas GmbH & Co.

Plauen, Germany

2005

Response to Adaptation Agent

○ Dynamic ● Static

ECONTROL® is a dimmable solar control glass developed by EControl-Glas that uses electrochromic glass to vary the tint of the glass and therefore its light transmittance and its solar factor. According to the shade of the glass, the light can be transmitted from 10 to 56%, maintaining a level of brightness even in its darkest state. As all the smart glazing, this solution protects the indoor climate during summer and reduces glare maintaining the view to the outside. It consumes electricity only when it changes the dimming level because the material has the capacity to memorize the information and maintain them until a new input is given. The dimming is of about 20-25 minutes. The control can be automated or controlled with the possibility for the users to adjust the diming level according to their preferences.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ● Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High

Sources: www.econtrol-glas.de

Smartbox Energy Facade

Cepezed & Energy Research Center of Netherlands

2006

Response to Adaptation Agent

○ Dynamic ● Static

Smartbox integrates building services components at the junction of the facade and the floor slab with the benefit of an unobstructed outside view since the floor to ceiling space remains free of obstacles. Smartbox Energy Facade contains a large amount of advanced climate-regulating equipment, such as a water pump, electrically driven ventilators and a heat exchanger. The project makes clever use of the sunlight in order to regulate the indoor environment and incorporates built-in photovoltaic solar cells to generate electricity. The project aimed to develop an 'active' façade concept that uses active and passive solar energy and intelligence in the façade. The result is a potential 50% reduction of building related energy use at market conformable prices, combined with improved comfort.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ● Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

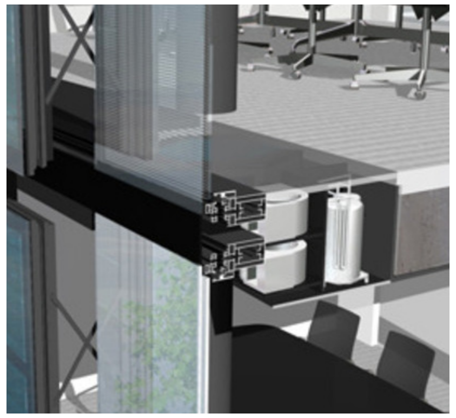
○ - ○ 0 ● +

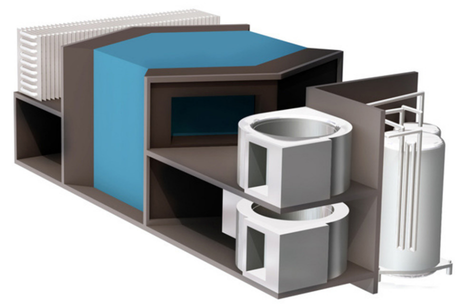
Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High





Sources: https://www.cepezed.com/projects/51-smartbox

https://www.ecn.nl/news/newsletter-en/archive-2007/july-2007/smartbox/

Schueco E^2 Facade

Schueco

Global company

2007

Response to Adaptation Agent

○ Dynamic ● Static

Schueco E^2 Facade is a multifunctional facade with the aim of saving and generating energy by the technologies in real time. It is a revolutionary combination of facade and system technology which provides four different function modules that allow customization. These modules are: concealed decentralised ventilation, thin-film modules, integrated solar shading and flush integrated opening units. This facade provides transparency and offers at the same time protection from excessive solar radiation and permission of the optimum natural illumination while carrying out additional functions like generating electricity. The new facade system is a combination of curtain wall and structural glazing system and offers the possibility to integrate building services components at a designated space in front of the floor slab with the benefit of an unobstructed outside view.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
○ Light
● Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

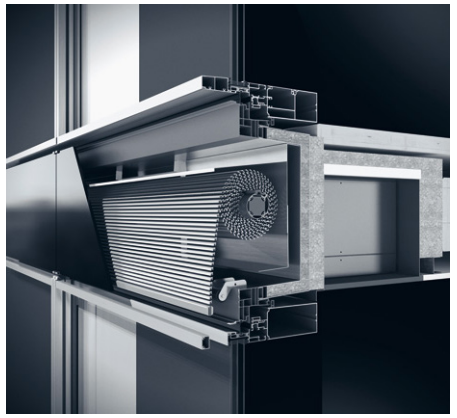
○ - ○ 0 ● +

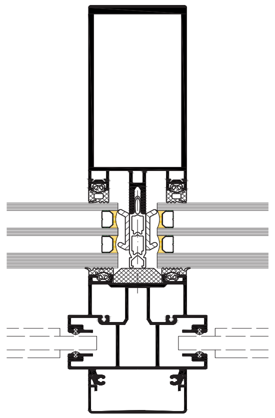
Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High





Sources: http://www.geopetaluminium.com/E2.html
http://www.creativealuminium.co.uk/downloads/Fasade_Saving_Energy_and_Generating_Energy.pdf

FLARE - Kinetic Membrane Facade

WHITEvoid interactive art & design

2008

Response to Adaptation Agent

● Dynamic ○ Static

FLARE consists of a modular system acting like a living skin which is able to respond to the exterior environment. FLARE turns the building facade into a penetrable kinetic-flexible membrane while giving a visual effect at the same time. The facade is made of flake metal outlines which are moved by individually controlable pneumatic cylinders. Each metal flake can reflect ambient or direct sunlight, thus creating different images on the outer layer of the building. The building's activity is monitored by sensors which are inside and outside of the building and the system is controlled by a computer in order to create any kind of surface animation.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

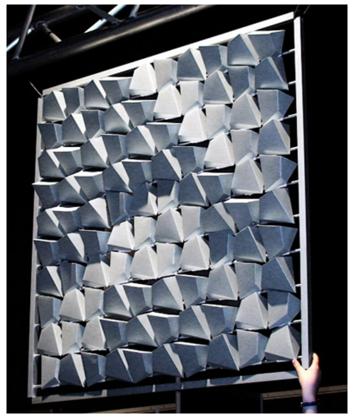
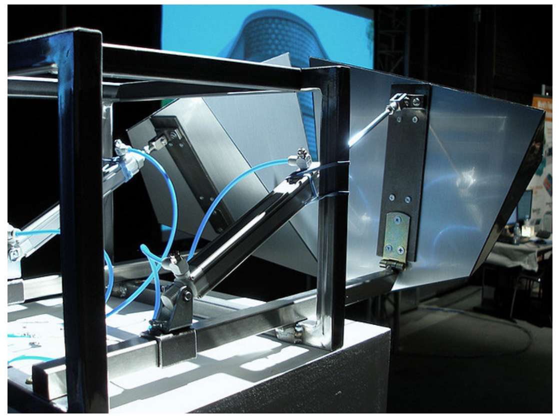
● - ○ 0 ○ +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://www.mediaarchitecture.org/flare-kinetic-membrane-facade/
http://www.whitevoid.com/#/main/architecture_spaces/flare_facade/description

PixelSkin02

Sachin Anshuman

UK

2008

Response to Adaptation Agent

● Dynamic ○ Static

PixelSkin02 is a surface composed by pixel-tiles divided into four triangular panels of shape memory alloys (SMA). The panel creates a transparent visual field that can also generate low-resolution images and low-refresh-rate videos via electromechanical imputs by 200mA SMA wires. The panels regulate the light by opening or closing. The amount of light can vary thanks to the 255 possible states of adjustments of the triangular elements.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

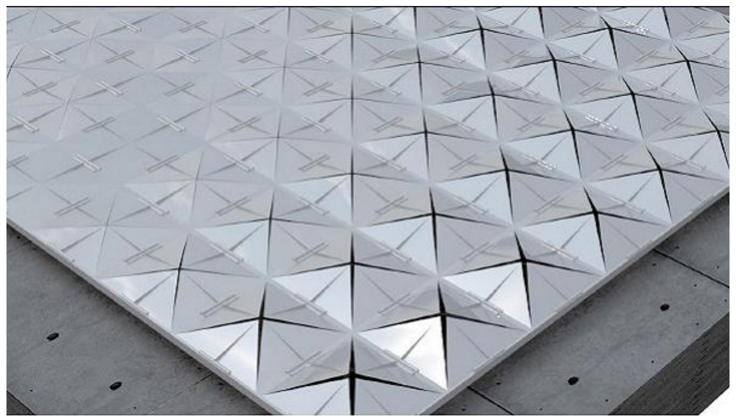
● - ○ 0 ○ +

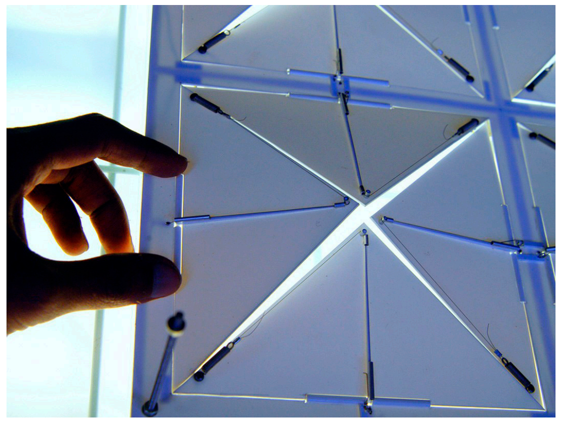
Highest cost

- ○ Materials
- ● Production
- ● Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High





Sources: http://transmaterial.net/pixelskin02/

NEXT Active Facade

Kawneer

global company

2010

Response to Adaptation Agent

○ Dynamic ● Static

Alcoa Architecture Systems, Somfy and Trox utilised the knowledge and expertise of the Cepezed Firm of Architects, Delft University of Technology, Hurks Facade Technology and Warema Nederland to develop a unique façade concept, which is an important link in the energy management of buildings. NEXT Active Facade has a modular set-up and offers fully integrated facilities such as climate cooling, heating, ventilation and regulation of sunlight. The facade can be freely divided and offers a low operating energy consumption. The facade filters and conditions sucked in outside air and brings it into the interior spaces draft-free. A heat exchanger regenerates the exhaust air, while night ventilation and automatic sun protection use natural resources.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ● Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ● Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

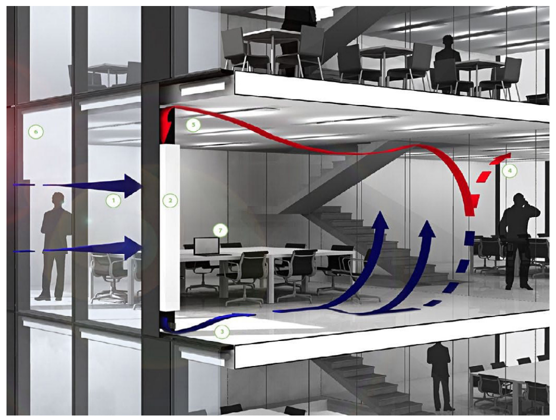
○ - ● 0 ○ +

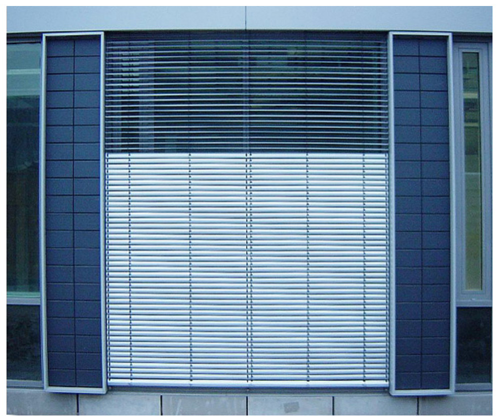
Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

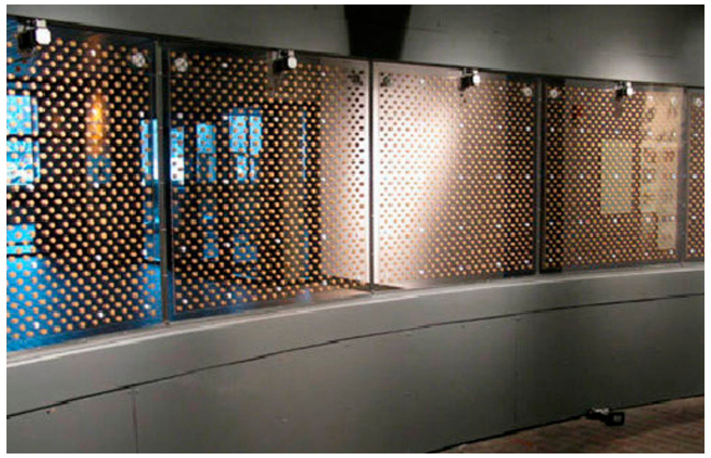
Architecture design freedom

- ○ Low
- ● Medium
- ○ High





Sources: https://www.kawneer.com/bcs/architectuursystemen/catalog/pdf/brochures/NEXT%20Active%20Facades%20brochure_FINAL.pdf
https://facadeworld.files.wordpress.com/2014/01/next-active-facades.jpg



Adaptive Fritting (GSD)

Hoberman

Harvard Graduate School of Design, Cambridge, Massachussetts, USA

2009

Response to Adaptation Agent

● Dynamic ○ Static

The system is a prototype for a shading system that can control heat gain and amount of daylight. The pattern allows different levels of transparency thanks to the adaptive fritting that, with a dynamic motion via motorized control, balances the opaque and transparent states. This effect is achieved by shifting a series of fritted glass layers, aligning or diverging the pattern.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

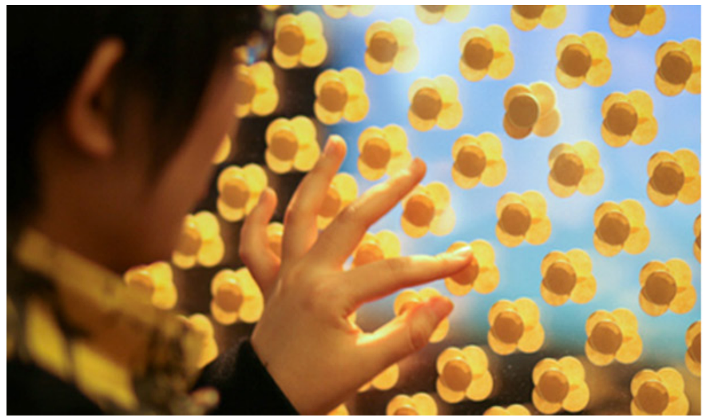
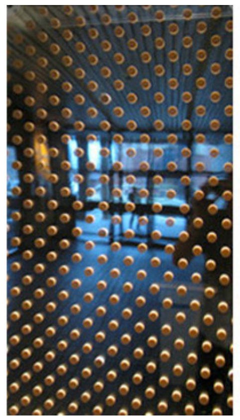
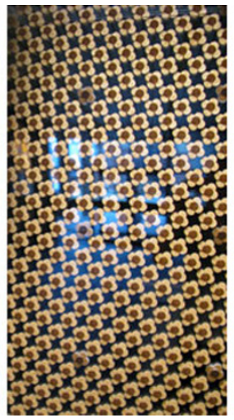
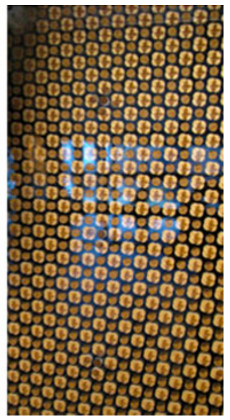
● - ○ 0 ○ +

Highest cost

○ Materials
● Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://www.hoberman.com/portfolio/gsd.php?rev=0&onEnterFrame=%5Btype+Function%5D&myNum=0&category=&projectname=Adaptive+Fritting+%28GSD%29

SageGlass®

Saint-Gobain

Flamatt, Switzerland

2010

Response to Adaptation Agent

○ Dynamic ● Static

SageGlass® is a smart window developed by Saint-Gobain that uses electrochromic glass as smart technology to maximize the daylight and minimize solar heat gain and glare. The window changes its tint, and therefore its light transmittance, with different shades of blue according to the amount of voltage that is applied. The application of the voltage can be automated thanks to light sensors, motion sensor, lighting control, thermostat or by the users. This solution allows the multi-zone: different portions of the glass can be tinted, independently from each other, with different shades withoud physically divide the facade with a frame.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
● Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High



Sources: www.sageglass.com

Solar Thermal Facade Collectors with Evacuated Tubes

© Universität Stuttgart, IBK 2

Stuttgart, Germany

2013

Response to Adaptation Agent

○ Dynamic ● Static

The solar thermal facade collector with evacuated tubes provides both thermal and lighting comfort. In particular, it collects the solar heat at high temperatures and, because ot the semi-transparecy of the elements, protects the indoor space from the glare and assures a light diffusion. The high-performance evacuated tubes are covered with perforated parabolic mirrors that direct the solar radiation onto the evacuated tubes. This helps reducing the solar gain and therefore, reduces the cooling demand in summer. From a visual comfort point of view, the system looks like venetian blinds, with the advantage to be more transparent, allowing to see the external environment.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

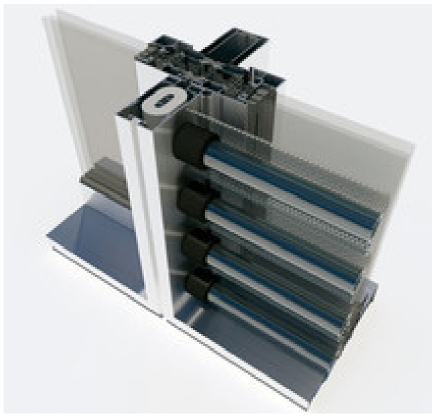
○ - ○ 0 ● +

Highest cost

● Materials
● Production
○ Assembly
○ Maintenance

Architecture design freedom

● Low
○ Medium
○ High



Sources: http://www.bine.info/en/publications/publikation/fassadenkollektoren-mit-durchblick/

Smart Window and Power Window

PHYSEE

Delft, Netherlands

2014

Response to Adaptation Agent

● Dynamic ○ Static

PowerWindow is a patented product of Physee. It looks exactly as a common window, because it is transparent and colourless, but it has the advantage that converts light into electricity. The SmartWindow connects the inside and outside environment by smart sensors that measure light intensity, temperature, pressure and air quality, helping in the improvement of the indoor condition and in decreasing the energy demand for heating and cooling.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
● Light
● Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

○ - ● 0 ● +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://www.physee.eu/products/

iSolar Blinds

LCG

Newcastle, United Kingdom

2014

Response to Adaptation Agent

● Dynamic ○ Static

iSolar Blinds are a transparent blinds that work as insulator. They allow natural daylight and control the solar heat gain. This is possible thanks to the design of this product that is made of an aluminium coated polyethylene sheet laminated to a sheet of carbon graphite, later perforated and laminated to a sheet of clear polyester. Each side of the material has a different benefit on the indoor climate: the aluminium reflects the solar radiation to the outside to decrease the solar heat gain in summer while it faces the indoor space during winter to maintain the heat into the building. The carbon graphite is a dark non-reflective layer that faces outward during winter, absorbing the heat and releasing it into the indoor space.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ○ Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

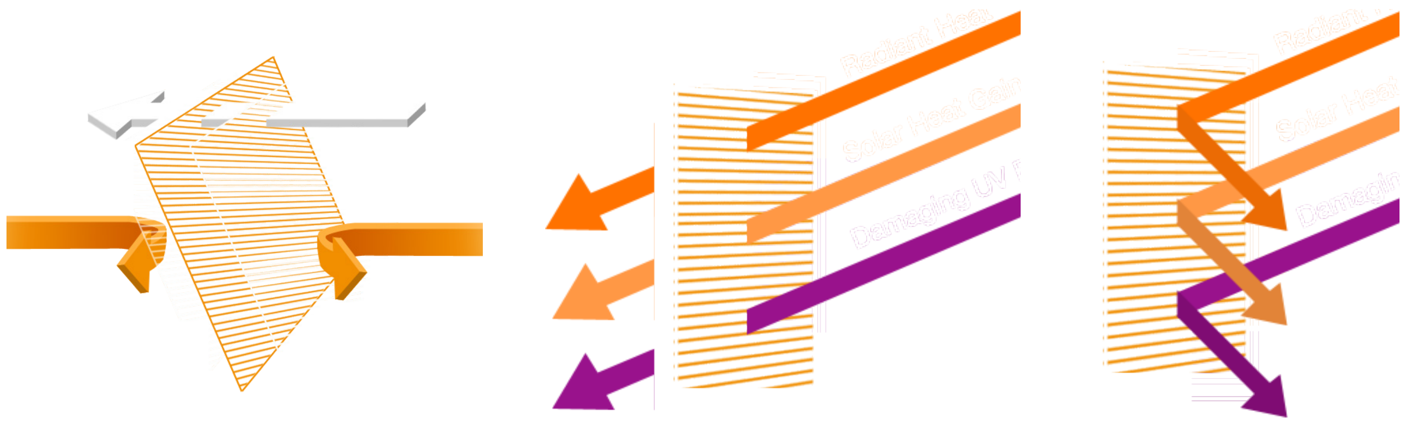
● - ○ 0 ○ +

Highest cost

- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High



Sources: www.lcgenergy.co.uk

licrivision™ - Liquid Crystal Window

Merck Window Technologies B.V.

Modular Innovation Center in Darmstadt

2015

Response to Adaptation Agent

○ Dynamic ● Static

LCW solar control glazing allows to control the amount of daylight through the window. The glazing has a layer composed by liquid crystals that, in 2 seconds, can switch their orientation and therefore the window transmission. This is achieved with a change from bright to dark and it is possible to choose both greyscale or different colours. The transparency of the glazing does not change, but is just the colour that varies. The system is applicable to different sizes and shapes without changing its performance. Licrivision™ prevents the energy loss and controls solar heat, enhancing facade performance in terms of energy efficiency and sustainability.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ● Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

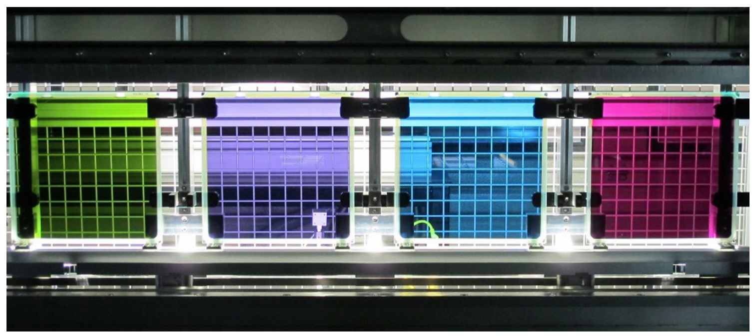
● - ○ 0 ○ +

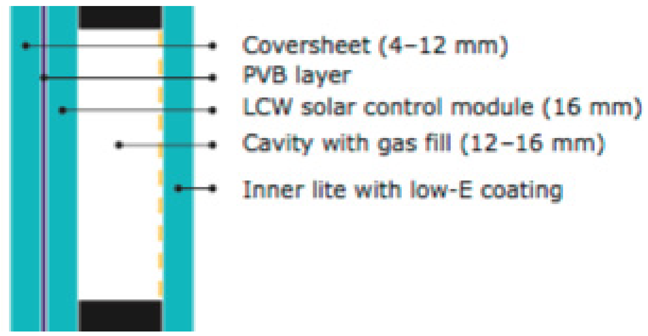
Highest cost

- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High





Sources: https://www.licrivision.com/en/LCW_solar_control_glazing.html

Closed Cavity Facade, JTI Headquarters

Josef Gartner GmbH

Geneva, Switzerland

2015

Response to Adaptation Agent

○ Dynamic ● Static

The innovative Closed Cavity Facade system offers a new approach to the double skin facade system, where the cavity with a fabric roller blind in between the inner and the outer skin is completely sealed. Dry and clean air is constantly fed into the façade cavity in order to prevent the formation of condensation on the glazing. This facade is able to respond to external climatic conditions, while at the same time maintaining the visual qualities of an all-glass facade with a low g and U-value. The outside conditions are monitored electronically in order to make adjustments to the occupants comfort. As a result, energy consumption is reduced to a minimum and carbon emissions are reduced.

Exterior Agent of Adaptation
- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation
- ● Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose
- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

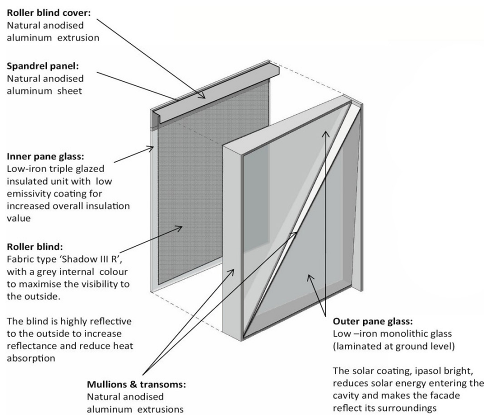
Control of Adaptivity
- ● Closed loop
- ○ Open loop

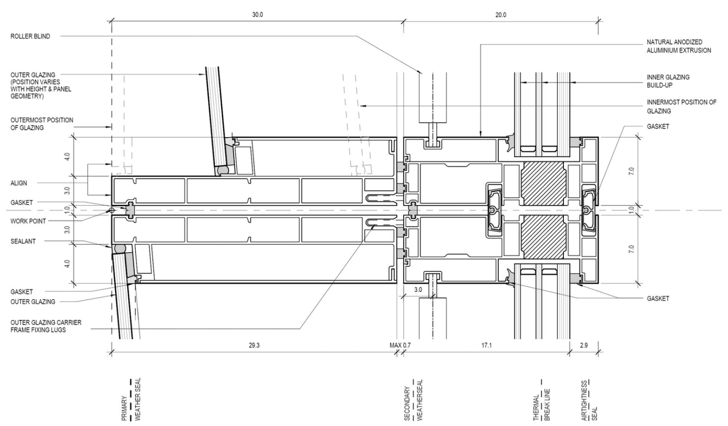
Energy

● - ○ 0 ○ +

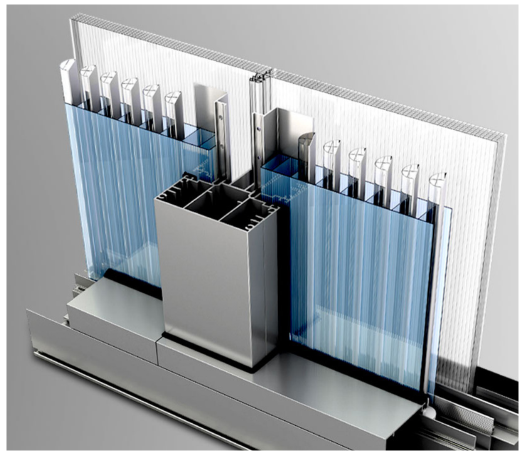
Highest cost
- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom
- ○ Low
- ● Medium
- ○ High





Sources: *https://architizer.com/projects/closed-cavity-facade/*
https://archpaper.com/2017/01/best-performing-glass-facade-system-soms-history/#gallery-0-slide-0



CONTROLITE ®- Intelligent Daylighting System

Danpal®

Global company

2016

Response to Adaptation Agent

● Dynamic ○ Static

Controlite® is a modular system that regulates the amount of daylight, reduces the glare and the heating/cooling demand. Therefore, it significantly contributes to reduce the energy consumption.The panel is composed by translucent glazing boards that encase rotating louvres. These adjust their position throughout the day according to the amount of daylight that is desired in the indoor space. The mechanism is regulated by two sensors: one outside the building and a second one in the indoor environment. By this way, the system can optimize its function according to both the indoor and outdoor situaton.

Exterior Agent of Adaptation
- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation
- ○ Temperature
- ○ Humidity
- ● Light
- ○ Air exchange rate
- ○ Sound level

Purpose
- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

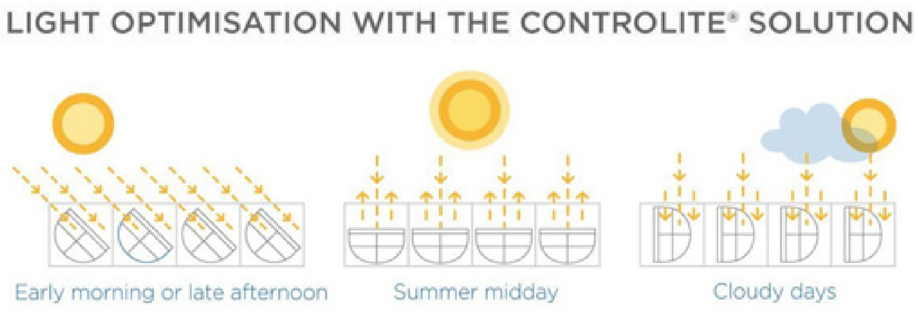
Control of Adaptivity
- ● Closed loop
- ○ Open loop

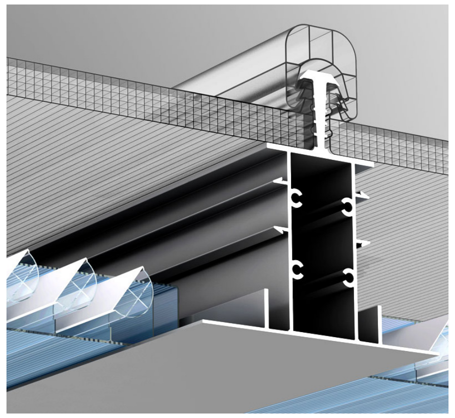
Energy

● - ○ 0 ○ +

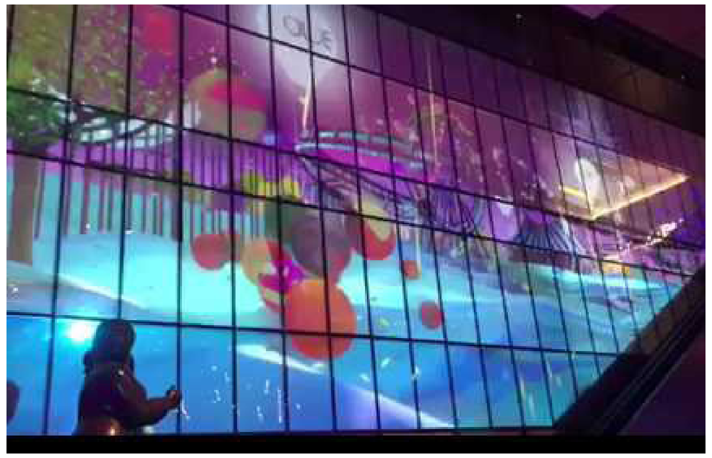
Highest cost
- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom
- ● Low
- ○ Medium
- ○ High





Sources: http://www.danpal.com/products/controlite/



White and Black Liquid Crystal Film

Gauzy

Tel Aviv - Yafo, Israel

2016

Response to Adaptation Agent

○ Dynamic ● Static

Gauzy uses Polymer Dispersed Liquid Crystals Films for lighting control. The Company has developed different solutions that change transparency when a voltage is applied. The film can have a white or dark dimming option that can be atomized or controlled by the users. A further option offered by this product is the possibility to project on the glass to have additional functions of advertisement or surface for office presentations.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
● Light
○ Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

● - ○ 0 ○ +

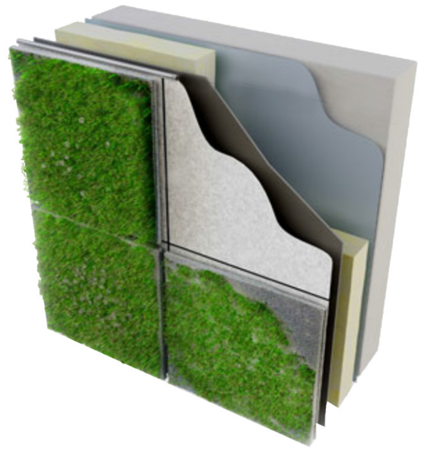
Highest cost

● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High

Sources: www.gauzy.com



Living Wall Facade

Arup

Leeds, United Kingdom

2016

Response to Adaptation Agent

○ Dynamic ● Static

The Living Wall Facade is an innovative zero earth system, which makes it really lightweight compared to typical green walls. In addition, hydroponics are used for the nutrients and the water delivery, thus leading to 90% reduction in water consumption. The seeds grow on site and it takes up to two months until full growth, however, it is also visually appealing without the green. The Living Wall facade improves thermal comfort due to evapotranspiration leading to energy savings, protects from direct solar radiation, dampens noise pollution, reduces air pollution and contributes substantially to the mitigation of the urban heat island effect.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
○ Visual and Lighting
● Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

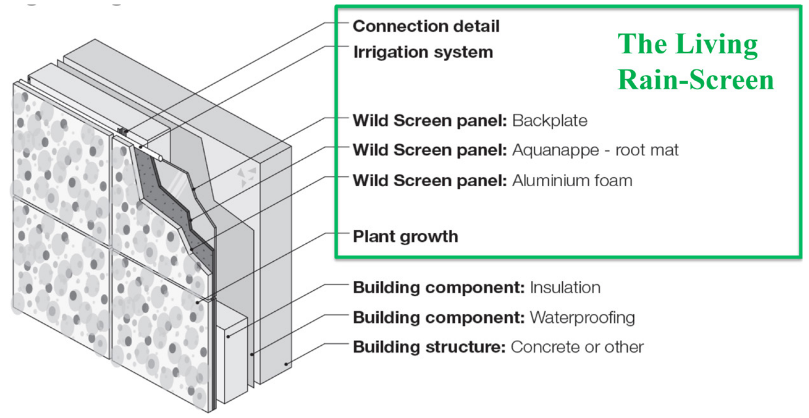
○ - ● 0 ○ +

Highest cost

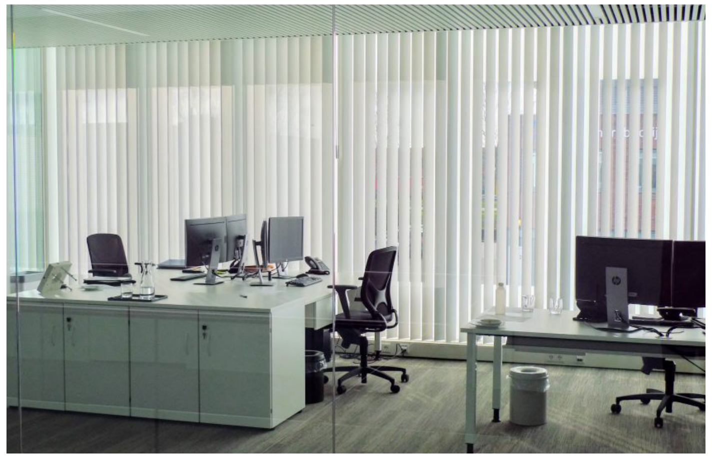
○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High



Sources: *http://greeninitiatives.cn/pdfdoc/presentation/1411885320333Innovative%20and%20Intelligent%20Facades_Jeff%20Tsai_Arup_rev.pdf*



Kindow Binds

Kindow BV

Delft, Netherlands

2017

Response to Adaptation Agent

● Dynamic ○ Static

Kindow Blinds are indoor blinds that consist of vertical slats that rotate during the day thanks to a sun tracking system. The slats are made of two different materials: on one side a highly reflective material reflects the solar radiation back to the window in summer and on the other side a dark absorbing material gains heat during winter. The face exposed to the sunlight depends on the season and it is always perpendicular to the sunrays. The result is 25% of saved energy on lighting, heating and cooling.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
● Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

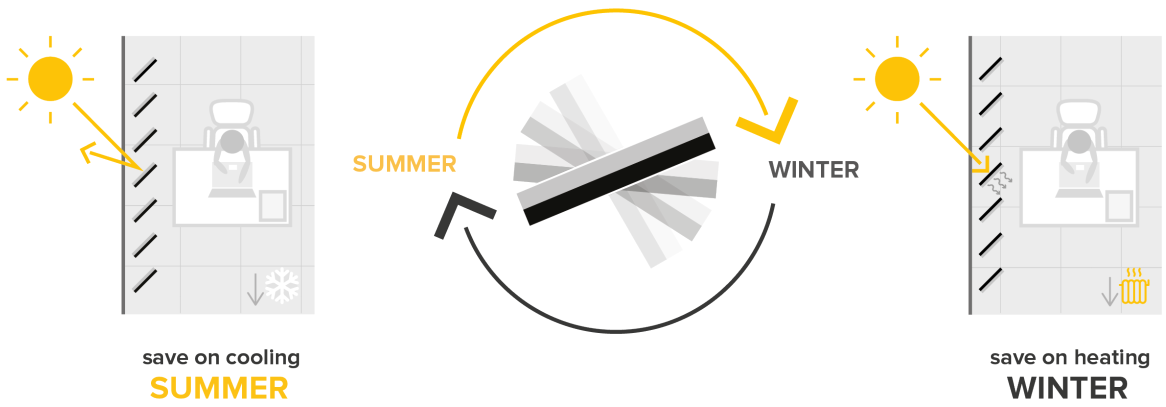
● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High

REASEARCH

PROJECTS



Sources: www.kindowblinds.com

Living Glass

Soo-in Yang and David Benjamin

2005

Response to Adaptation Agent

● Dynamic ○ Static

Living Glass is a material that monitors CO_2 concentration in the air by opening and closing in responce to the human presence. This is a thin transparent element that does not require mechanical imput to work, but its movement is regulated by a silicon surface embedded with Dynalloy Flexinol wires that contracts under electrical stimulus. This happens when the percentage of carbon dioxide is high and works like a breathing skin.

Exterior Agent of Adaptation
- ○ Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation
- ○ Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

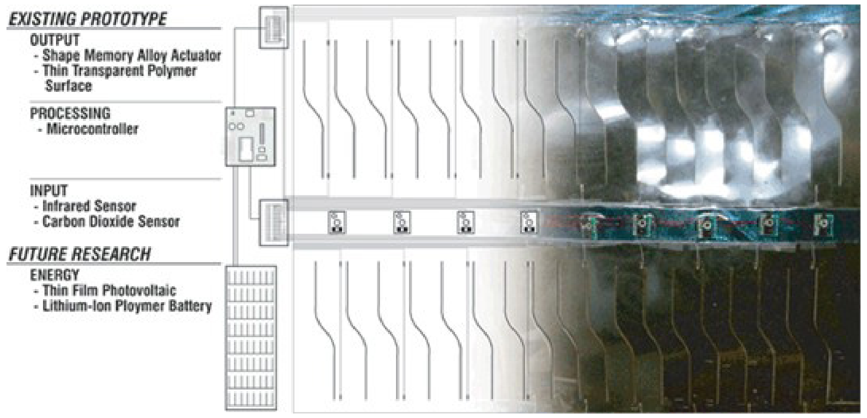
Purpose
- ○ Thermal comfort
- ● IAQ
- ○ Visual and Lighting
- ○ Acoustic
- ○ Energy production

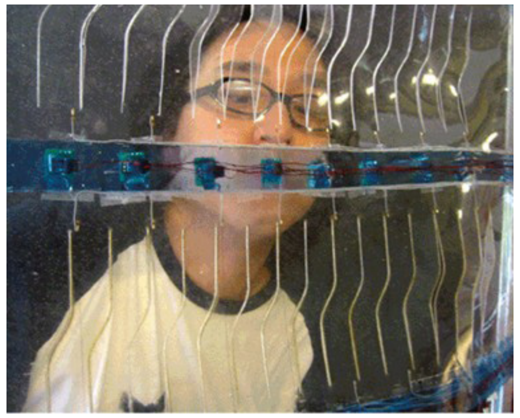
Control of Adaptivity
- ● Closed loop
- ○ Open loop

Energy
- ● - ○ 0 ○ +

Highest cost
- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom
- ○ Low
- ● Medium
- ○ High





Sources: https://inhabitat.com/carbon-dioxide-sensing-living-glass/:

ACTRESS (ACtive RESponsive and Solar)

TEBE Research Group, Department of Energy

Politenico di Torino, Torino, Italy

2007

Response to Adaptation Agent

○ Dynamic ● Static

ACTRESS is a multi-functional facade module (MFM) with “standalone attitude” which incorporates different technologies with the aim of reducing the building’s energy demand and converting energy from renewable energy sources (RES). It is comprised of an opaqe (OSM) and a transparent sub module (TSM) which consist of various different material layers. The opaque sub module can be operated as a thermal buffer or as a supply air facade in the winter and as an outdoor air curtain facade during summer. The transparent sub module is made up of two different triple glazing systems. An ACTRESS module was tested in Torino for almost two years and the conclusions showed that it is “energy positive”.

Exterior Agent of Adaptation
- ● Solar radiation
- ● Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation
- ● Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

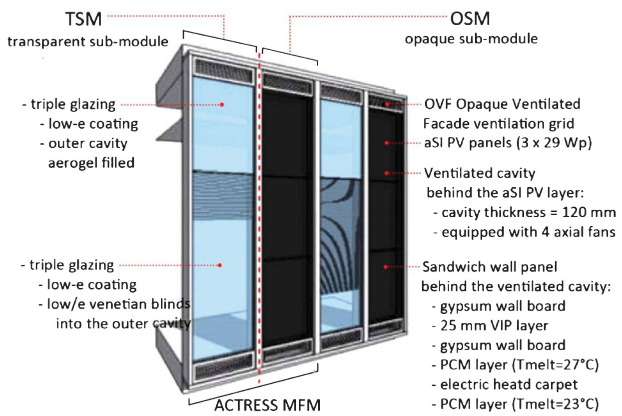
Purpose
- ● Thermal comfort
- ○ IAQ
- ○ Visual and Lighting
- ○ Acoustic
- ● Energy production

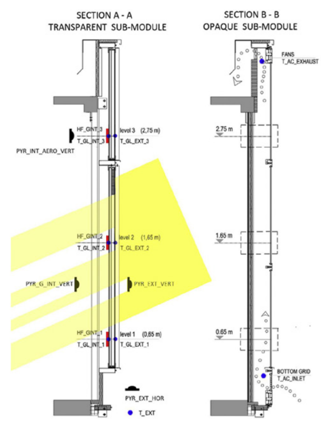
Control of Adaptivity
- ○ Closed loop
- ● Open loop

Energy
- ○ - ○ 0 ● +

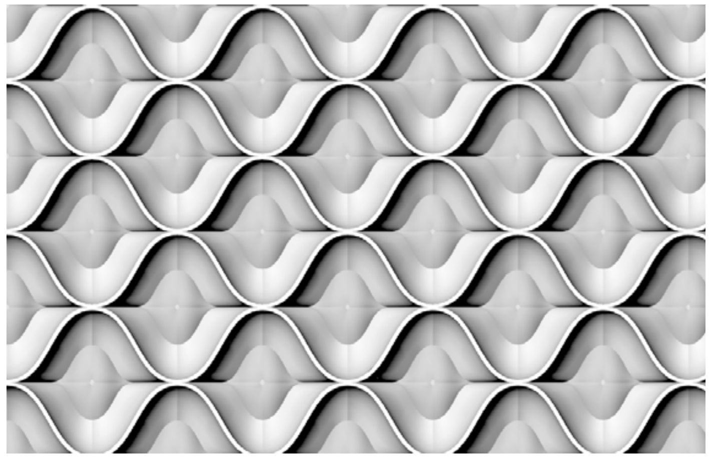
Highest cost
- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom
- ○ Low
- ○ Medium
- ● High





Sources: Favoino, F., et al. (2014). “Experimental assessment of the energy performance of an advanced responsive multifunctional façade module.” Energy and Buildings 68(Part B): 647-659.



Bionic breathing skin

L. Badarnah & U. Knaack

Departmen of Building Technology, Delft University of Technology, Delft, The Netherlands

2007

Response to Adaptation Agent

● Dynamic ○ Static

The bionic breathing skin has been inspired by the sponge principle. It is composed by three layers assembled in a way that when thy are deformated, a difference of preassure is created that allows the introduction and expulsion of air. The expansion and contraction of the layers is generated by piesoelectric wires and the amount of air exchanged is due to the velocity of the deformation. The air exchanged helps in the regualtion of the indoor climate.

Exterior Agent of Adaptation

○ Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
● Air exchange rate
○ Sound level

Purpose

○ Thermal comfort
● IAQ
○ Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

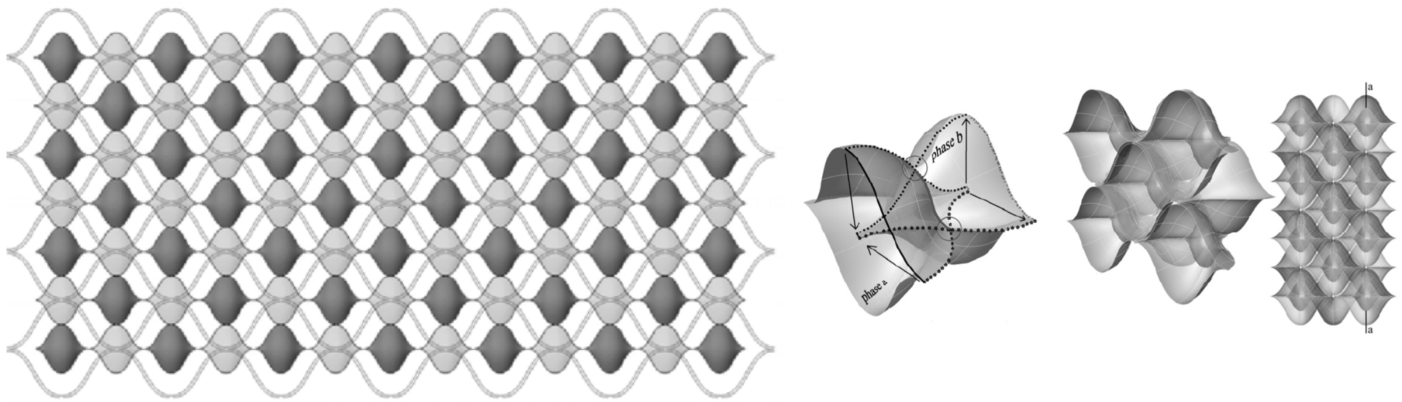
● - ○ 0 ○ +

Highest cost

○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

○ Low
● Medium
○ High



Sources: https://www.researchgate.net/publication/278667232_Bionic_breathing_skin_for_buildings

Bloom

DO|SU Studio Architecture

Materials & Application Gallery, Los Angeles, California

2011

Response to Adaptation Agent

● Dynamic ○ Static

Bloom is a temporary sun tracking installation inspired by mimicking the human body and it is not technically a facade but a similar technique could be applied in buildings in the near future. Bloom combines together material experimentation, structural innovation, and computational form and pattern resulting into an environmentally responsive form. The sun shade is made by thermobimetal, which is a laminated material composed of two different metals that react differently when exposed to sunlight, causing thus a curling effect. Consequently, specific areas of the shell are ventilated when the sun heats up its surface. The structure is self-supporting and it is composed of 414 hyperbolic paraboloid-shaped stacked panels, which combine a double-ruled surface of bimetal tiles with an interlocking, folded aluminum frame system.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
○ Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

○ - ● 0 ○ +

Highest cost

○ Materials
○ Production
● Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High

Sources: http://dosu-arch.com/bloom.html
https://www.archdaily.com/215280/bloom-dosu-studio-architecture

ADAPTIWALL

TNO & Partners

Delft, The Netherlands

2012

Response to Adaptation Agent

○ Dynamic ● Static

The project is a climate adaptive multi-functional lightweight prefab panel suitable for the construction of cost-efficient, rapid and energy efficient facades. This facade is able to reduce heating and cooling demand by 50-80% compared to typical highly insulating solutions and it is also able to almost eliminate auxiliary heat recovery and ventilation installations. The core element of the panel is a load-bearing, lightweight concrete layer, which is used as a buffer to store heat and cold. Moreover, adaptive insulation consisting of non-traditional polymer materials is installed on both sides of the buffer, in order to control the heat flows. In addition, a total heat exchanger is used to provide compact ventilation and an energy recovery system. The cladding and windows are not considered as key components, however, a glass cladding and a solar collector are used to collect energy.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
○ Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
● Open loop

Energy

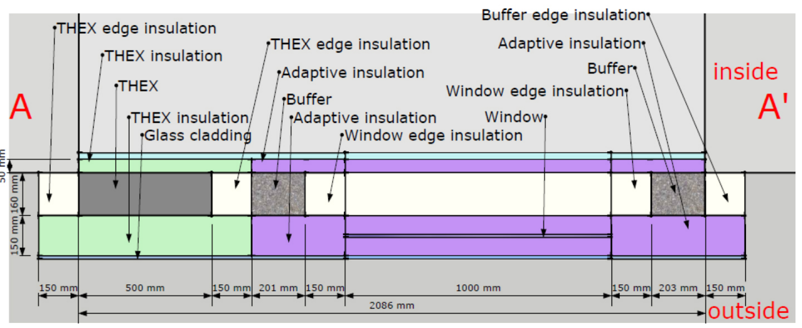
○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High



Sources: http://www.adaptiwall.eu/mainmenu/home/

MeeFS (Multifunctional energy efficient Facade System for building retrofitting)

Acciona Infraestructuras

Spain

2012

Response to Adaptation Agent

○ Dynamic ● Static

The MeeFS project is a multifunctional energy efficient façade system for building retrofitting. This new system will allow a 27% reduction of the total energy demand, in order to increase energy efficiency and indoor comfort of residential buildings in European climate zones. It will incorporate innovative solutions by means of active and passive technologies solutions combination. The MeeFS project consists of seven technological units - insulation, green façade, ventilated façade, solar protection, building-integrated photovoltaics (BIPV), an advanced passive solar protector/energy absorption auto mobile unit, and an advanced passive solar collector/ventilation module. These technological units have both opaque and transparent properties and are integrated into modules and then into structural panels and into existing facades. The project was demonstrated in a real building in Spain.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
● Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
● IAQ
● Visual and Lighting
○ Acoustic
● Energy production

Control of Adaptivity

● Closed loop
● Open loop

Energy

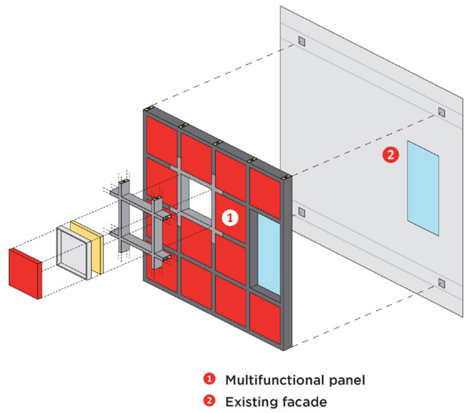
○ - ○ 0 ● +

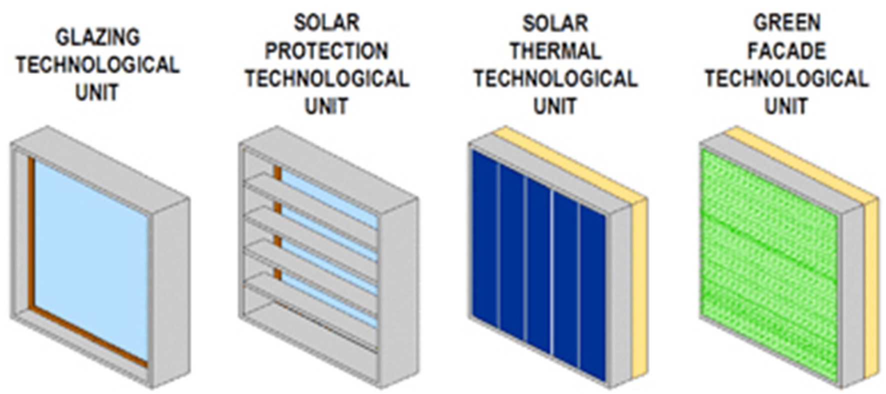
Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

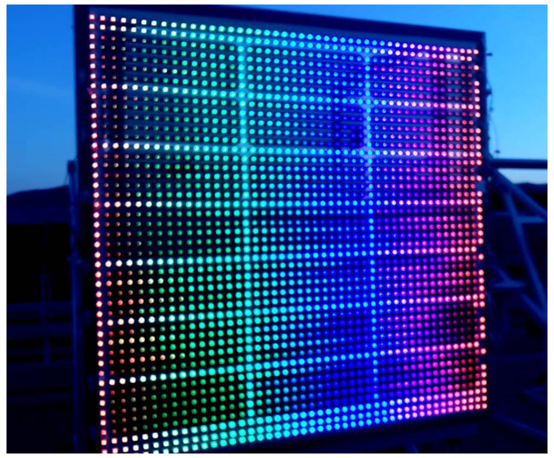
Architecture design freedom

○ Low
● Medium
○ High





Sources: http://www.meefs-retrofitting.eu/



ETFE Multifunctional Modules

European Commission department

Europe

2014

Response to Adaptation Agent

○ Dynamic ● Static

The ETFE-MFM project project is developing a multifunctional ETFE (Ethylene TetraFluoroEthylene) module with integrated photovoltaics and LED technologies, for sustainable architectural facade lighting. The ETFE multifunctional module will generate electricity during the day, in order to power its LEDs at night, giving a boost to the emerging field of Building Integrated Photovoltaics. Moreover, this module acts as a glazing system and has external battery storage, while it also includes flexible integrated control devices and a high architectural flexibility.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ○ Thermal comfort
- ○ IAQ
- ○ Visual and Lighting
- ○ Acoustic
- ● Energy production

Control of Adaptivity

- ○ Closed loop
- ● Open loop

Energy

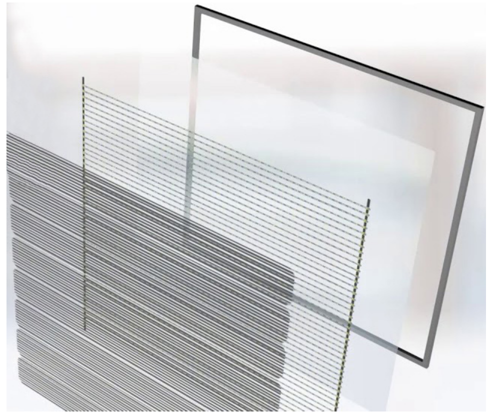
○ - ○ 0 ● +

Highest cost

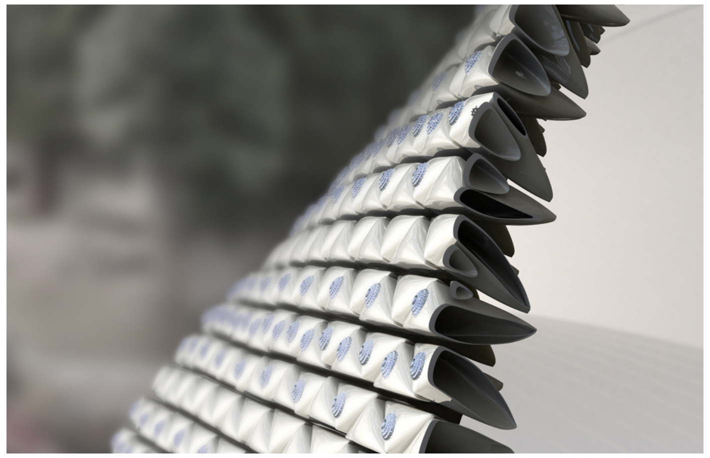
- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ○ Medium
- ● High



Sources: *http://www.etfe-mfm.eu/*



SABER (Self-Activated Building Envelope Regulation)

BIOMS team of researchers

University of California, Berkeley

2014

Response to Adaptation Agent

● Dynamic ○ Static

SABER is a new membrane that wraps around a building and it is inspired by the human skin that is able to breathe with the aim of a fully self-regulating system. Resembling the pores of the skin, the membrane is filled with micro-scale valves and lenses that open and close as they sense light, heat, and humidity. It works with a geometrical network of a temperature-responsive phase-change hydrogel capable of swelling or shrinking at a given temperature, releasing or absorbing water vapour. The facade does not require an external power and it offers hygrothermal and light transmission control. This membrane is a net zero cooling option, which doesn't actually cool the air, but it makes buildings in hot, humid tropical countries more comfortable.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ● Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ○ Closed loop
- ● Open loop

Energy

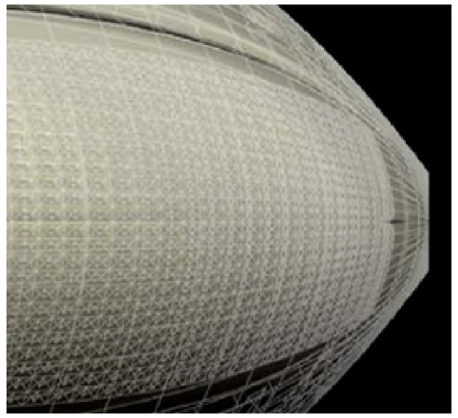
○ - ● 0 ○ +

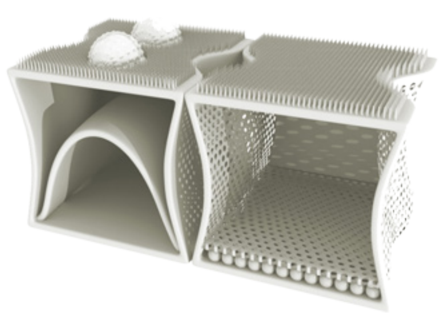
Highest cost

- ○ Materials
- ● Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High





Sources: Casini, M. (2016). 6 - Advanced building skin. Smart Buildings, Woodhead Publishing: 219-245.
https://materia.nl/article/saber-self-cooling-material/

BRESAER (BREakthrough Solutions for Adaptable Envelopes in building Refurbishment)

Acciona Infraestructuras & Partners

Spain

2015

Response to Adaptation Agent

○ Dynamic ● Static

BRESAER project is an innovative envelope system that combines active and passive components, integrating them into a lightweight structural mesh. It is composed of multifunctional and multilayer insulation panels made of Ultra High Performance Fibre Reinforced Concrete, multifunctional lightweight ventilated facade modules and dynamic automated windows with insulated solar blinds, which adjust automatically according to the position of the sun and the occupants comfort. In addition, Combined Solar Thermal Air and PV envelope components are used for indoor space heating and ventilation, thermal insulation and electricity generation. Moreover, preheated air can be used for indoor space heating and dehumidification. The project is tested in four virtual demonstrations located in different European climate zones and a real one in Ankara, Turkey, expecting to record a reduction by at least 60% of the total primary building's energy consumption and to reach a near zero energy building.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ● Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ● Energy production

Control of Adaptivity

- ● Closed loop
- ● Open loop

Energy

○ - ○ 0 ● +

Highest cost

- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High

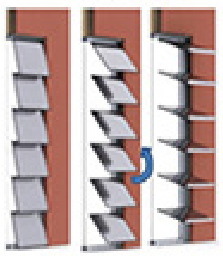
SolarWall

Combined solar thermal and PV envelope component

ULMA

Multifunctional lightweight ventilated façade module

ascamm technology centre



Dynamic window with controlled air-tightness and insulated solar blinds

Stam

Multifunctional UHPFRC panels for envelope

Sources: *http://www.bresaer.eu/about/*

Adaptive Solar Facade

ETH Foundation

House of Natural Resources (HoNR), Campus ETH Honggerberg, Zurich, Switzerland

2015

Response to Adaptation Agent

● Dynamic ○ Static

The ETH House of Natural Resources (HoNR) develops, implements and monitors in-situ novel façade elements and innovative structural elements made of wood at original scale. The facade includes several new technologies: adaptive solar facade, facade control and user interaction, soft robotic actuators, wooden solar trackers. The building envelope allows for active shading and glare reduction, daylight distribution, and sun tracking and energy generation. It is conceived as a modular system, which allows these functions to be distributed and mixed across the envelope and even across a window in the most optimal way. This results in a dynamic multifunctional envelope, which increases the building's energy performance and the user's comfort.

Exterior Agent of Adaptation

- ● Solar radiation
- ○ Temperature
- ○ Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ○ Temperature
- ○ Humidity
- ○ Light
- ○ Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ● Visual and Lighting
- ○ Acoustic
- ● Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

○ - ○ 0 ● +

Highest cost

- ○ Materials
- ○ Production
- ○ Assembly
- ● Maintenance

Architecture design freedom

- ● Low
- ○ Medium
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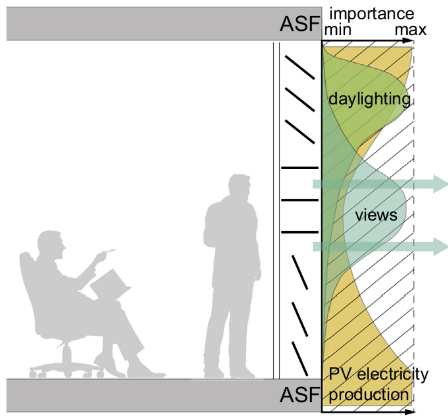
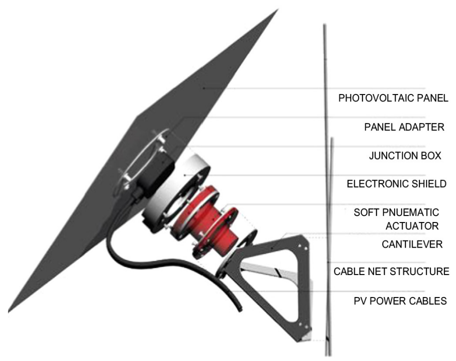
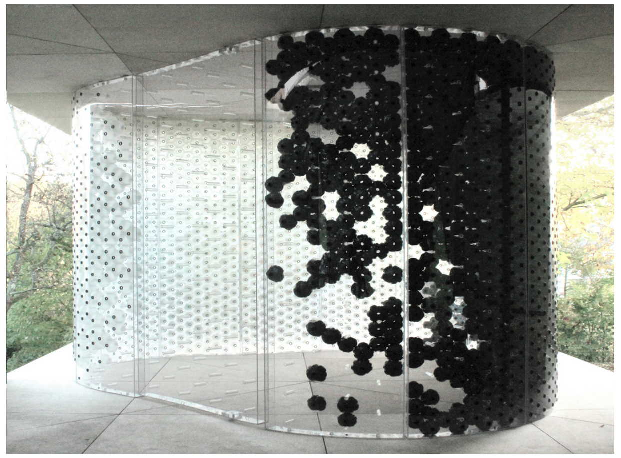




Sources: Nagy, Z., et al. (2016). "The Adaptive Solar Facade: From concept to prototypes." Frontiers of Architectural Research 5(2): 143-156.
http://www.honr.ethz.ch/en/the-group/facade/solar-facade.html



Breathing Skins

Tobias Becker

Mandelbachtal, Germany

2015

Response to Adaptation Agent

● Dynamic ○ Static

The project “Breathing Skins” is based on the concept of biomimicry. Like the skin’s pores open and close, the organic skins of this pneumatic facade technology adjust their permeability to control the necessary flow of light, matter and temperature between the inside and the outside. This way, the building skin “breathes” by changing constantly its appearance and thus providing an interesting interplay between the interior and exterior environment. On every spquare meter of breathing skin there are placed 140 air channels, described by Tobias Becker as “pneumatic muscles”, which are sandwiched between two glass surfaces. In order for these muscles to open, a small energetic input is required to create a slight underpressure so as to provide the desirable indoor conditions according to the users’ preferences. The project offers customization since the glass panels can have different geometric configurations and the “peumatic muscles” offer different color possibilities.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ● Humidity
- ○ Wind
- ○ Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ● IAQ
- ● Visual and Lighting
- ○ Acoustic
- ○ Energy production

Control of Adaptivity

- ● Closed loop
- ○ Open loop

Energy

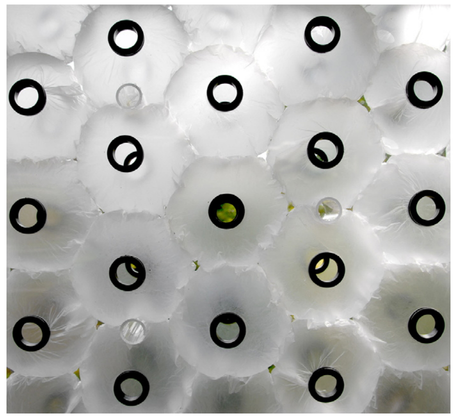
● - ○ 0 ○ +

Highest cost

- ○ Materials
- ○ Production
- ● Assembly
- ● Maintenance

Architecture design freedom

- ○ Low
- ● Medium
- ○ High



Sources: https://www.breathingskins.com/

SELFIE (Smart and Efficient Layers for Innovative Envelopes)

Italian Ministry of University and Research & Regional Administration of Tuscany

University of Florence, Florence, Italy

2016

Response to Adaptation Agent

○ Dynamic ● Static

SELFIE facade is a unitized curtainwall system that allows not only easy on-site installation but also customization through the possibility of the modular components to be placed with different geometric configurations, different types of materials and different colors. SELFIE facade consists of three different components, two opaque and one transparent with various different material layers. All three components have integrated sensors and equipment for data management, in order to guarantee a smart control of energy flows inside the building envelope and to ensure the ability of changing their energy performance according to external climatic conditions.

Exterior Agent of Adaptation

- ● Solar radiation
- ● Temperature
- ○ Humidity
- ○ Wind
- ● Precipitation
- ○ Noise

Interior Agent of Adaptation

- ● Temperature
- ○ Humidity
- ○ Light
- ● Air exchange rate
- ○ Sound level

Purpose

- ● Thermal comfort
- ○ IAQ
- ○ Visual and Lighting
- ○ Acoustic
- ● Energy production

Control of Adaptivity

- ○ Closed loop
- ● Open loop

Energy

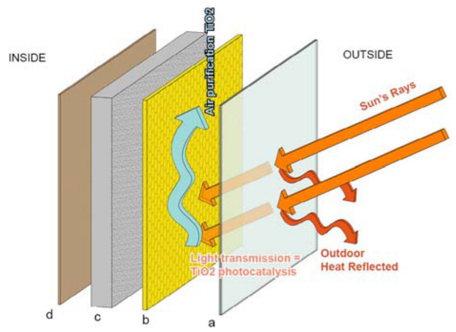
○ - ● 0 ○ +

Highest cost

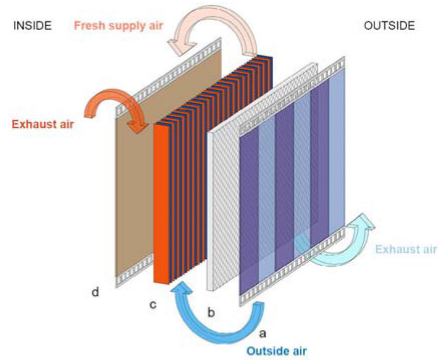
- ● Materials
- ○ Production
- ○ Assembly
- ○ Maintenance

Architecture design freedom

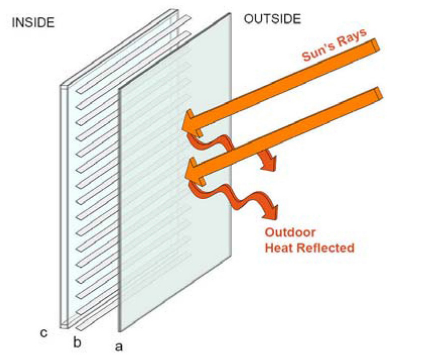
- ○ Low
- ○ Medium
- ● High



Selfie_1: a. Glass layer with PVB and IR reflecting coatings; b. Honeycomb with TiO2; c. Foam glass with PCM; d. closure panel



Selfie_2: a. Pv panels with air grids; b. Insulating panel; c. Heat exchanger; d. Closure panel



Selfie_3: a. Glass layer with PVB and IR reflecting coatings; b. Air gap and shading device; c. Double glazing

Sources: Romano, R. and P. Gallo (2016). “The SELFIE Project Smart and efficient envelope’ system for nearly zero energy buildings in the Mediterranean Area.”
Gallo, P. and R. Romano (2017). “Adaptive Facades, developed with Innovative nanomaterials, for a sustainable architecture in the Mediterranean area.” Procedia Engineering 180: 1274-1283.

Allwater Panel

Allwater Ltd

Kecskemét, Hungary

2017

Response to Adaptation Agent

○ Dynamic ● Static

The product is a panel composed of two layers of glass and a cavity filled with water. The element works as a thermal mass thanks to the property of water of storing heat. The heat collected can be transported by the water into a storage system and used later in winter. The same process can be applied in winter to cool down the temperature during summer. Because the water is free to move in the facade, a uniform thermal balance is assured. A positive aspect is that the panel can be built and assempbled empty and later filled with water, making the production and construction process easier. Moreover, becuause of the transparency of water, the outside view is not obstructed and the natural light can almost entirely enter into the building.

Exterior Agent of Adaptation

● Solar radiation
● Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

○ Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
○ Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

○ Closed loop
● Open loop

Energy

○ - ○ 0 ● +

Highest cost

○ Materials
○ Production
○ Assembly
● Maintenance

Architecture design freedom

○ Low
● Medium
○ High

Sources: http://allwater.hu/?page_id=278

Polyarch

TU Delft and TU/e

Delft and Eindhoven, Netherlands

2017

Response to Adaptation Agent

○ Dynamic ● Static

Polyarch is a project developed by TU Delft in collaboration with the Department of Functional Organic Materials and Devices at the TU/e. The goal is the production of a responsive coating of Cholesteric Liquid Crystals. This technology operates on the Infrared spectrum, resulting invisible to the human eye. The result is an adaptive coating that controls the amount of solar heat gain entering the building, working as a thermal regulator and reducing the energy required for heating and cooling. The product has still to be further developed to eliminate some drawback like the dependency on the light angle that can cause a colour disturbance at some incident light angles.

Exterior Agent of Adaptation

● Solar radiation
○ Temperature
○ Humidity
○ Wind
○ Precipitation
○ Noise

Interior Agent of Adaptation

● Temperature
○ Humidity
○ Light
○ Air exchange rate
○ Sound level

Purpose

● Thermal comfort
○ IAQ
○ Visual and Lighting
○ Acoustic
○ Energy production

Control of Adaptivity

● Closed loop
○ Open loop

Energy

● - ○ 0 ○ +

Highest cost

● Materials
○ Production
○ Assembly
○ Maintenance

Architecture design freedom

○ Low
○ Medium
● High

Sources: https://www.4tu.nl/bouw/en/LHP2015/Polyarch/

B

APPENDIX

In collaboration with Maria Mourtzouchou

Sustainable Design Graduation Studio
MSc Architecture, Urbanism and Building Sciences/ track Building Technology
Students: Shirin Masoudi, Maria Mourtzouchou
1st mentor: Dr. Ir. T. Klein

Future of Adaptive Facades and Components Questionnaire

The façade accounts for the biggest part of energy consumption of a building. Therefore, a major challenge is to design the façade for minimum energy demand for heating, cooling, ventilation and lighting through maximum exploitation of the natural energy flows. By 2020 there is the requirement of ZEB or nZEB and adaptive facades seem to be a promising solution to achieve this goal towards the objective of a "smart, sustainable and inclusive" building industry.
The goal of the first research and the questionnaire is to understand what the actual relationship is between the available products and the design requirements of the architects. Do the architects think that the products available are satisfactory according to the current design needs? What do the architects consider as state-of-the-art nowadays?
The following questionnaire intends to get an insight to the architect's opinion on this topic.

Answers:
F.S: Ir. Frank Schnater
S.H.V: Ir. S.H. Verkuijlen
A.C.B: Ir. A.C. Bergsma

Q1: What is your opinion about adaptive facades? Do you believe that adaptive façades really improve the performance of a building or a passive design would be adequate?

F.S: Adaptive facades regulate a lot of things and they incorporate automated aspects. There are already traditional forms of adaptive elements, like windows. Moreover, the use of sensors is involved in the adaptive facades. In general, I believe it is a good thing.

S.H.V: I think it is obvious that adaptive facades could really improve performance of a building

A.C.B: Yes, I do, but it is not a goal on itself. It depends on the strategy that are mainly two. If the there is more opaque surface, the level of adaptivity is lower and it is easier to control the building physics. On the contrary with big transparent surfaces the intervention is more extreme and complex. In this case the risk of damage is more.

Q2: Have you already applied adaptive solutions in your designs and in what extent? If so, do you calculate and monitor the performance of adaptive facades and how does this influence your decisions? What do you calculate and how do you monitor it if you do so?

F.S: I have used sunshading, screens, adaptive louvers, CO2 sensors, operable windows and register, which operates manually. I haven't monitored their performance.

S.H.V: Of course, opening windows and sun shading are very basic forms of adaptive facades and I have used these techniques many times. I have never used a more technological advanced adaptive façade system.

A.C.B: Yes, I applied adaptive solution mainly for daylight and solar control. But I do not monitor the performance of the design applied.

Q3: Are you aware of the adaptive facade systems that are already available in the market and do you think they would be prone to restrict your design freedom or contribute to the design quality of the project?

F.S: I am aware of the systems that I have already used like automatic louvers and screening. I also know about electric glass, however, it is very costly. I believe that these systems are very adaptable, easy to apply and can fit to any size so they provide freedom.

S.H.V: Again, opening windows (automatic or manual) and sun shading (automatic or manual) are readily available. These are basic forms of adaptive facades. Making use of a system restricts design freedom, but this doesn't make the design of a façade worse. A design restriction or design parameter (which is actually the same thing) can improve design.

A.C.B: Yes, mainly for daylight and solar control purposes. I don't think it restrict the design freedom.

Q4: Would you sacrifice performance in virtue of design purposes and how do you think they should be combined?

F.S: No, I wouldn't. I believe that a good design comes from the performance and that it is technically driven so they are strongly combined.

S.H.V: For me well designed façade performs well. If it doesn't perform, it is not designed very well. When designing a building you have to take many design parameters into account. There is always a bit of give and take between the different parameters.

A.C.B: Sometimes, it depends on priorities and on limitation of the systems.

Q5: Put the following aspects that an adaptive façade should regulate in order of importance (1 being the most important and 5 being the least)
_ thermal performance
_ energy production
_ visual and lighting
_ acoustic
_ indoor air quality

F.S: 2, 5, 1, 3, 4

S.H.V: All equally important although air quality can also be dealt with by other systems in the building.

A.C.B: 3, 4, 1, 5, 2

Q6: Which of the above parameters would you like to be combined in a product?

F.S: Thermal performance & IAQ
Acoustics & visual (if you open a window…)

S.H.V: All of them

A.C.B: I think that a mass variation between summer and winter would be interesting. In the past, for example, the shading systems were used also as thermal mass in winter. The triple glazing works good in winter but not in summer. Bothe these cases are examples about how a change of thermal mass would increase the performance.

Q7: Where do you think the market should orient itself from a product production point of view? Do you think there are aspects that are being neglected?

F.S: I think that the market should orient itself to user friendliness and user control and adaptability. The user should be able to regulate easily the light, the fresh air and the noise. So, visual quality, IAQ, and acoustics.

S.H.V: Adaptive facades usually focus on office buildings. Residential building are just as important. Consider what an adaptive façade can do for the design of the building interior. Make sure the adaptive façade is not just a bolt-on machine but an integral part of the building.

A.C.B: The market should orient on the thermal performance and in the integration of different solutions.

Q8: Adaptive façades are strongly connected with customization but there are also already studies about Multi-functional Façade Modules (MFM). MFM is a category of Advanced Integrated Facades (AIF) and it is a development of integrated and modular multifunctional systems which incorporate different technologies with the aim of energy efficiency. They consist of prefabricated units with several functionalized layers which can be assembled with several combinations depending on the architectural design. Would you consider that a unitized system is adaptive?

F.S: With a unitized system everything is fixed and it is not easy to be changed later. So, it should be perfect from the beginning and thus adaptability should be incorporated in the system from the start.

S.H.V: It can be designed to be adaptive.

A.C.B: There are many unitized solutions that are already adaptive. Yes, depends on the system.

Q9: What is in your opinion the future of adaptive facades?

F.S: The future should be simple and not complex. A lot of systems have failed in the past because of their complexity. In relation to the previous question, I would say yes to an integrated system only if it is done simple and in an effective way. Complex systems are also maintenance sensitive. On the other hand, curtain walls offer many options. They are a successful basic system that fits many solutions.

S.H.V: A adaptive façade with high performance, low maintenance and durability will have a future. Use movable mechanical parts as little as possible as they can break.

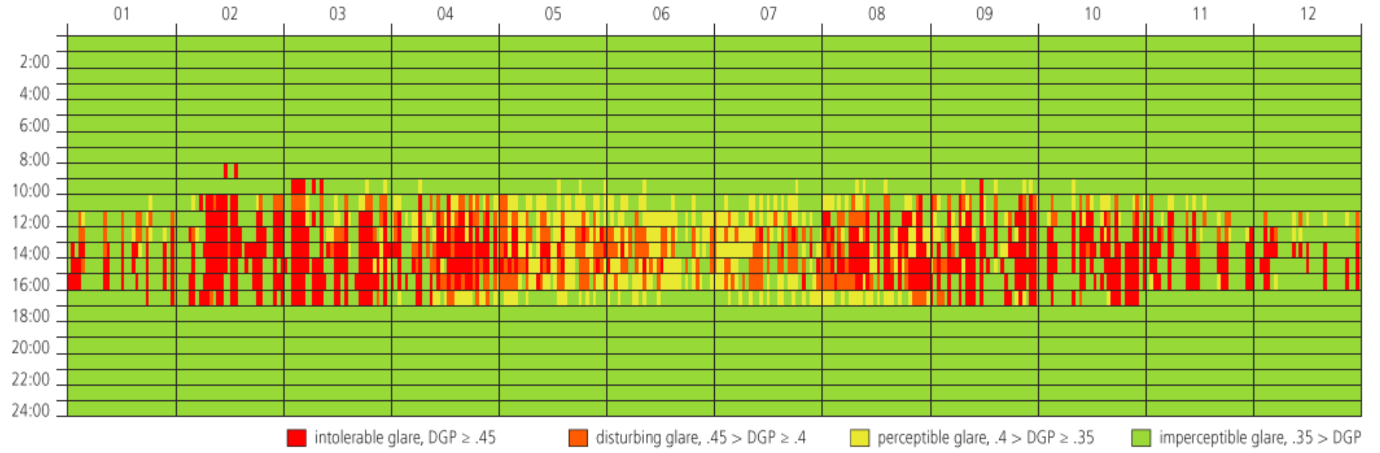
A.C.B: They should focus on the variation of performance of the façade. An interesting simulation would be about day and night cycle. The calculation and the performances should be given according different parameters and situations and not just winter and summer. An important future development would be to reduce the cooling demand in summer situation.

C

APPENDIX

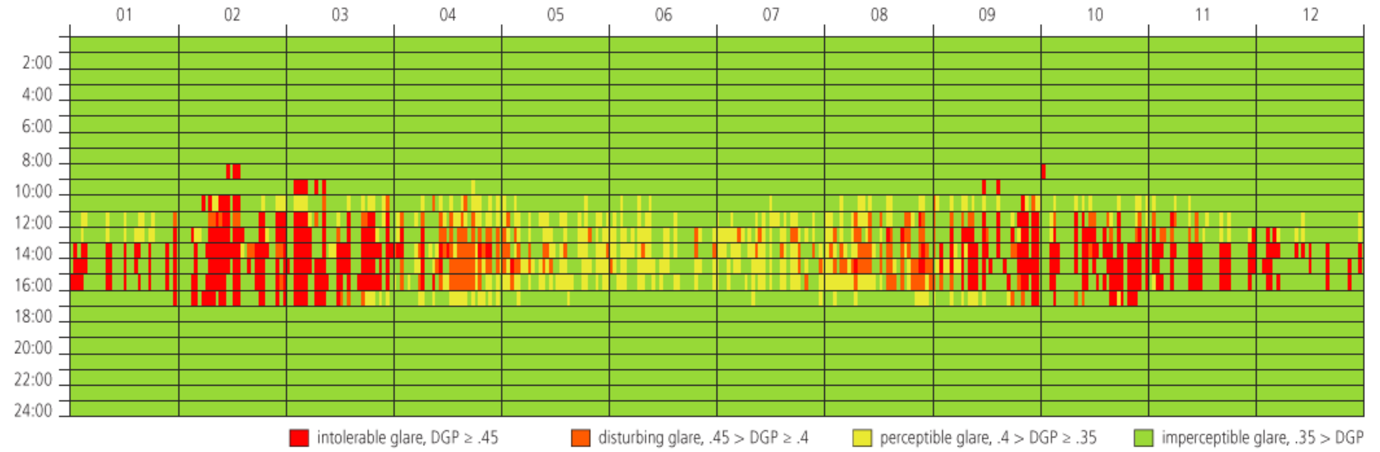
Annual Daylight Glare Probability (DGP)

No shading

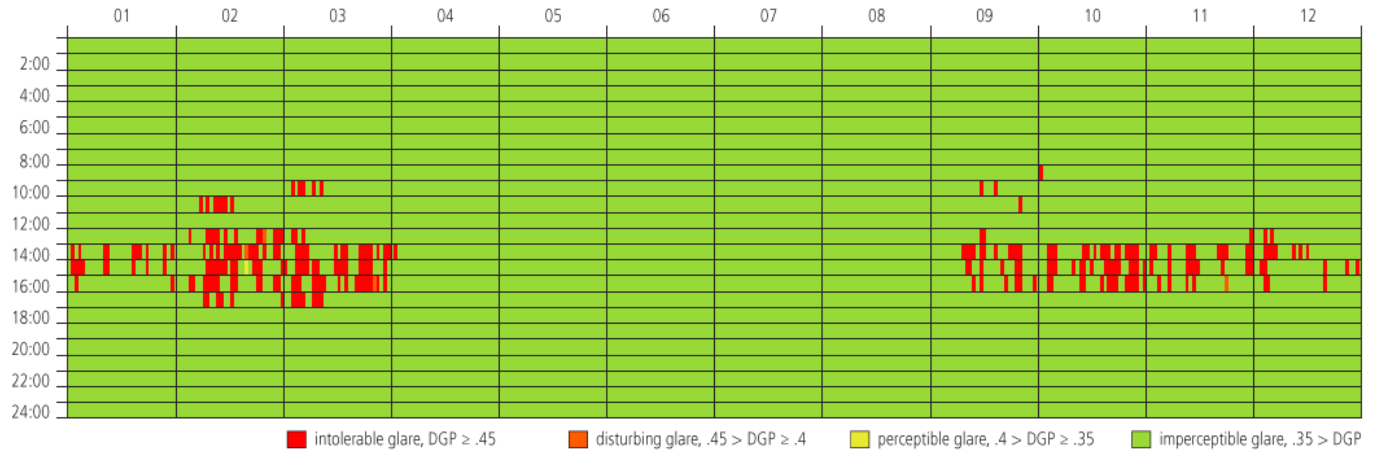


Reference project 1 - Roller shading

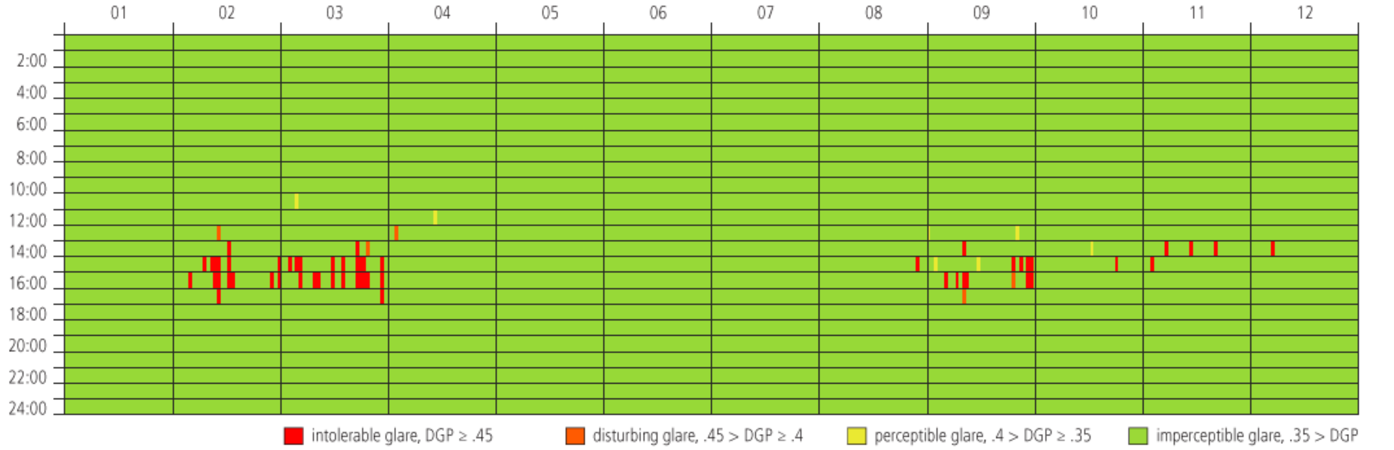
Stage 1



Stage 2

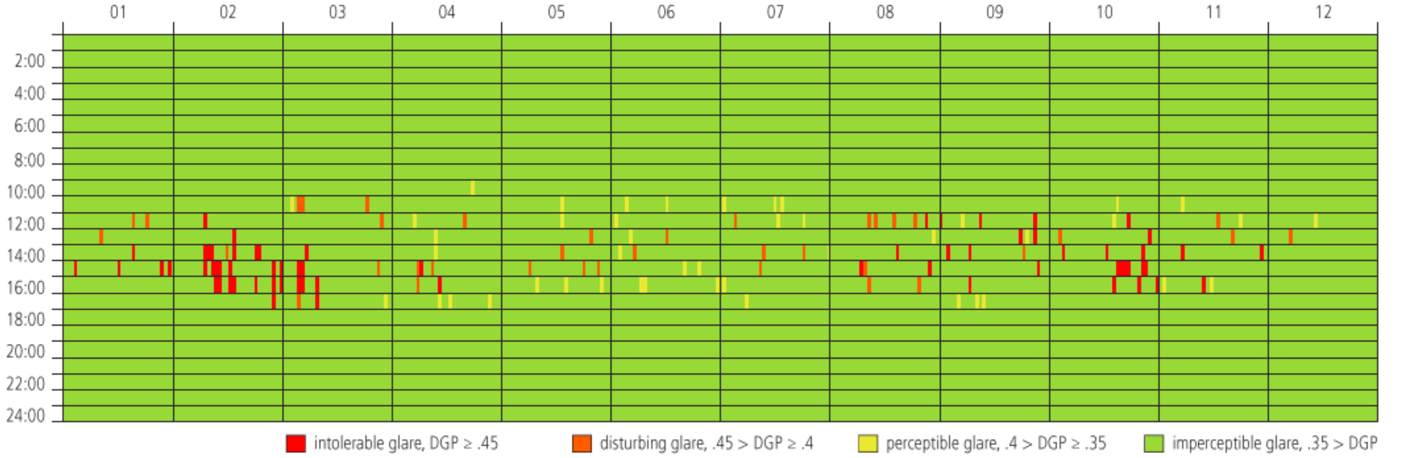


Final stage

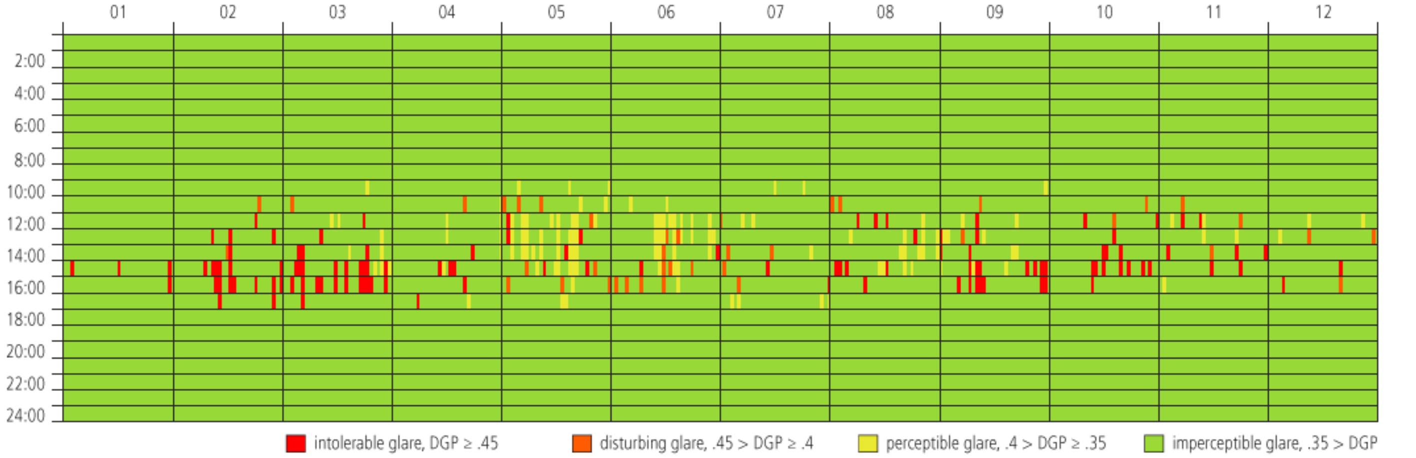


Reference project 2 - Venetian blinds

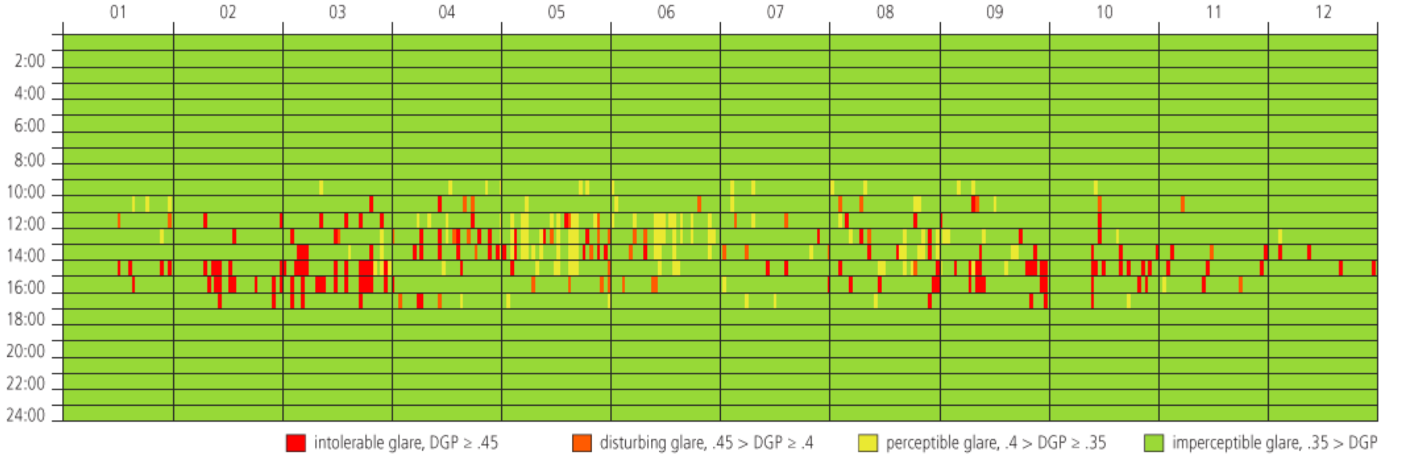
Group 1 Stage 1



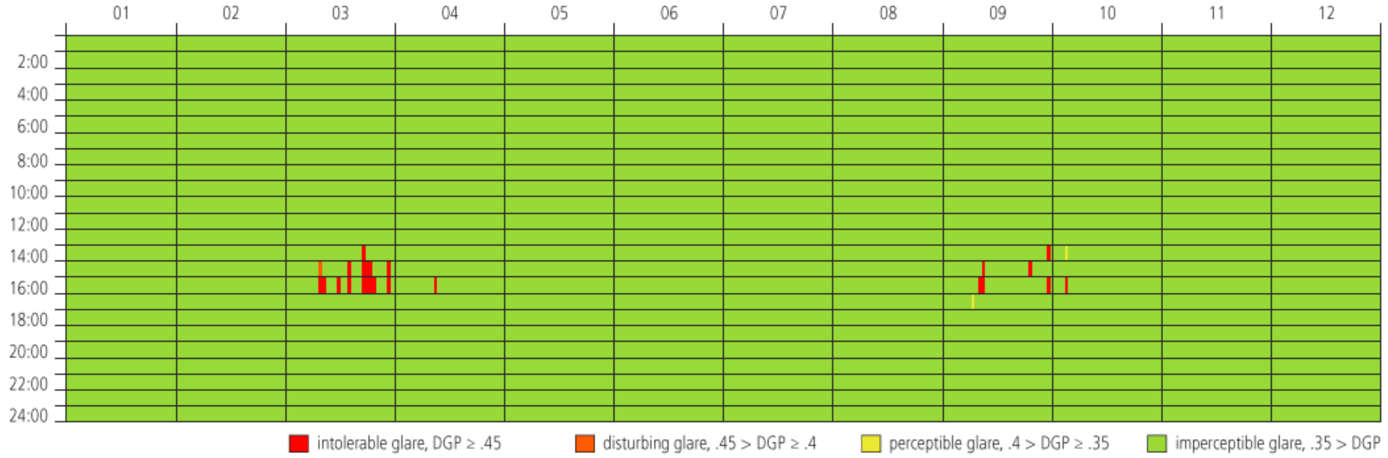
Group 1 Stage 2



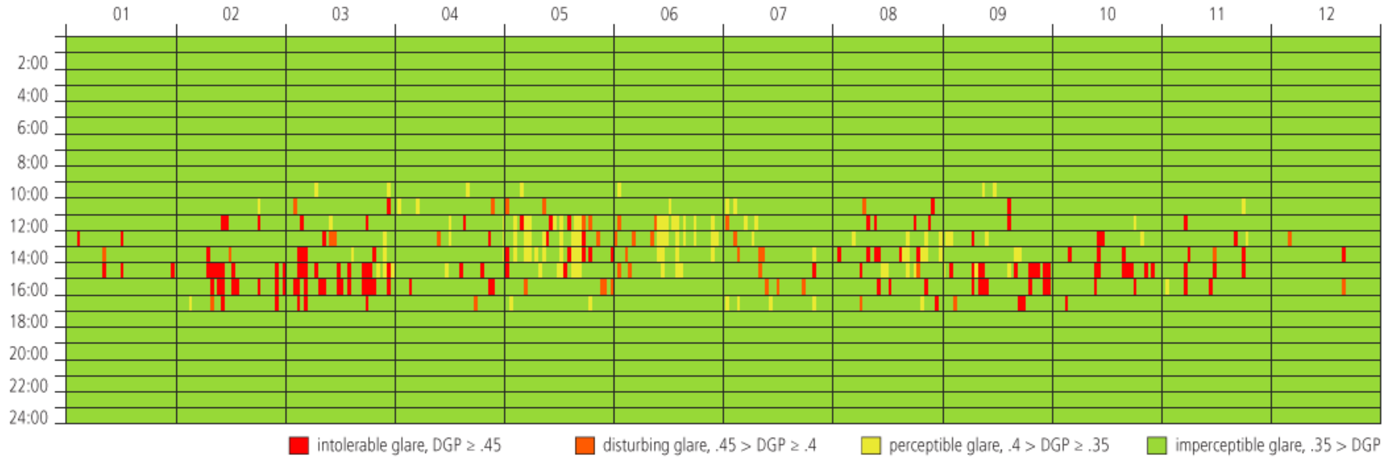
Group 1 Stage 3



Group 2 Stage 1

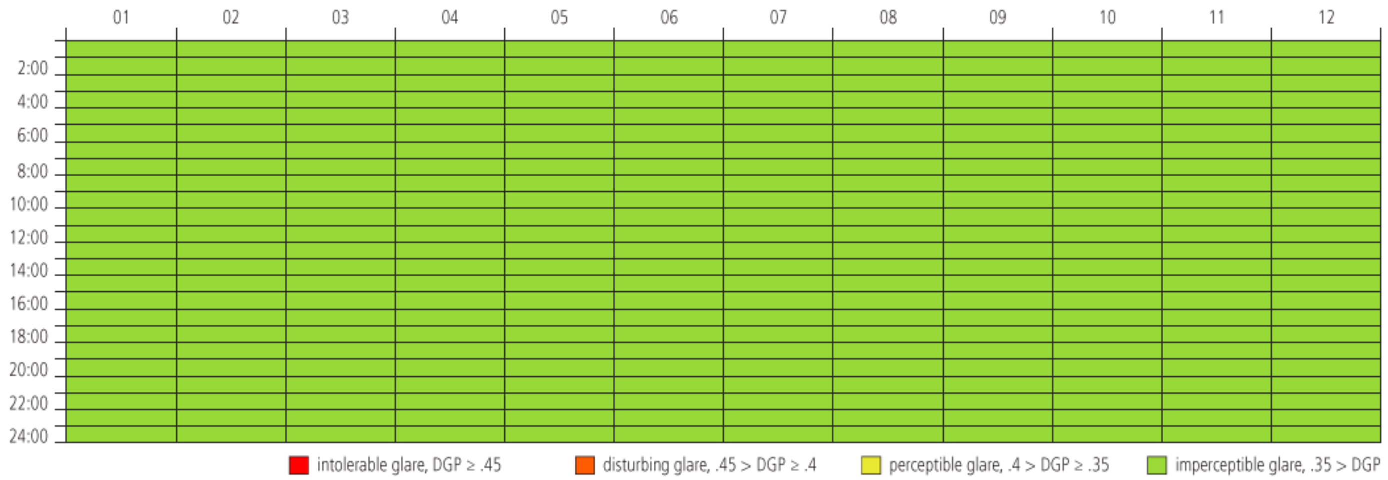


Group 2 Stage 2



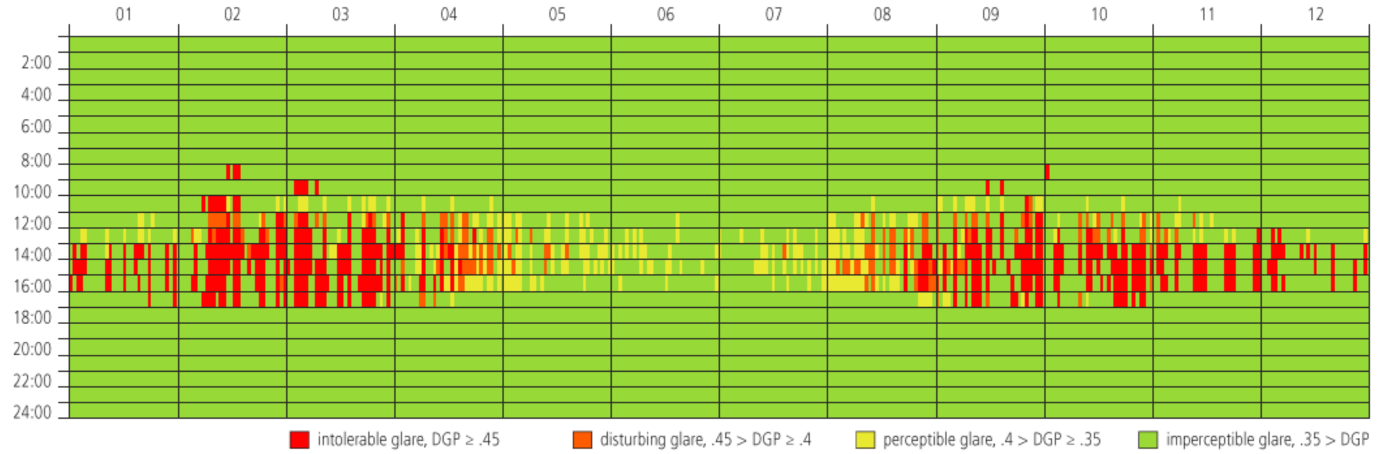
Group 2 Stage 3

Effective

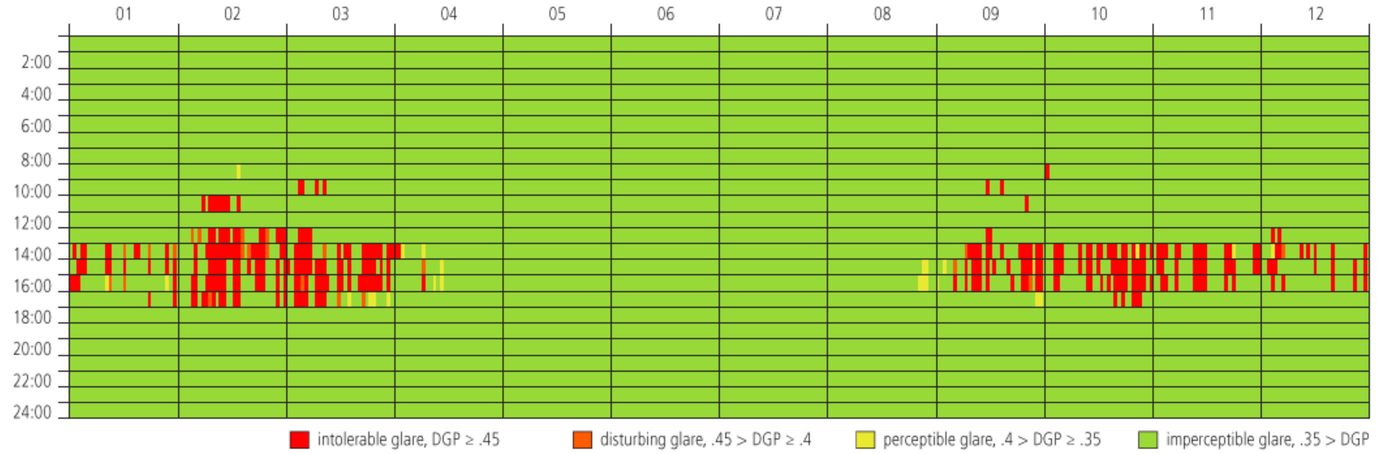


Design (automated calculation)

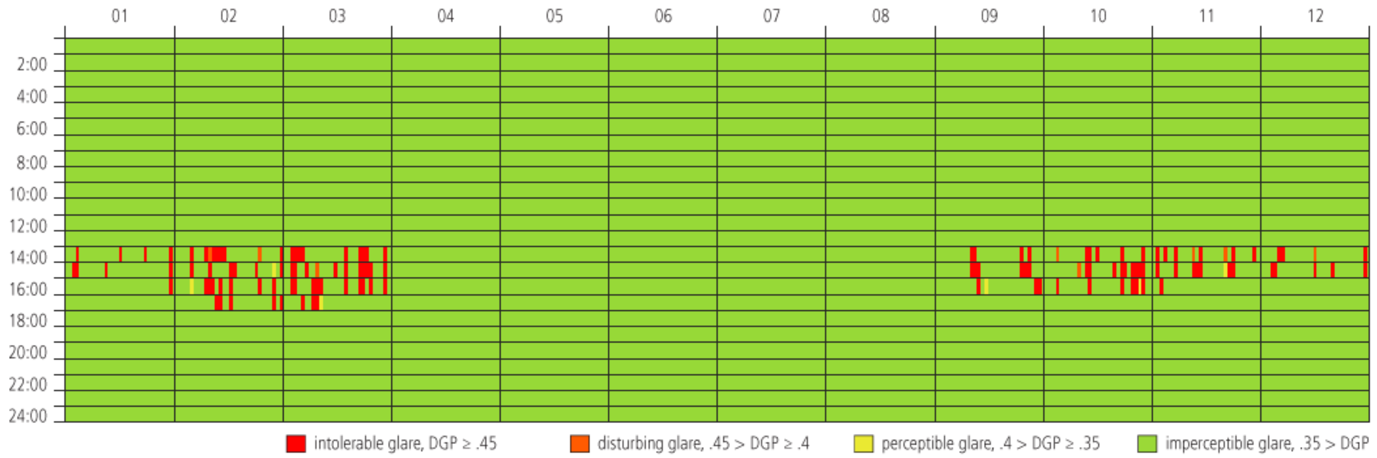
0 Clear State (0)



State 1

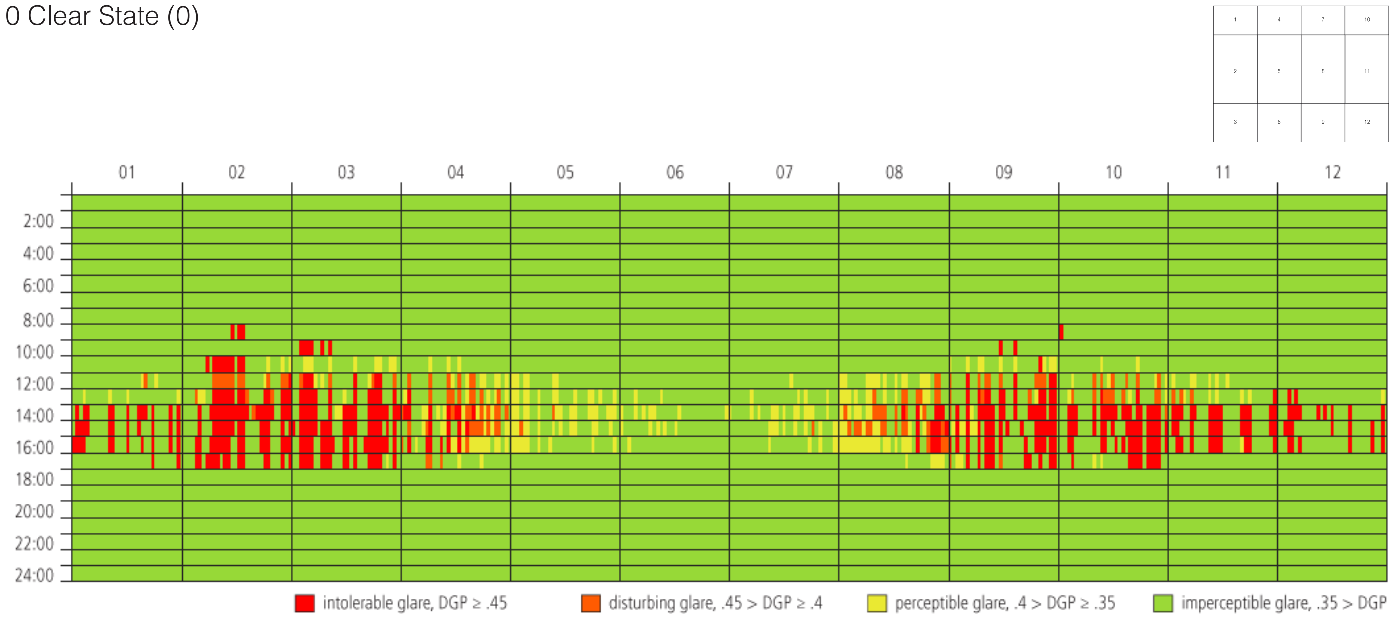


State 2

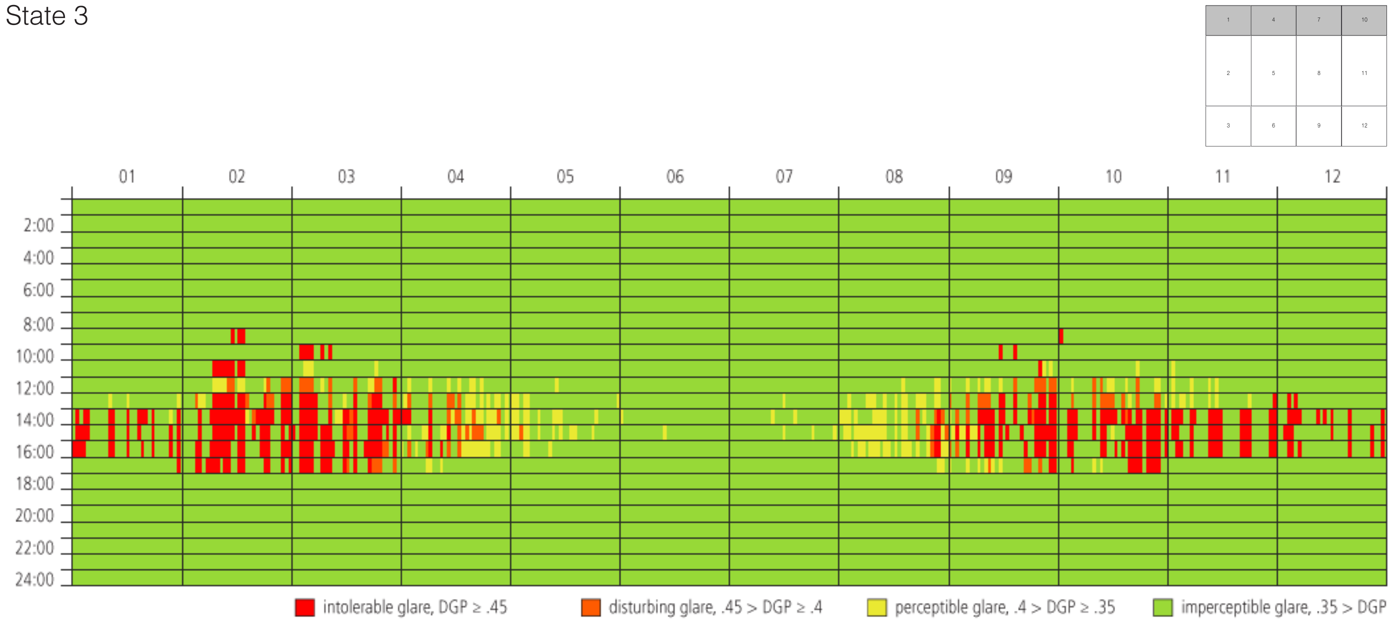


Design (manual calculation)

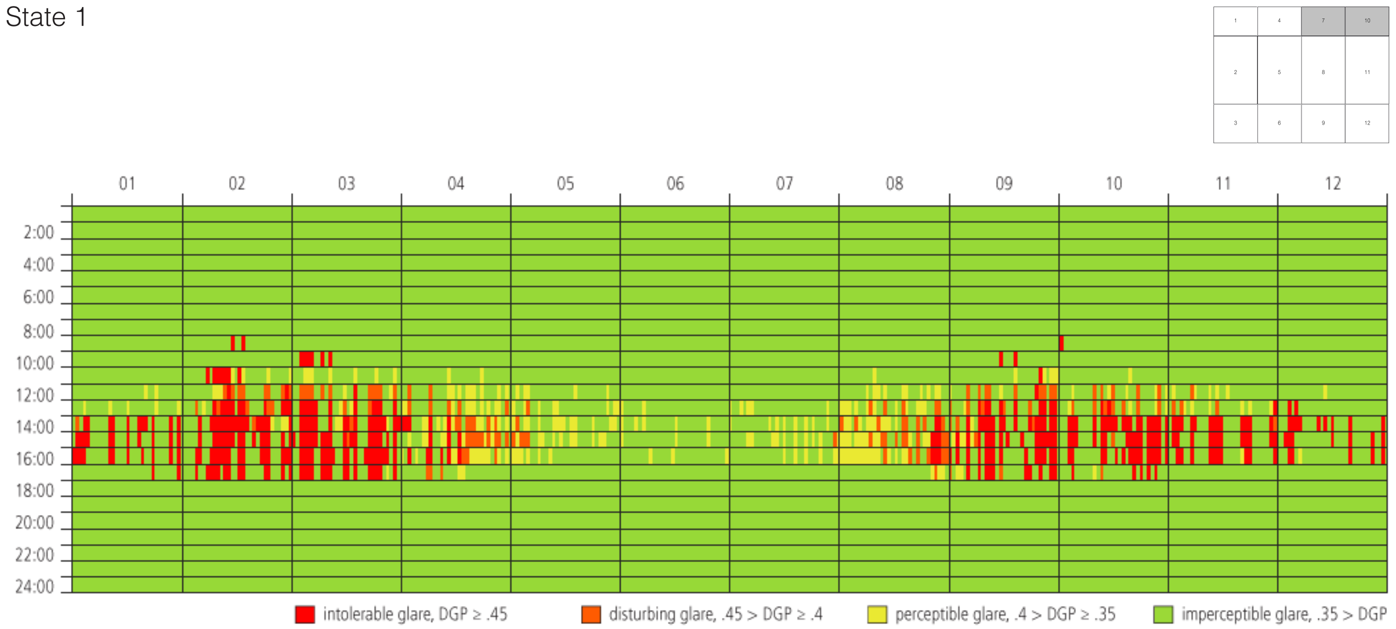
0 Clear State (0)



State 3



State 1



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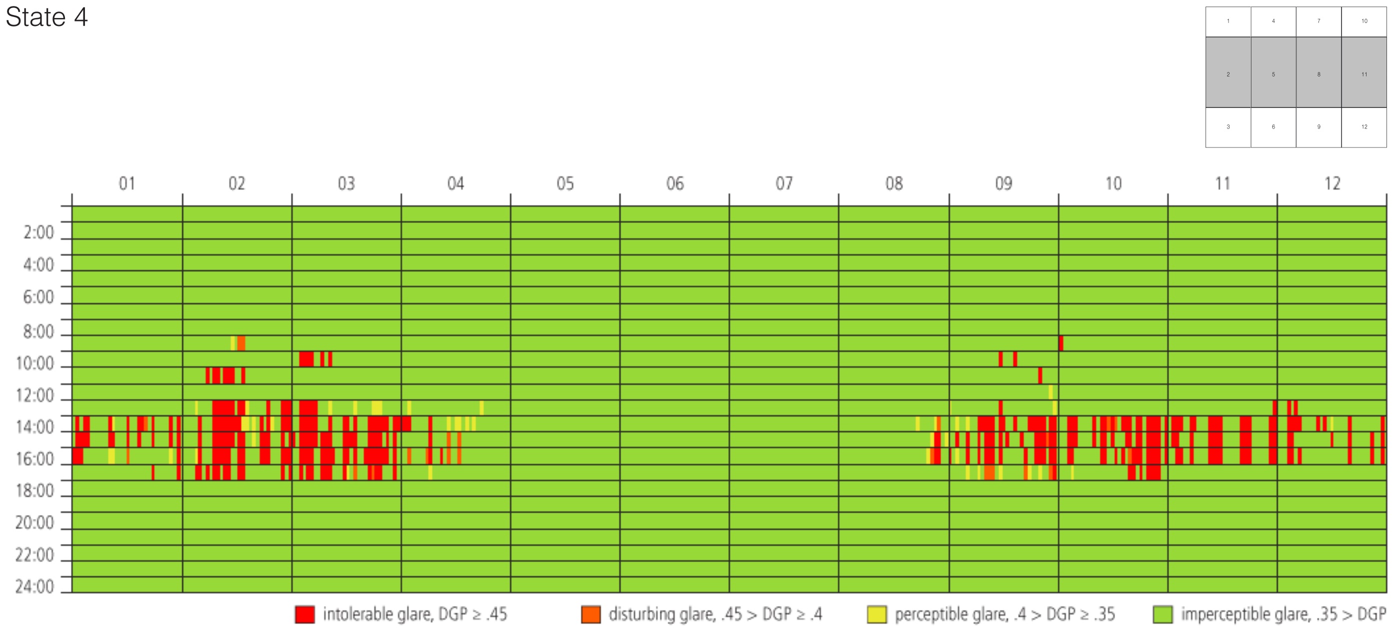
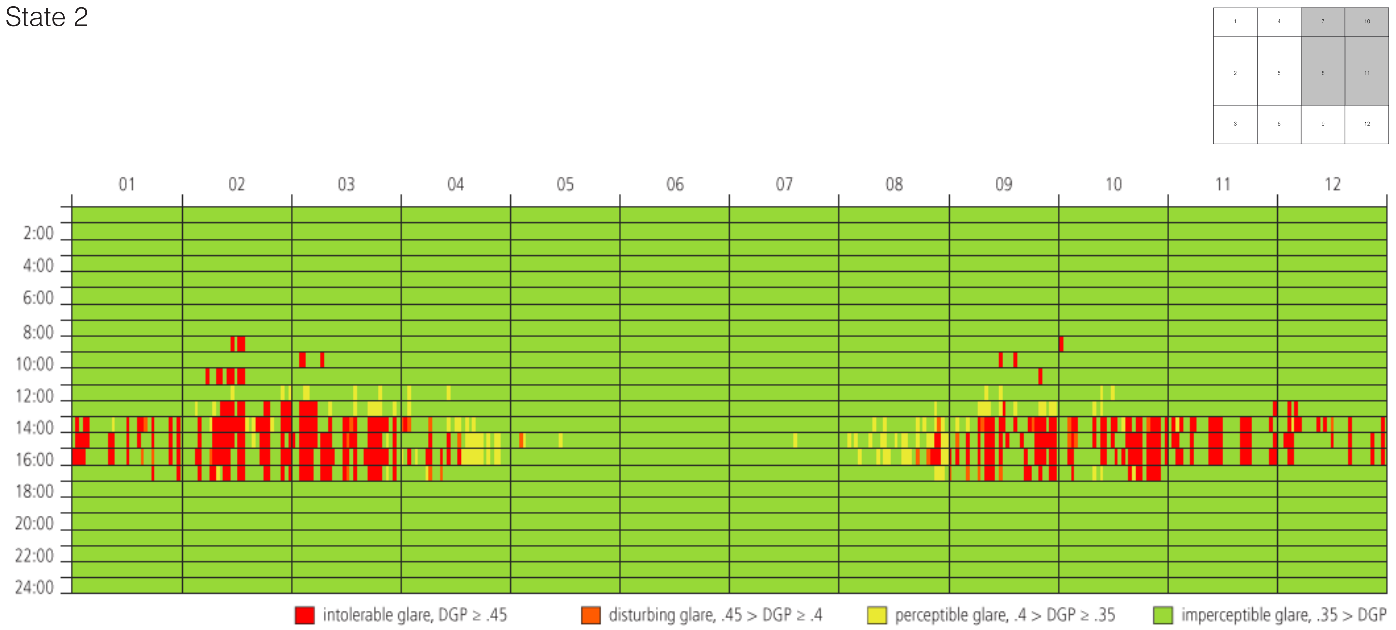


State 2



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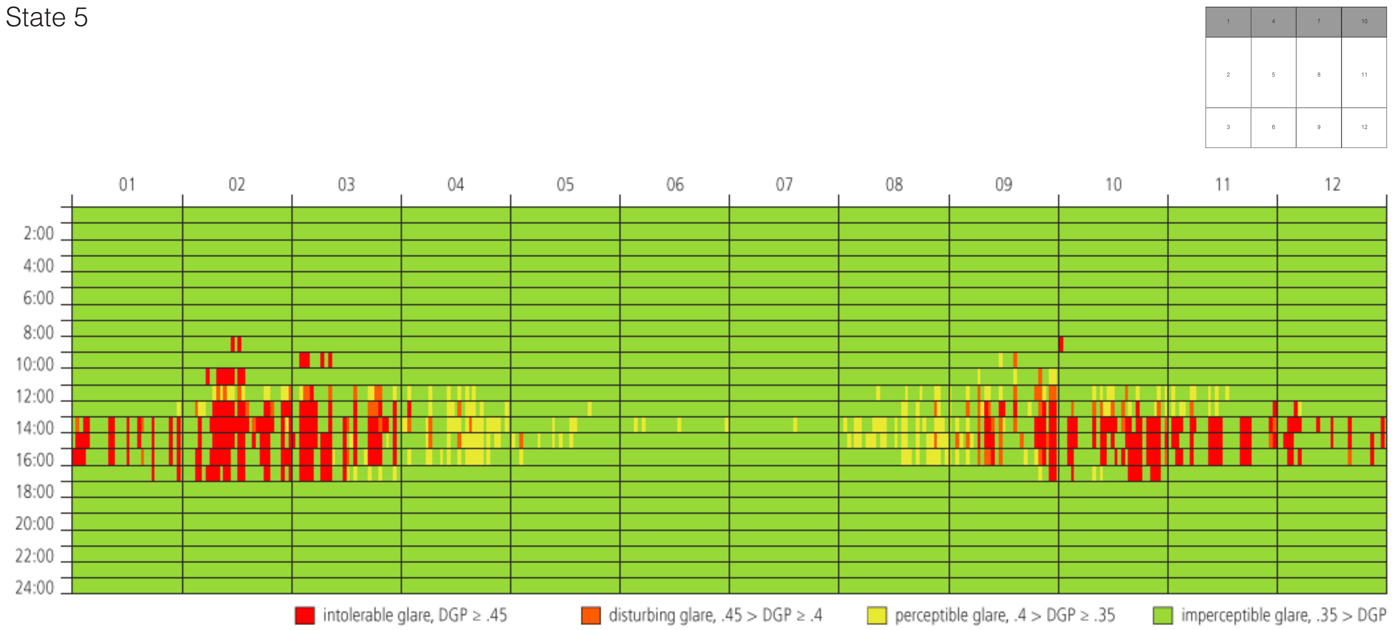
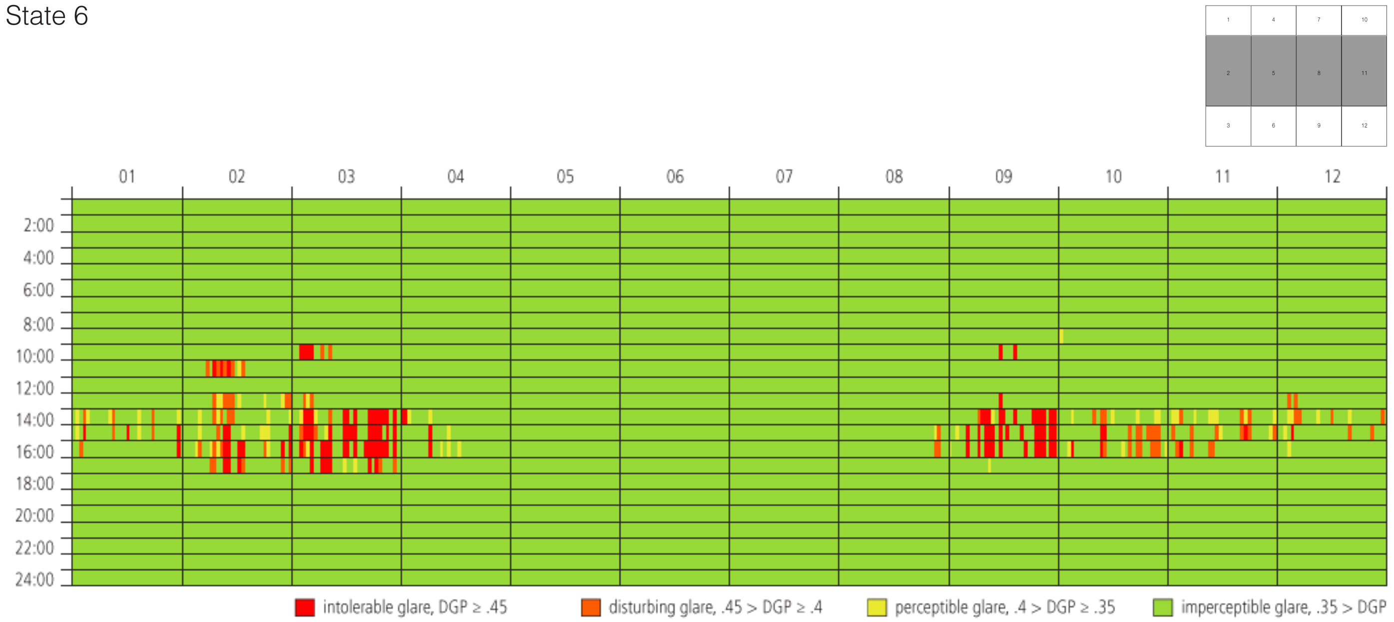
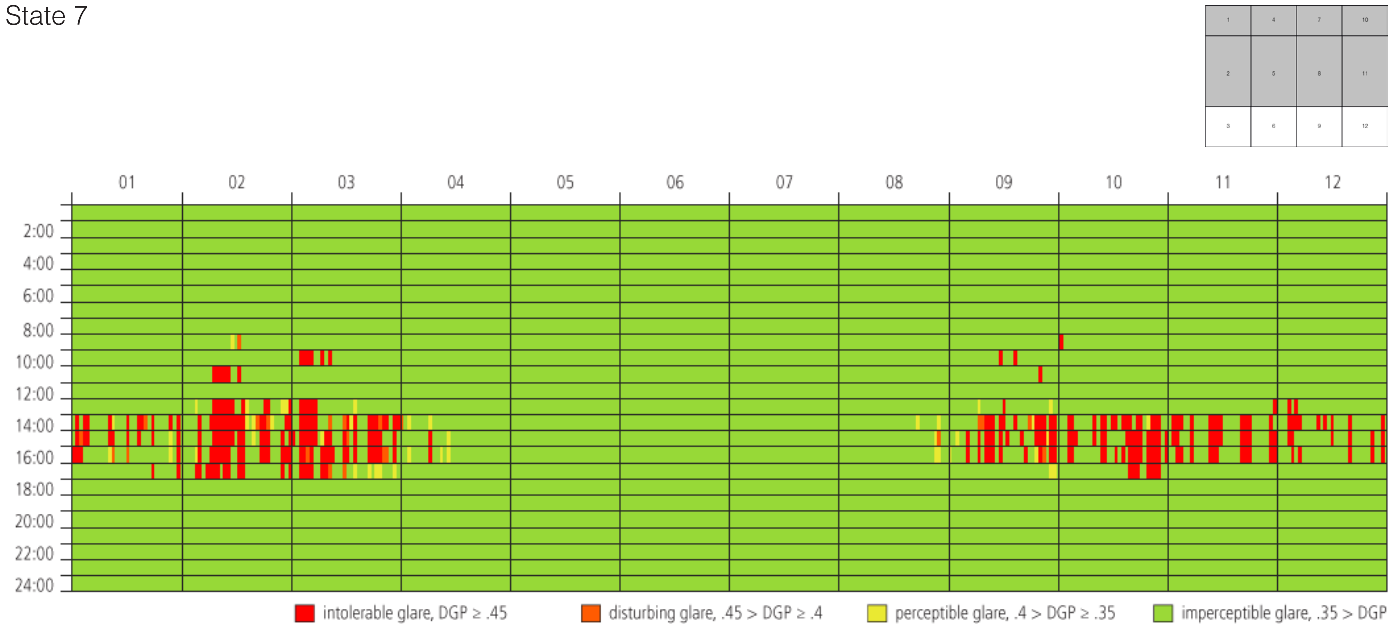


State 6

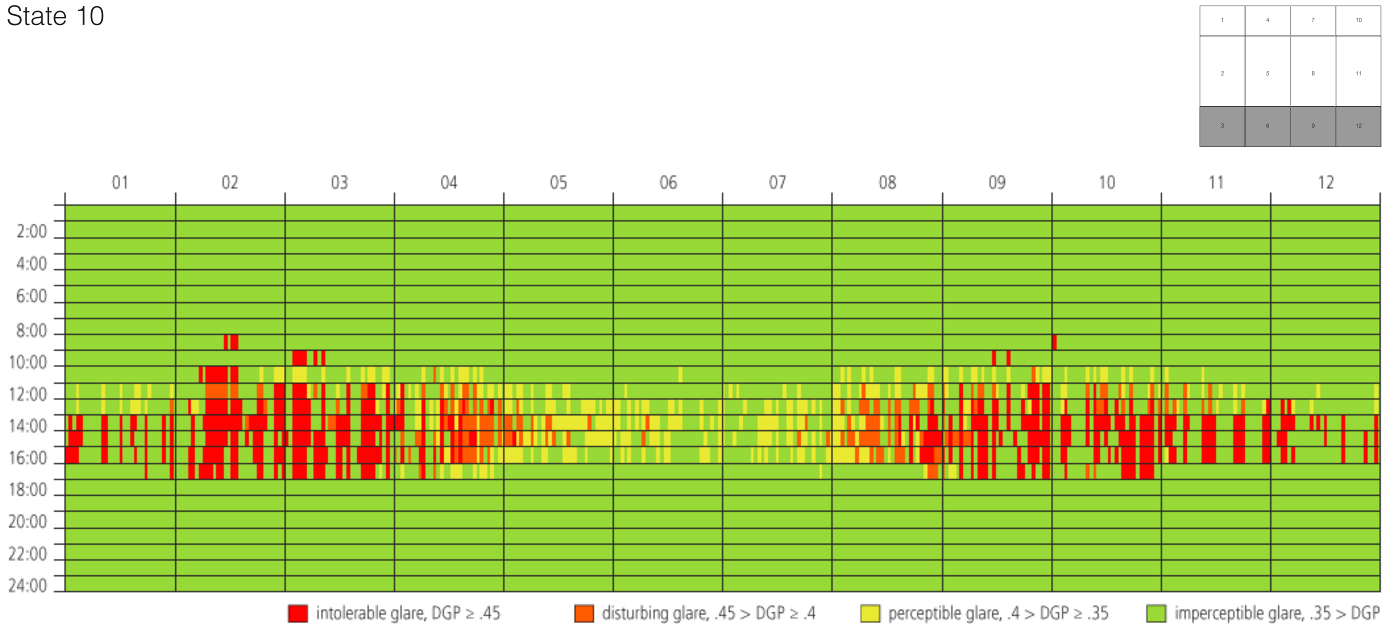


State 9

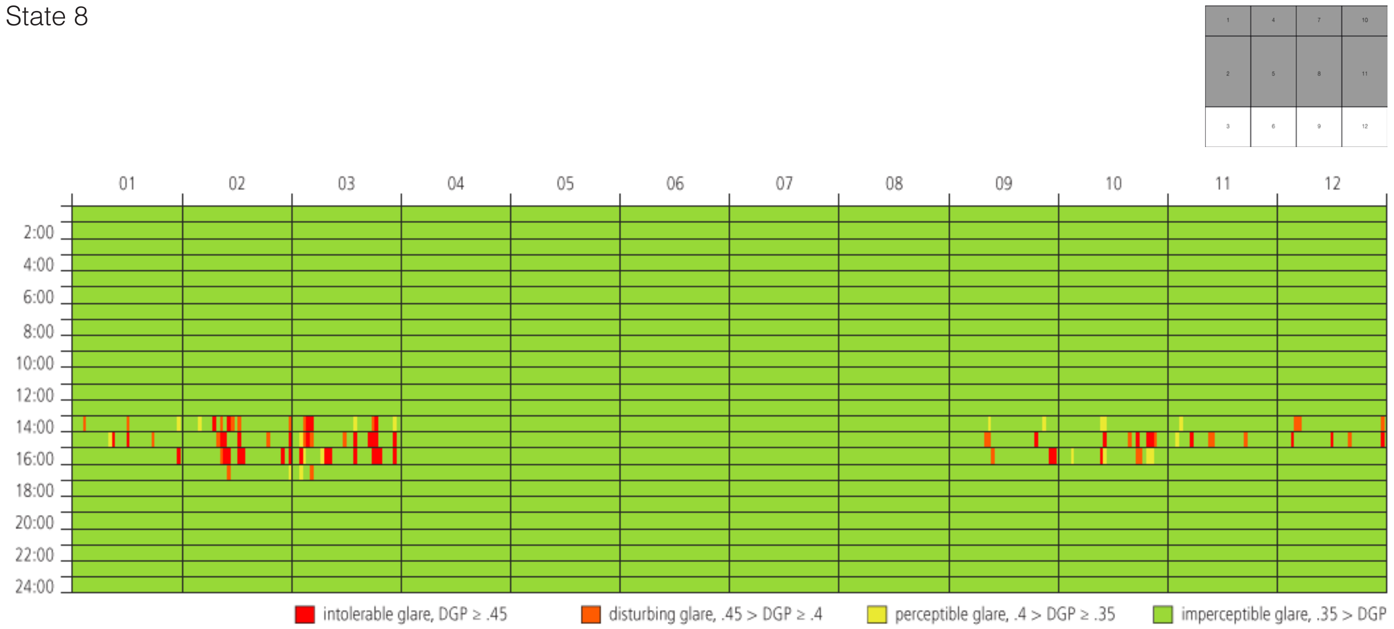
State 7



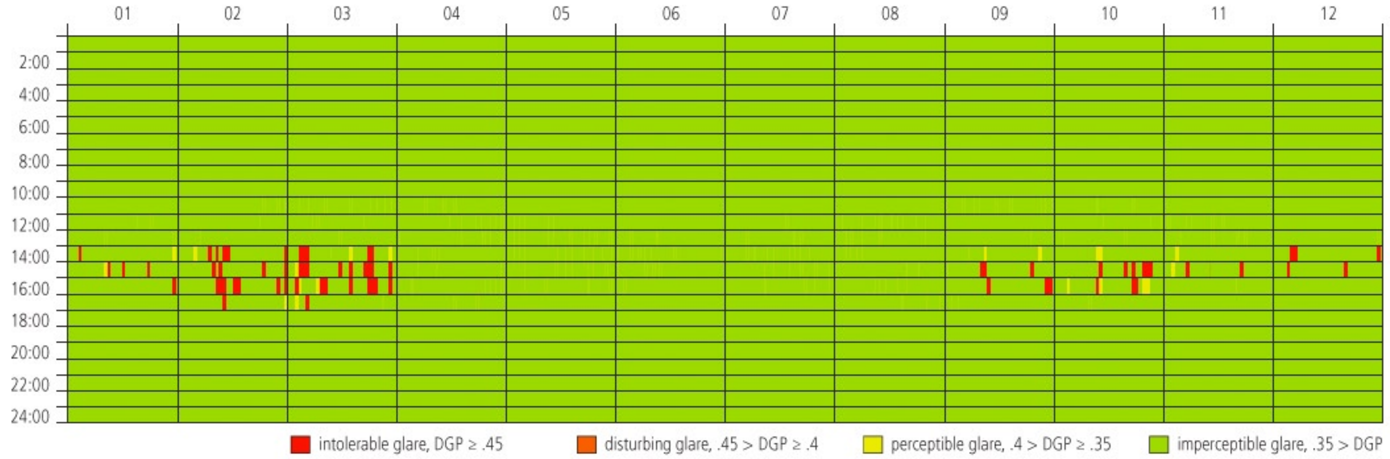
State 10



State 8

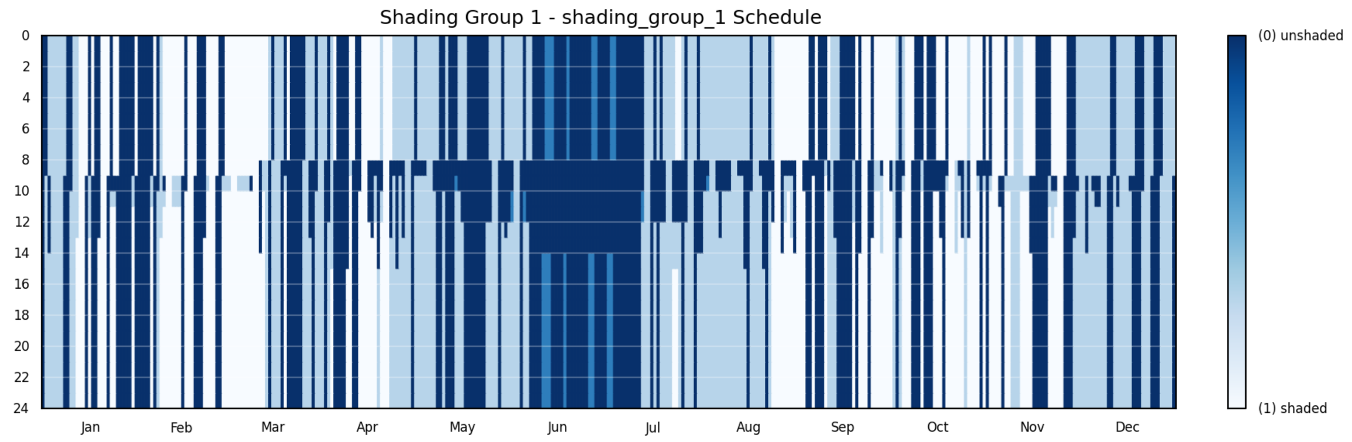


Composition

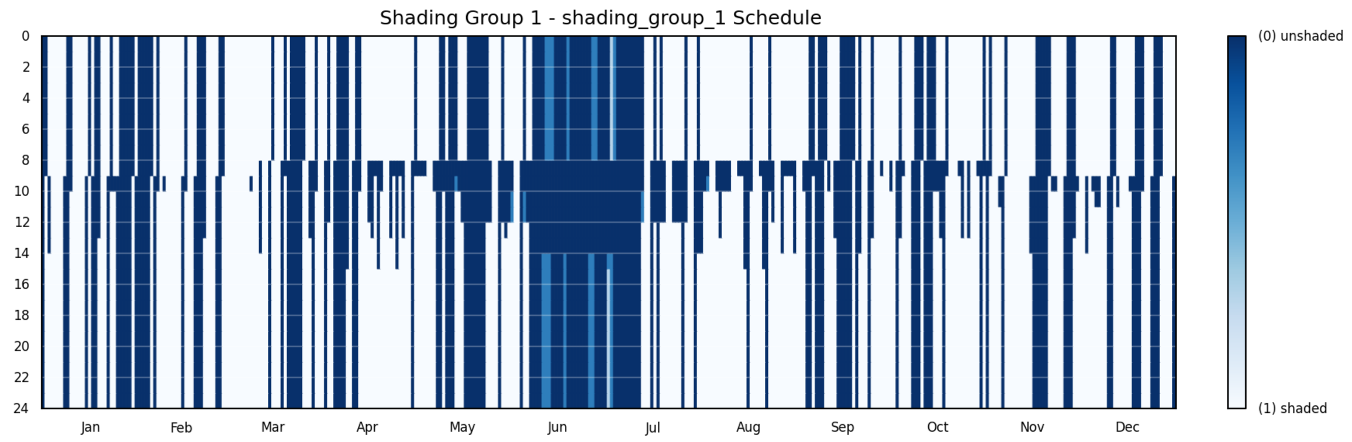


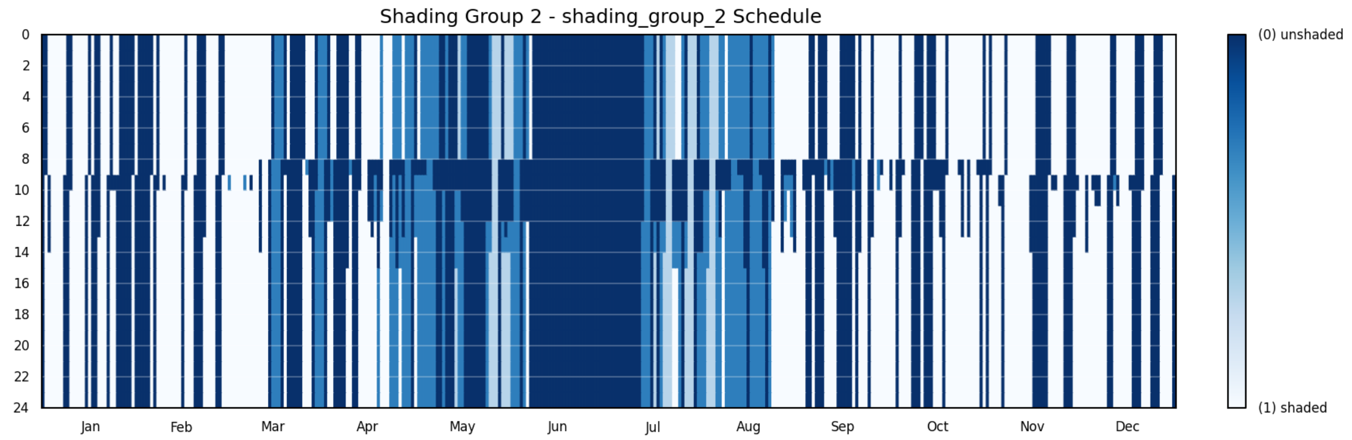
Shading Schedule

Reference project 1

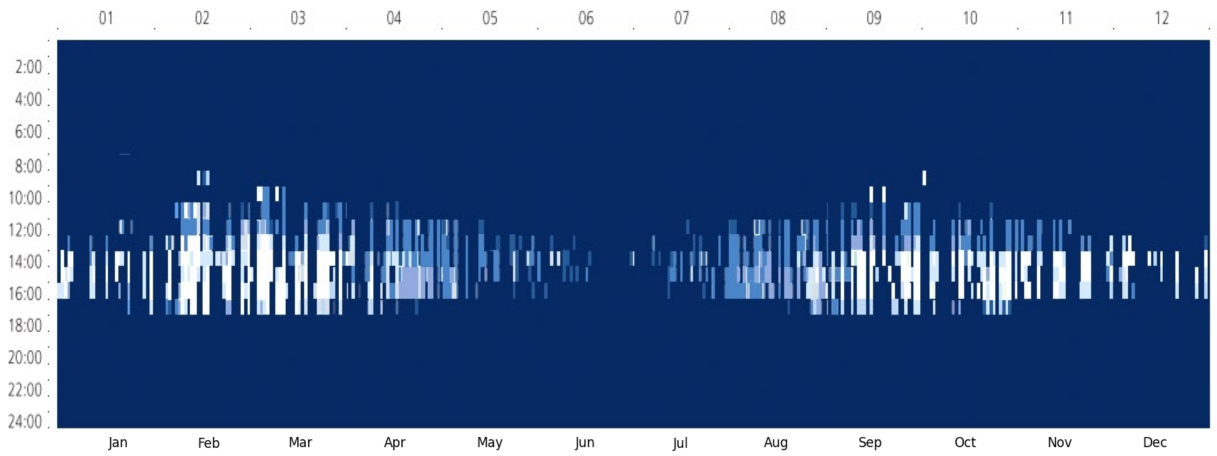


Reference project 2



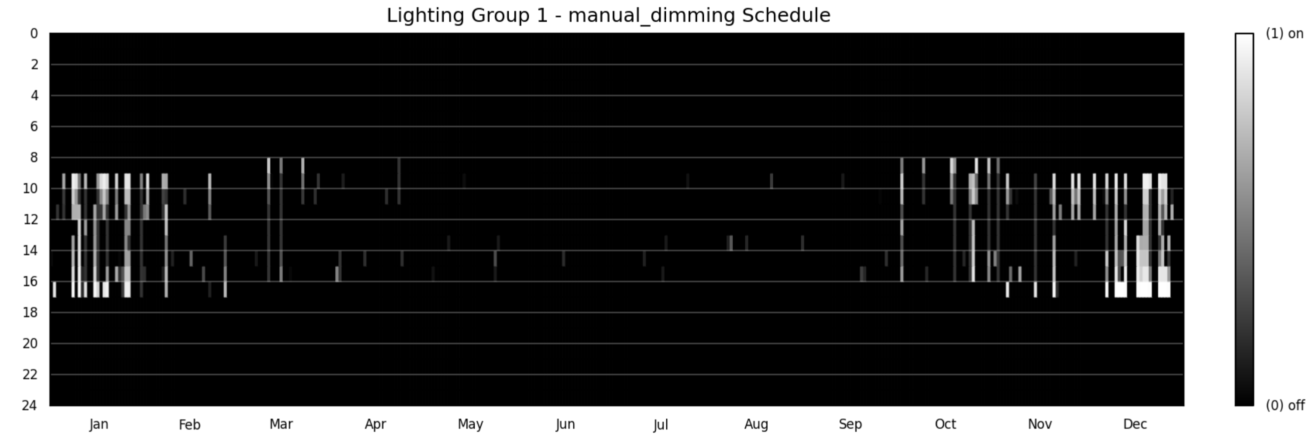


Design (manual caculation)

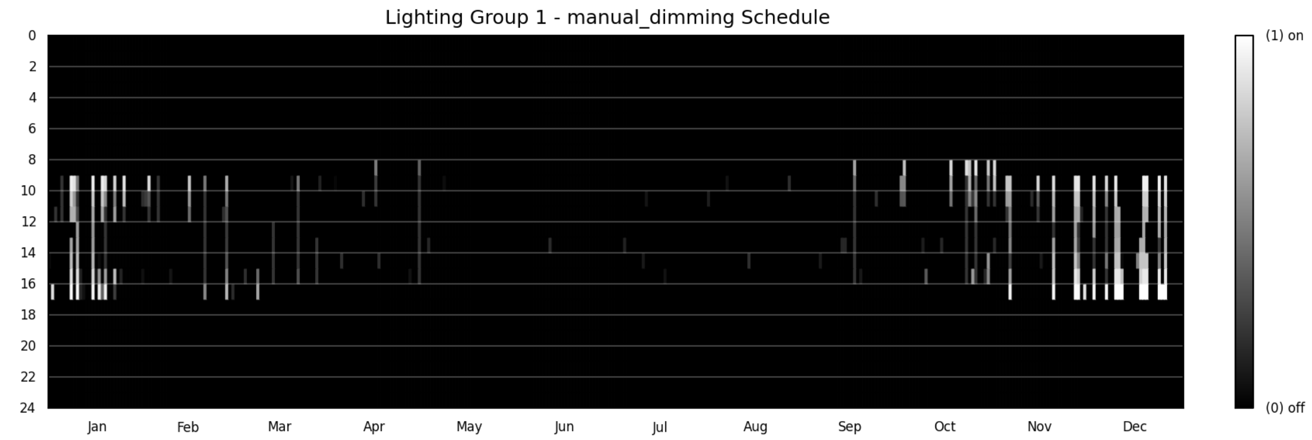


Lighting Schedule

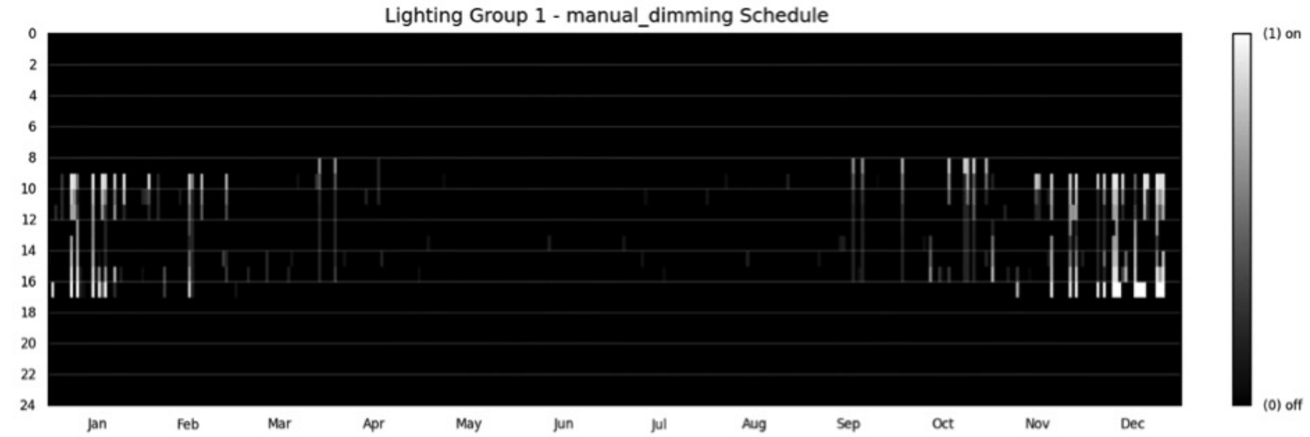
Reference project 1



Reference project 2

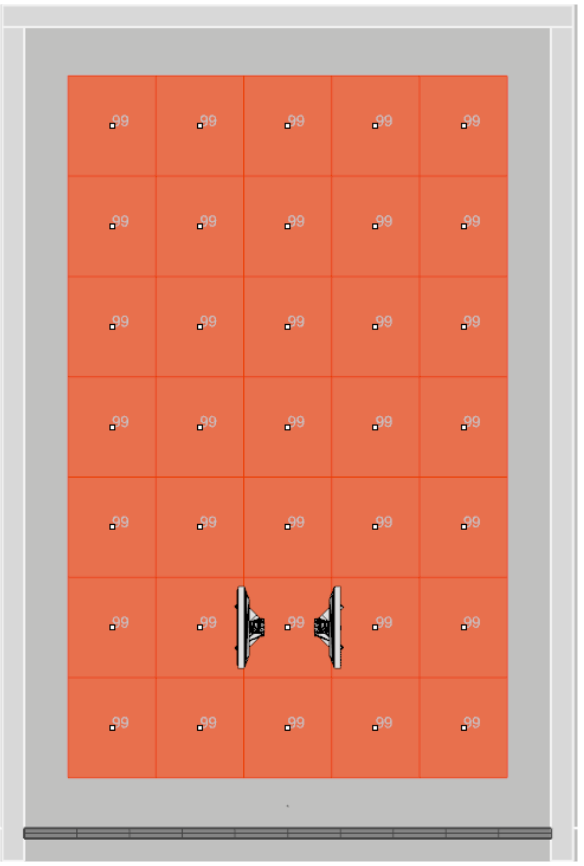


Design

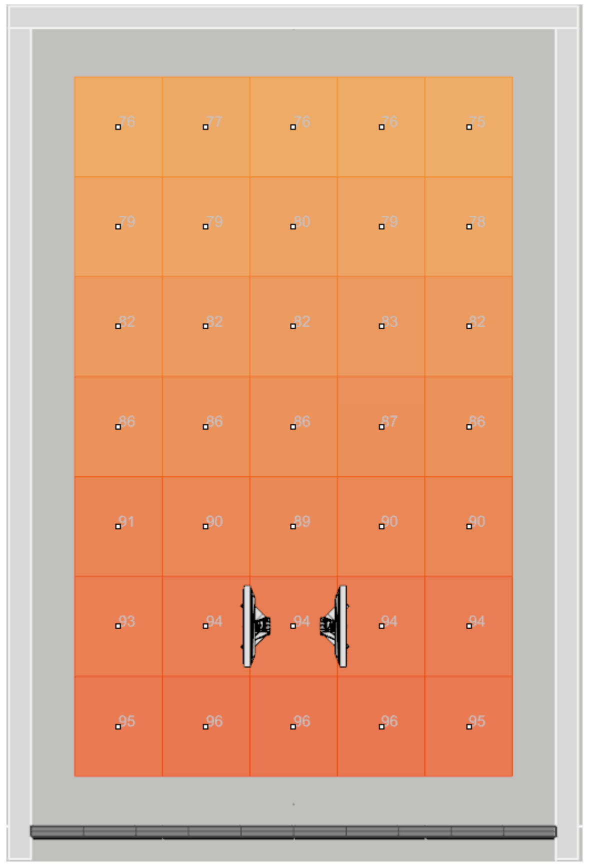


Daylight Autonomy

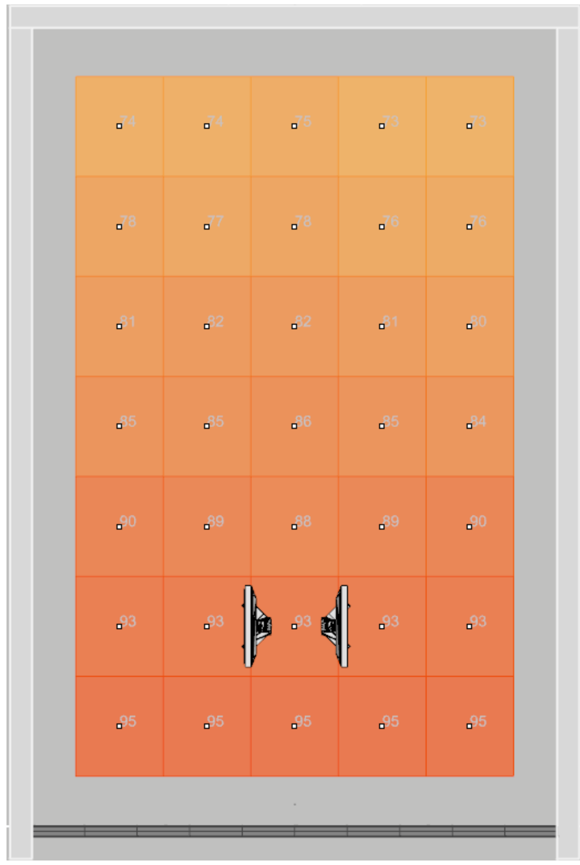
Reference project 1



Reference project 2



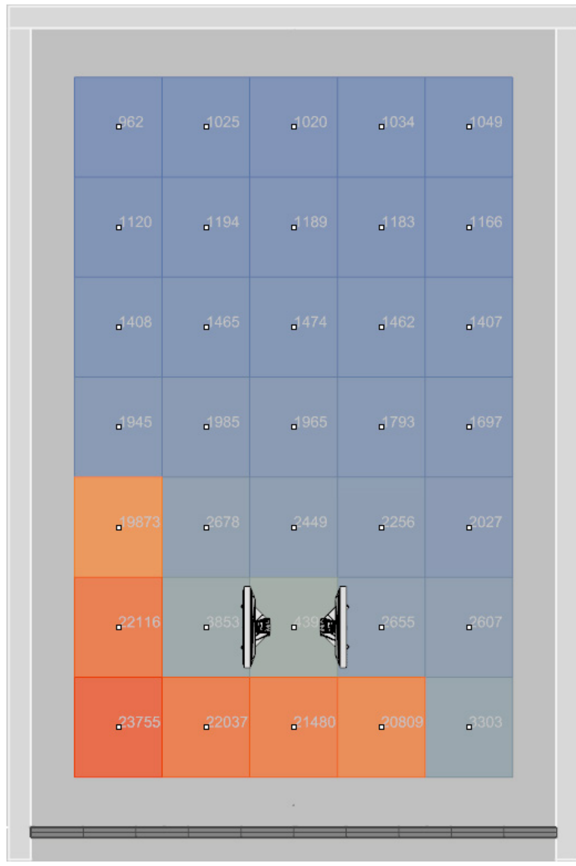
Design (automatic calculation)



Illuminance

21st March 10:00

Reference project 1



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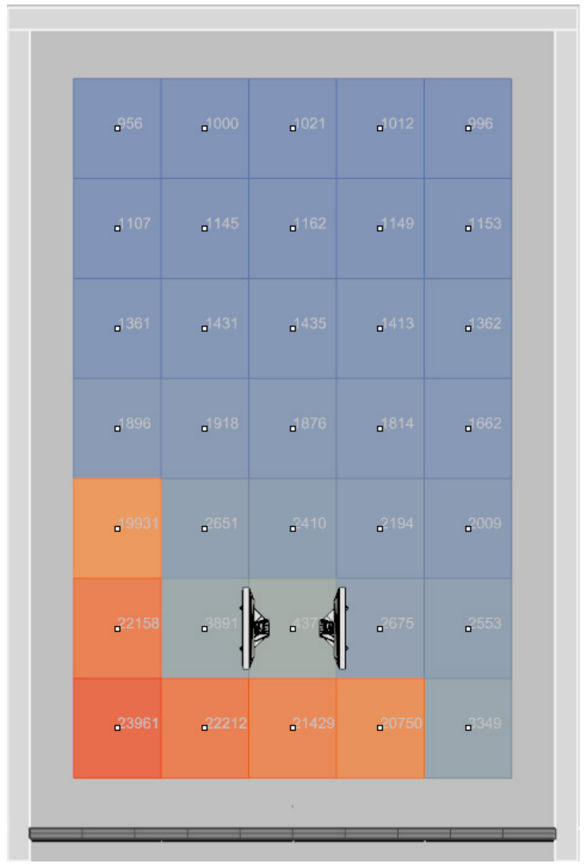
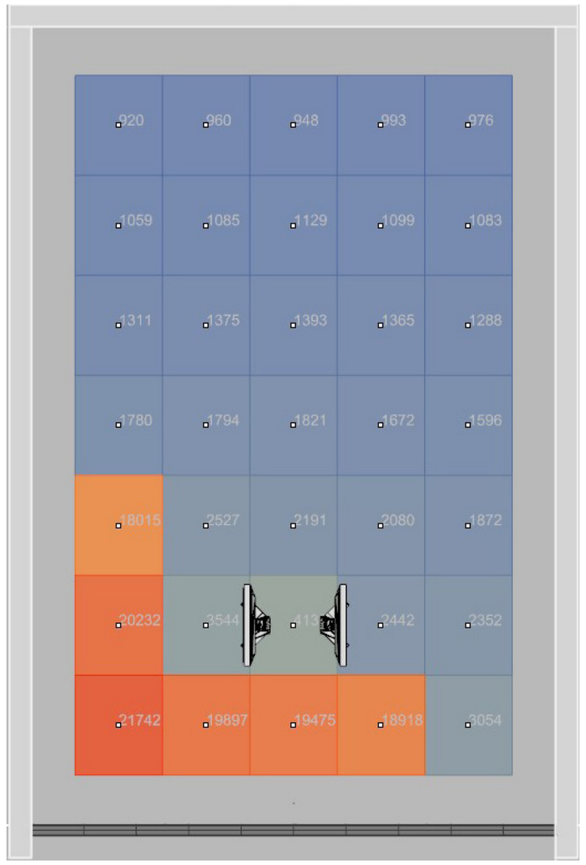
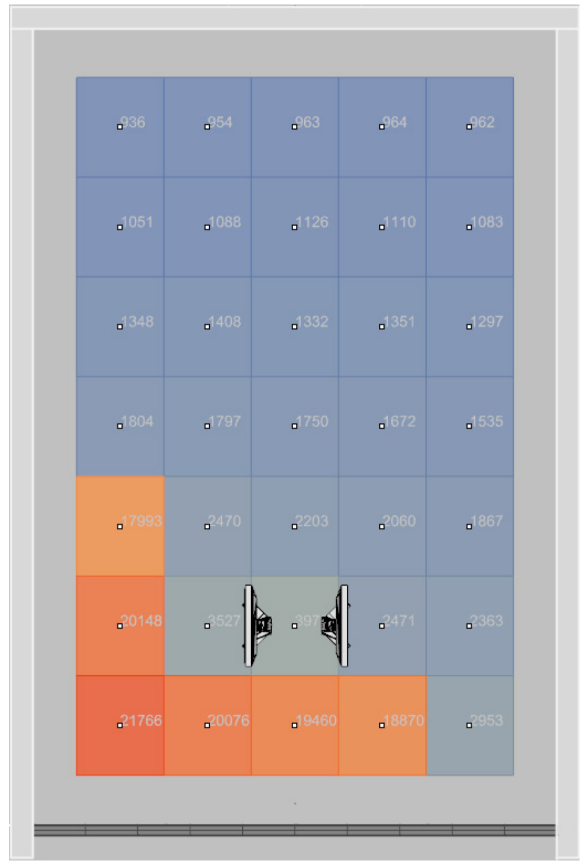


Design (automatic calculation)



Design (manual calculation)



21st March 13:00

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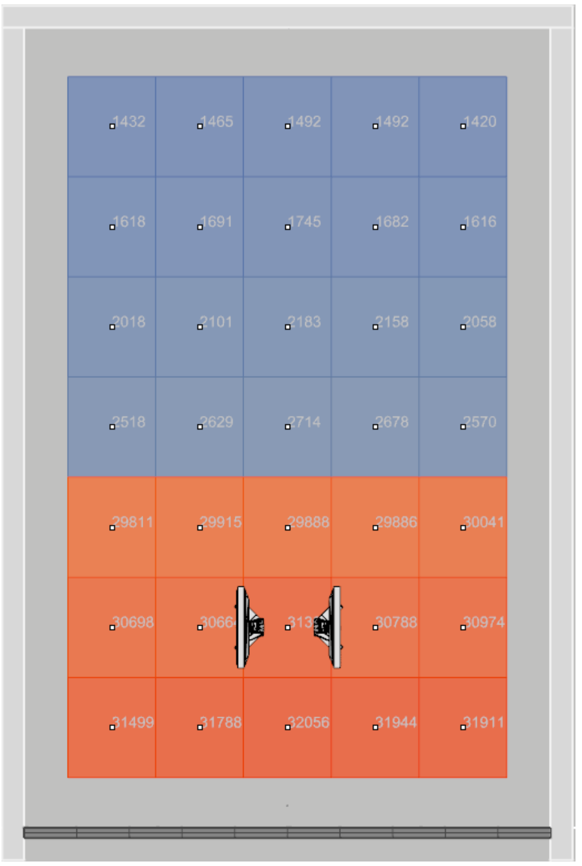

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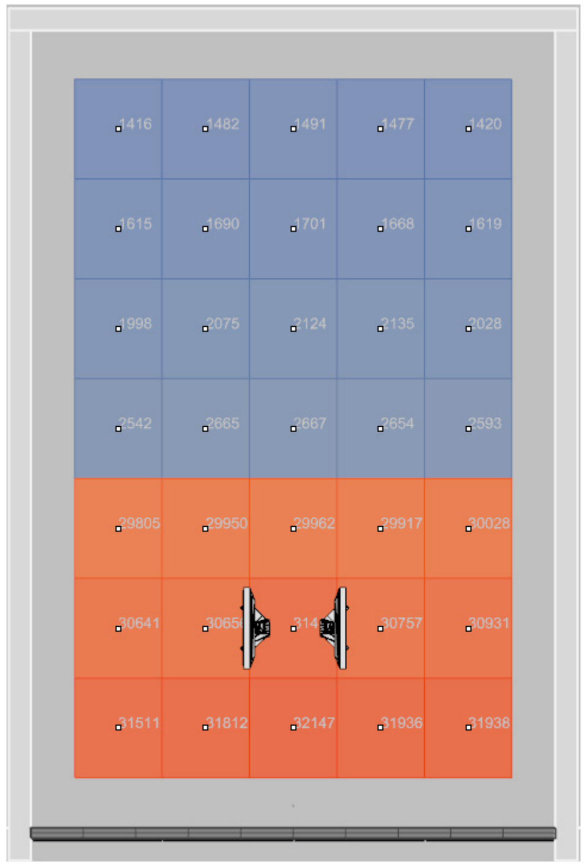

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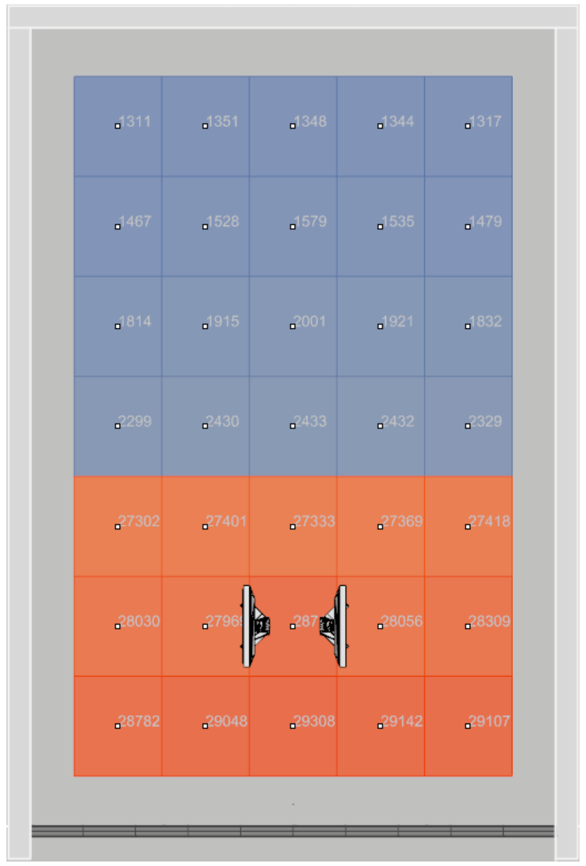

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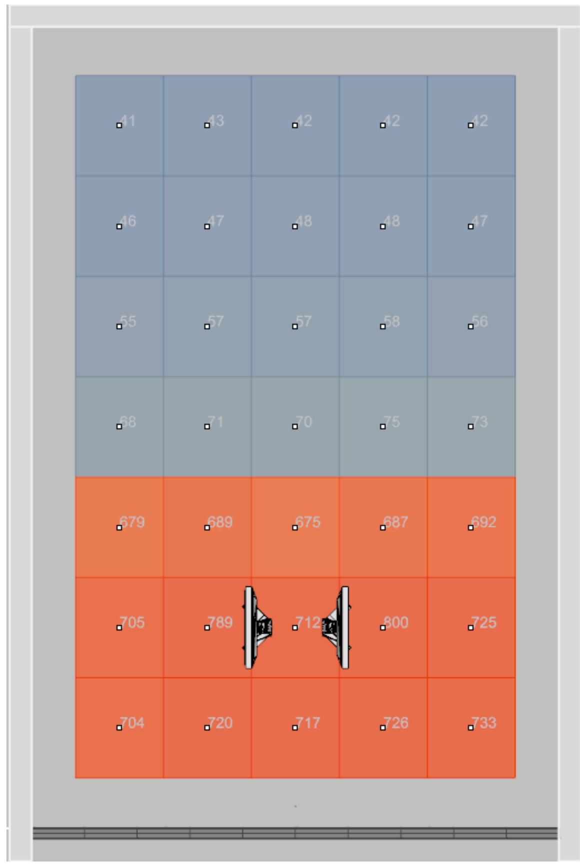

21st March 16:00

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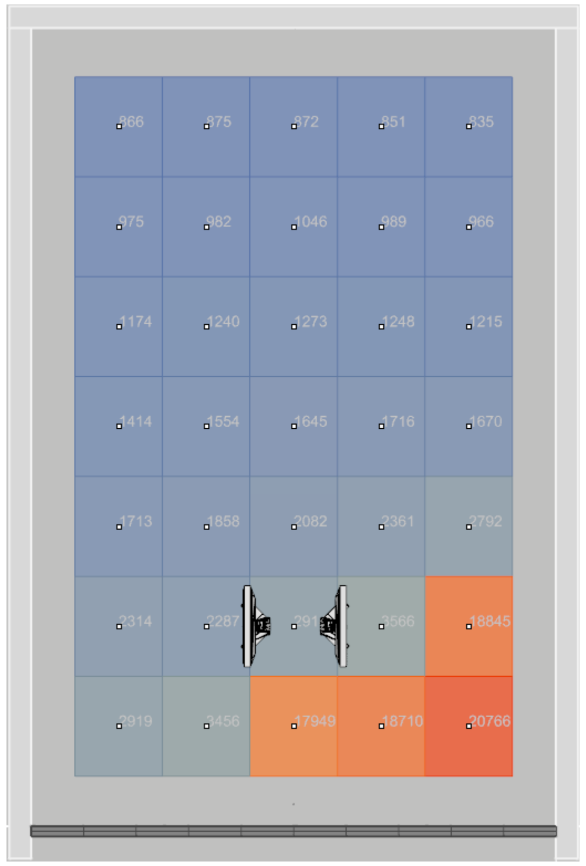

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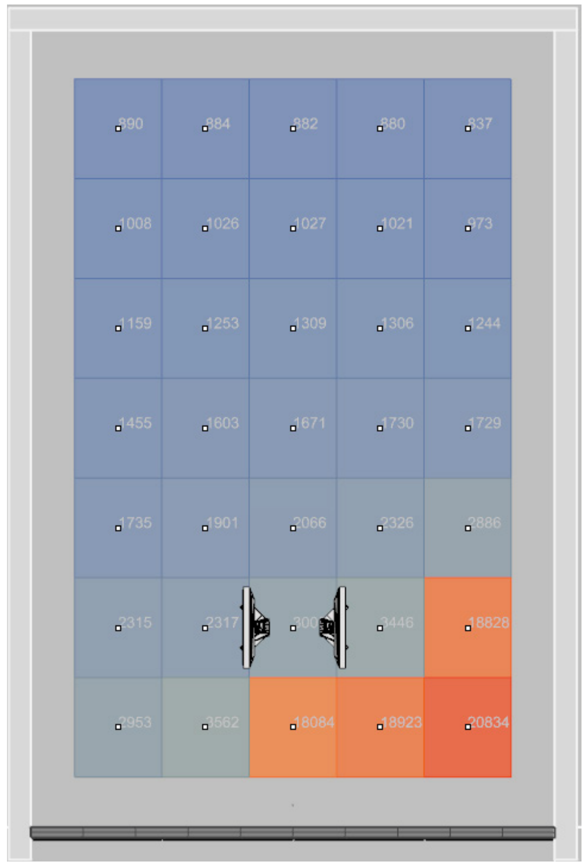

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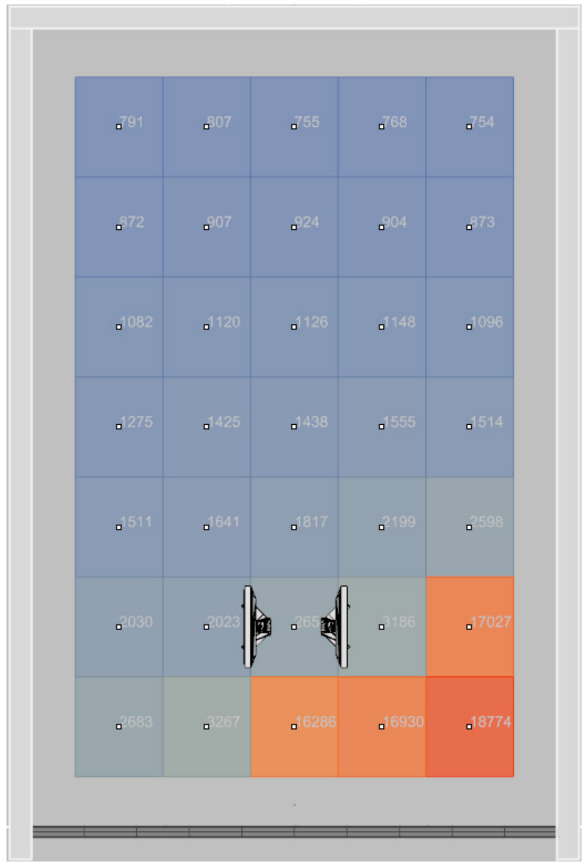

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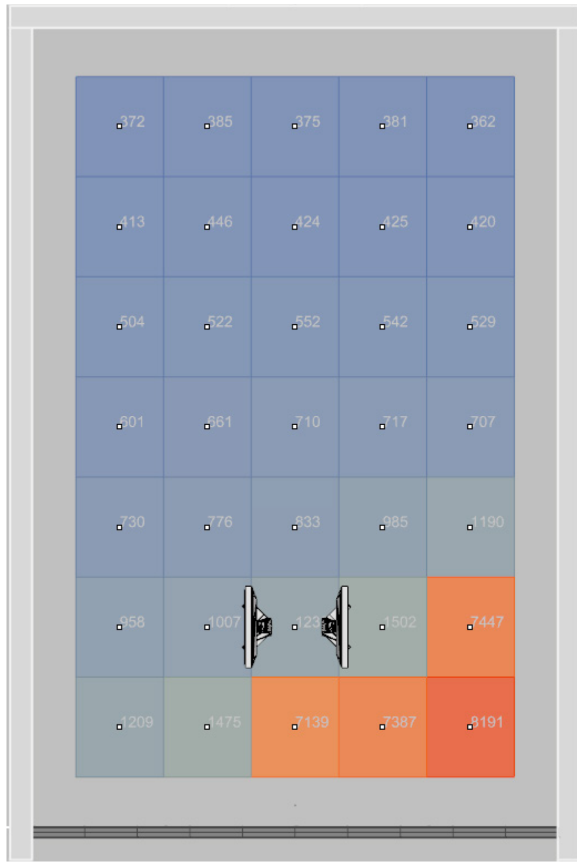

21st June 10:00

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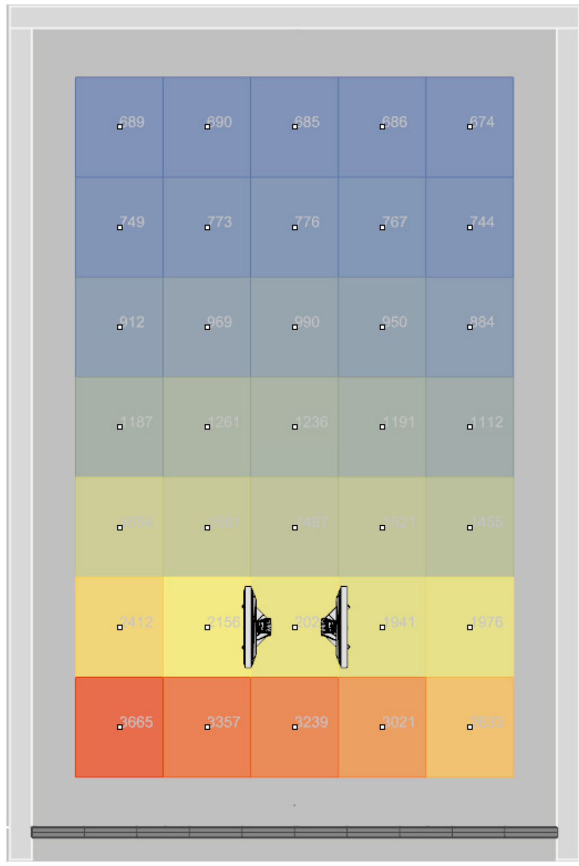

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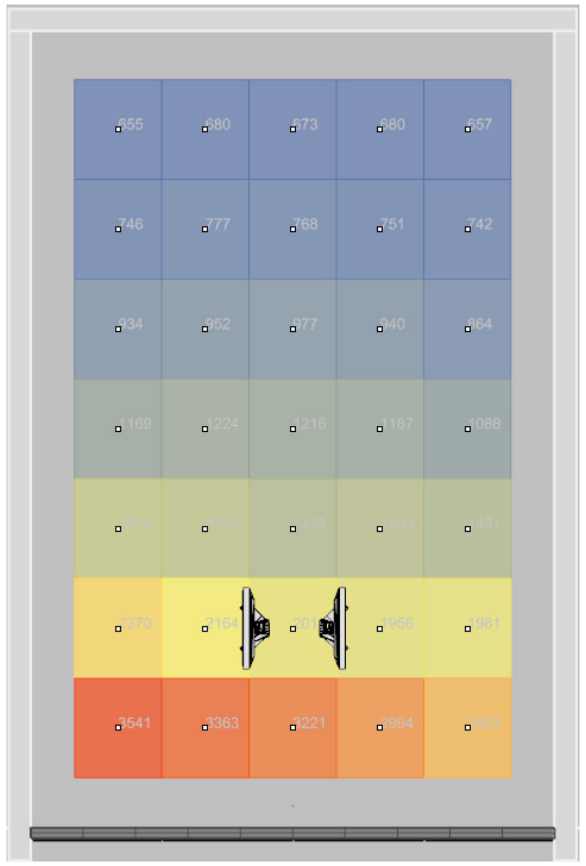

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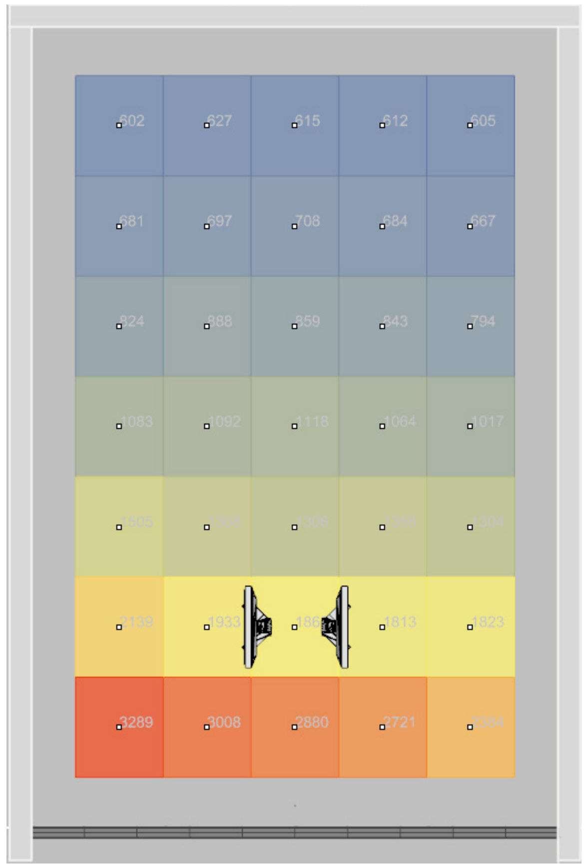

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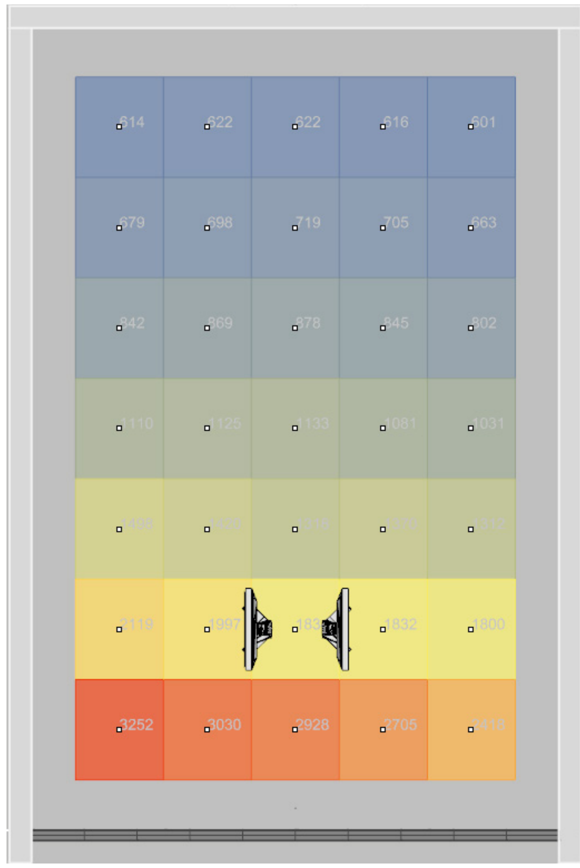

21st June 13:00

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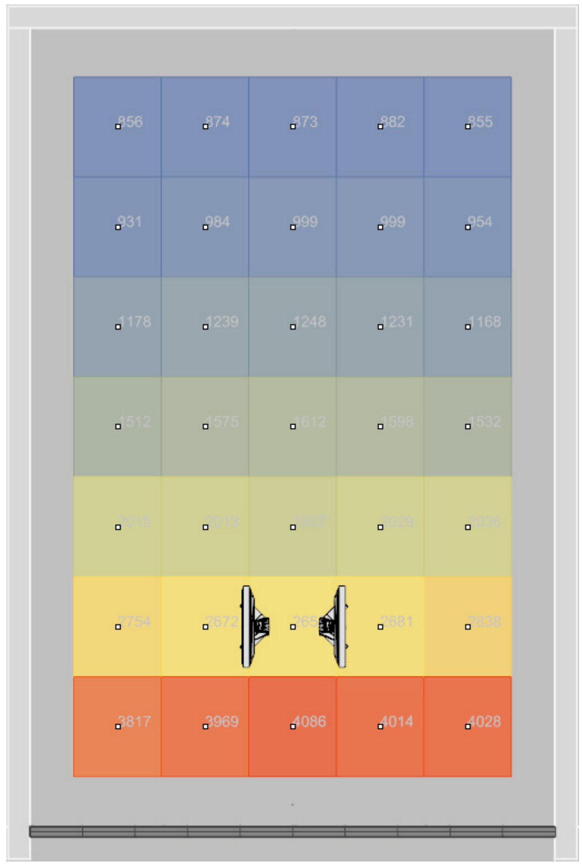

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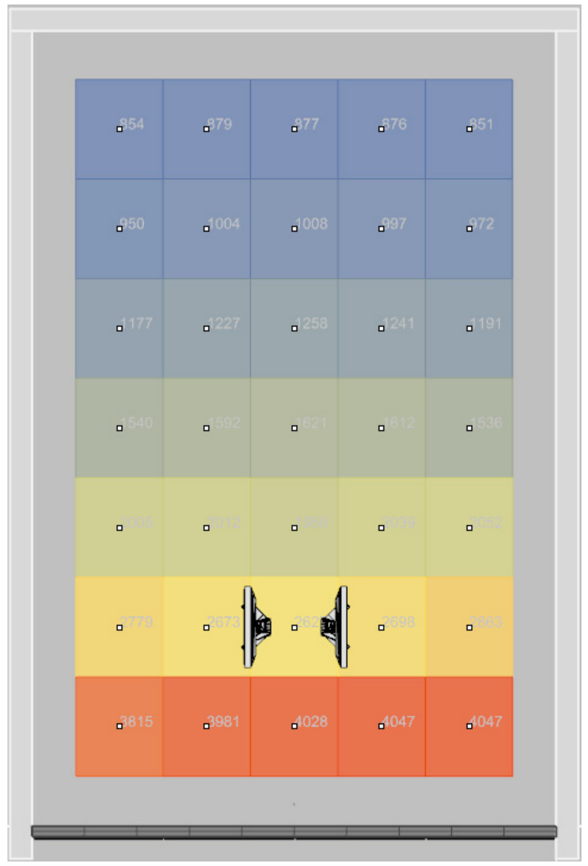

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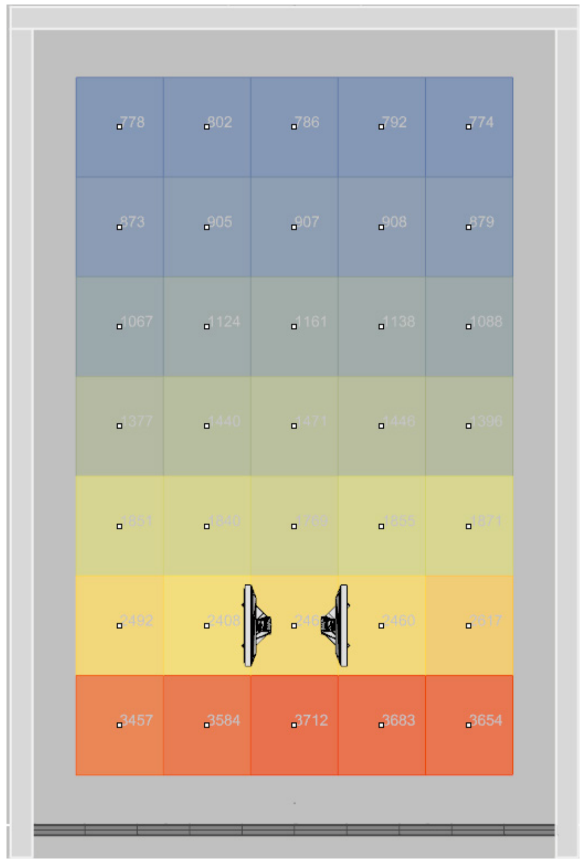

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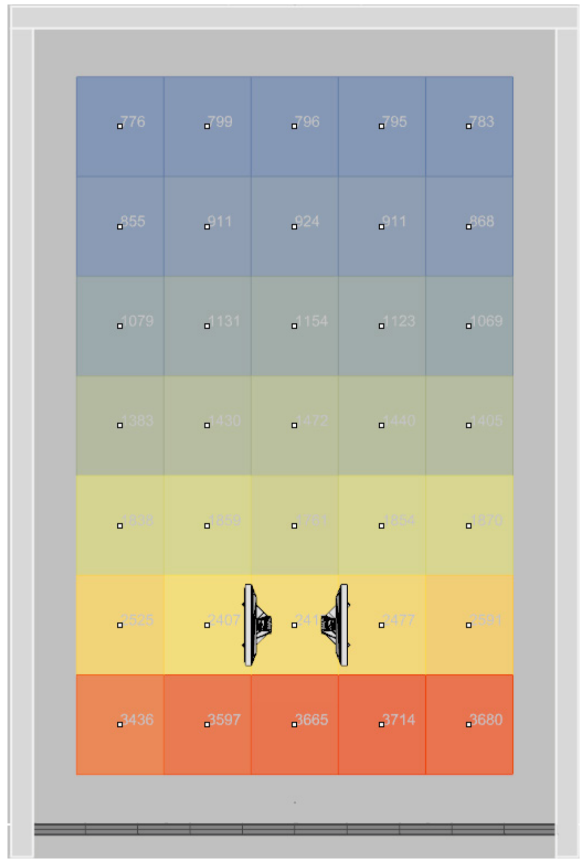

21st June 16:00

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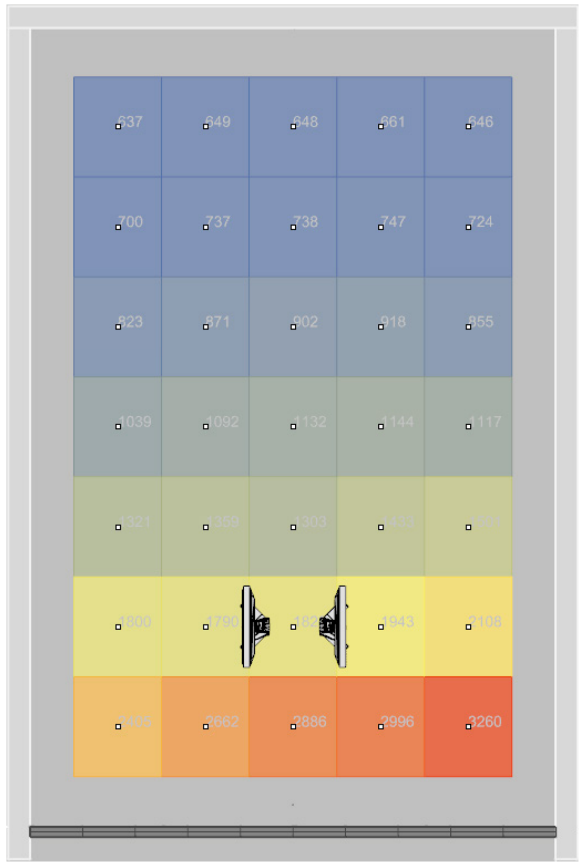

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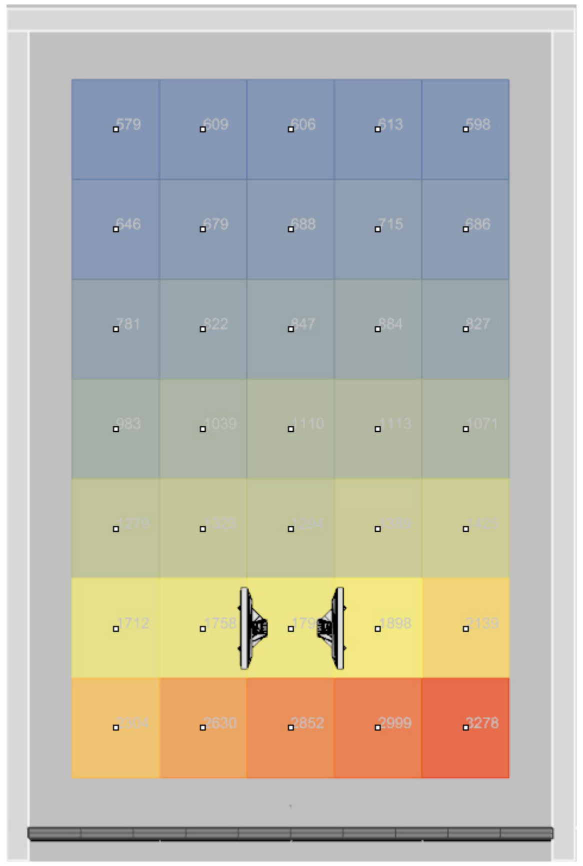

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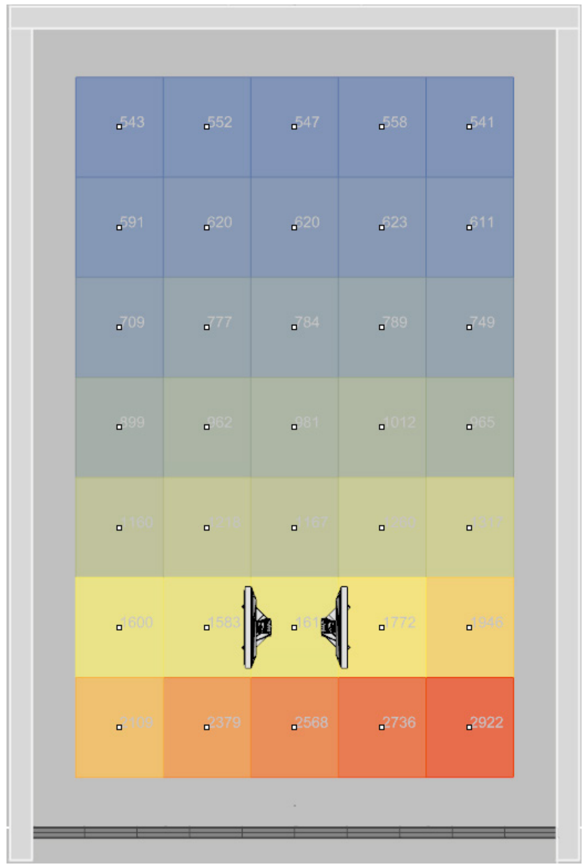

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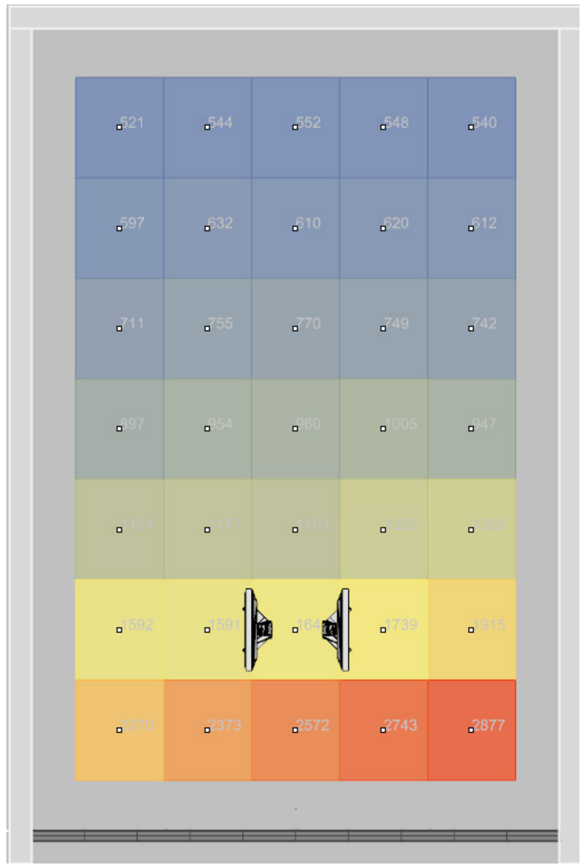

23rd December 10:00

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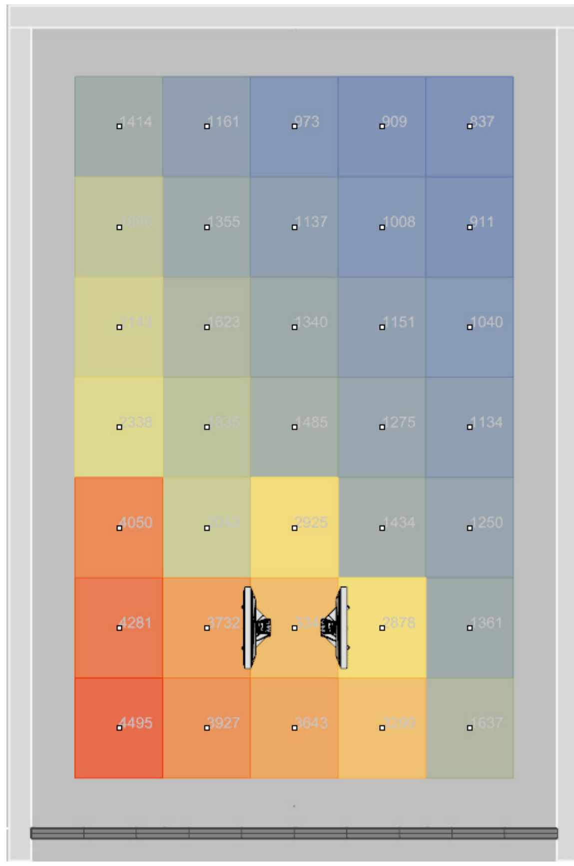

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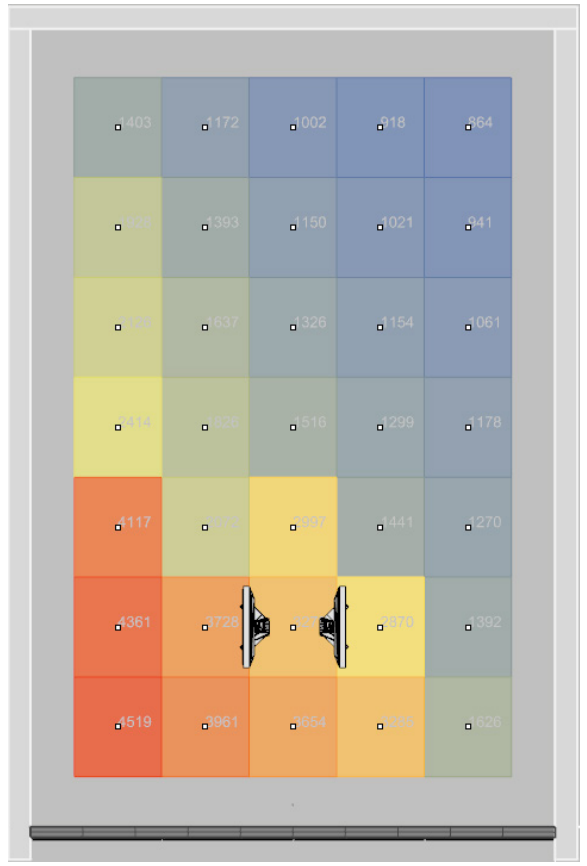

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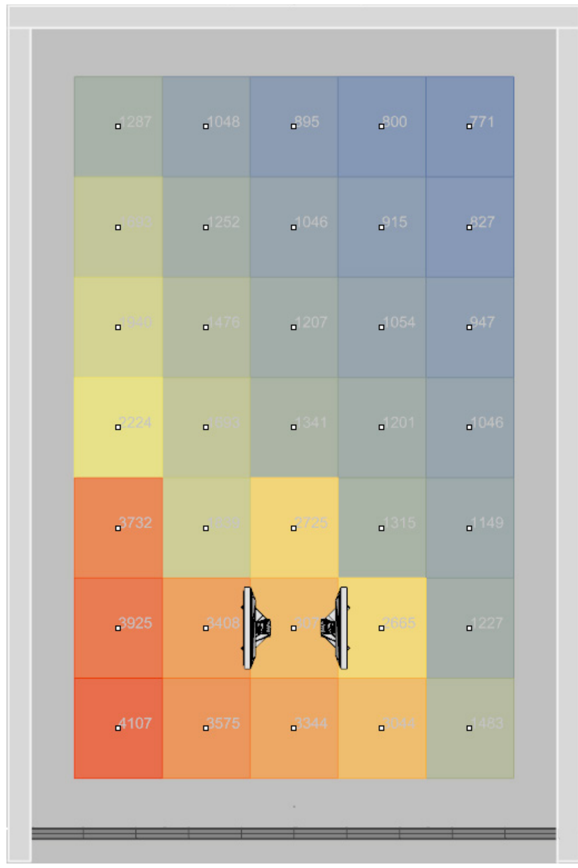

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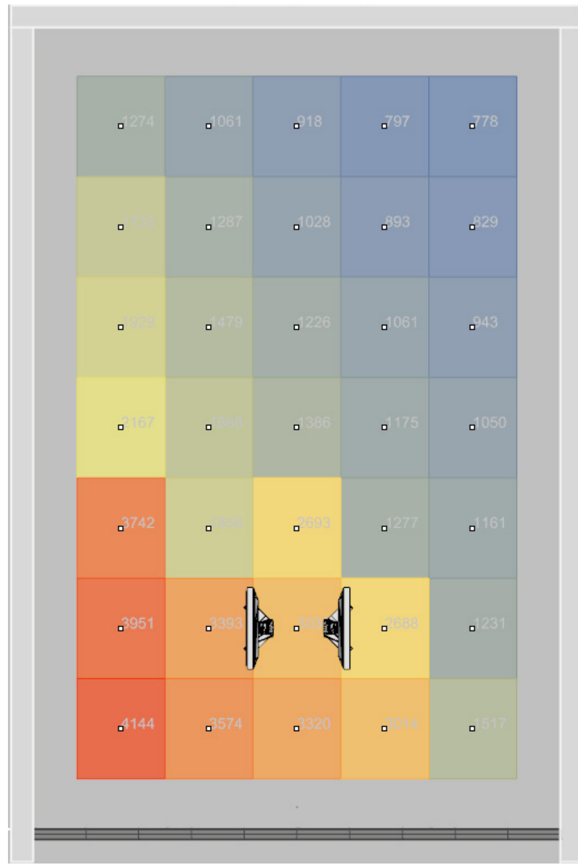

23rd December 13:00

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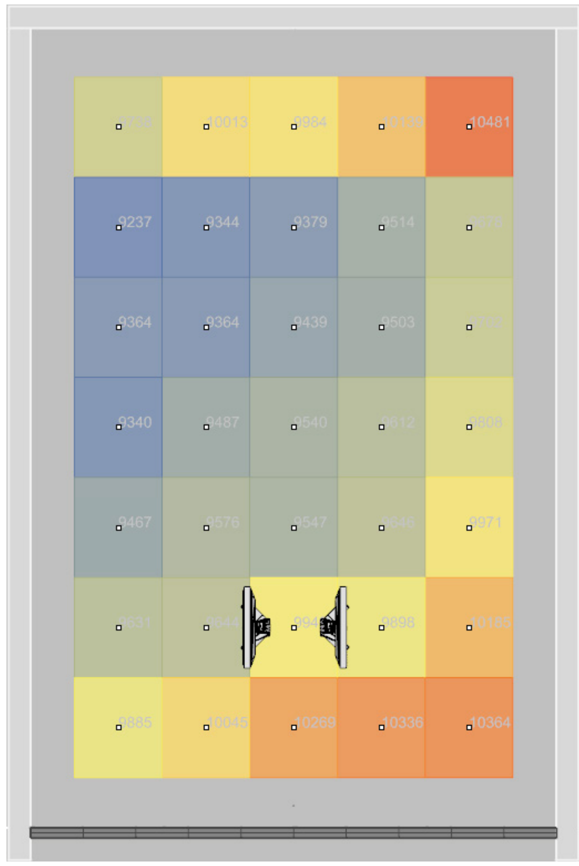

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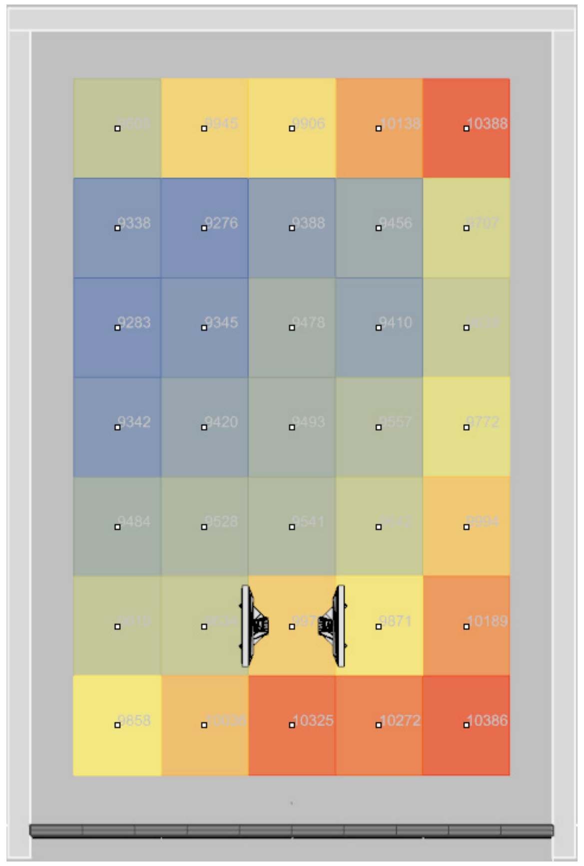

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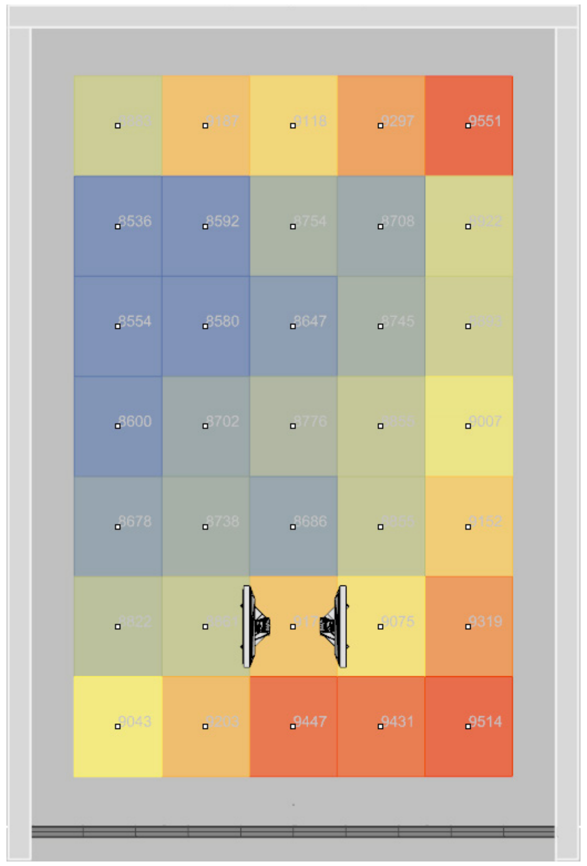

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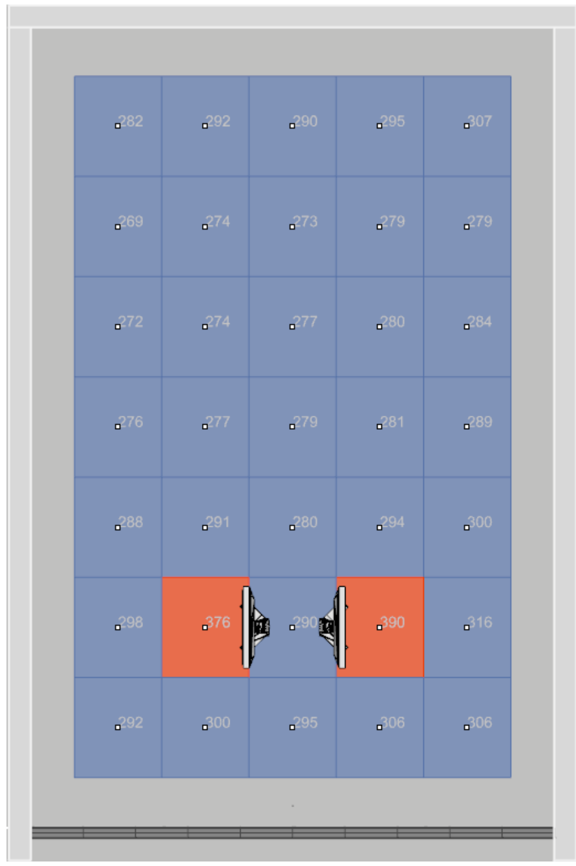

23rd December 16:00

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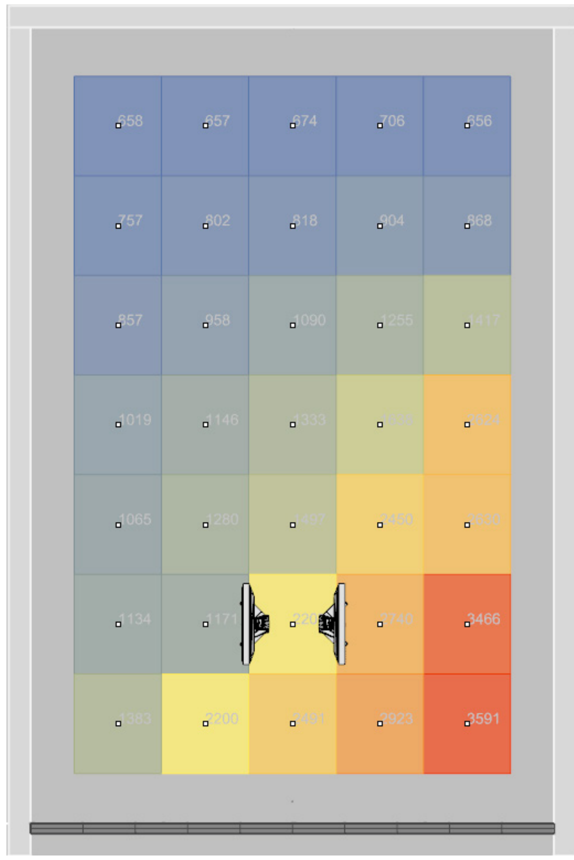

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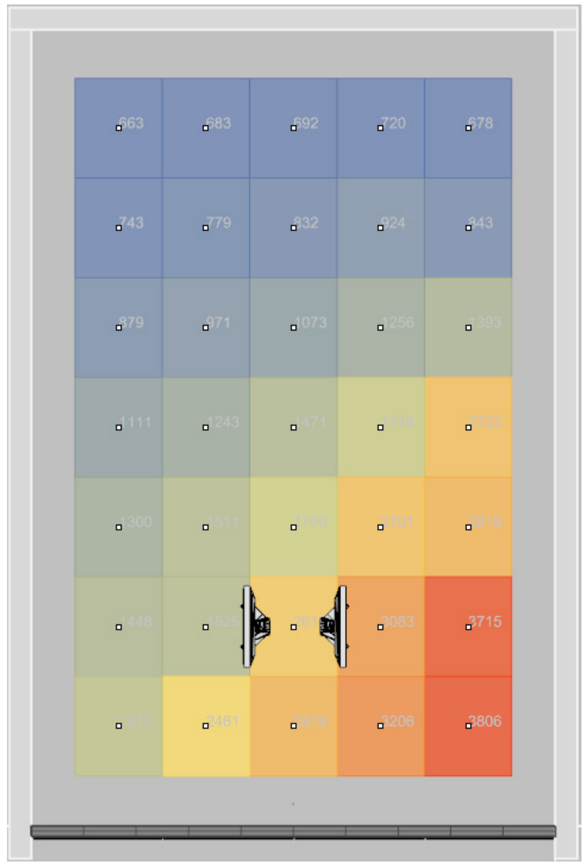

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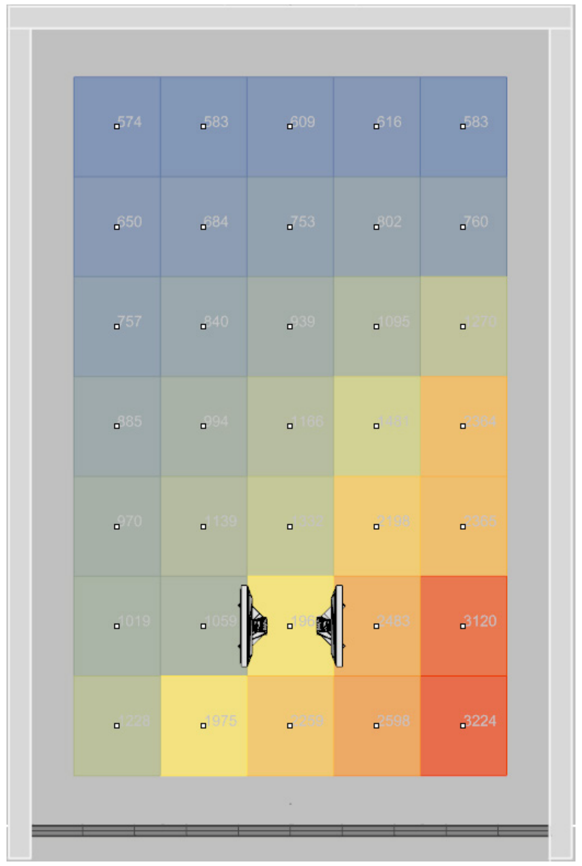

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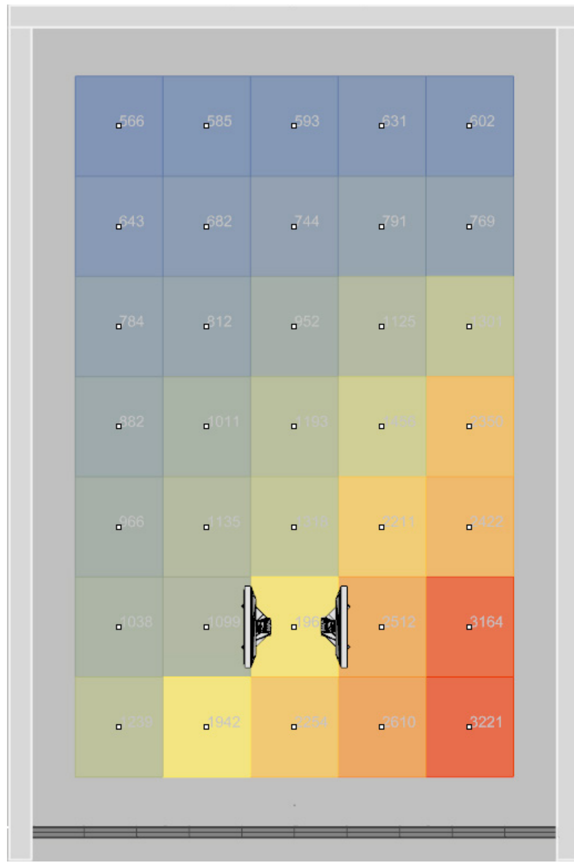
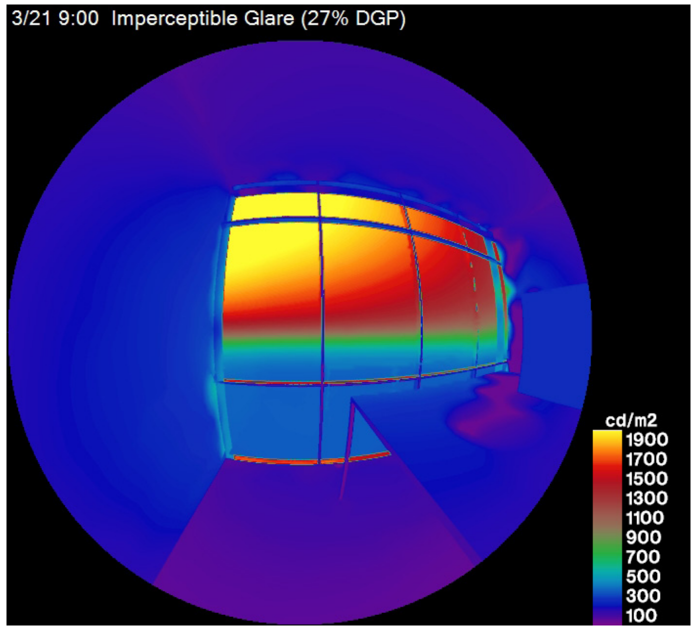


21st March 9:00, User 1, View to the window

Reference project 1



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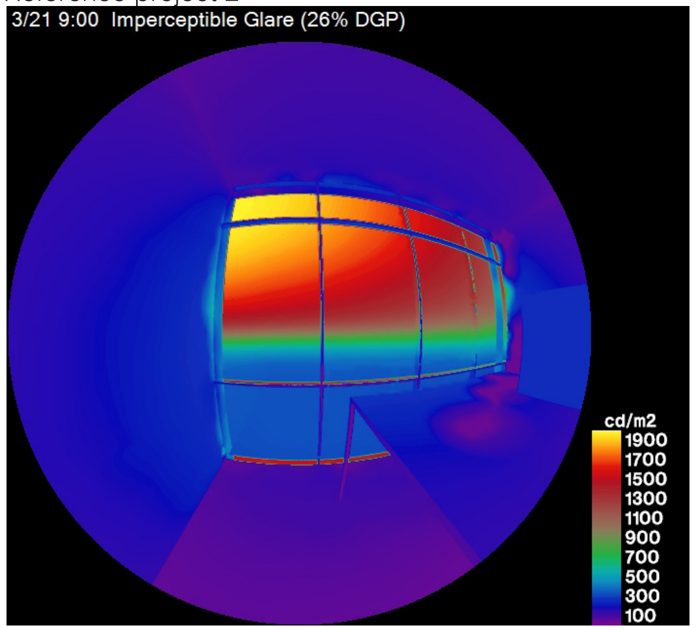

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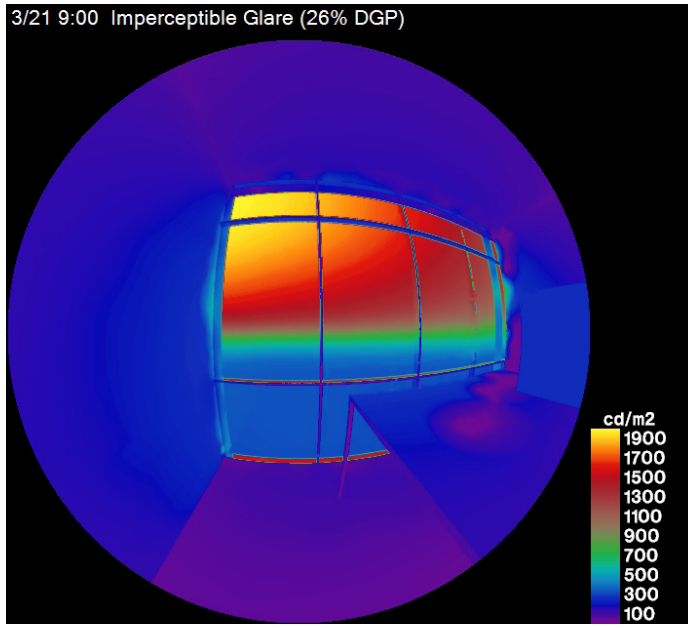

21st March 9:00, User 1, View to the computer screen

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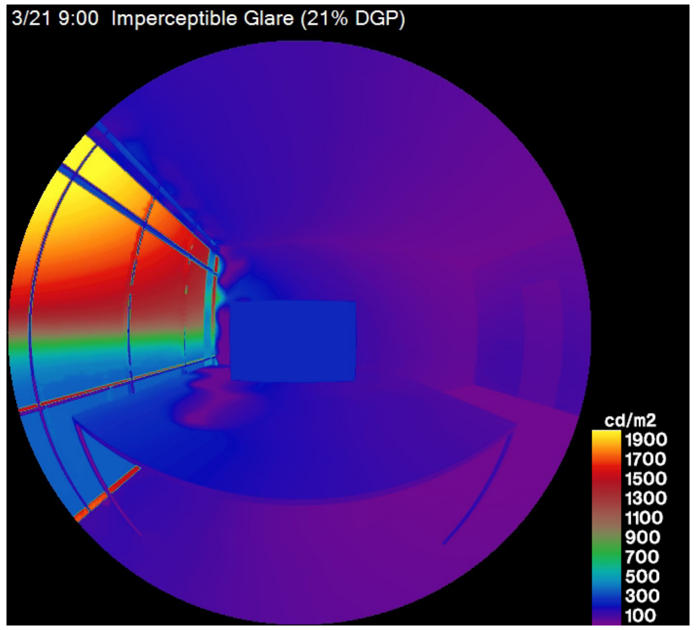

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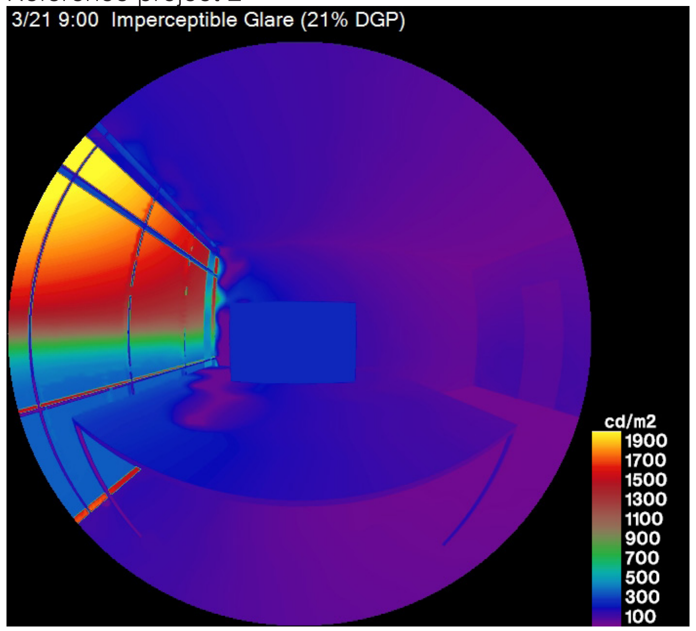

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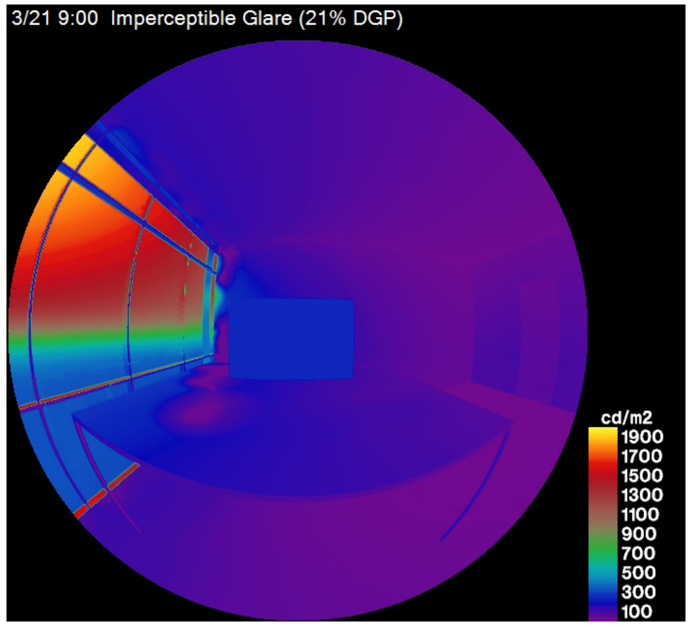

21st March 9:00, User 2, View to the window

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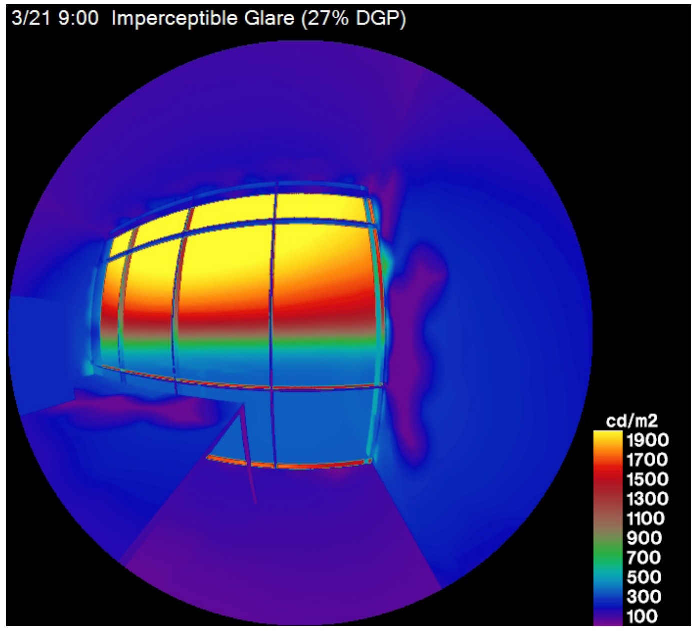

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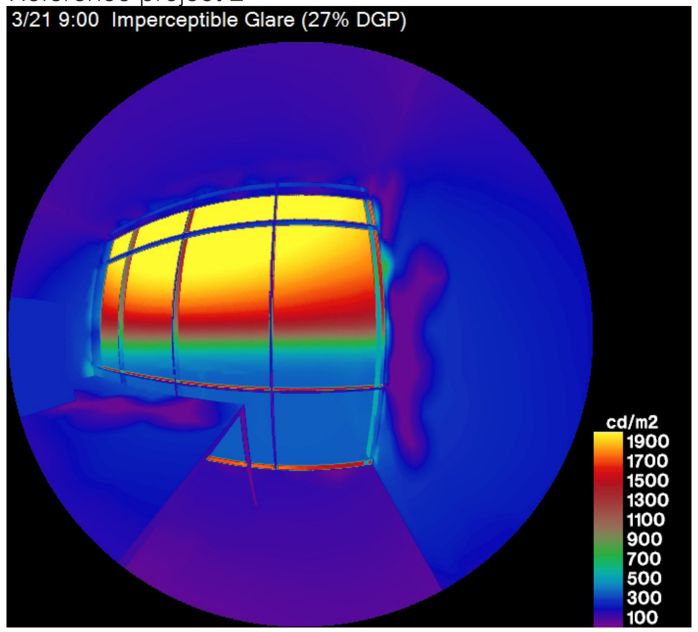

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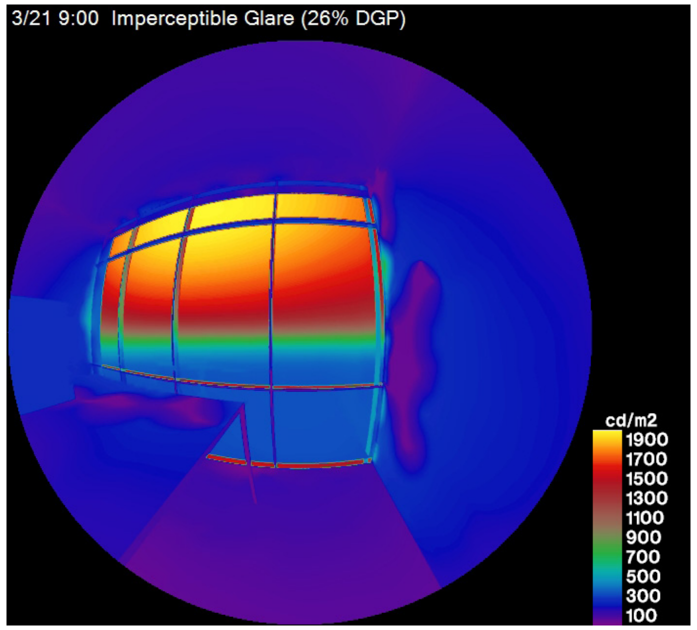

21st March 9:00, User 2, View to the computer screen

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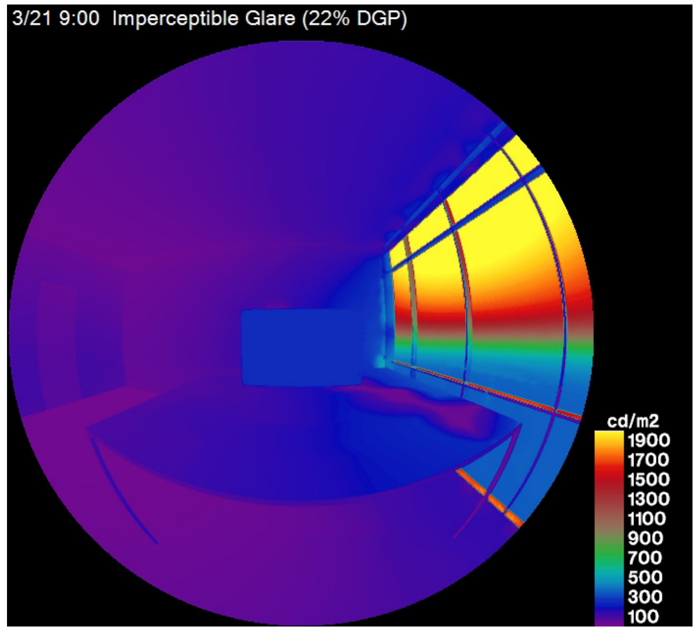

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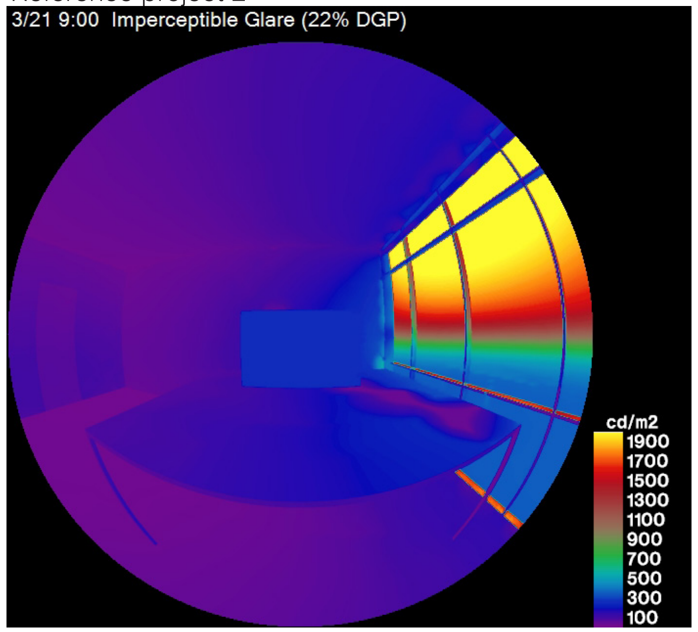

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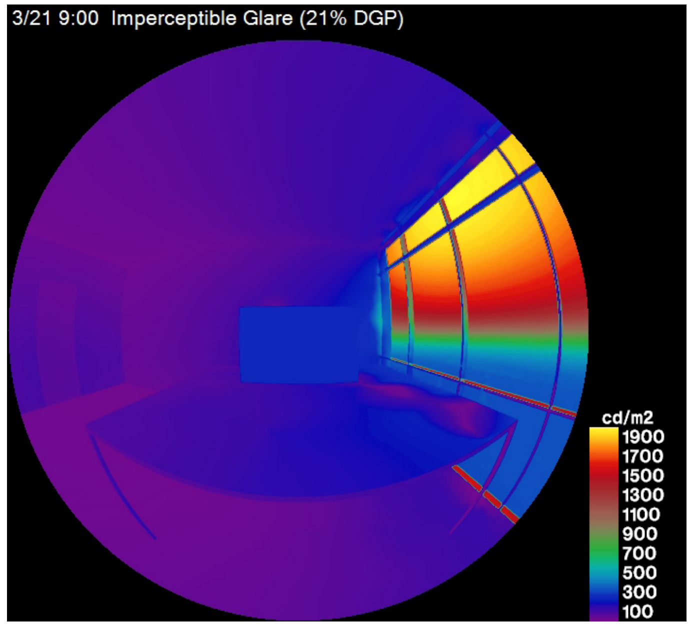

21st March 10:00, User 1, View to the window

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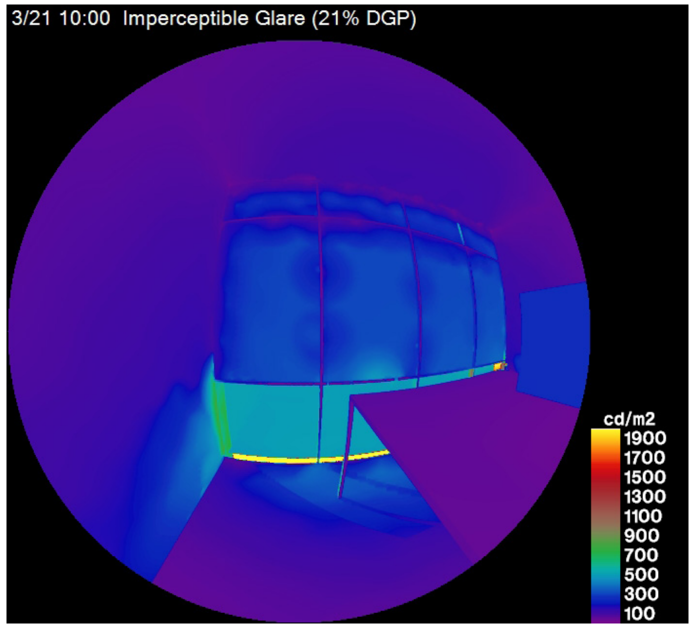

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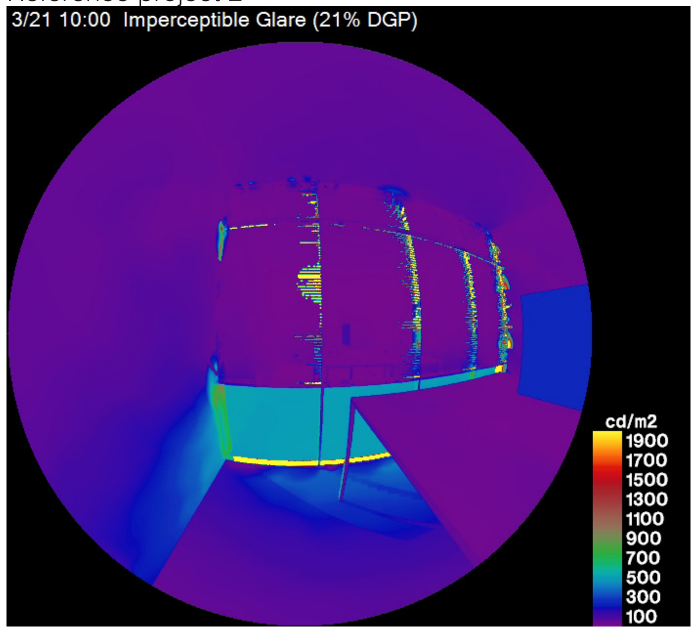

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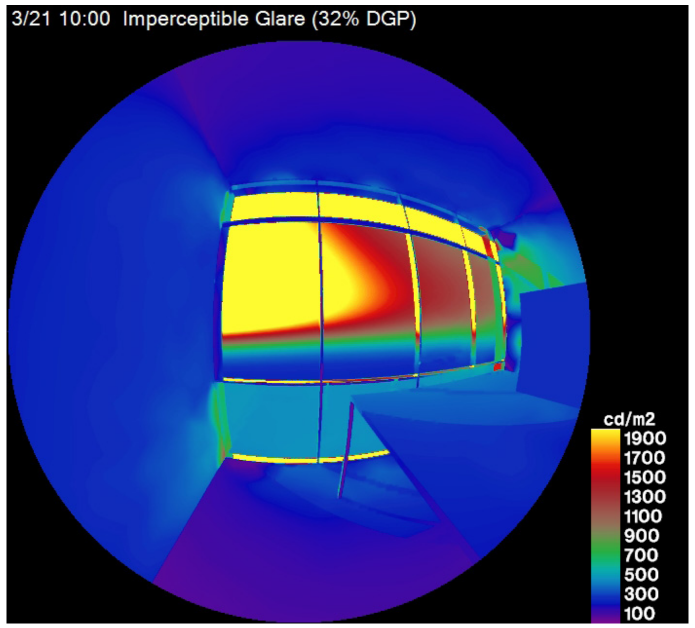

21st March 10:00, User 1, View to the computer screen

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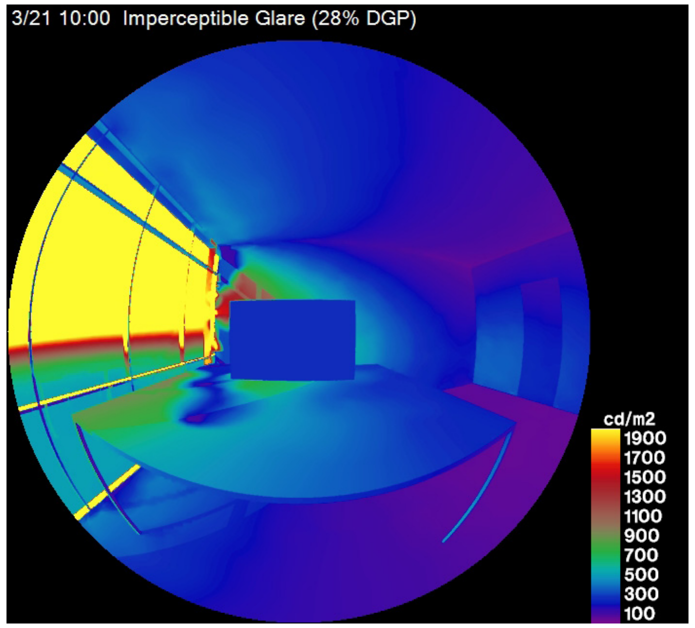

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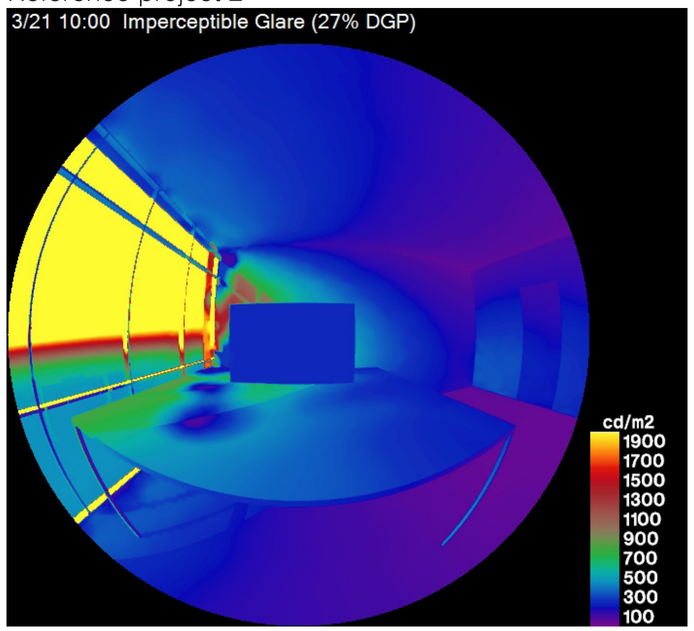

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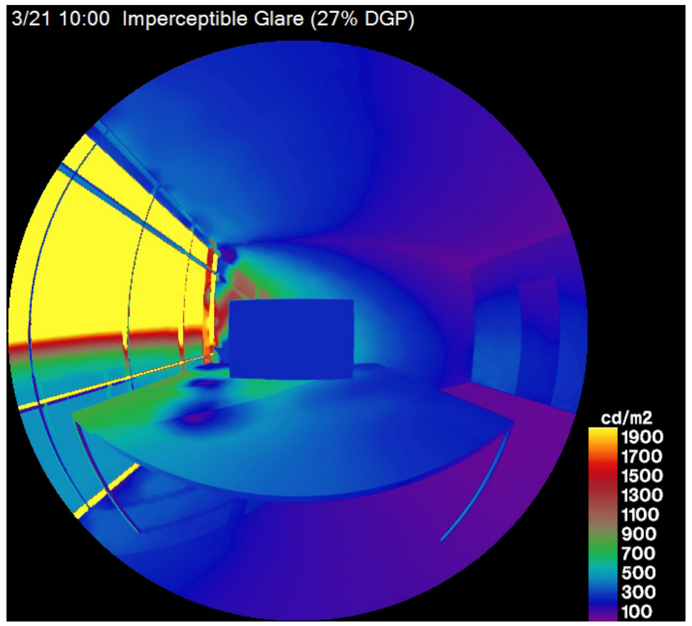

21st March 10:00, User 2, View to the window

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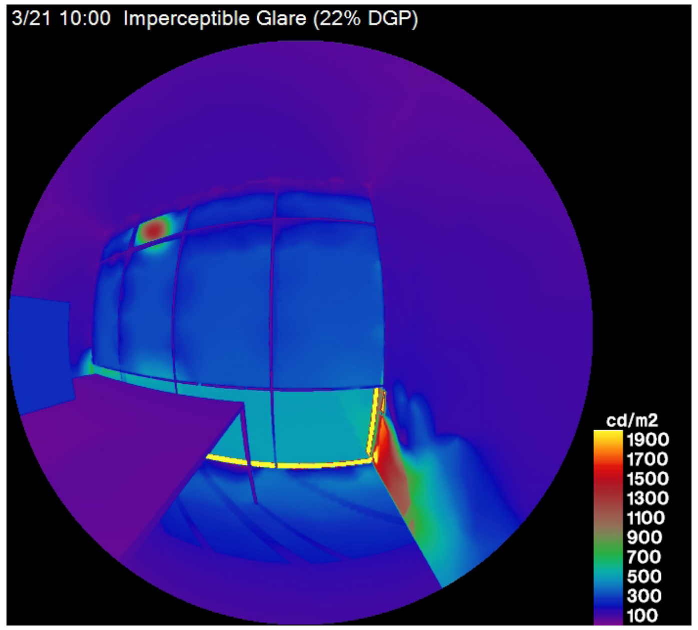

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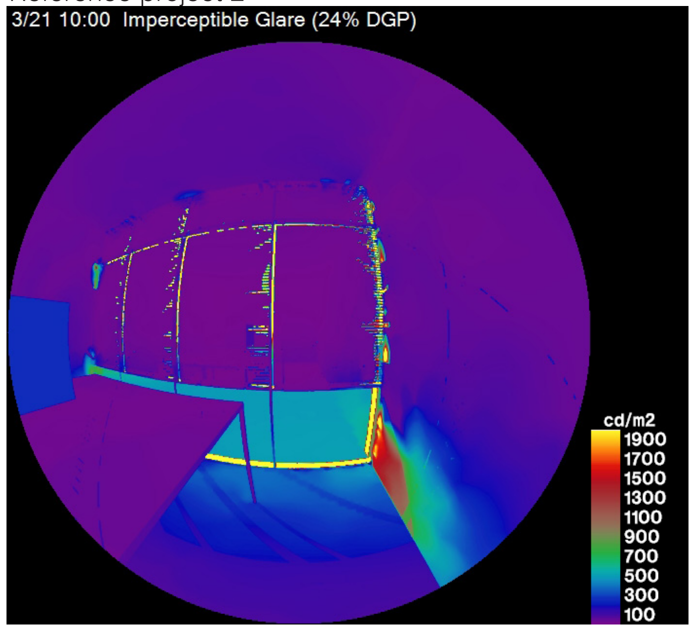

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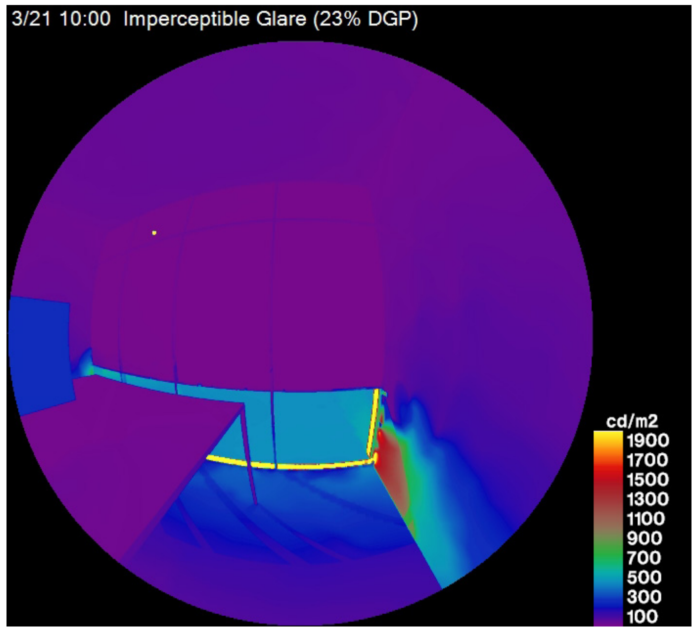

21st March 10:00, User 2, View to the computer screen

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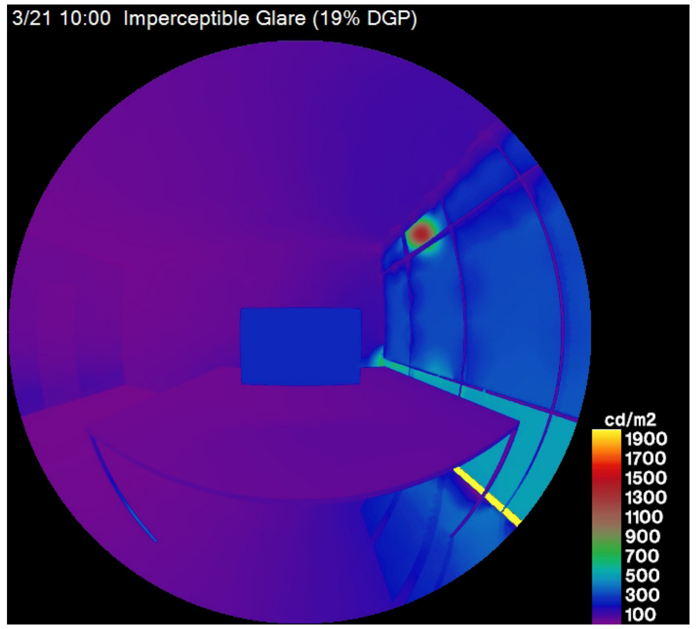

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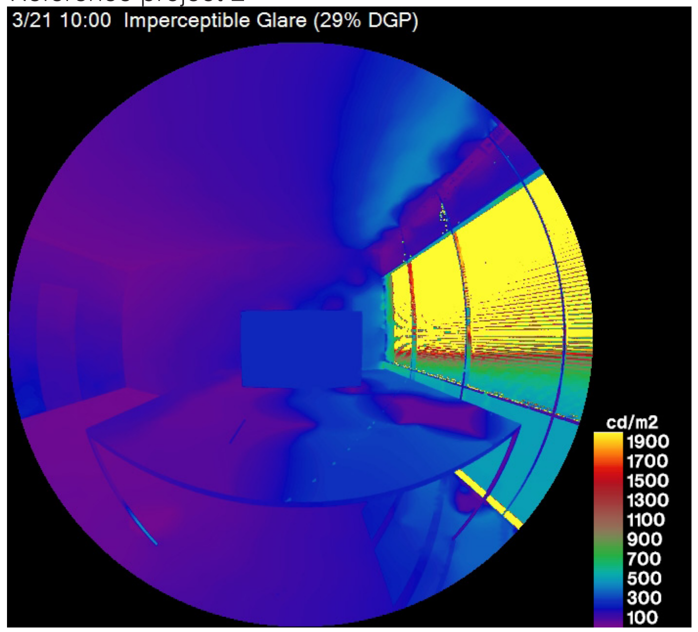

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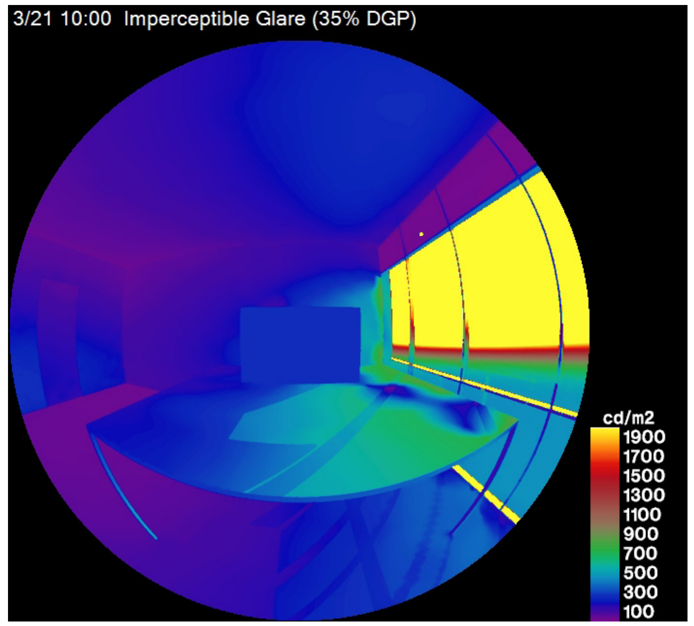
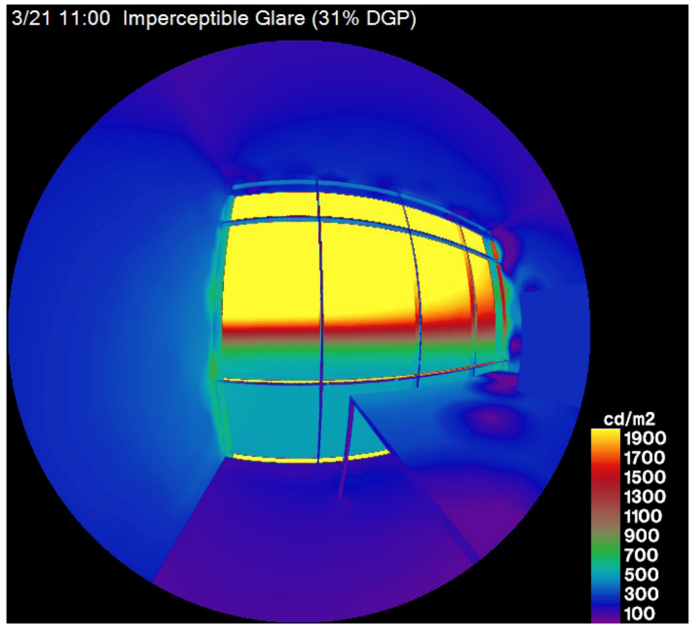


21st March 11:00, User 1, View to the window

Reference project 1



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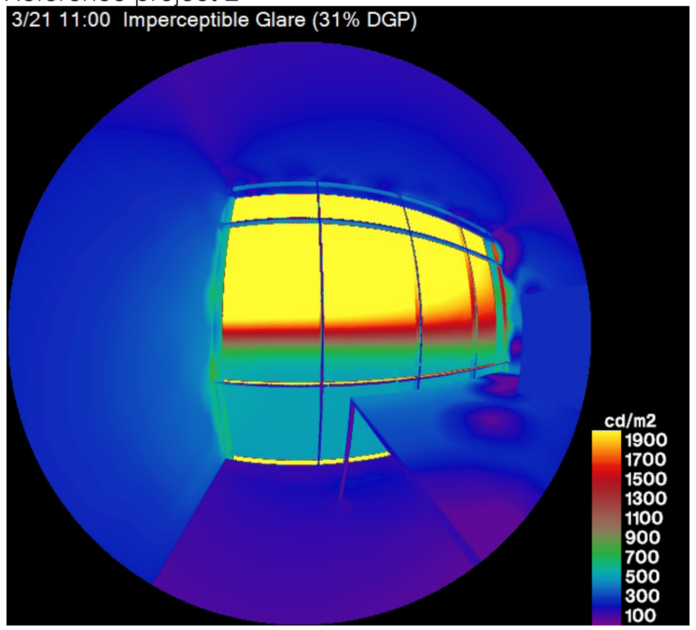

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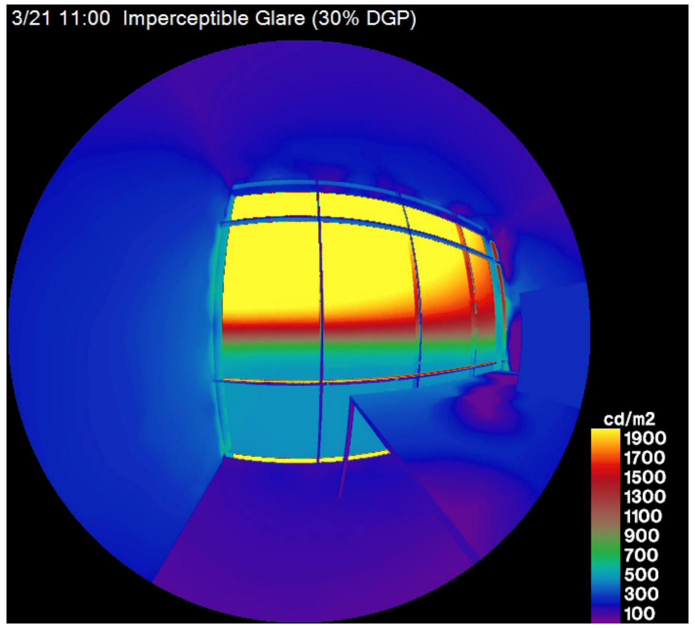
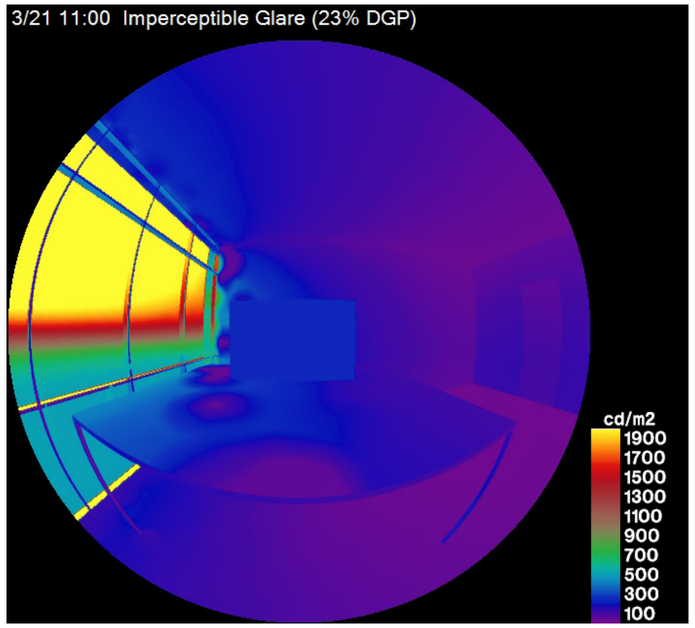


21st March 11:00, User 1, View to the computer screen

Reference project 1



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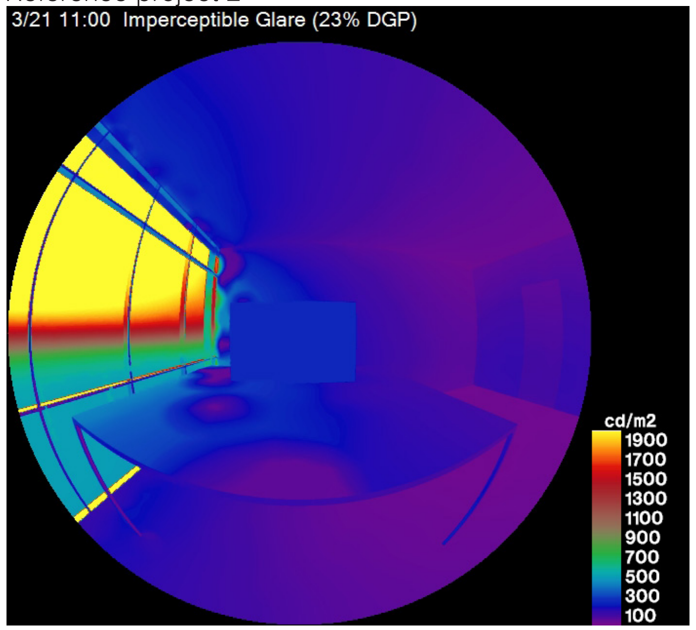

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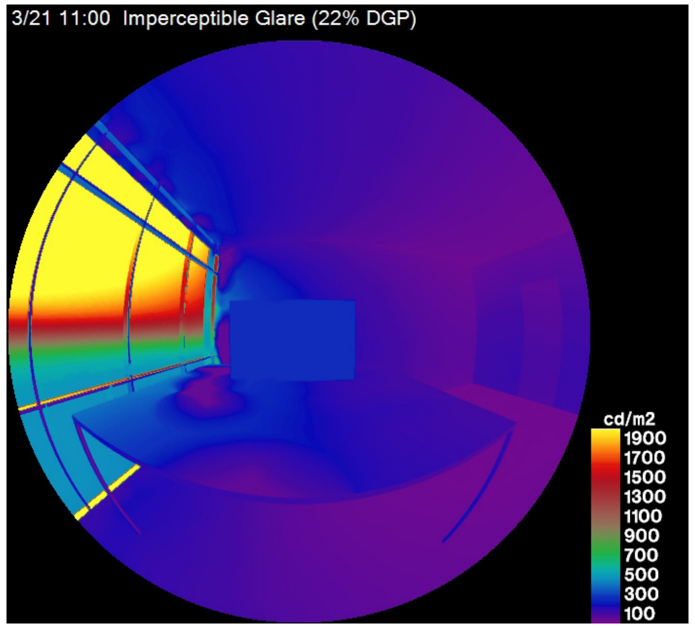

21st March 11:00, User 2, View to the window

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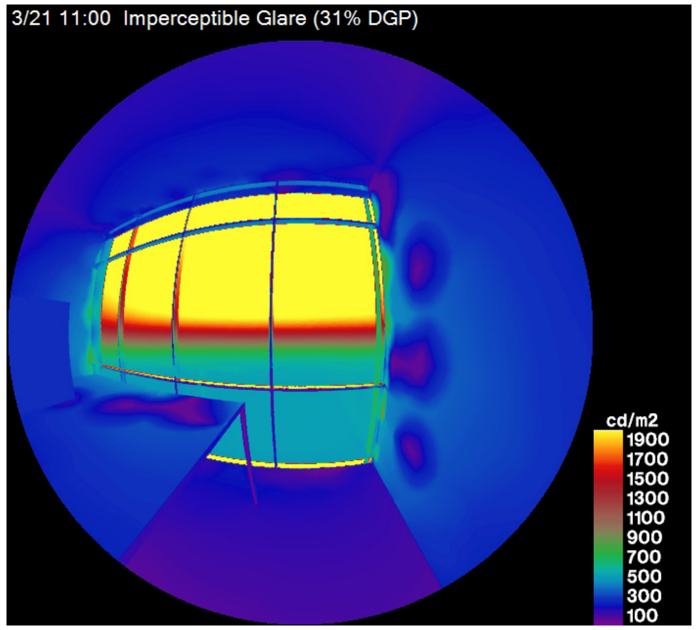

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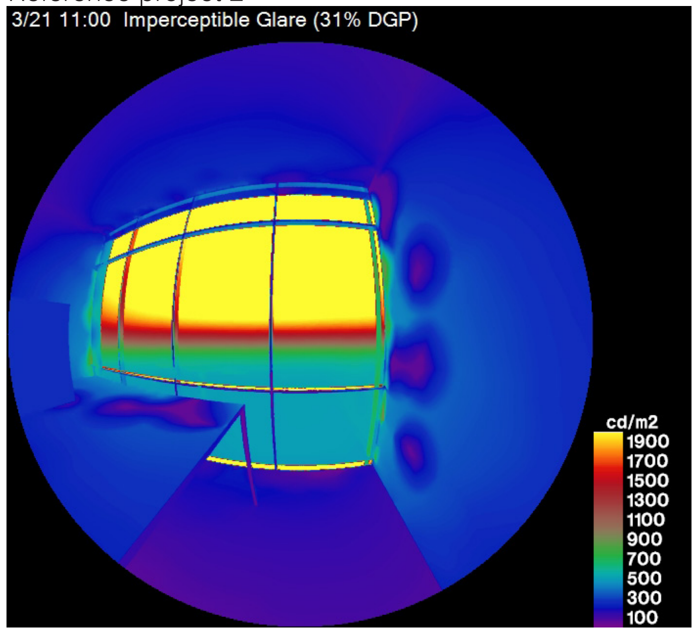

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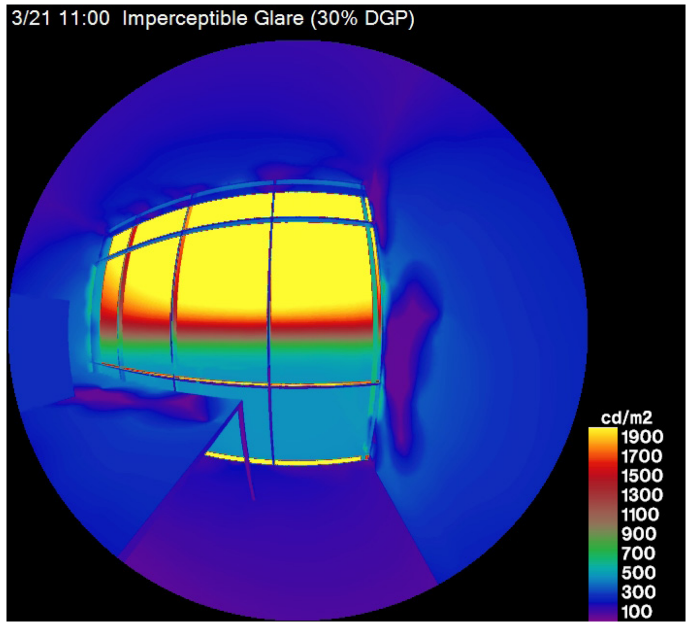
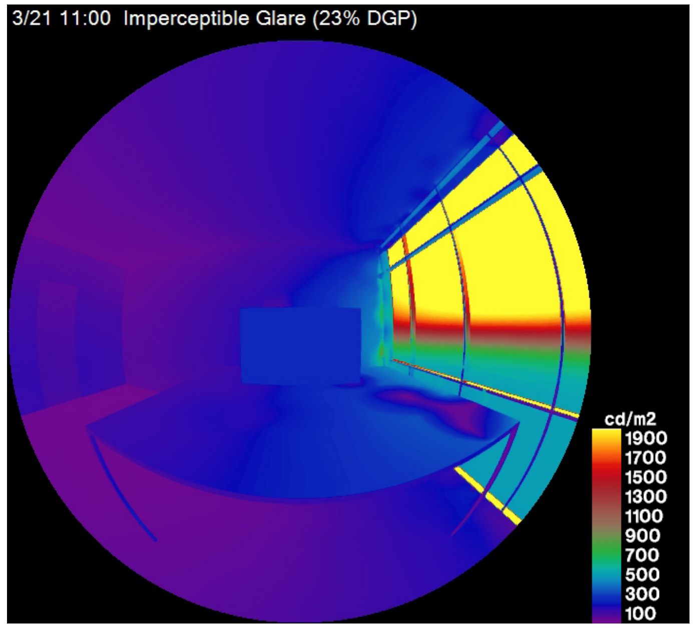


21st March 11:00, User 2, View to the computer screen

Reference project 1



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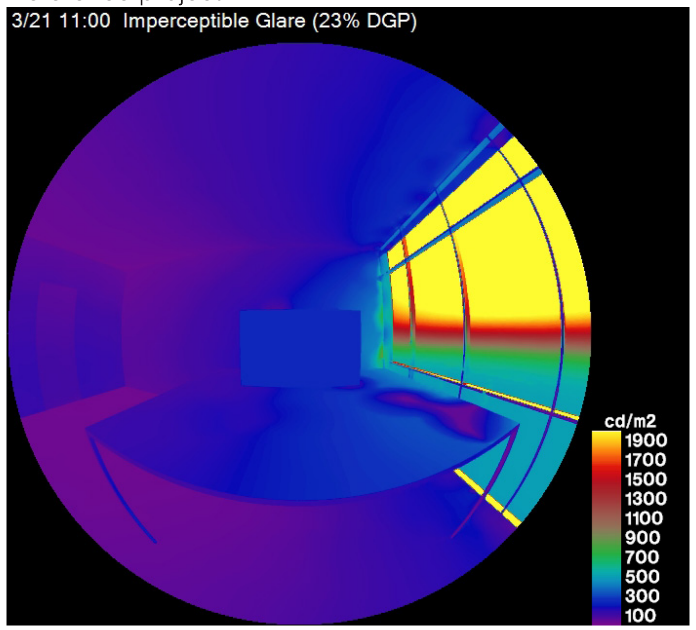

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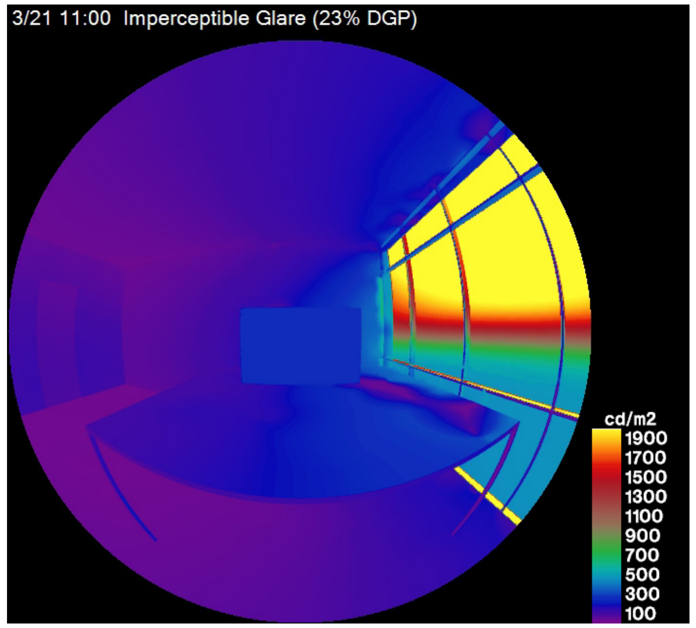

21st March 12:00, User 1, View to the window

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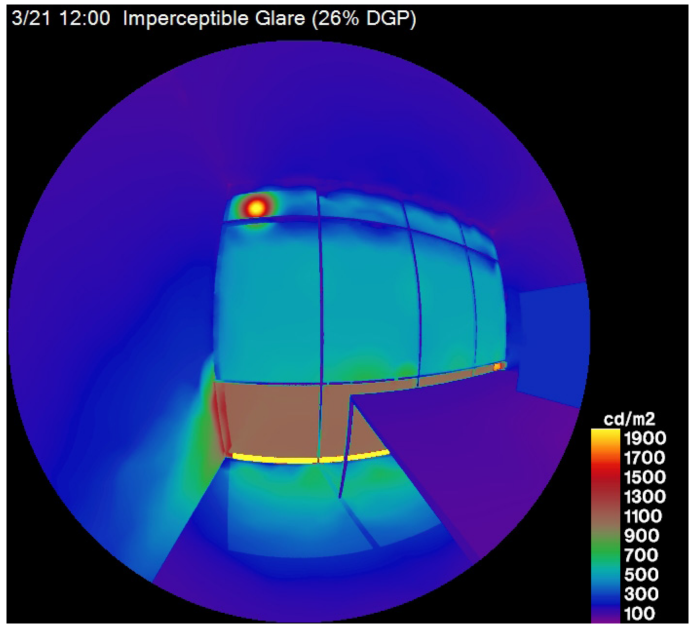

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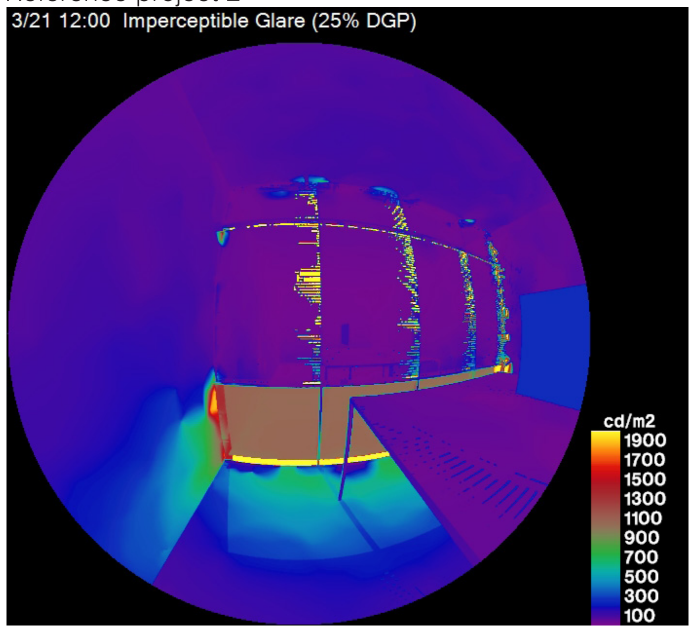

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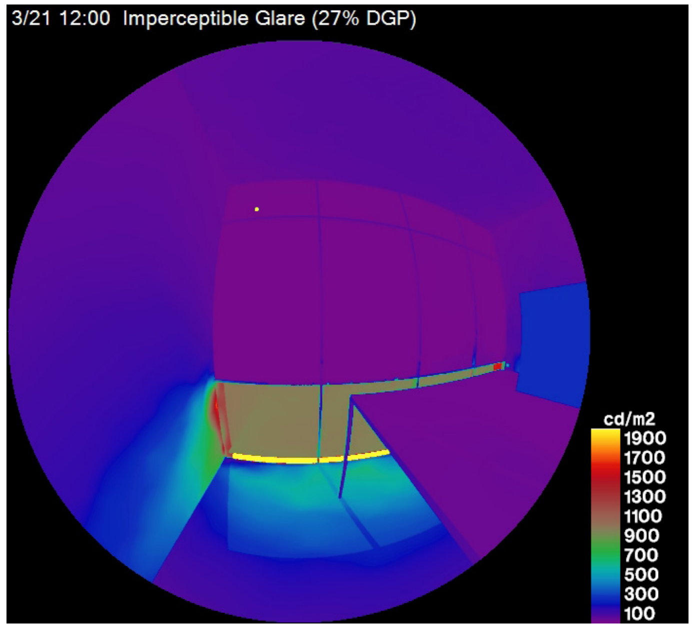

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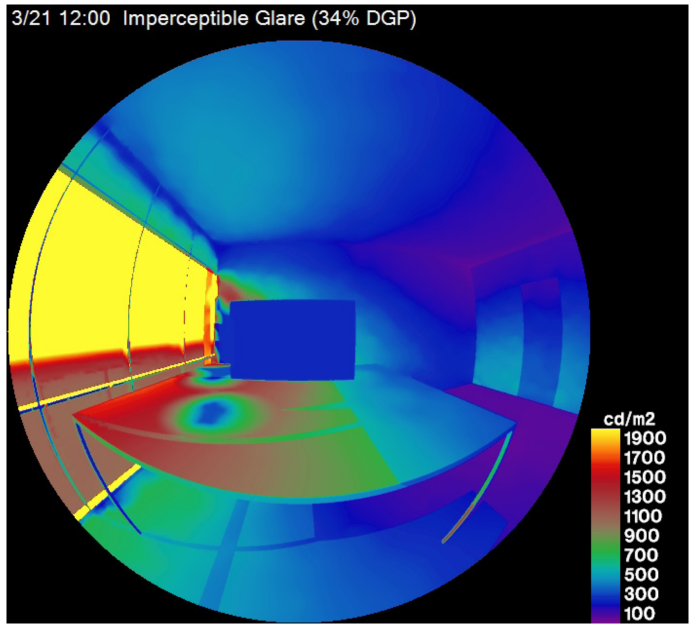

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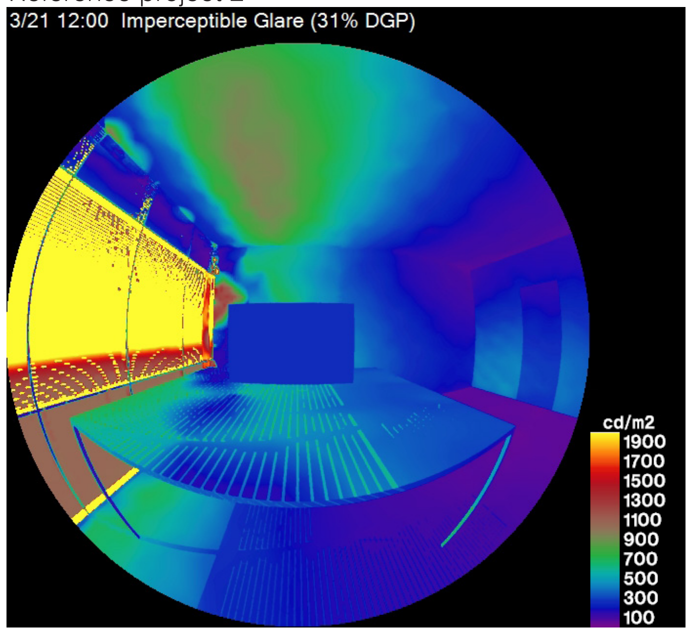

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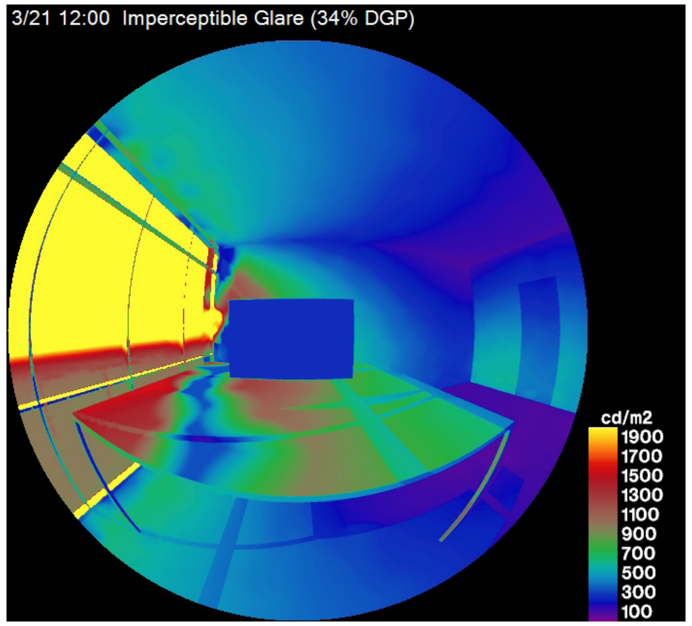

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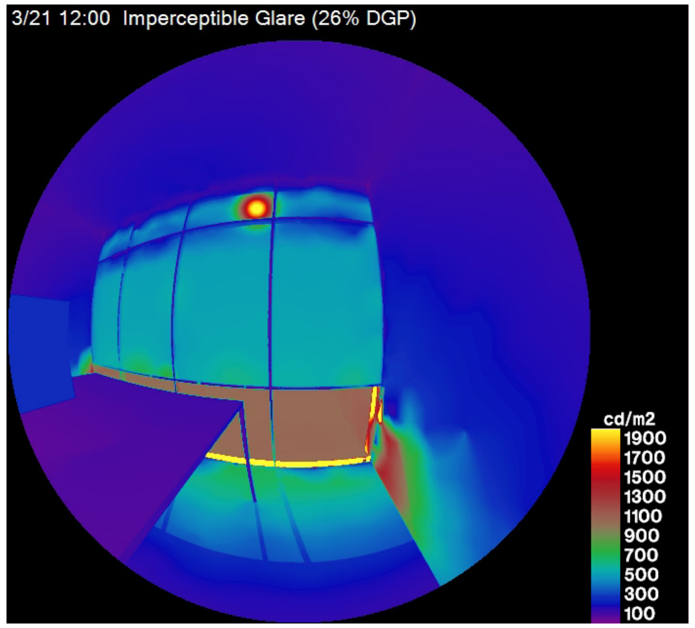

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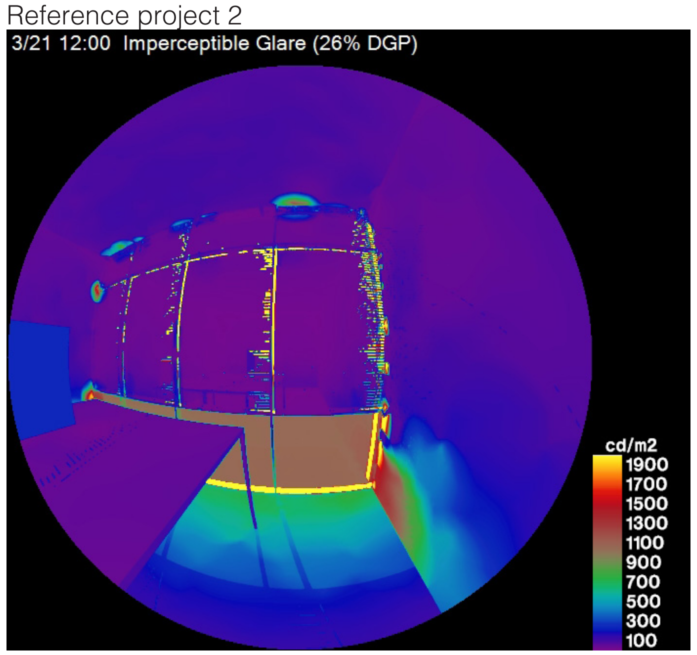

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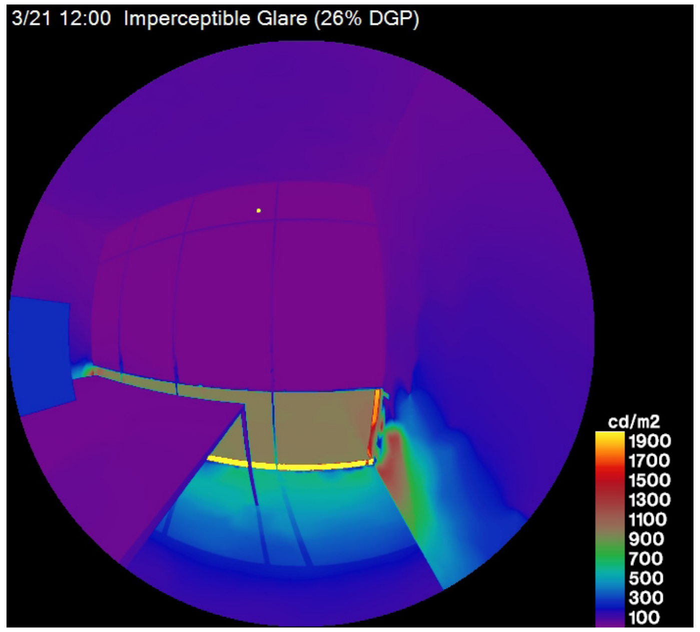

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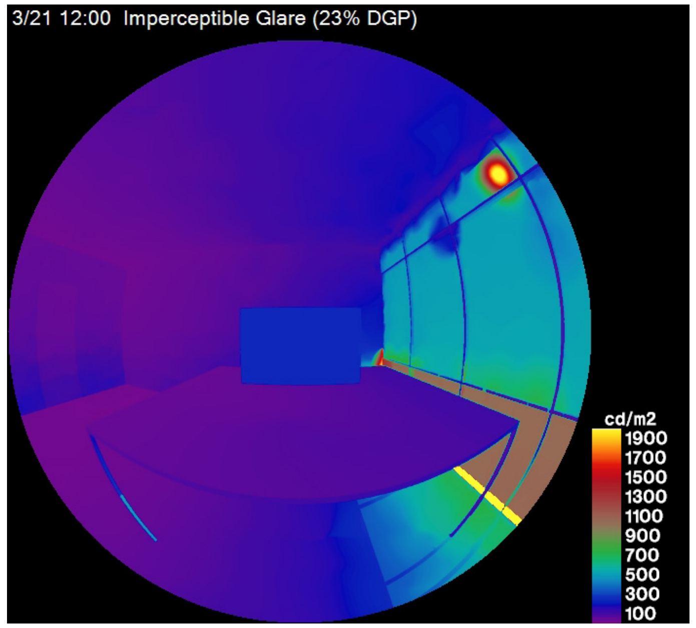

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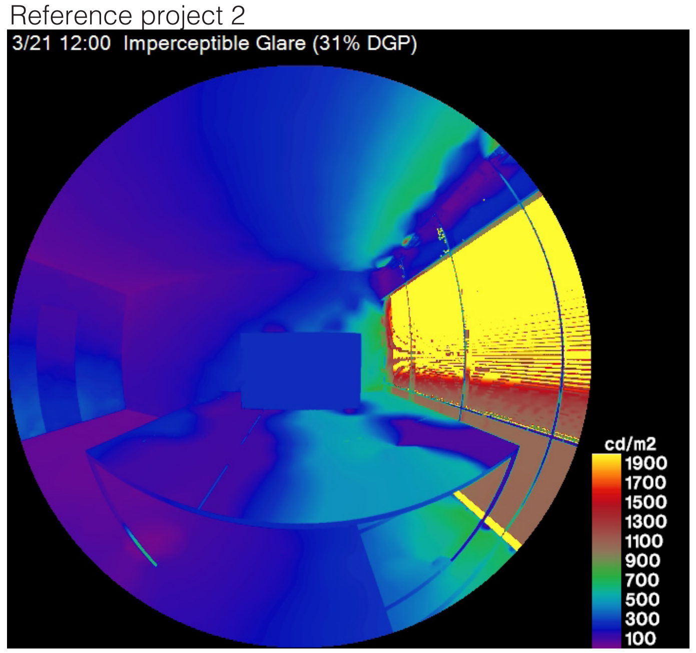

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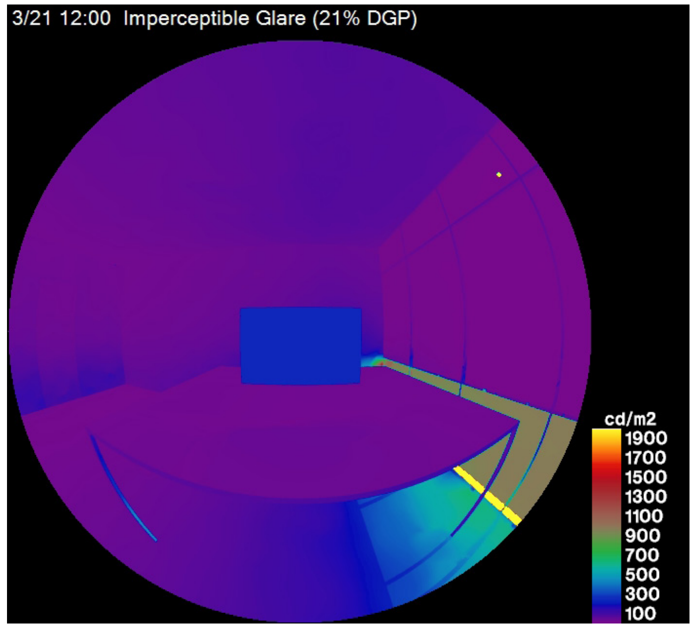

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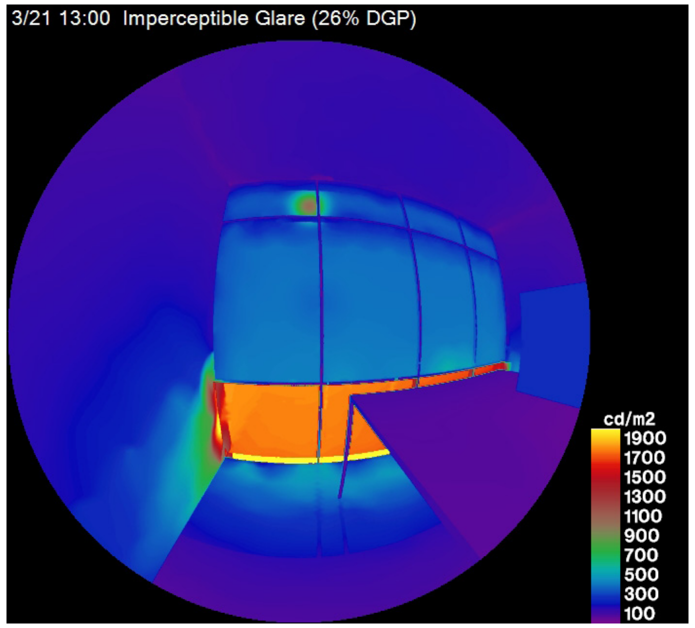

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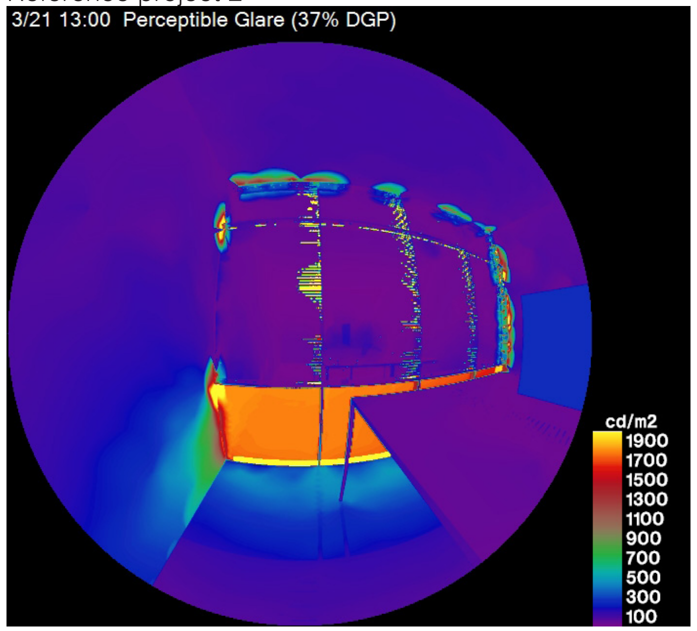

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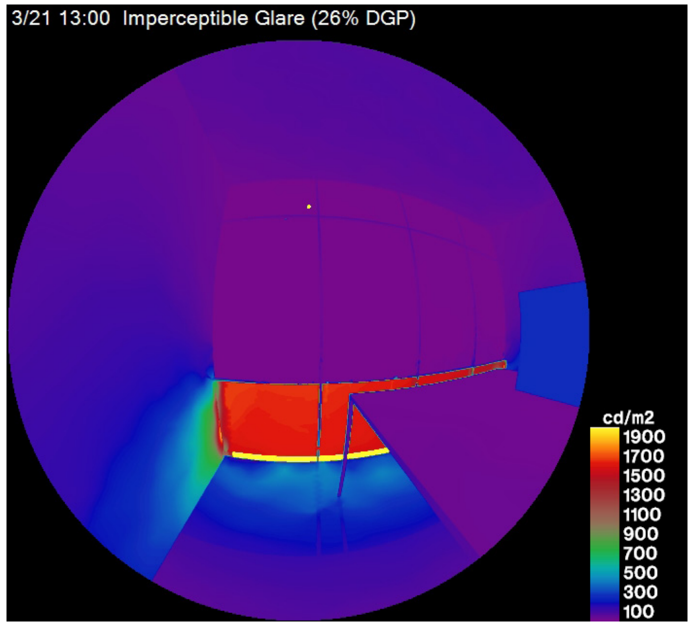

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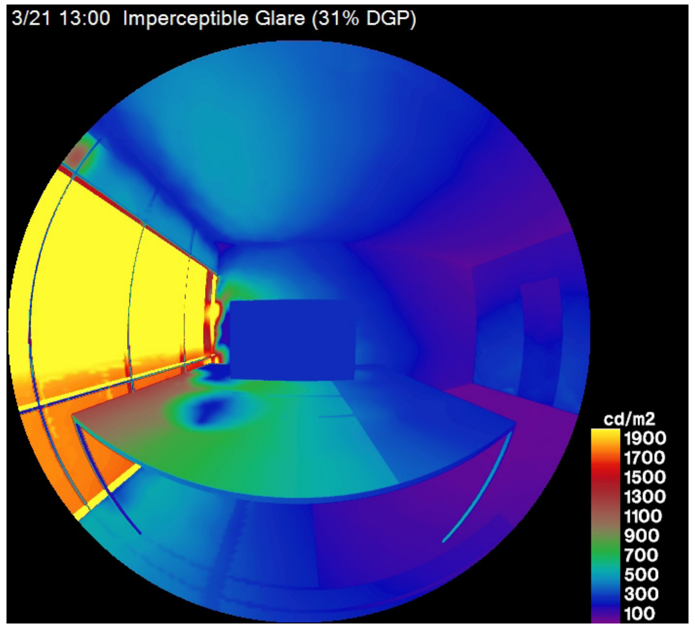

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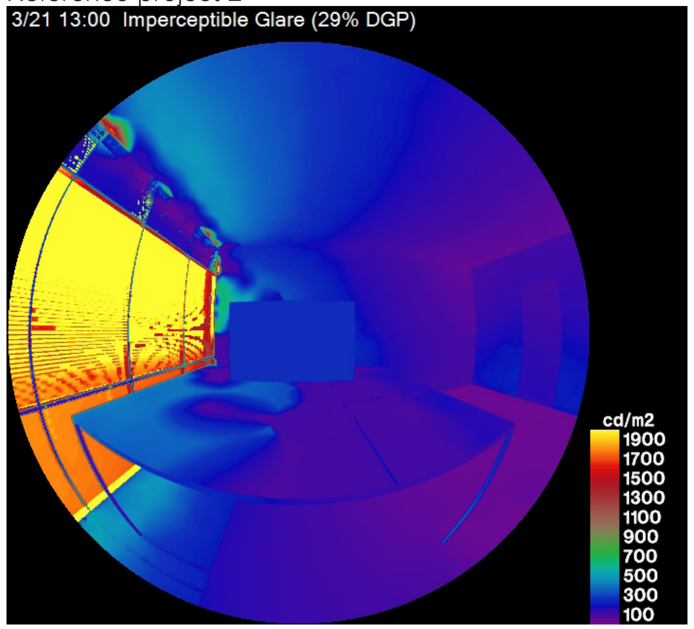

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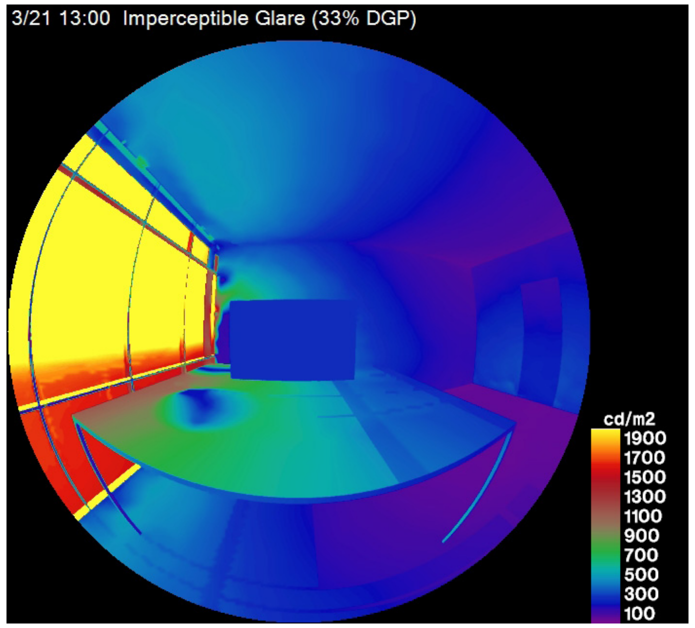

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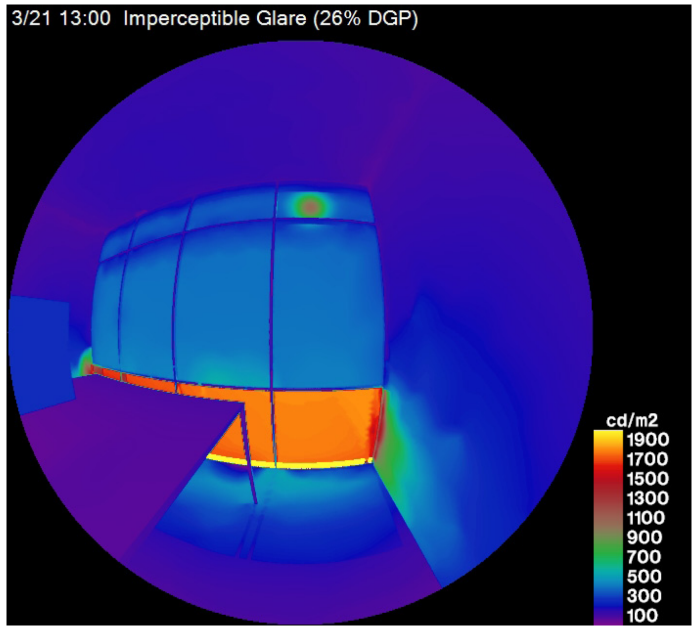

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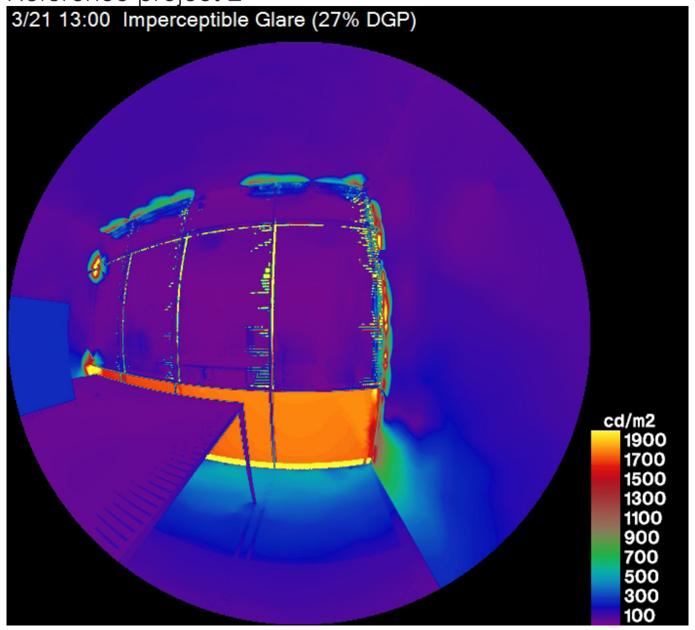

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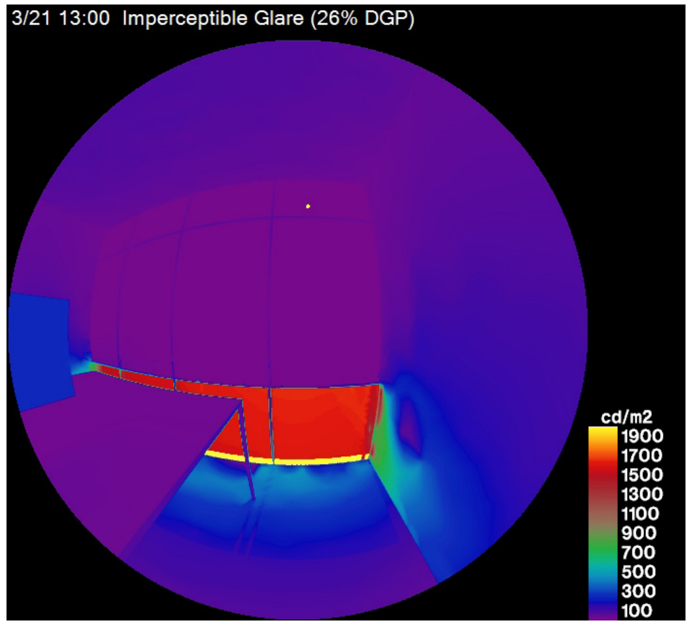

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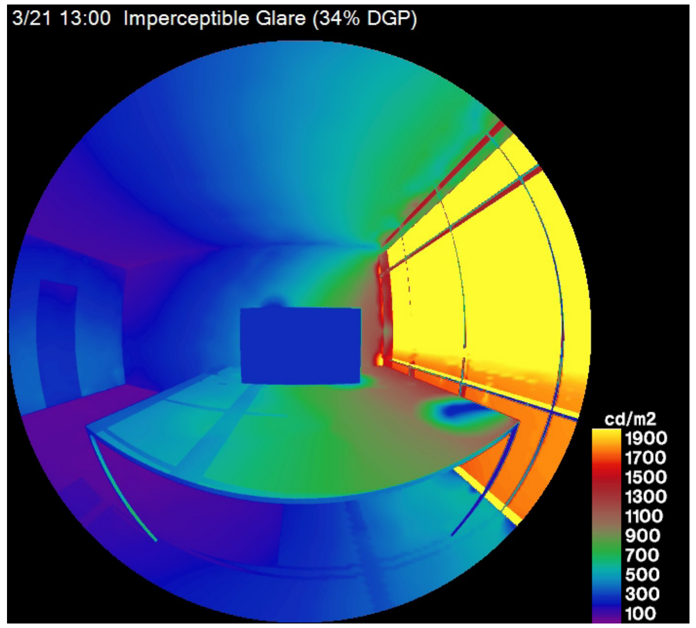

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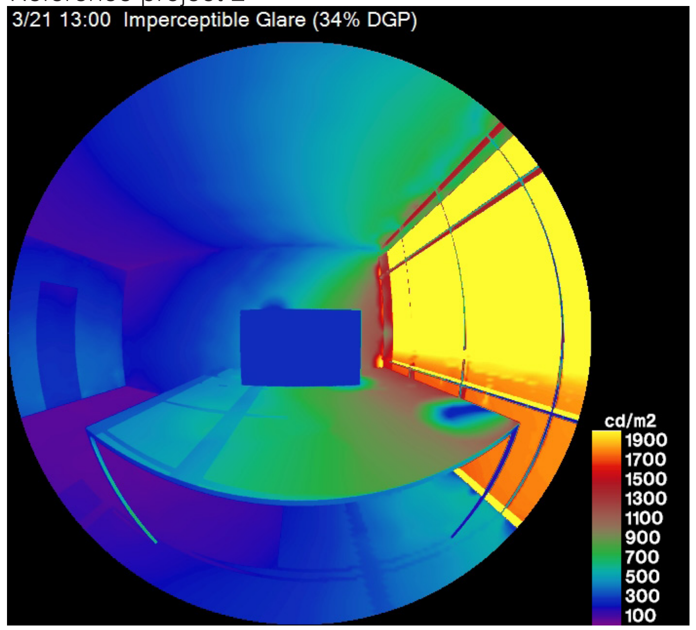

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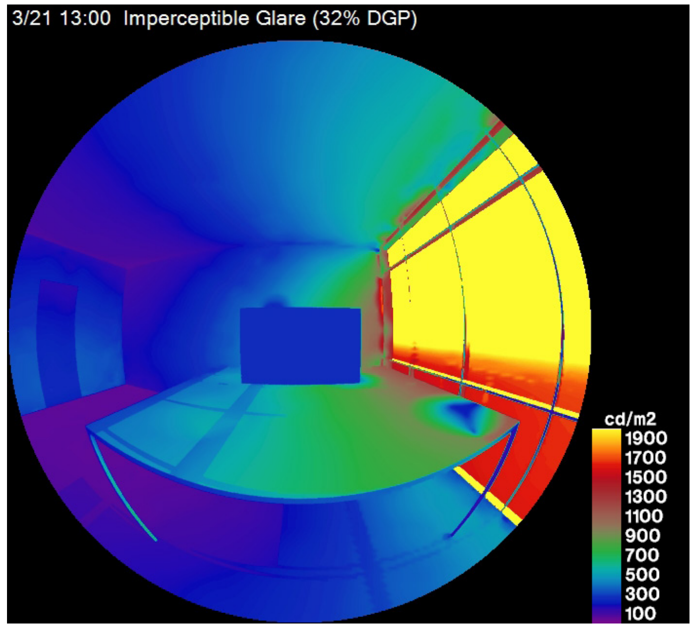

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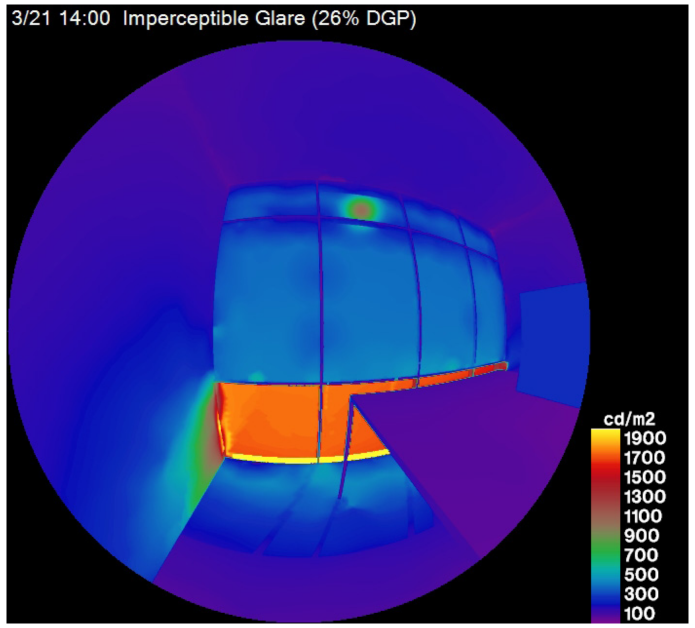

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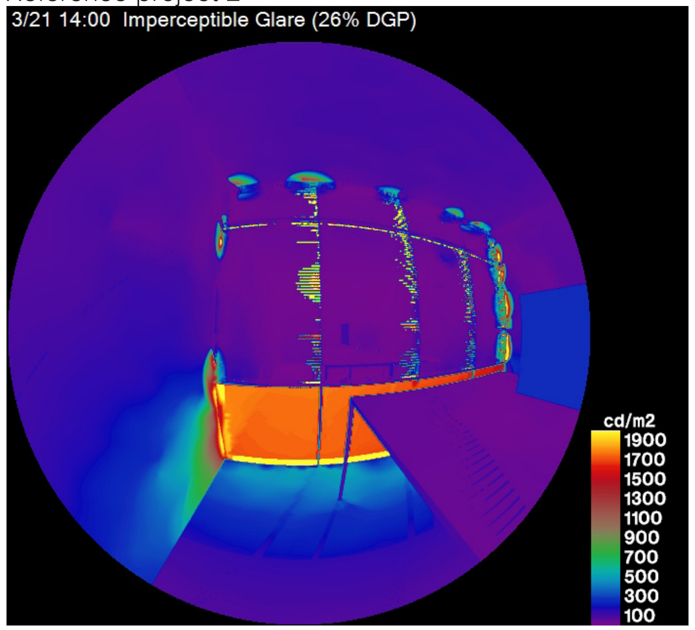

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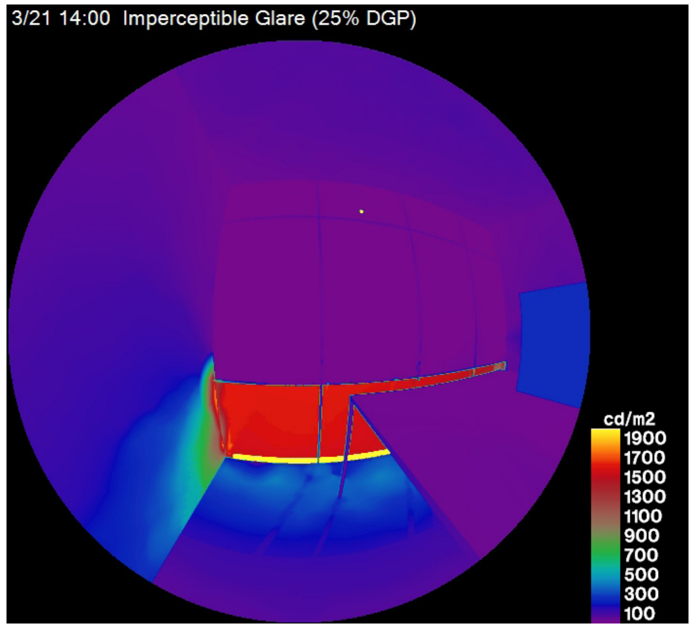

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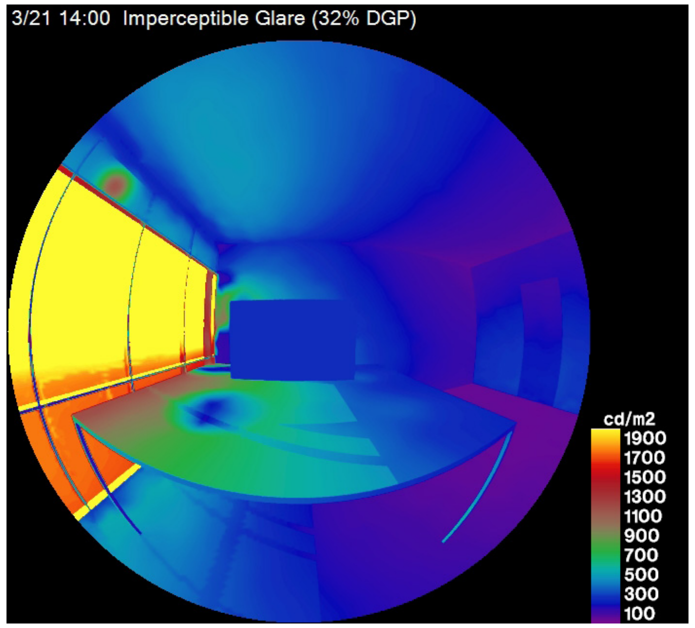

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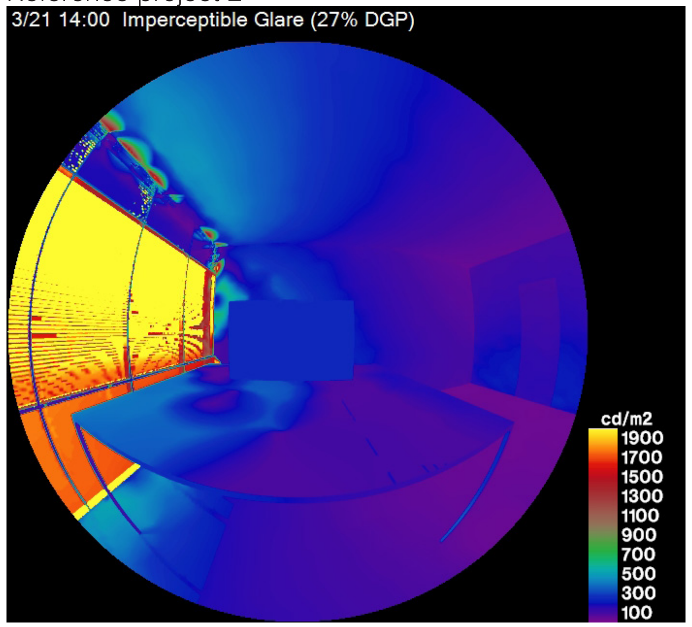

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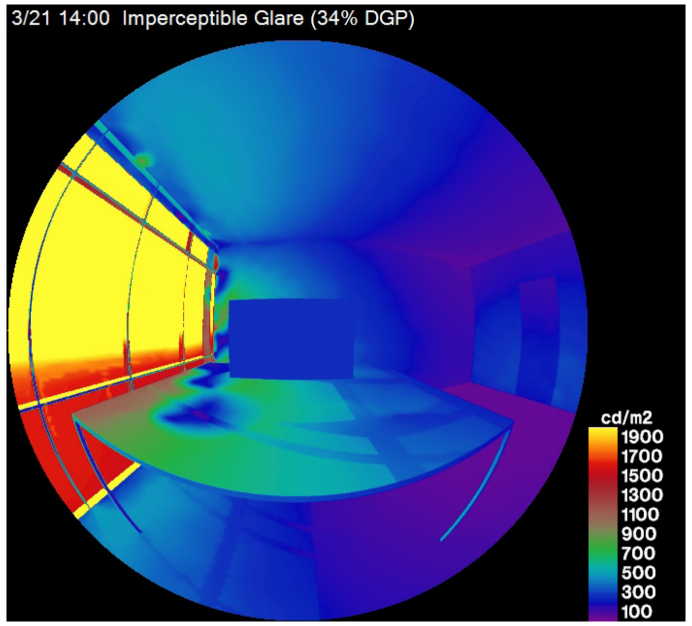

21st March 14:00, User 2, View to the window

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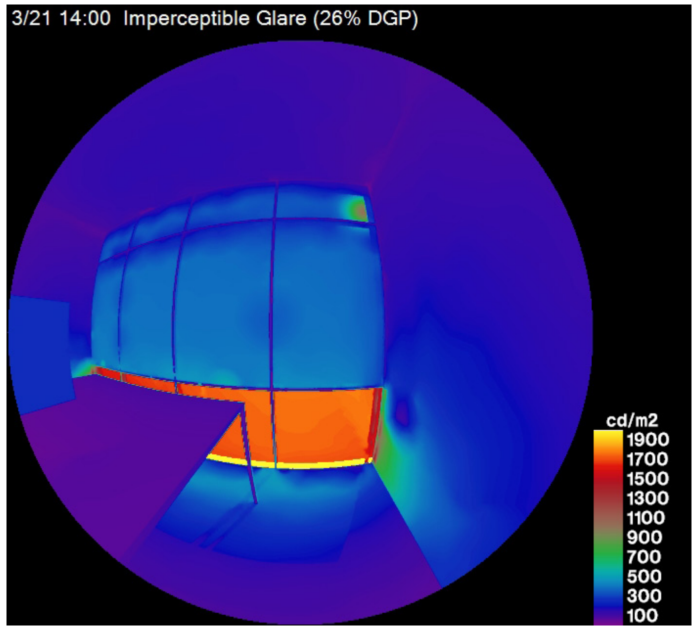

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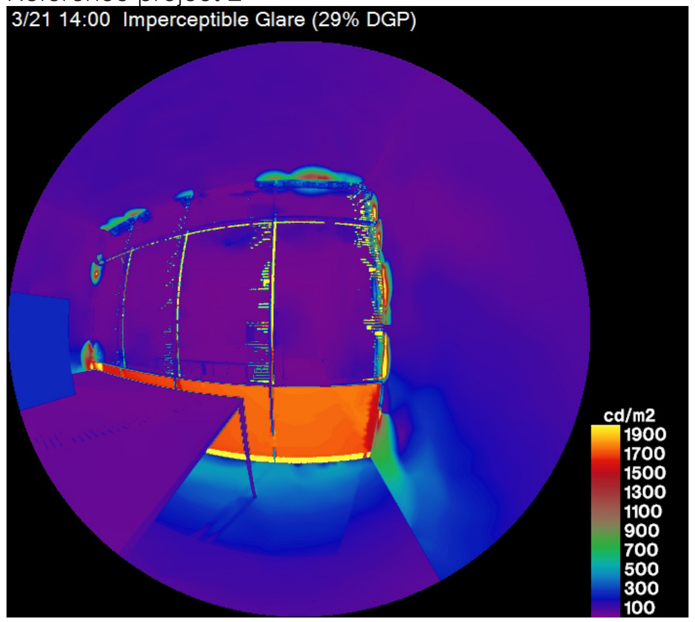

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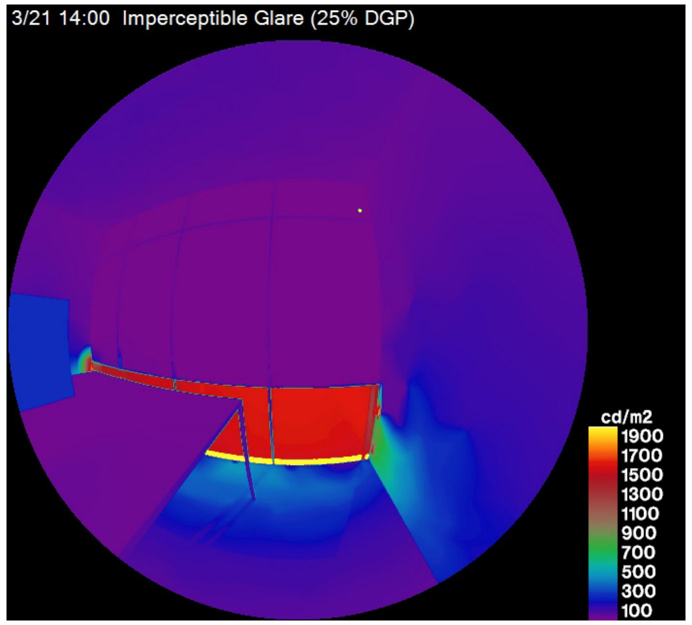

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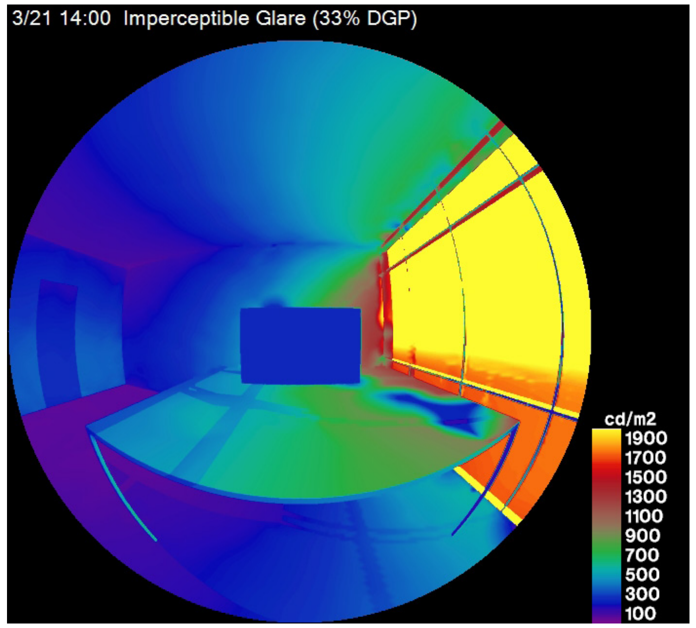

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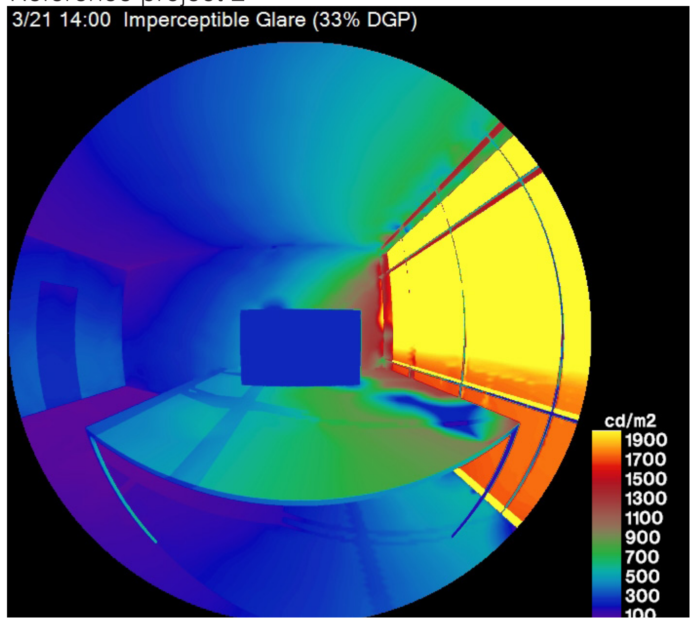

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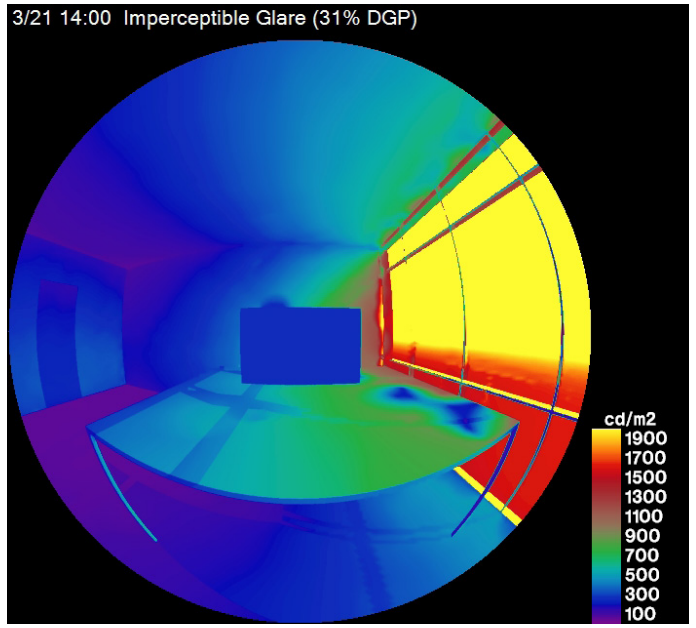

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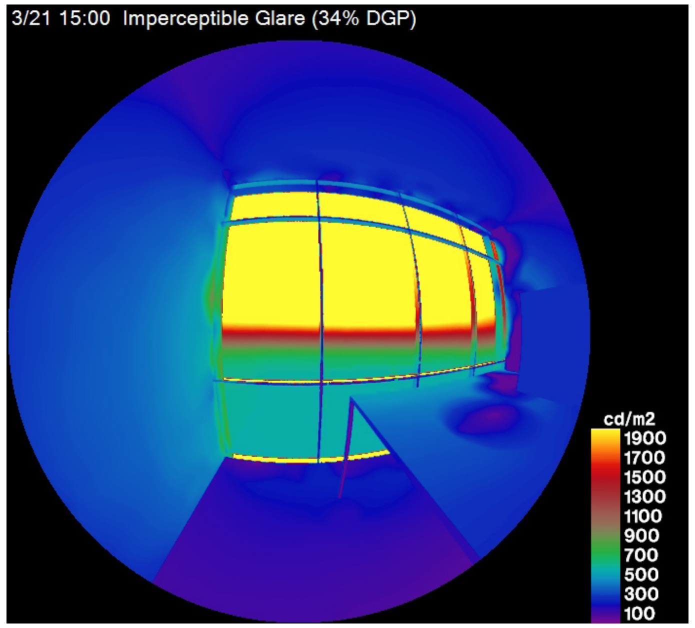

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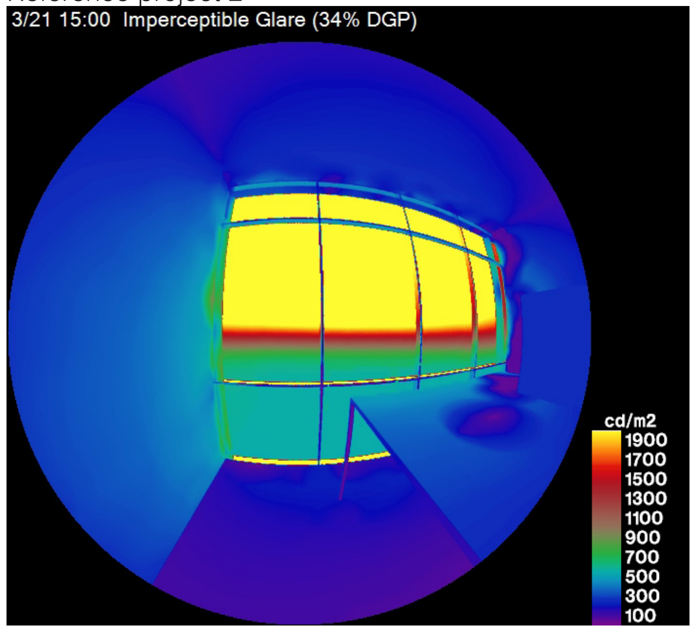

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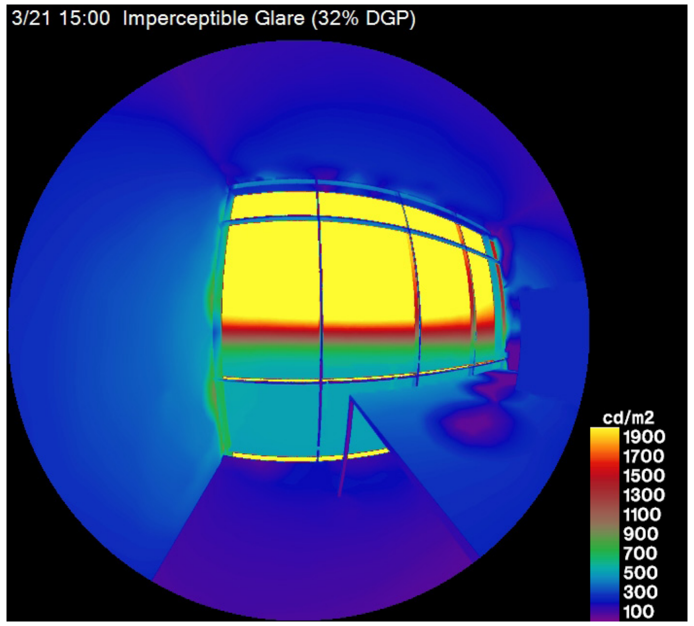

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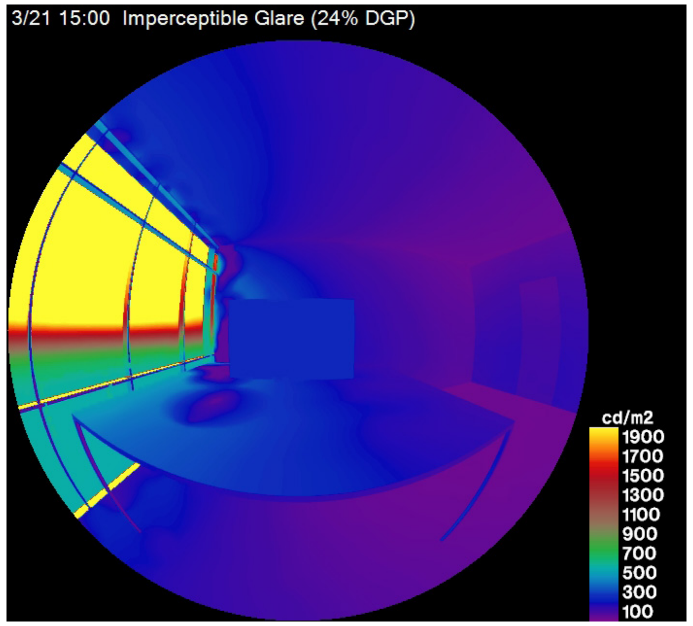

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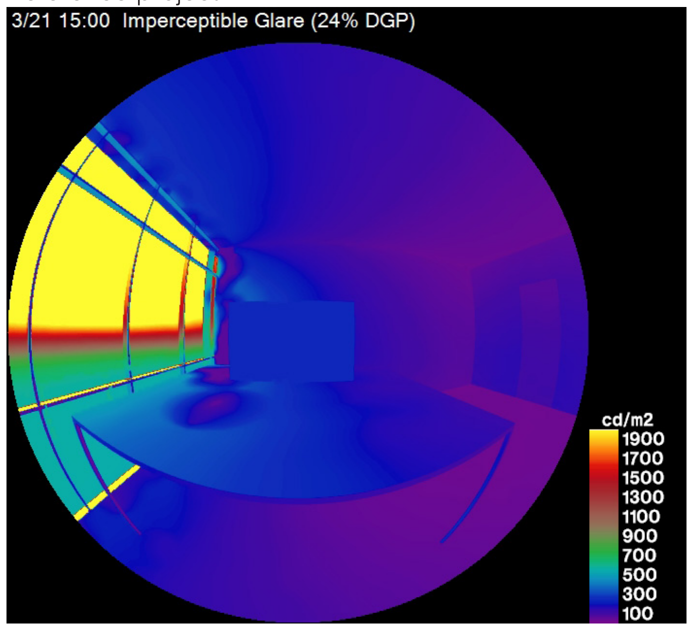

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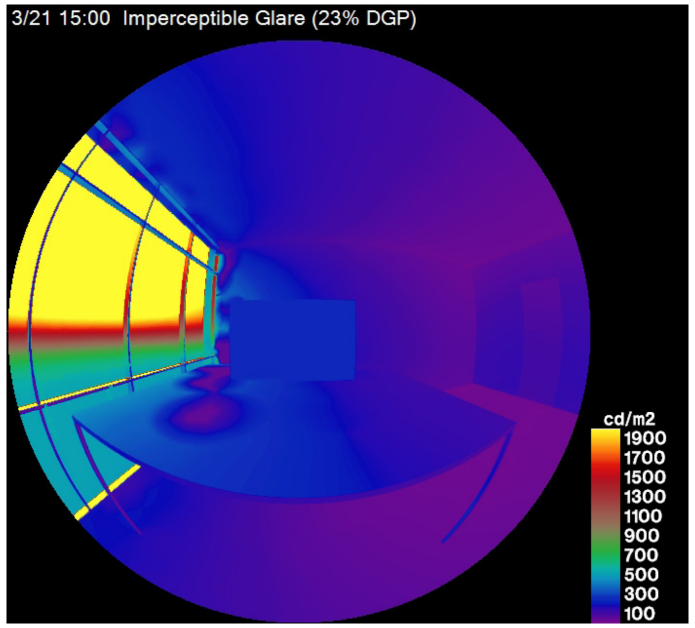

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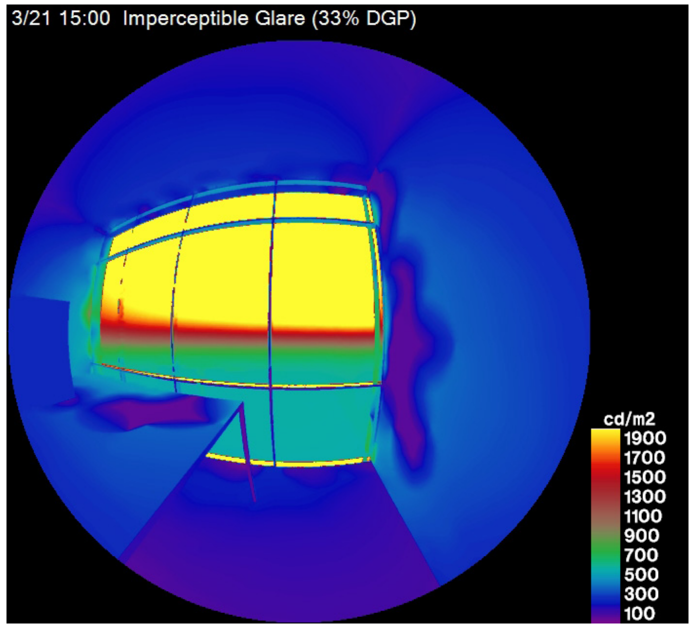

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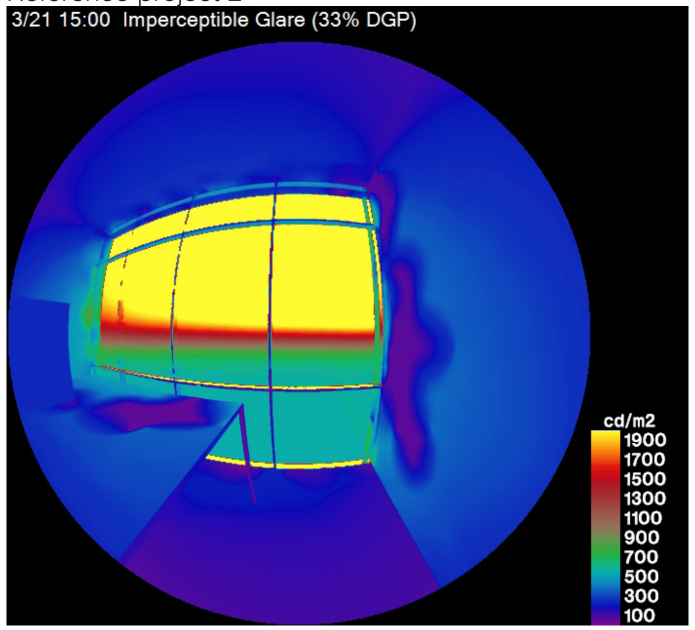

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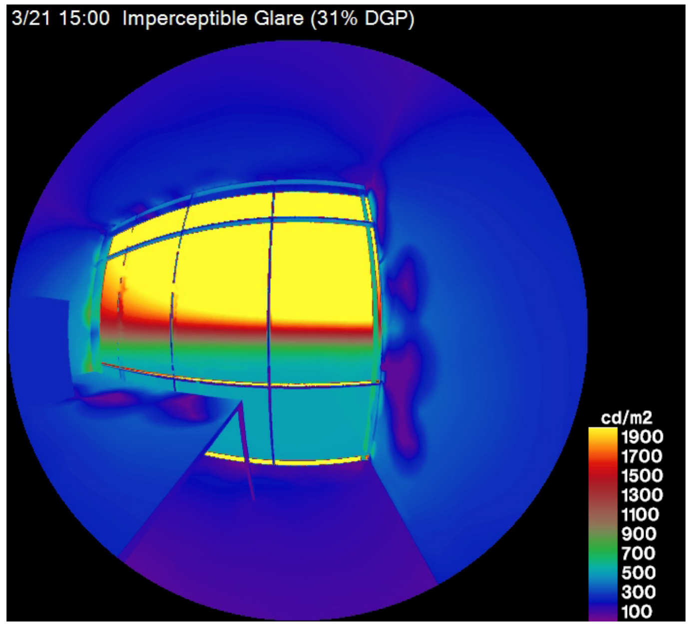

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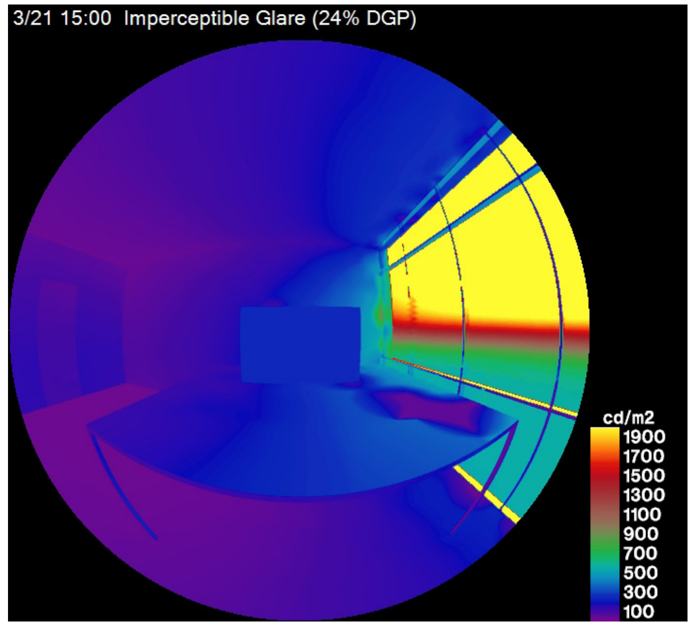

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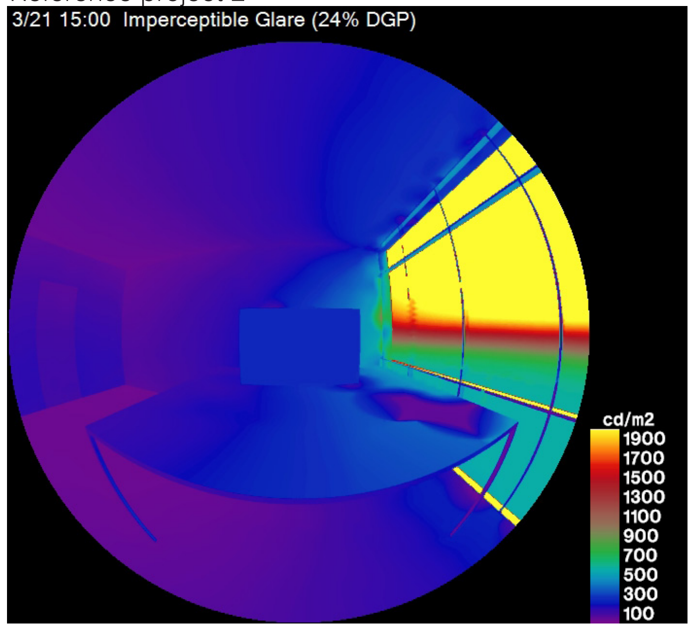

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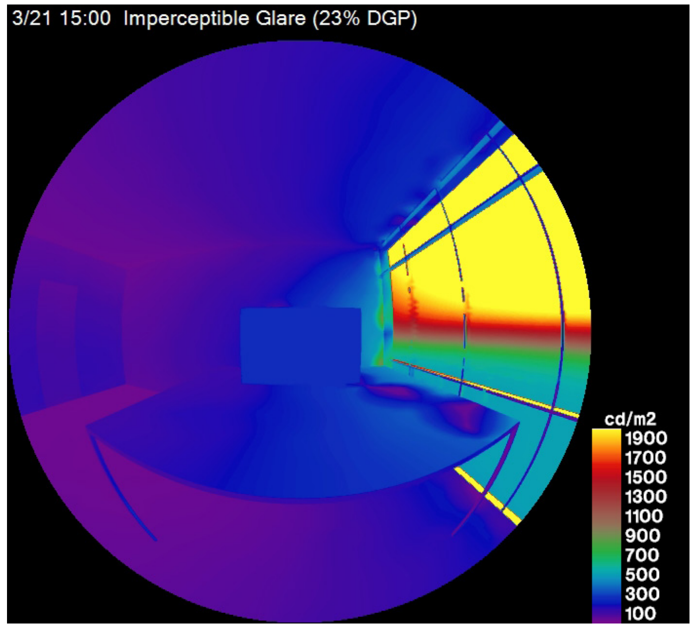

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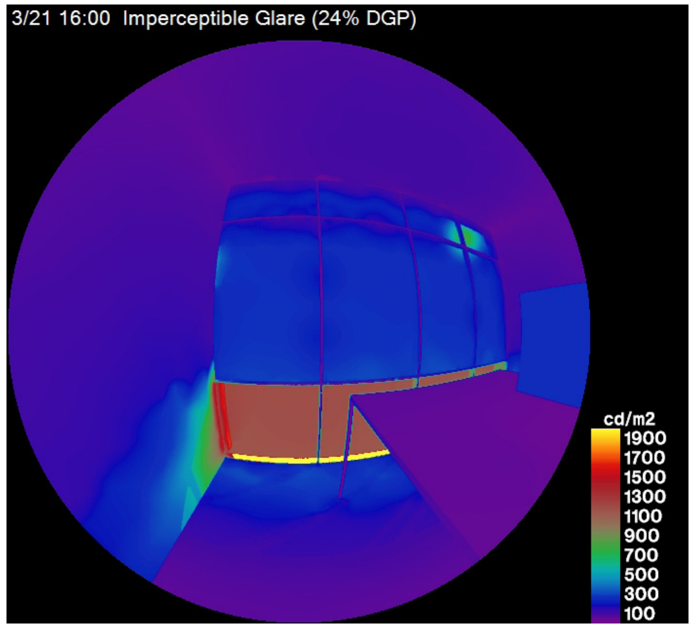

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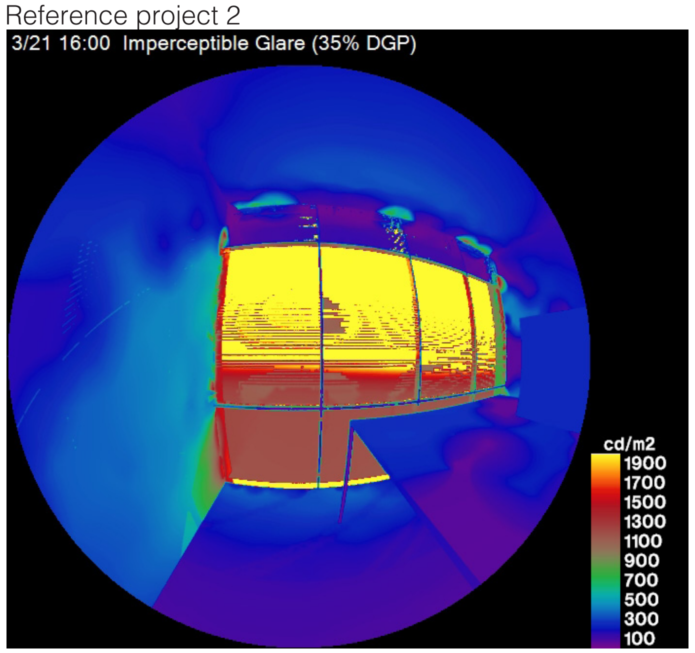

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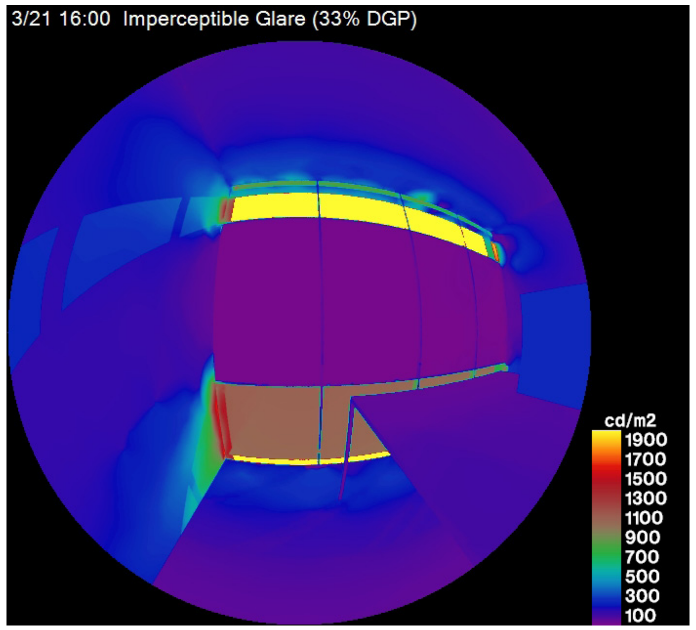

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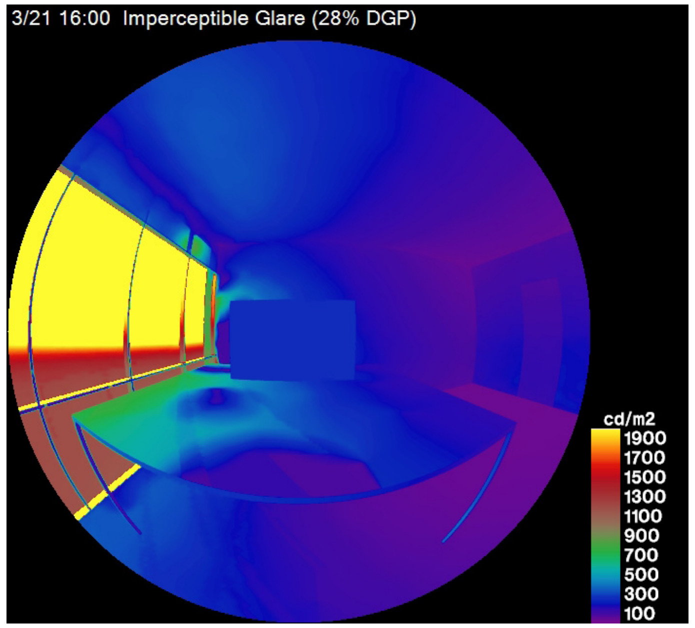

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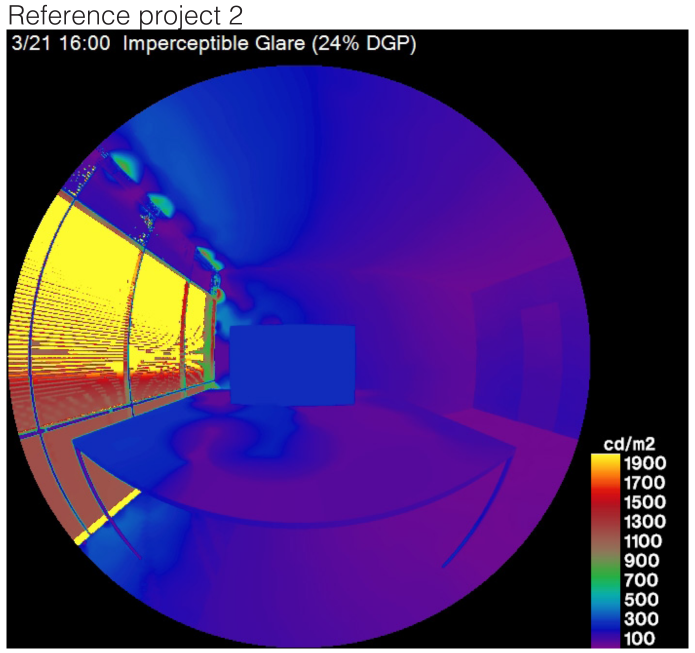

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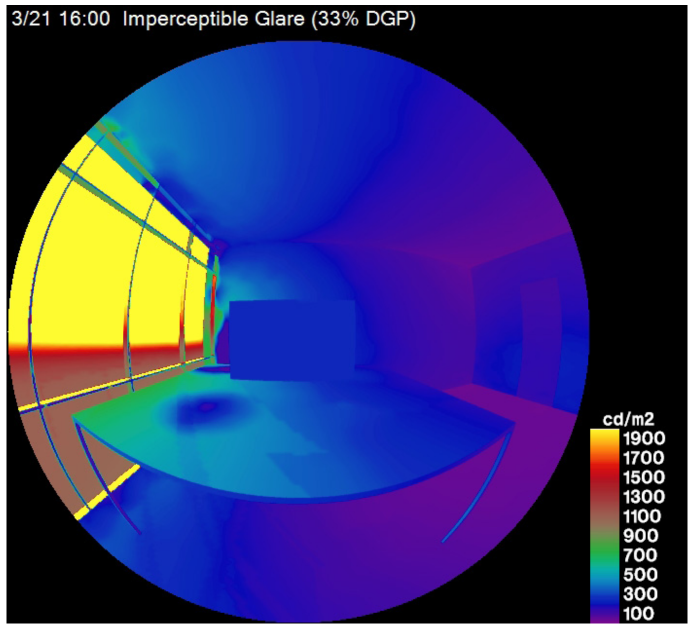

21st March 16:00, User 2, View to the window

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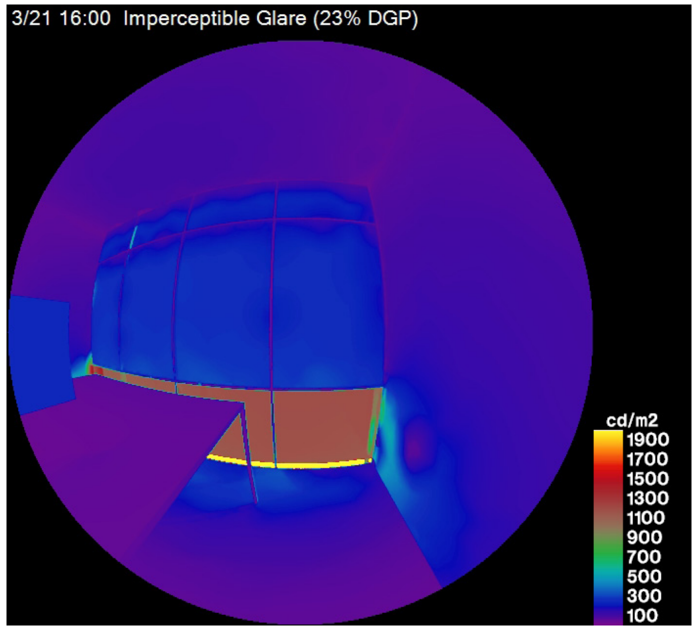

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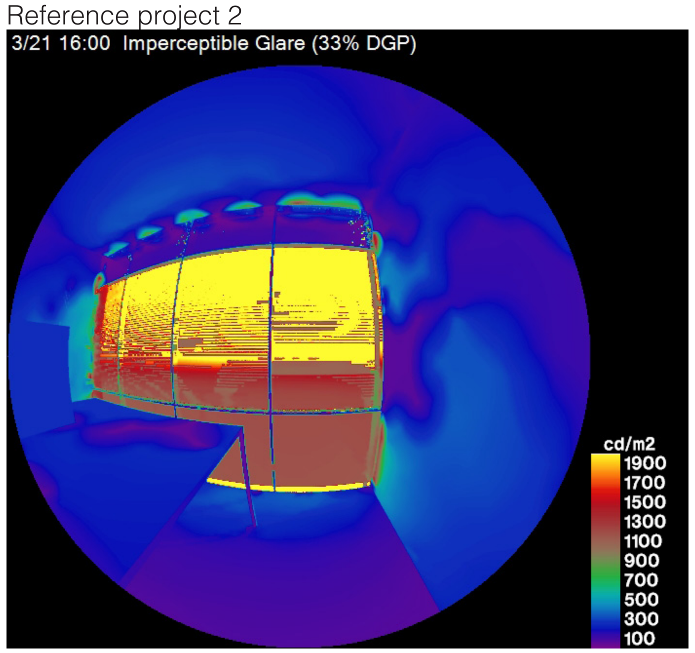

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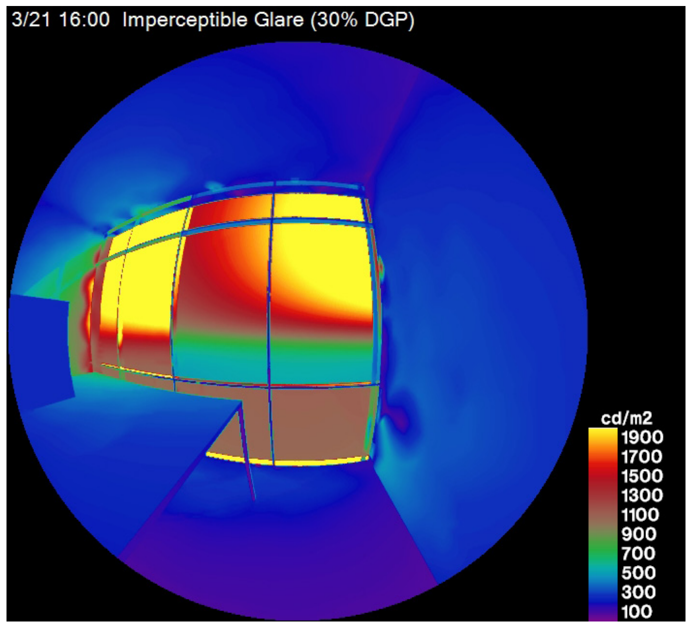

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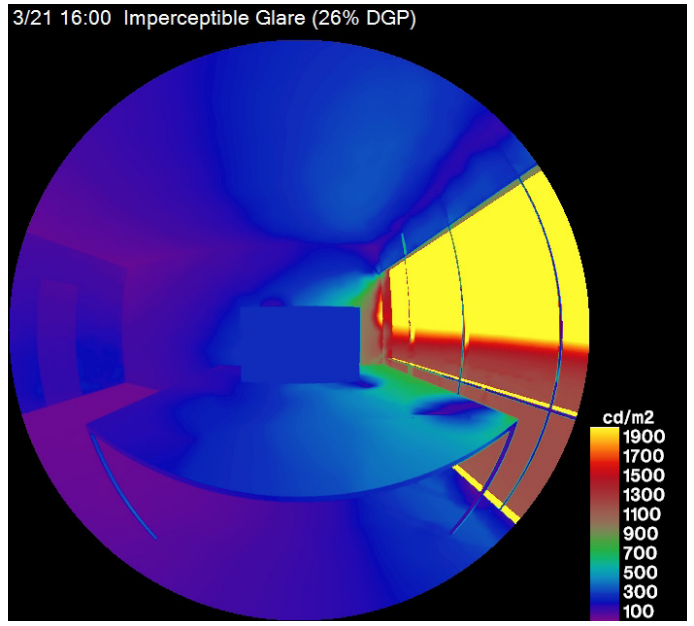

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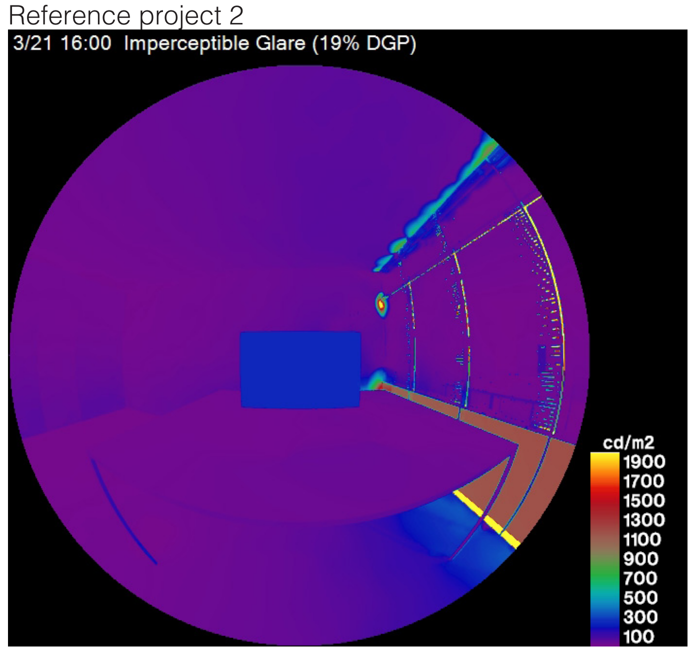

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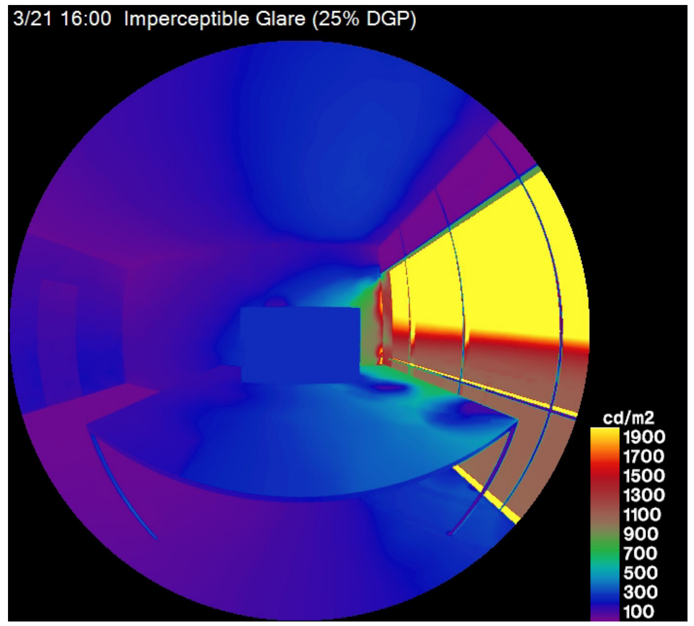

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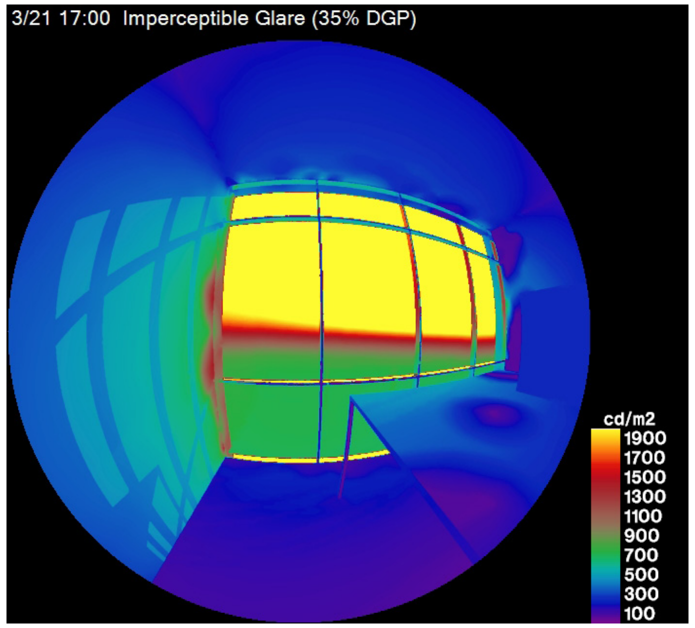

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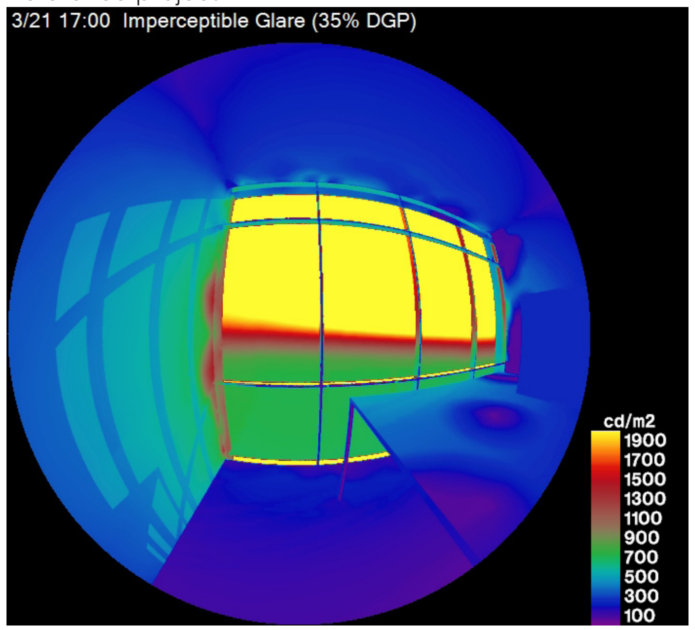

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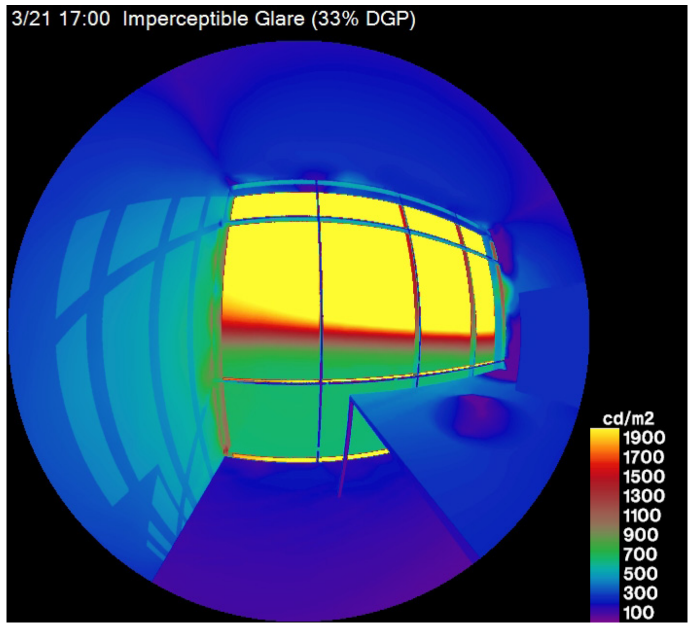

21st March 17:00, User 1, View to the computer screen

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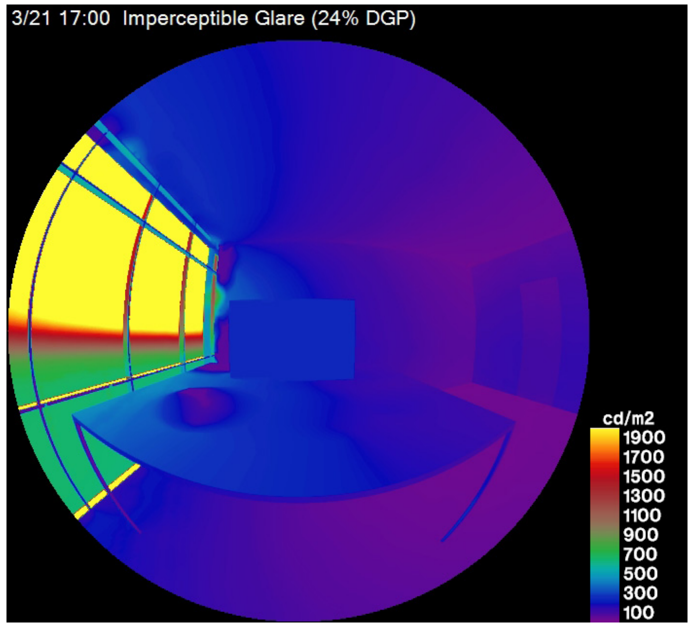

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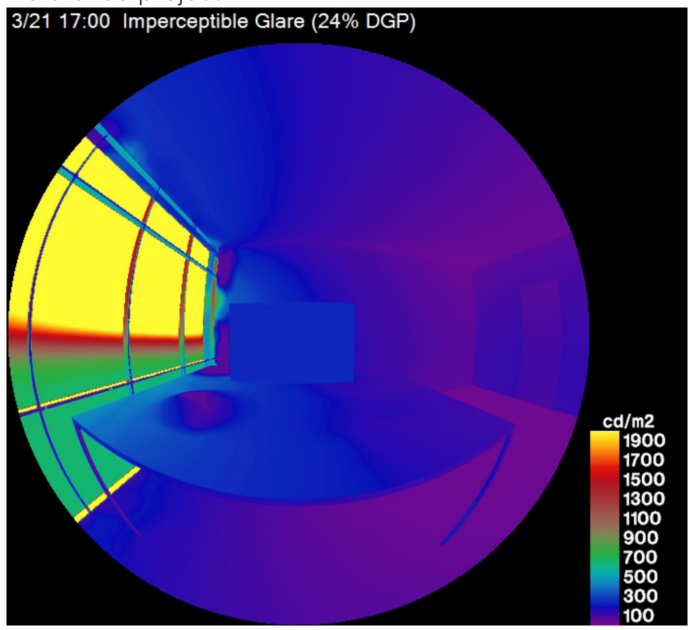

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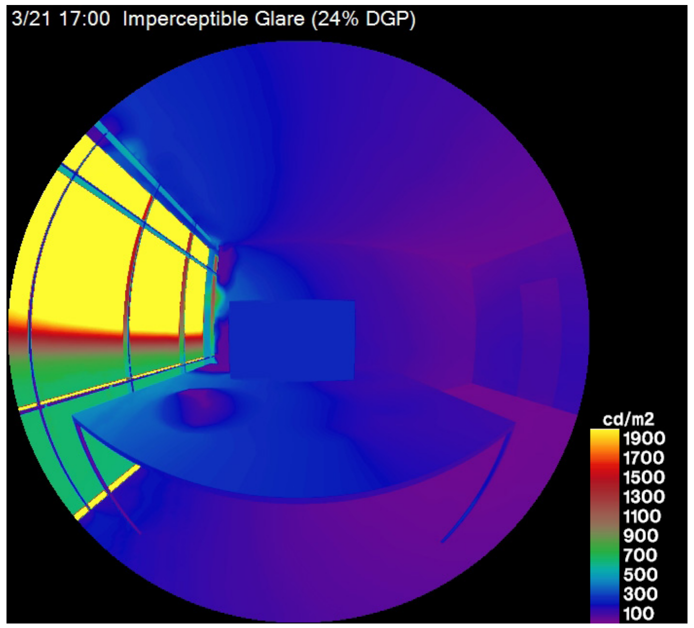

21st March 17:00, User 2, View to the window

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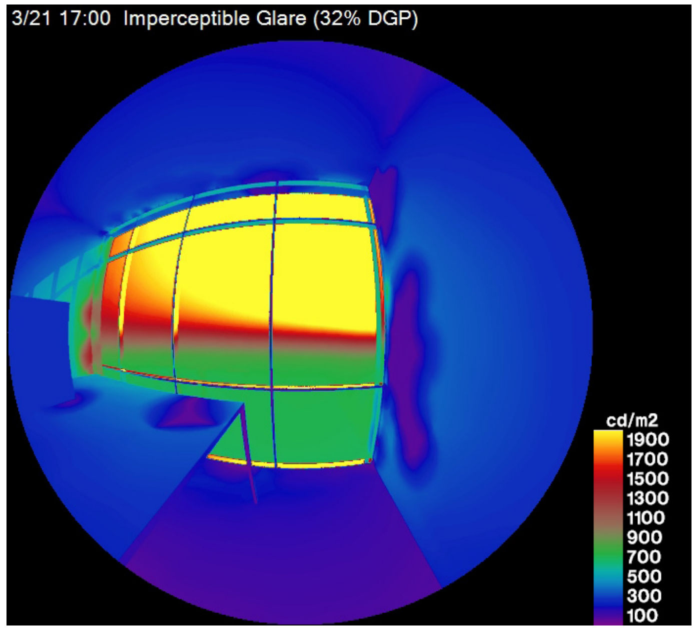

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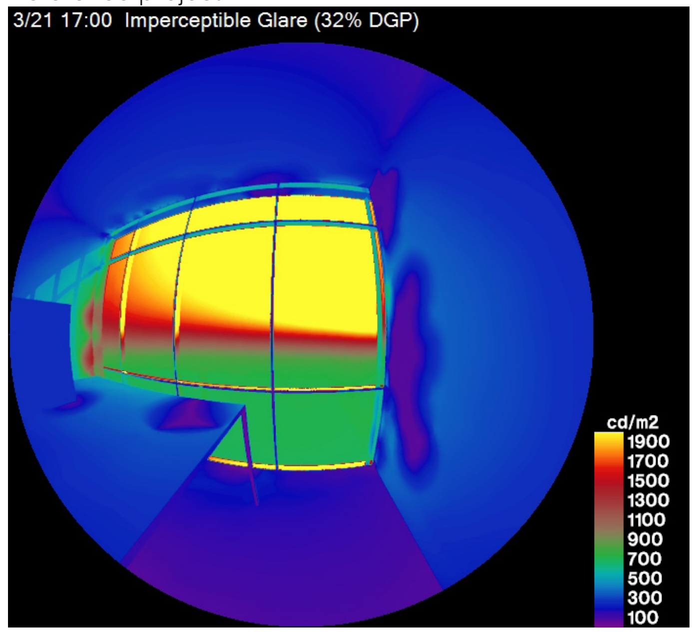
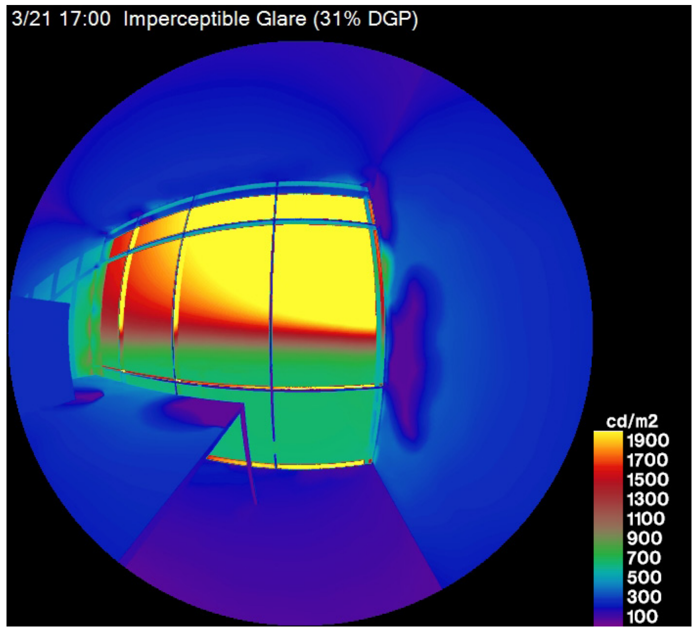


Design (manual calculation)



21st March 17:00, User 2, View to the computer screen

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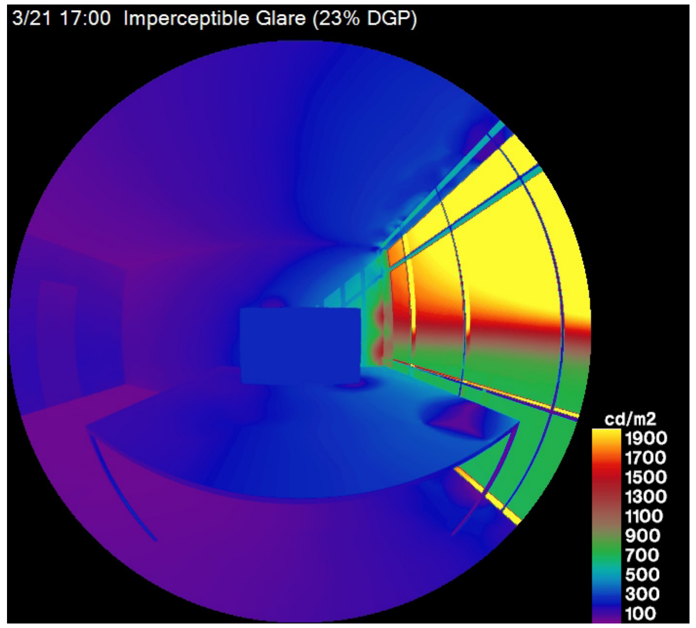

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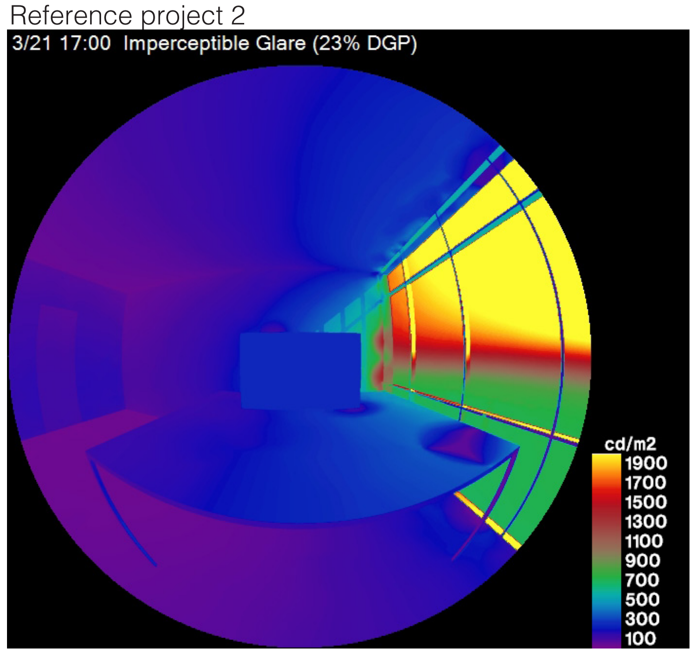

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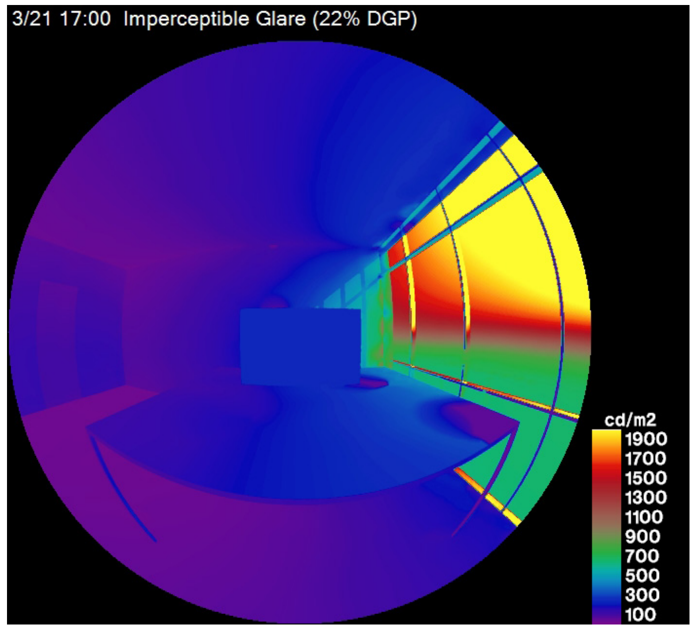

21st March 18:00, User 1, View to the window

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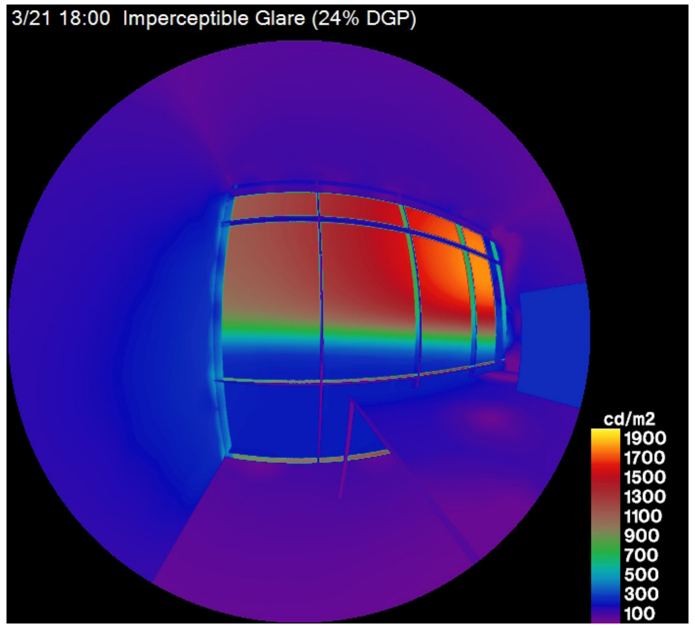

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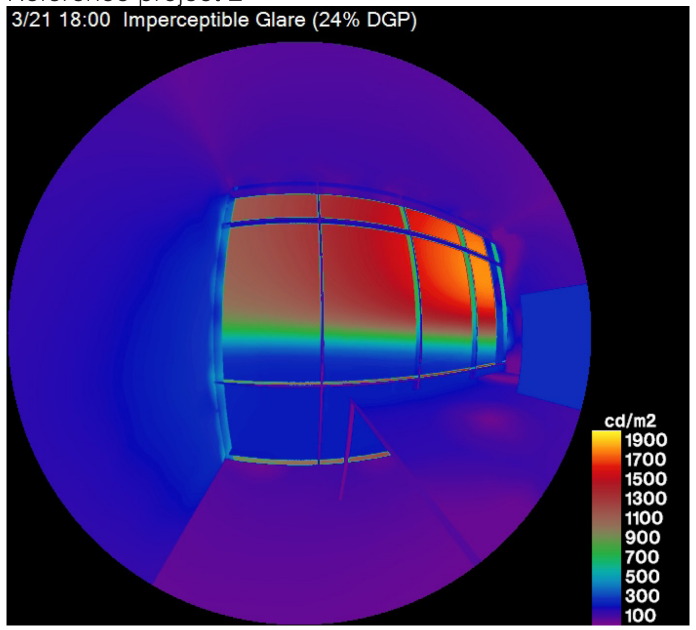

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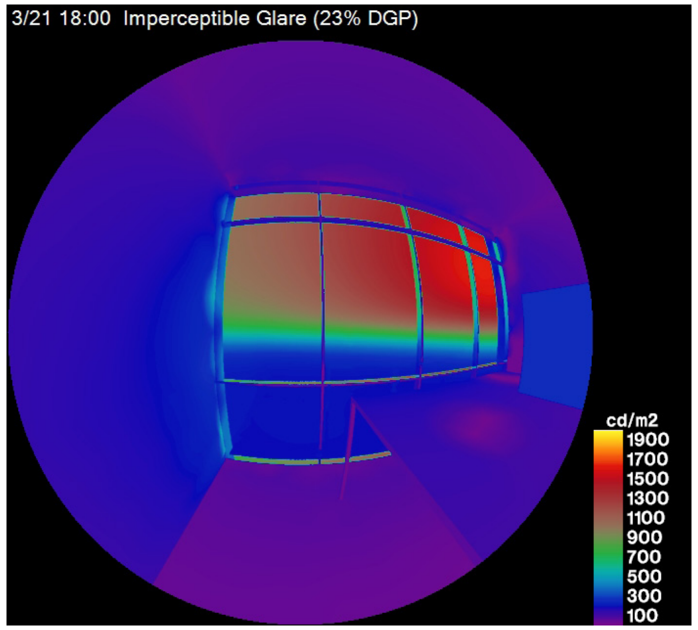

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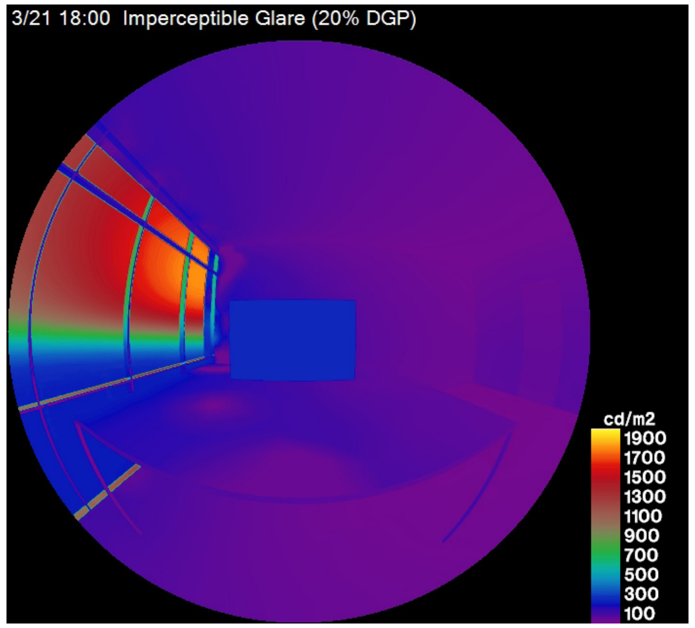

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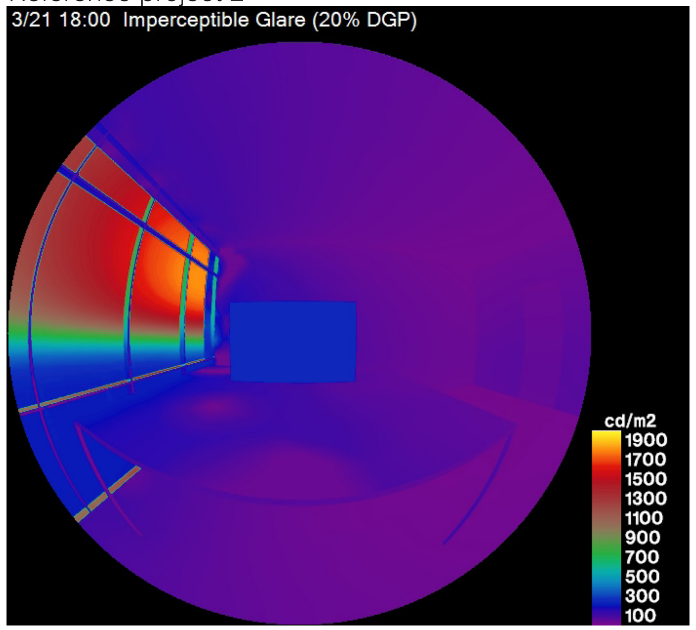

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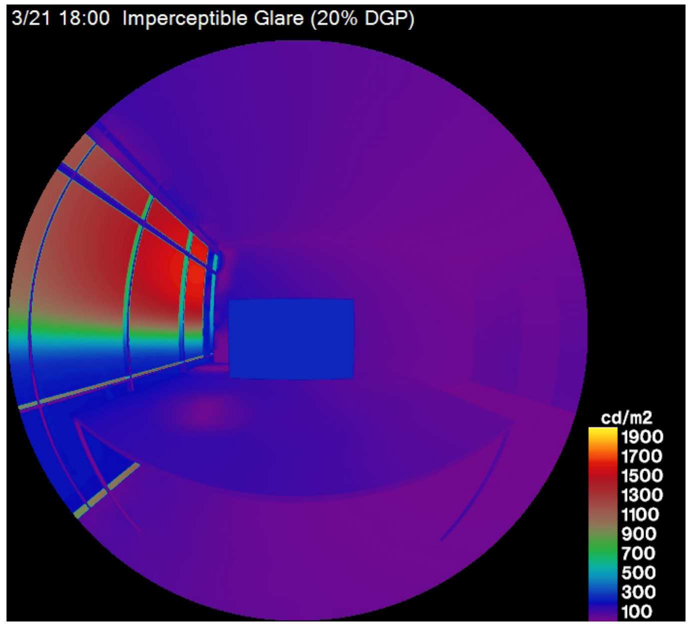

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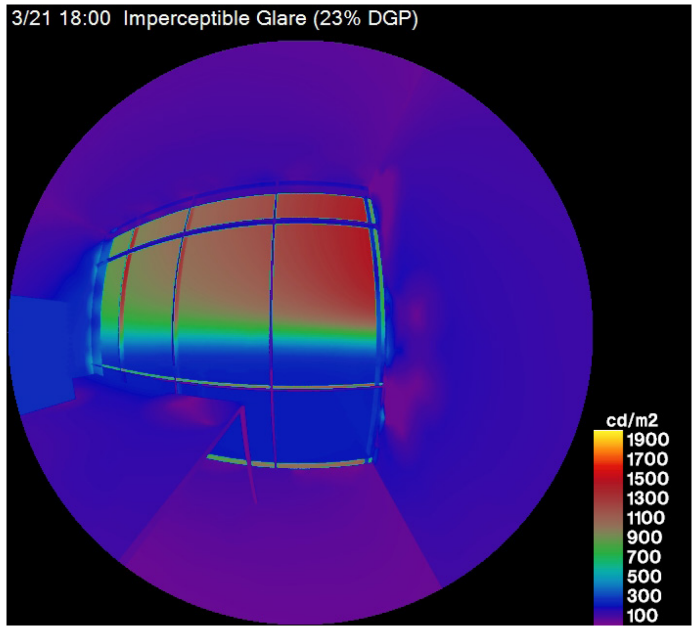

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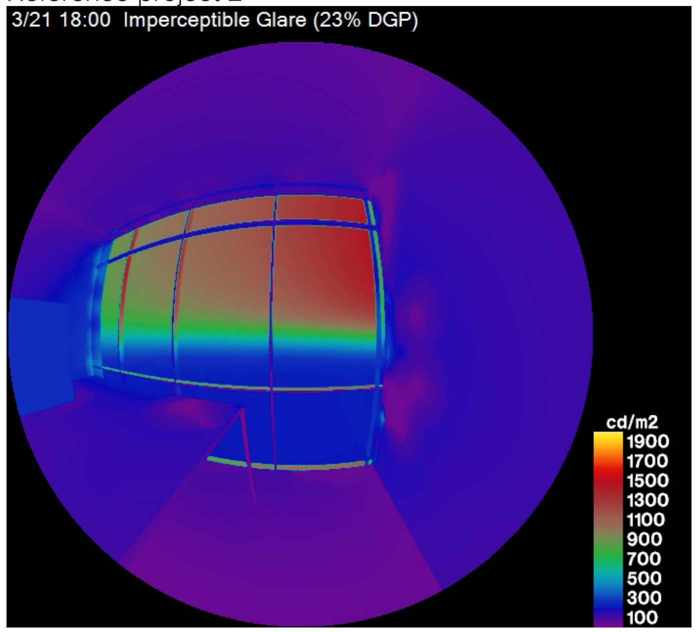

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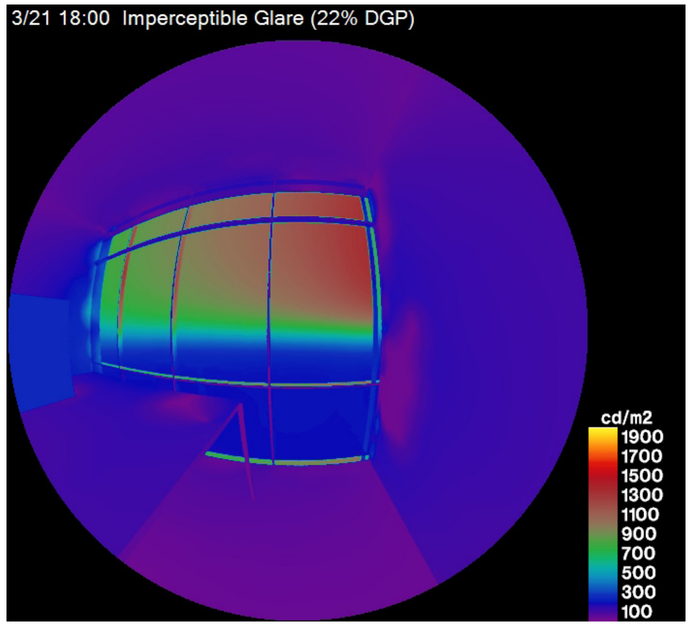

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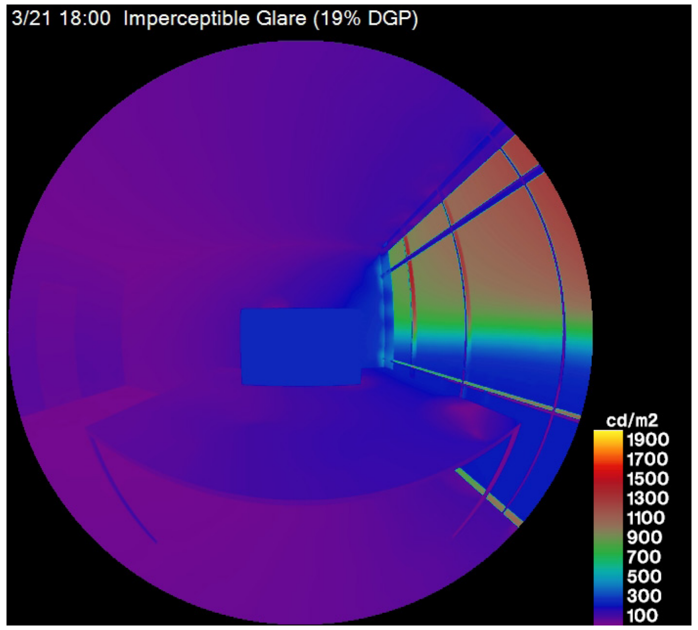

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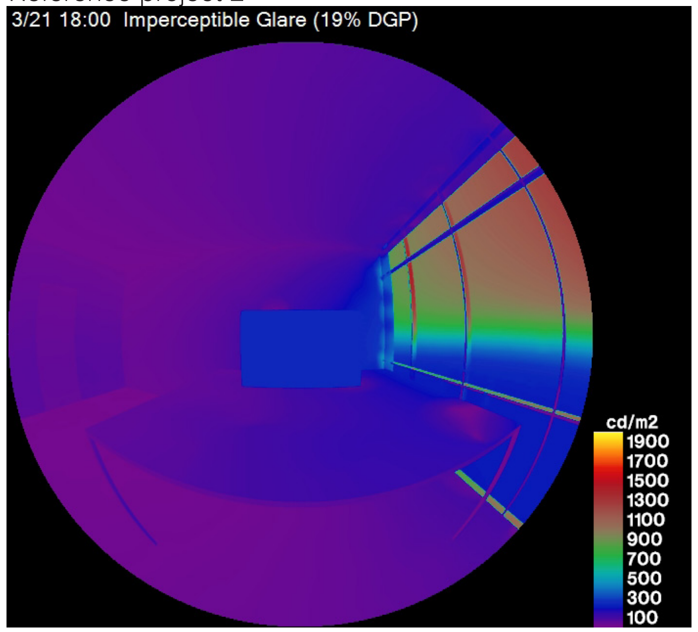

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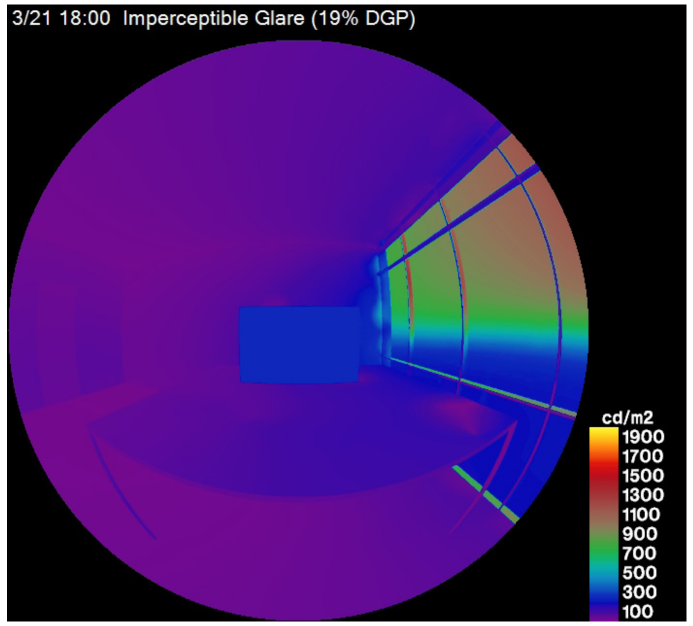
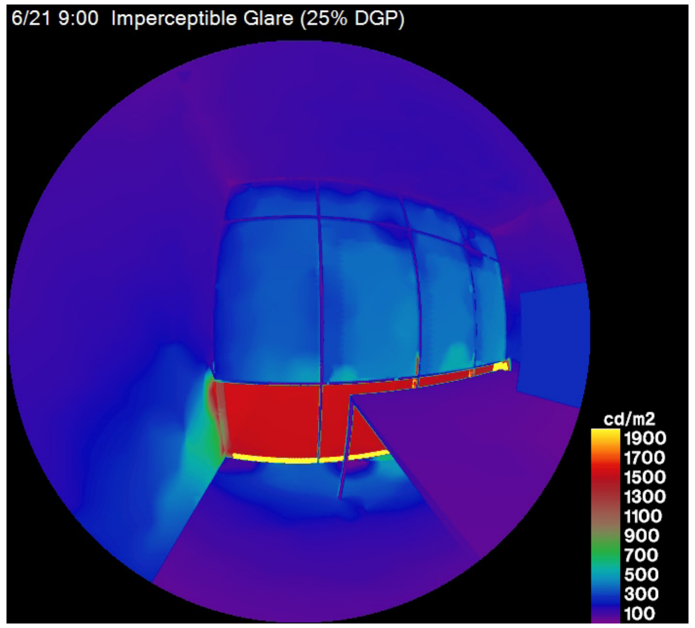


21st June 9:00, User 1, View to the window

Reference project 1



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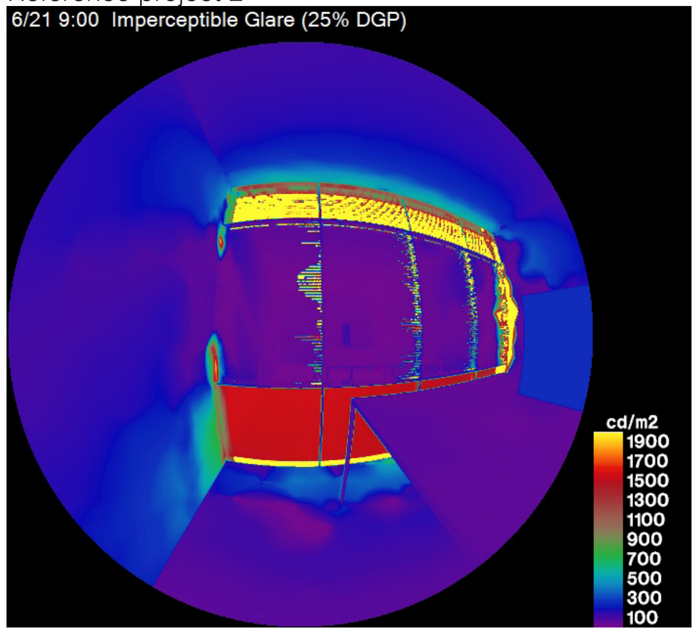

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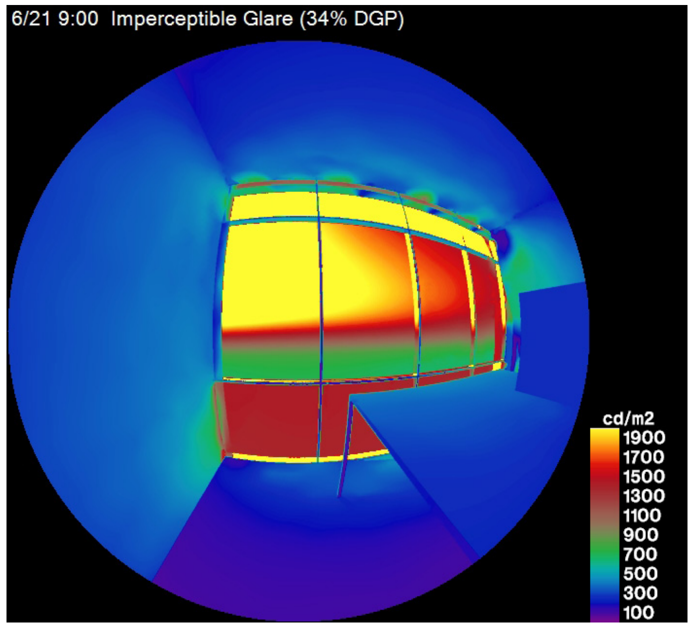

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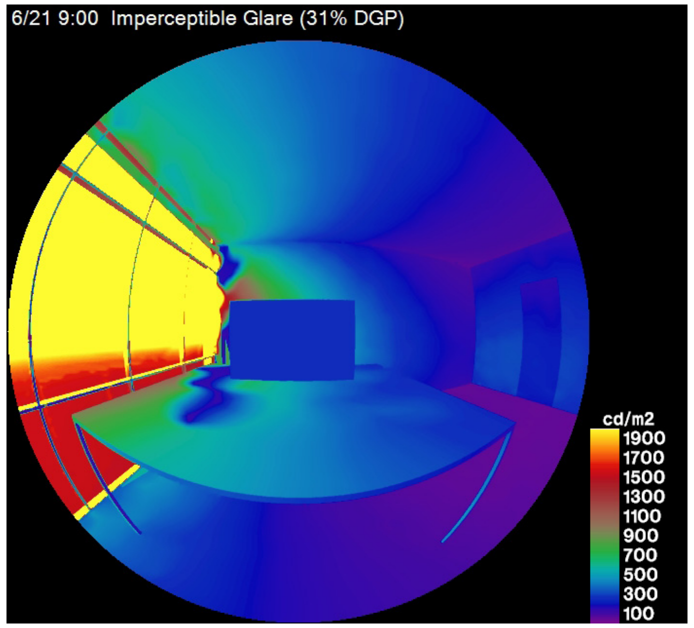

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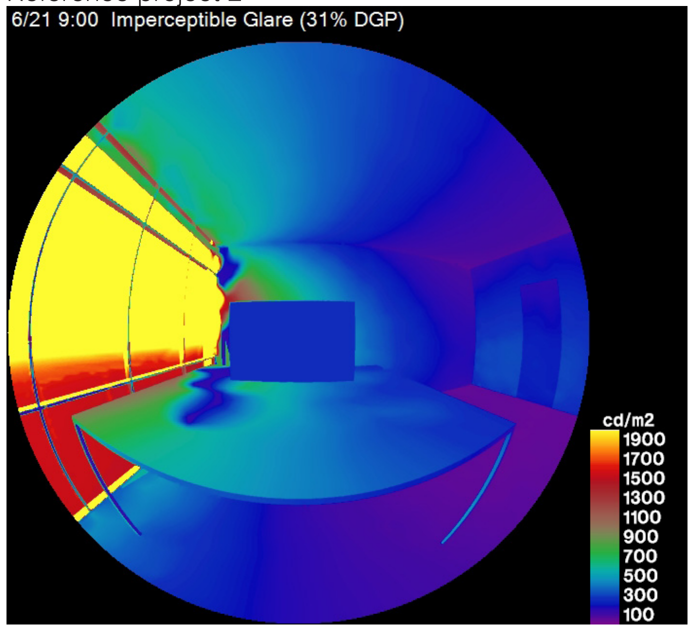

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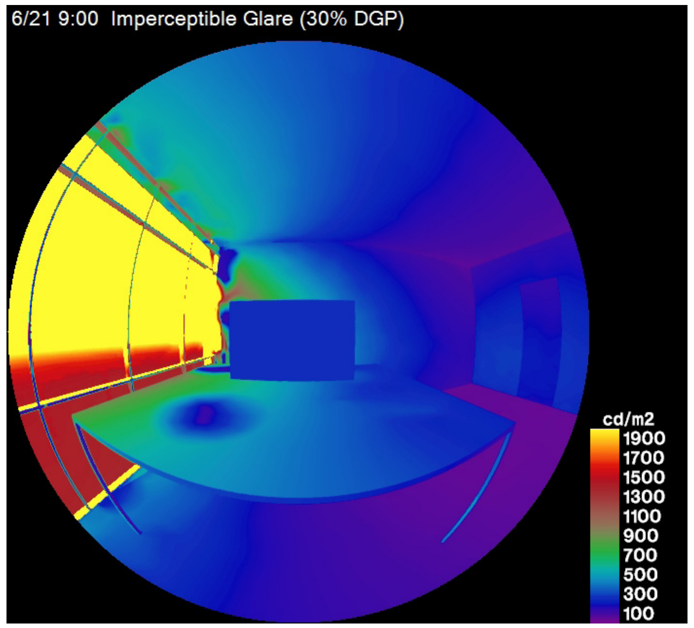

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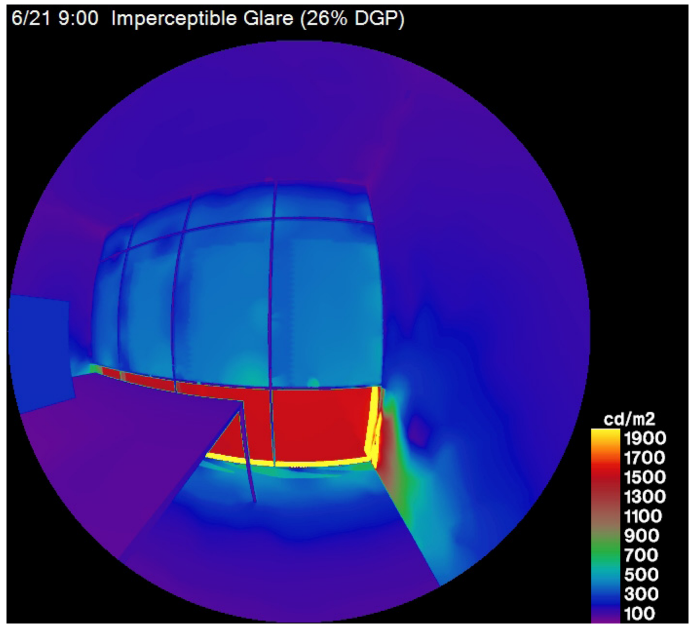

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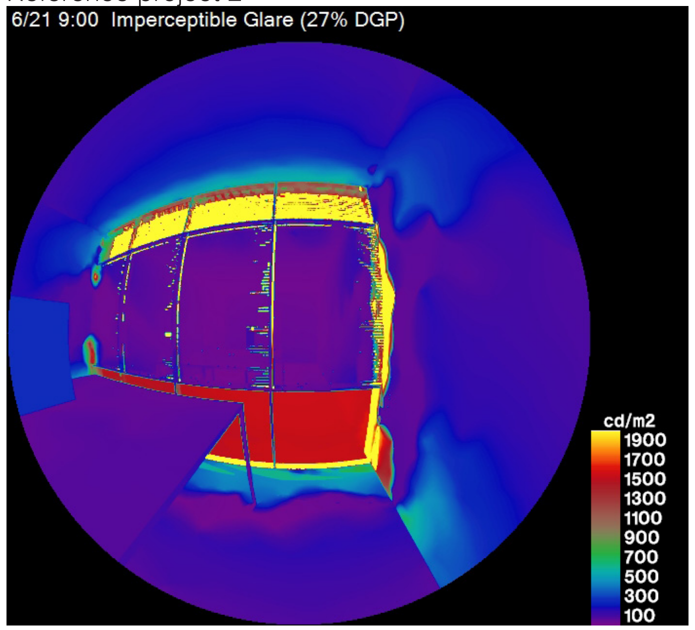

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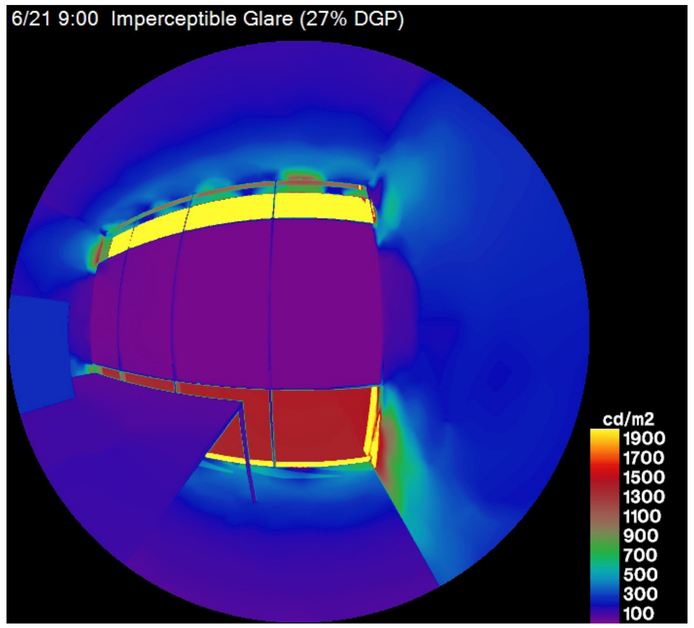

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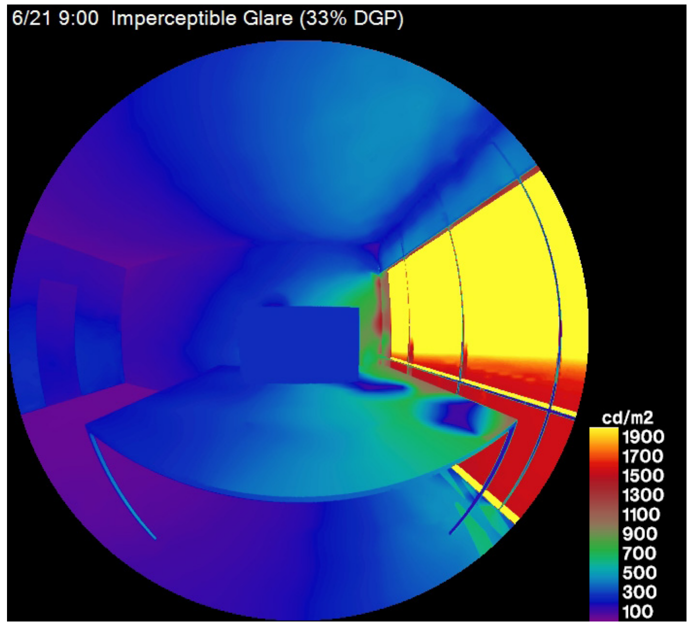

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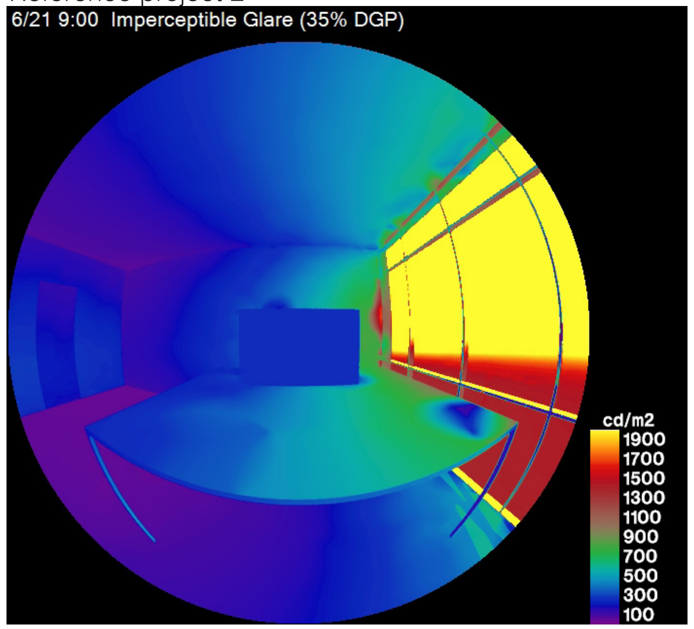

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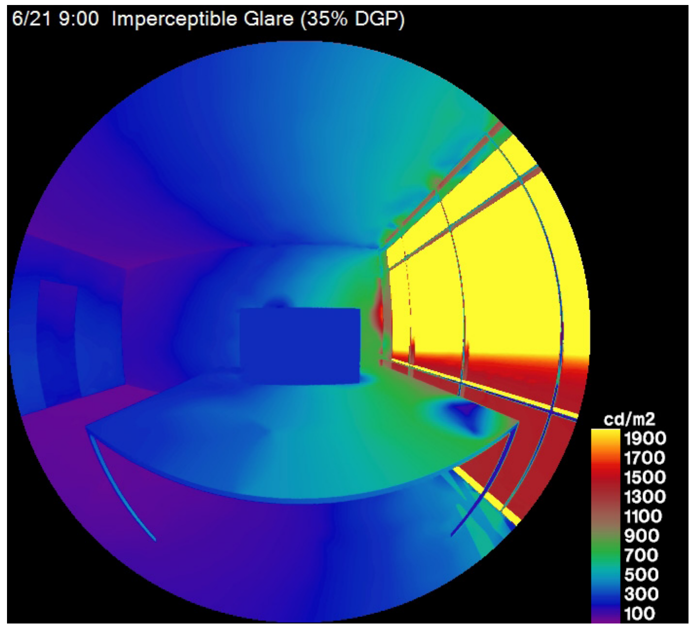
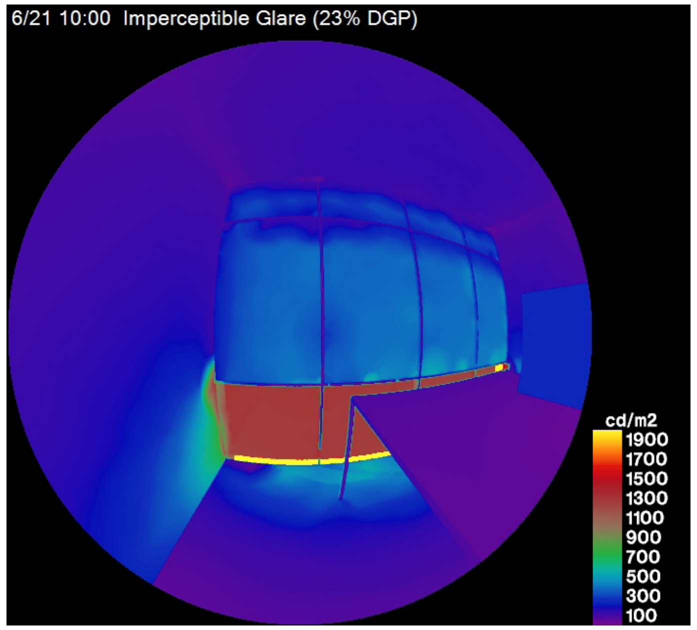


21st June 10:00, User 1, View to the window

Reference project 1



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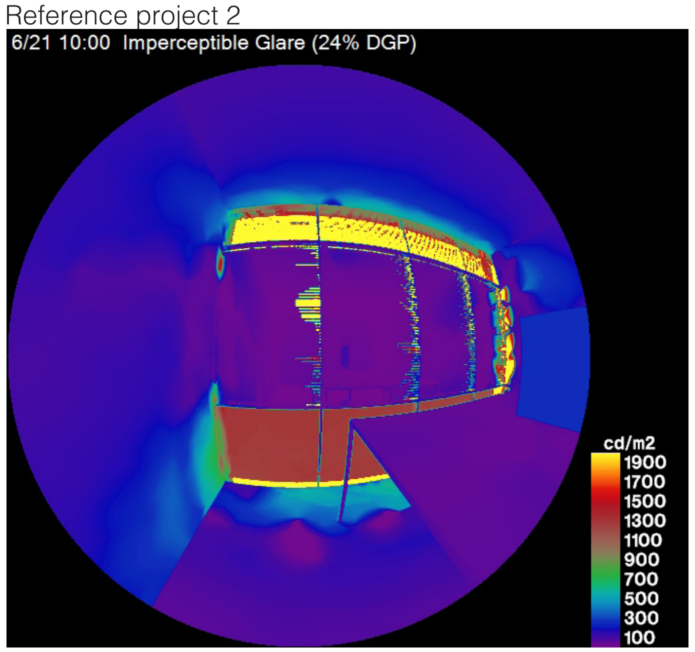

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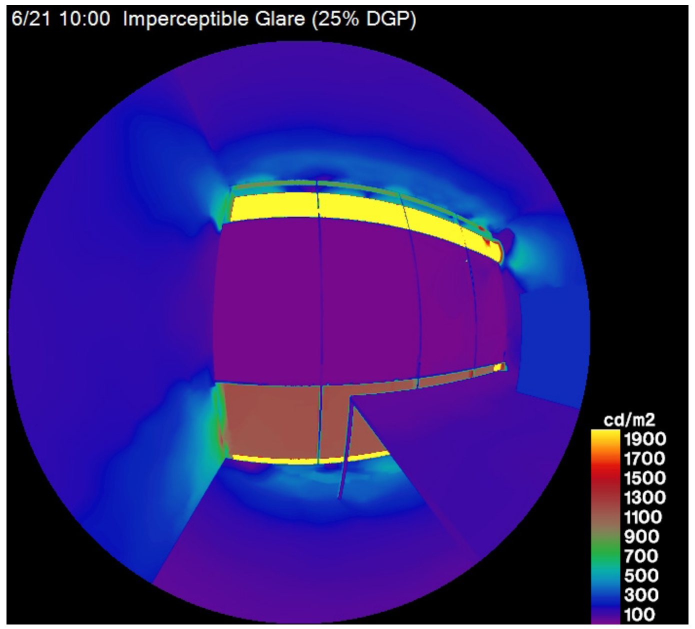

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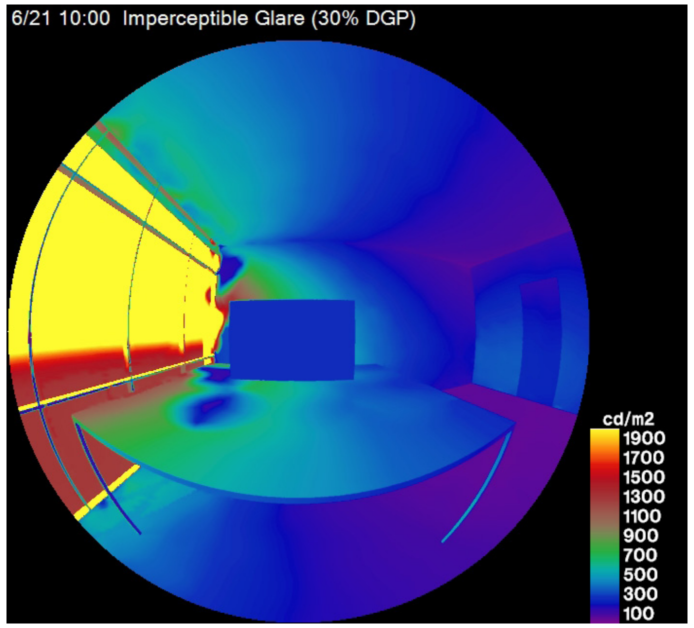

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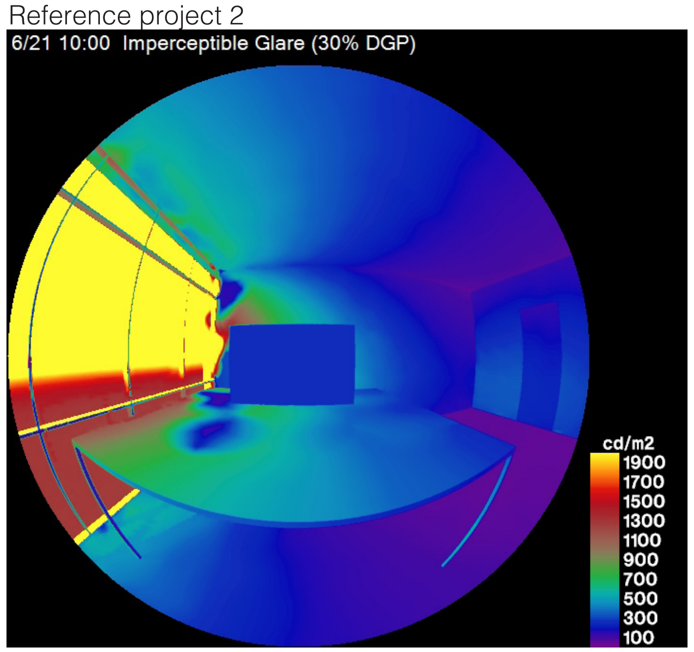

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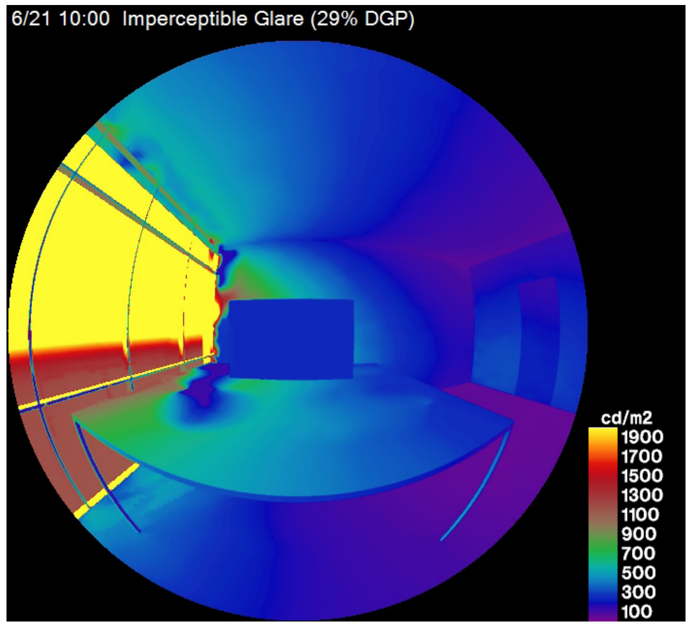

21st June 10:00, User 2, View to the window

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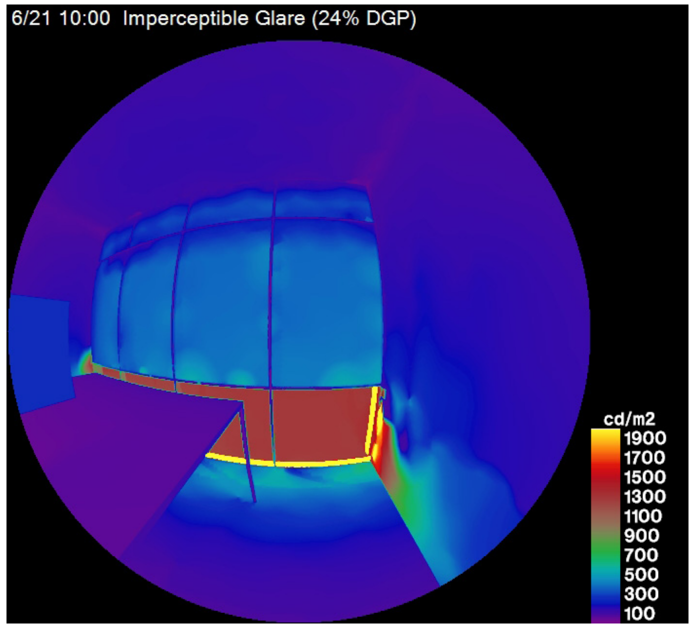

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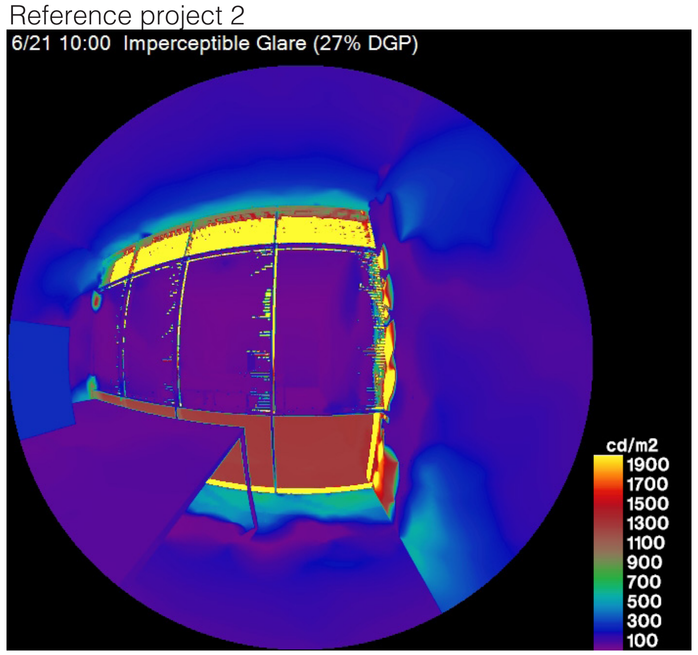

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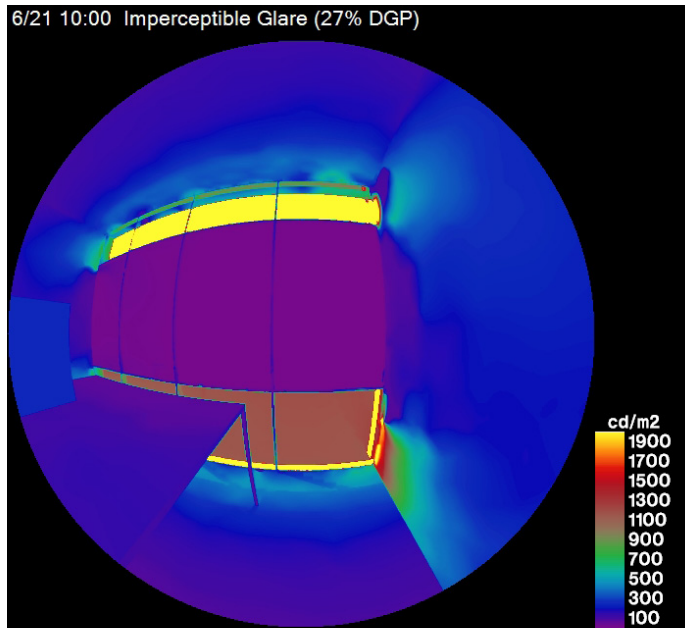

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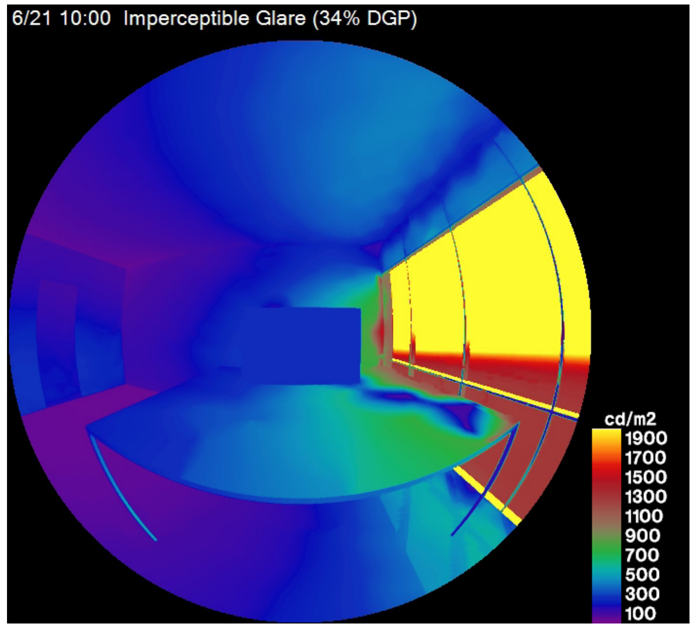

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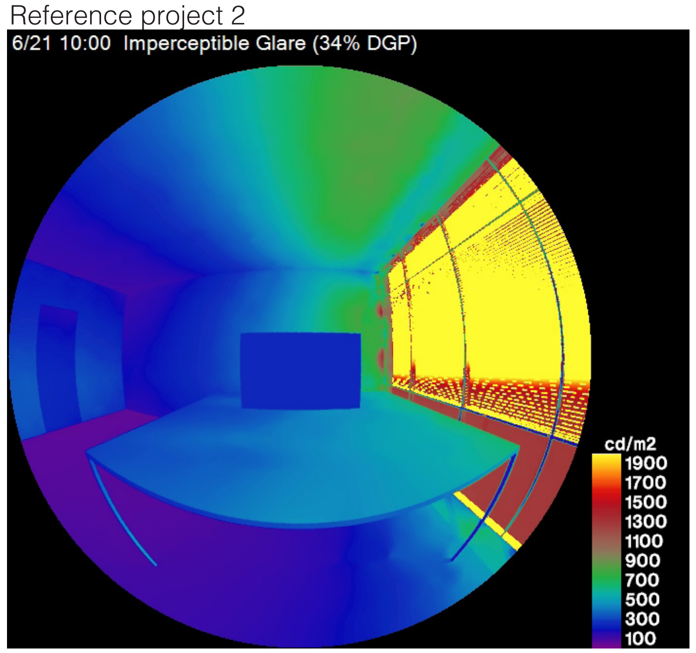

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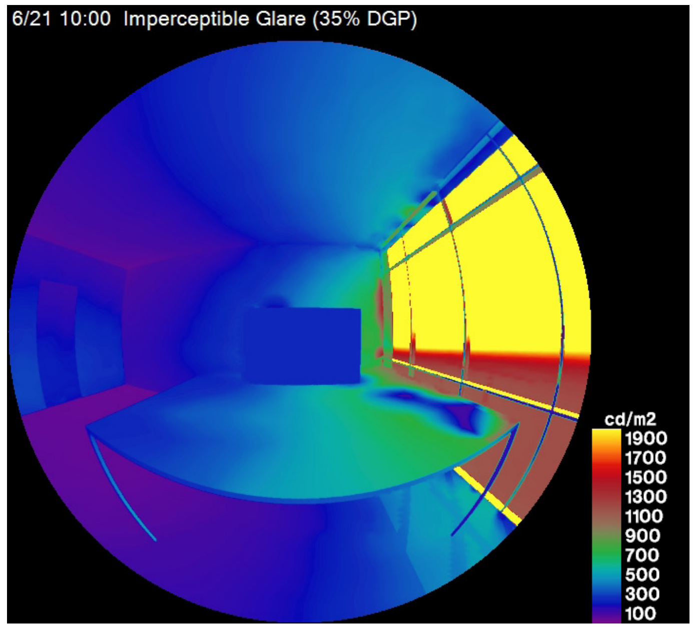

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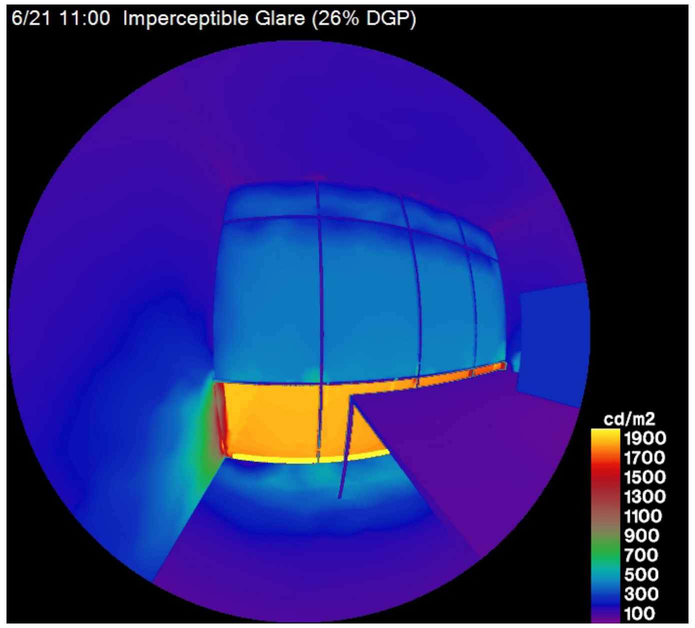

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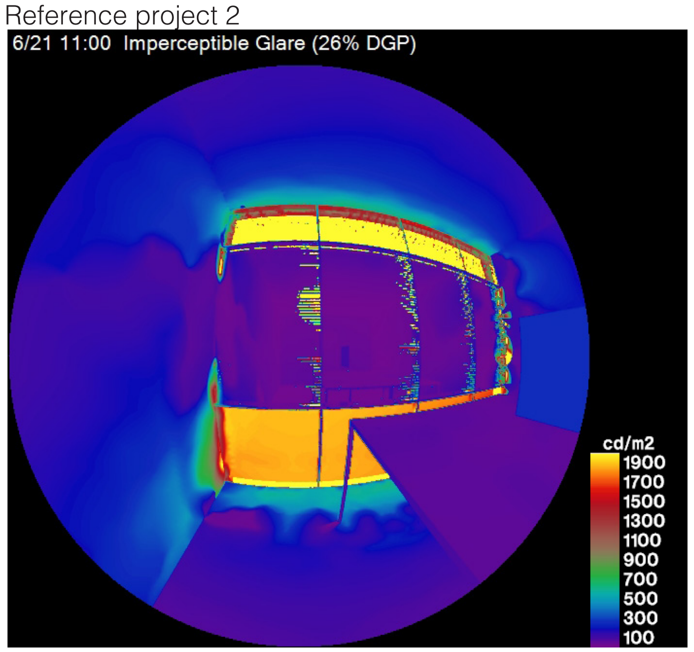

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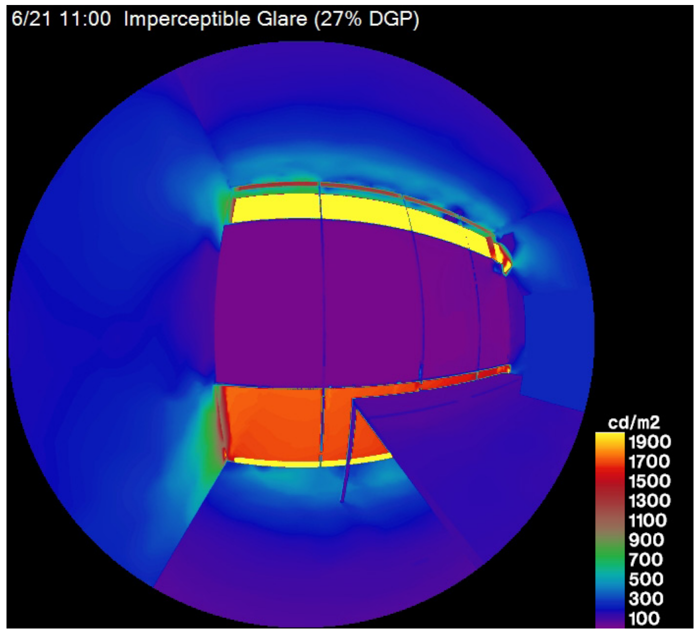

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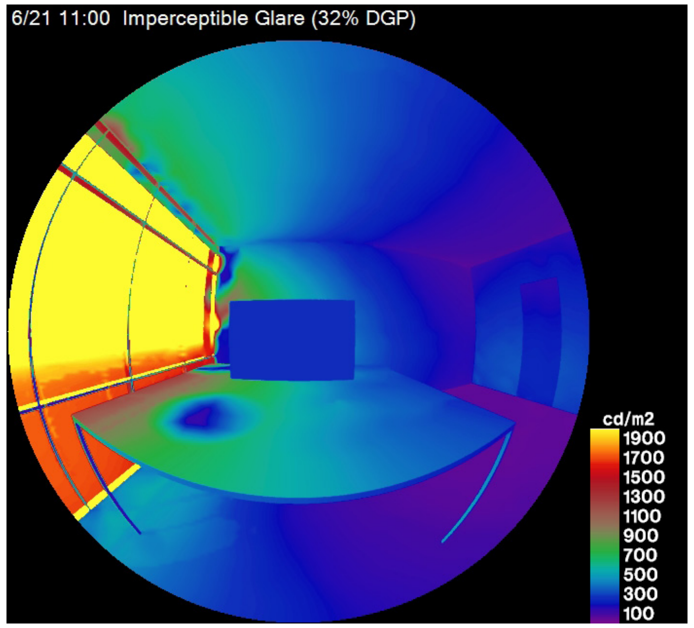

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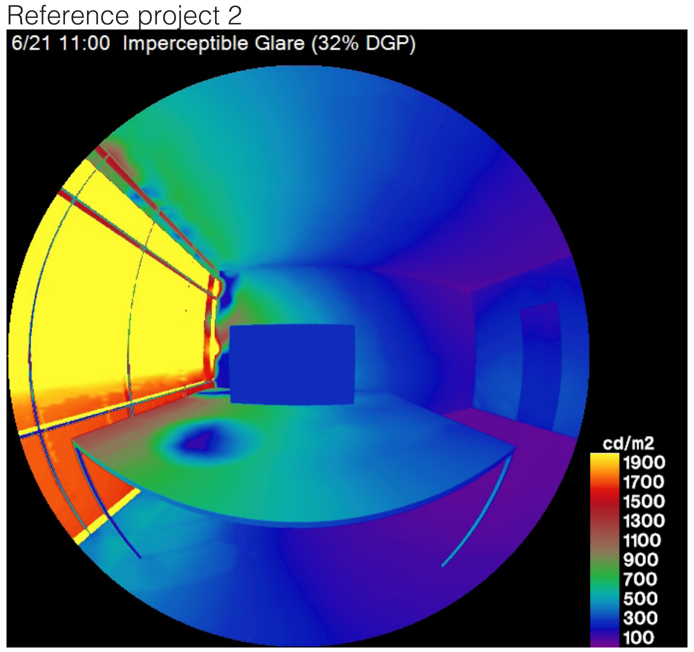

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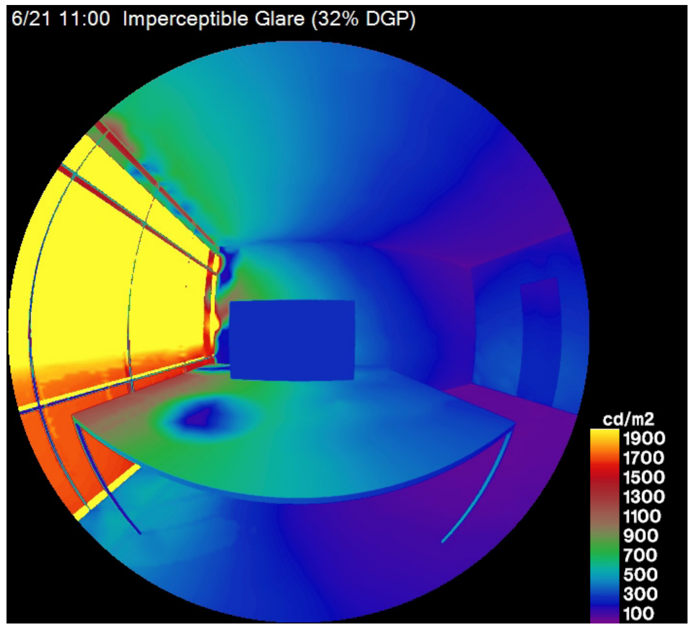

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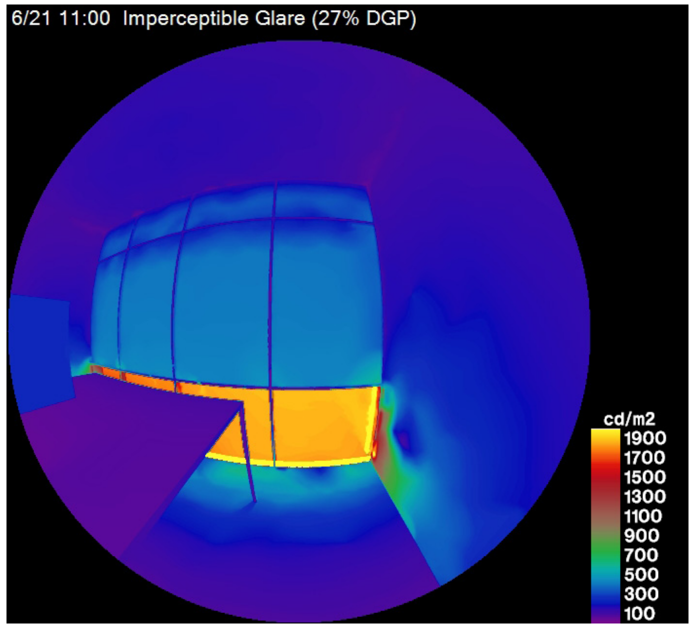

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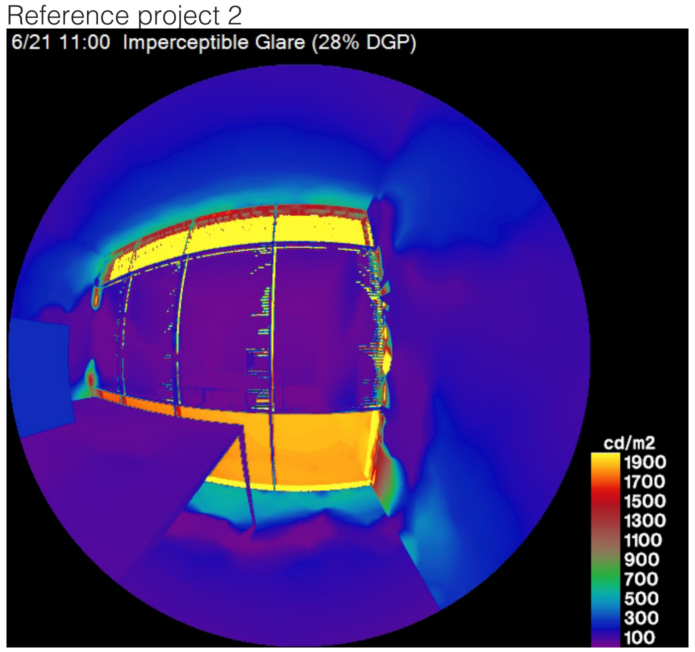

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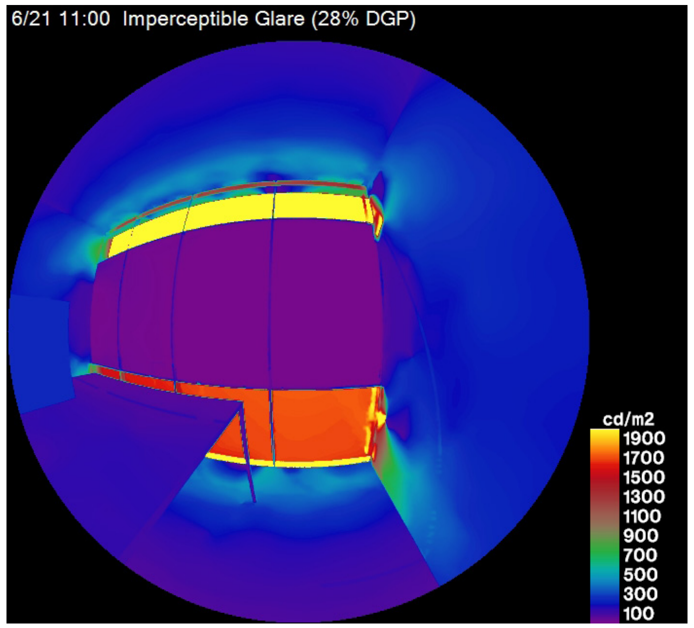

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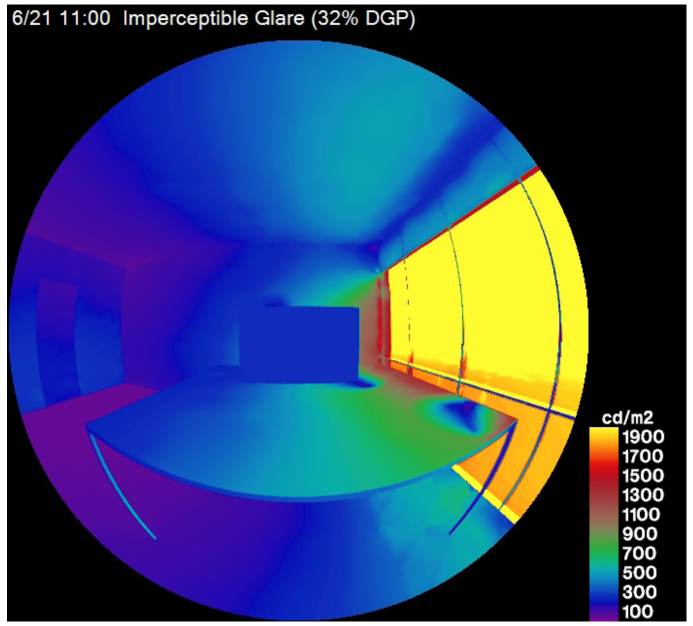

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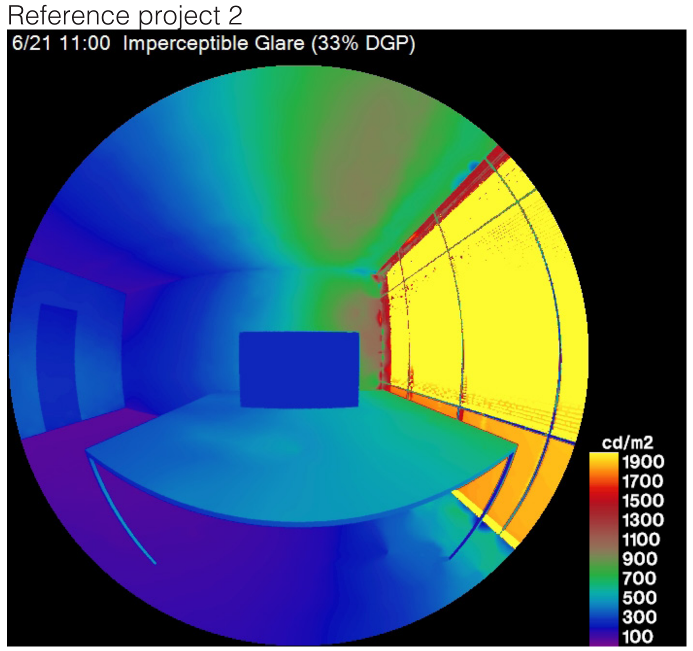

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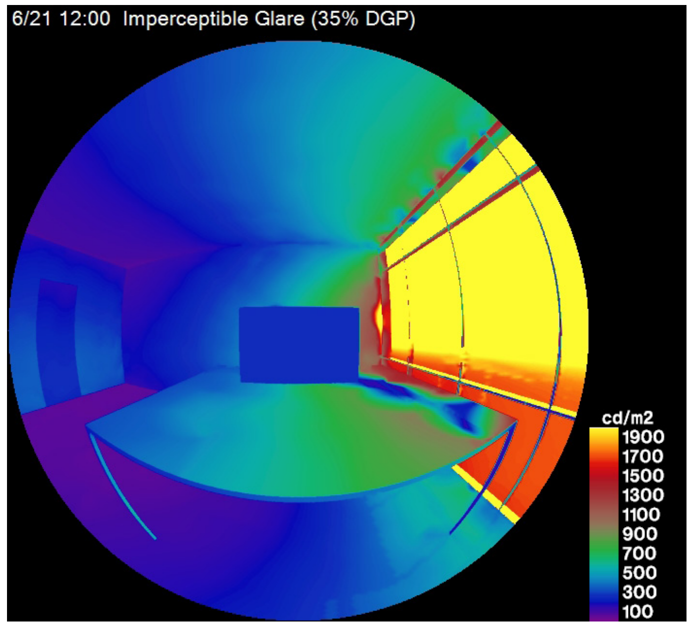

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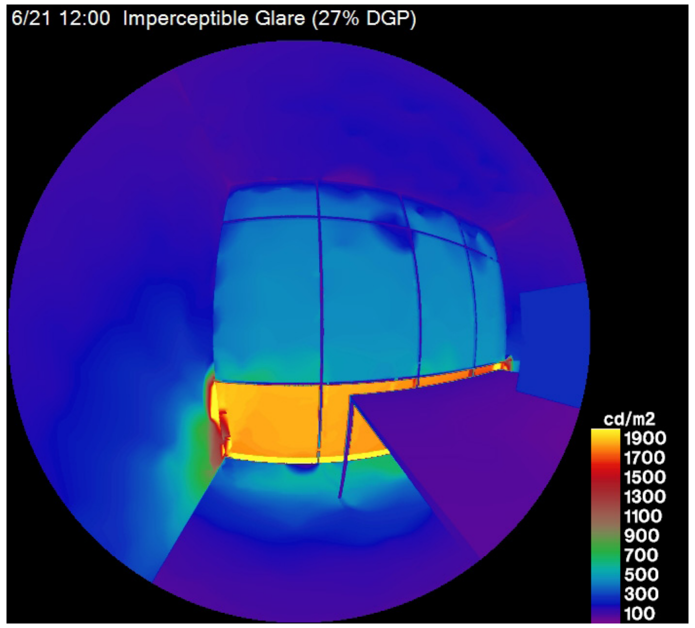

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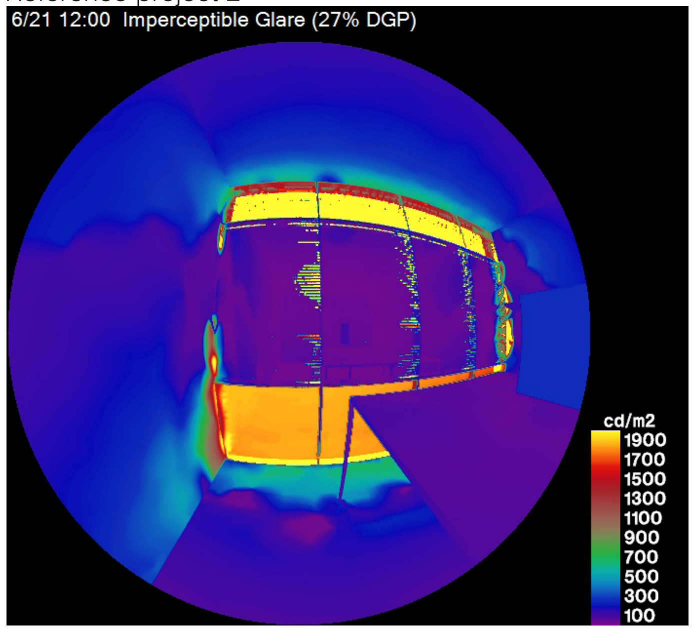

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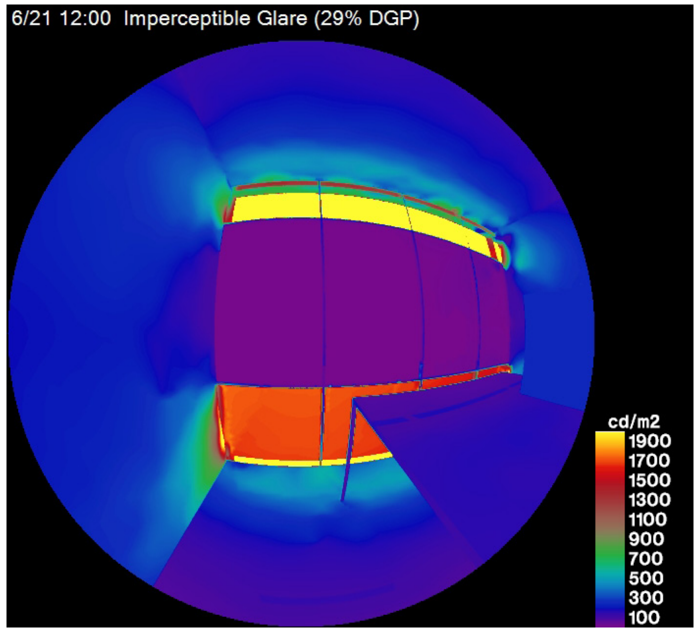

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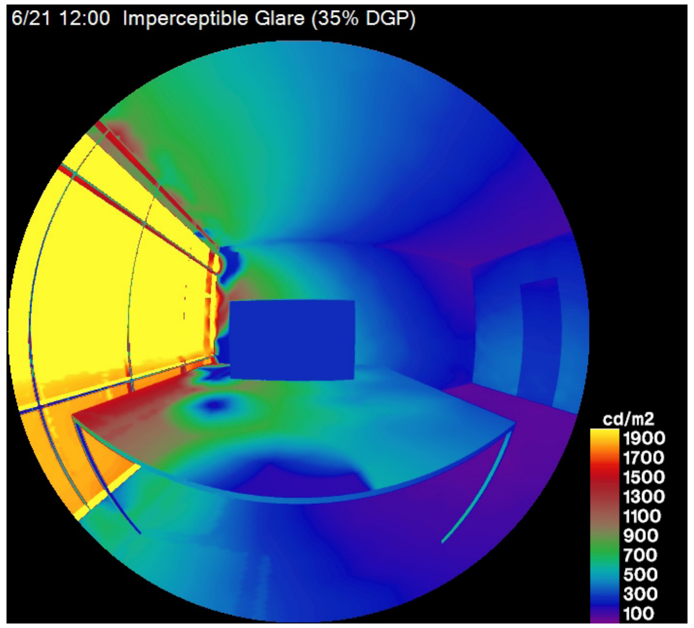

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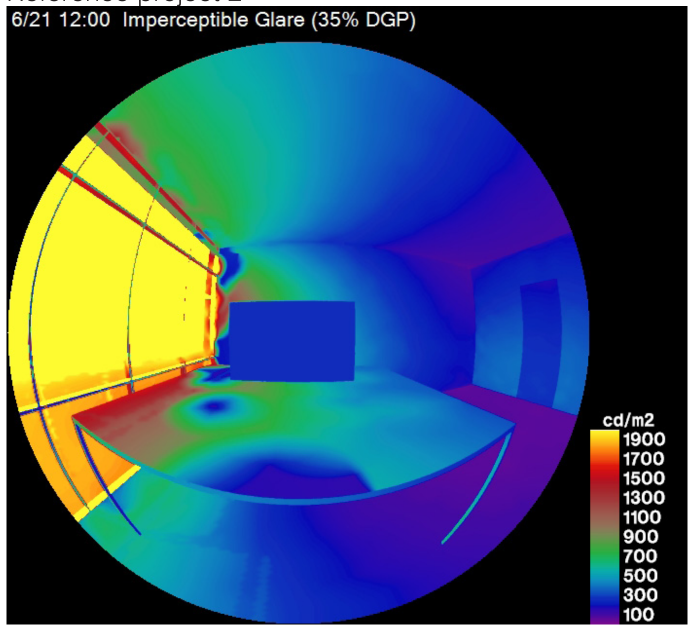

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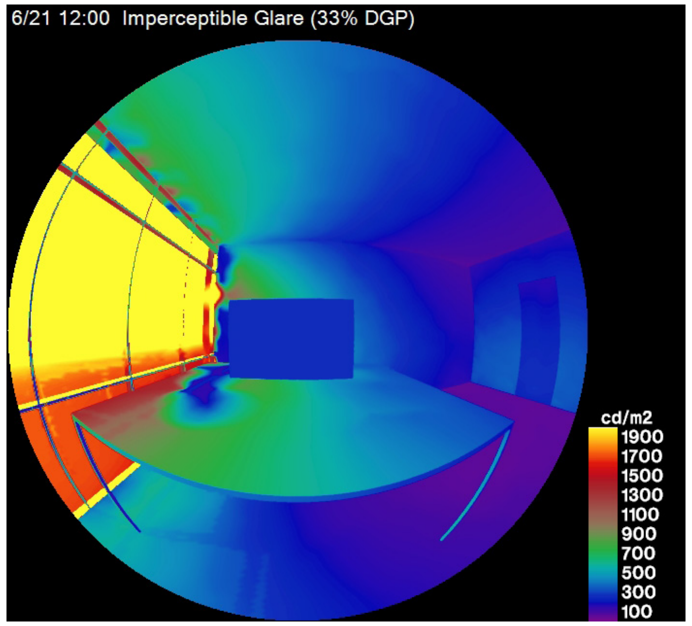

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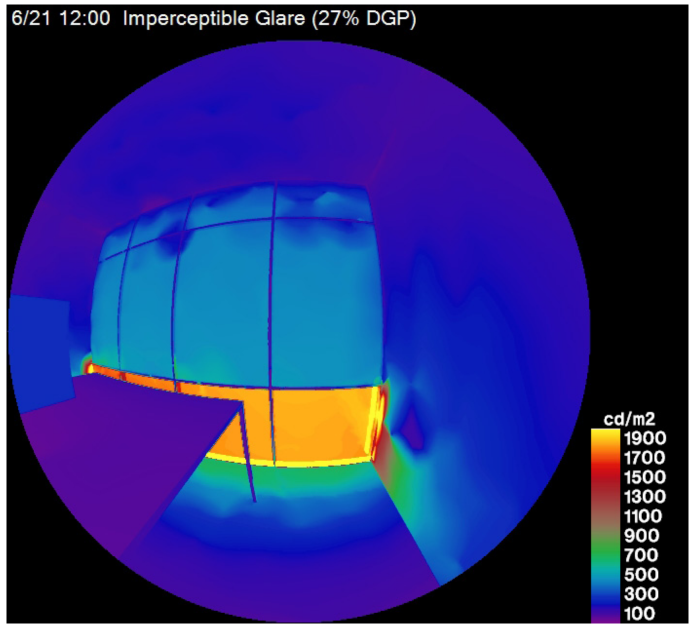

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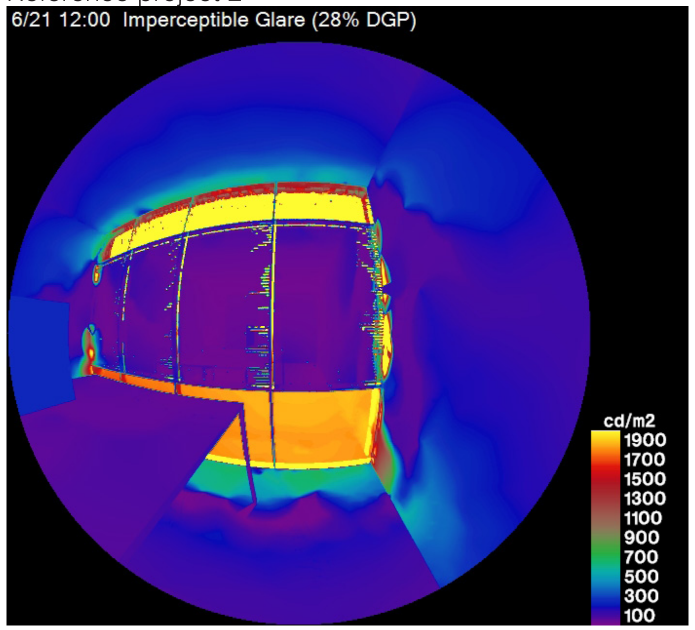

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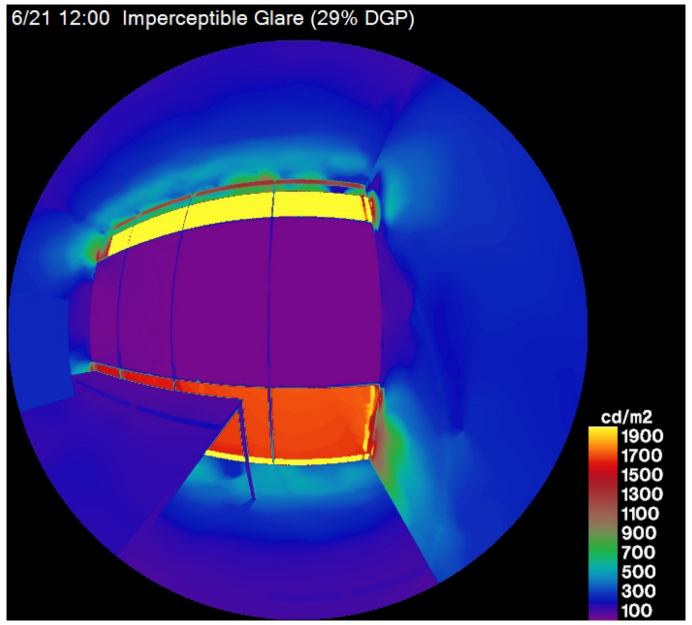

21stJune 12:00, User 2, View to the computer screen

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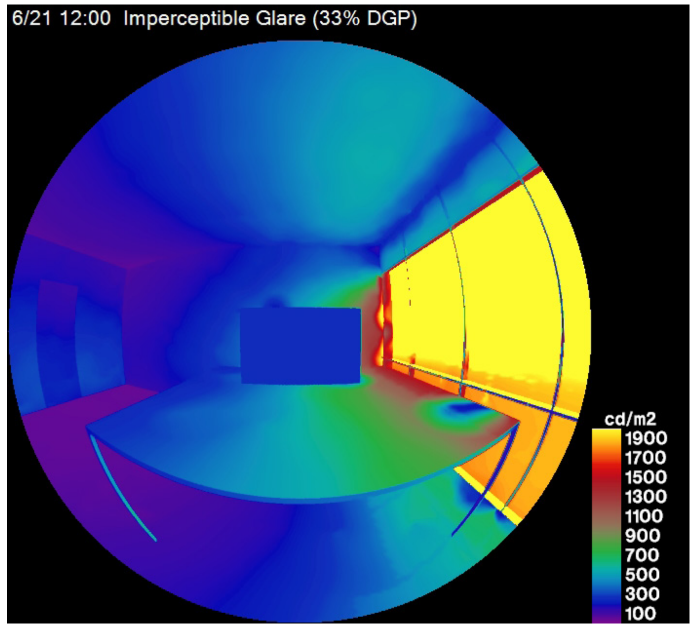

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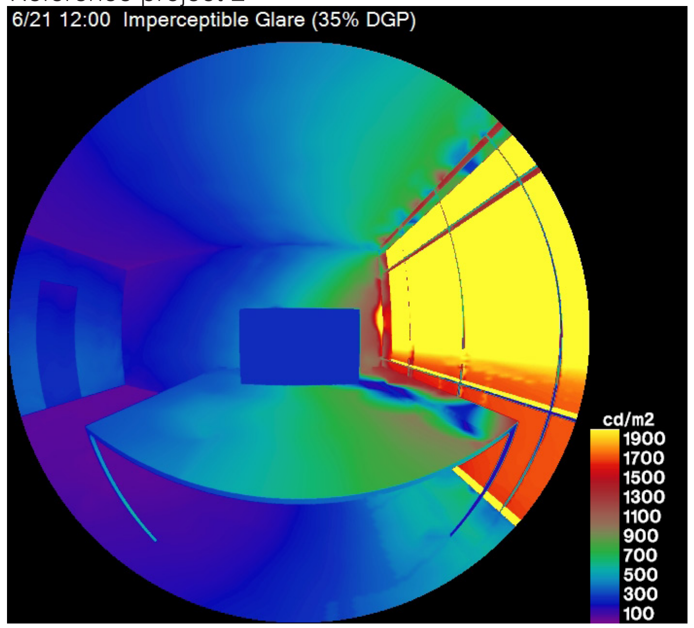

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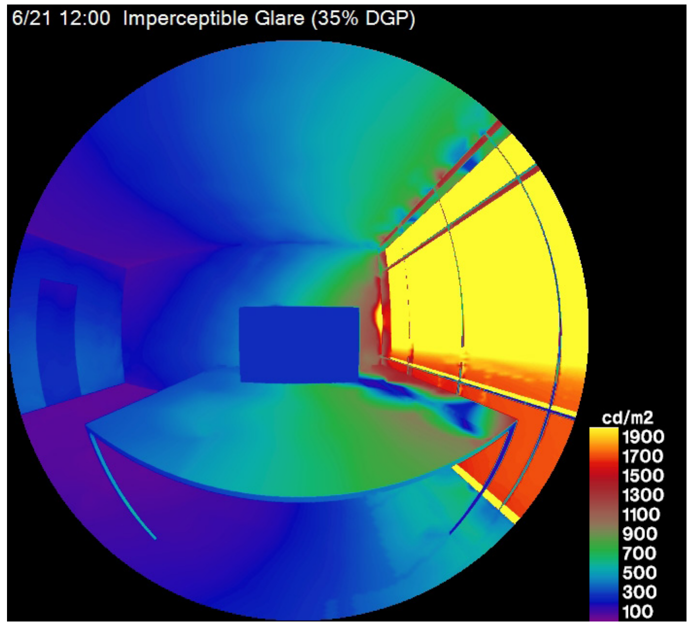

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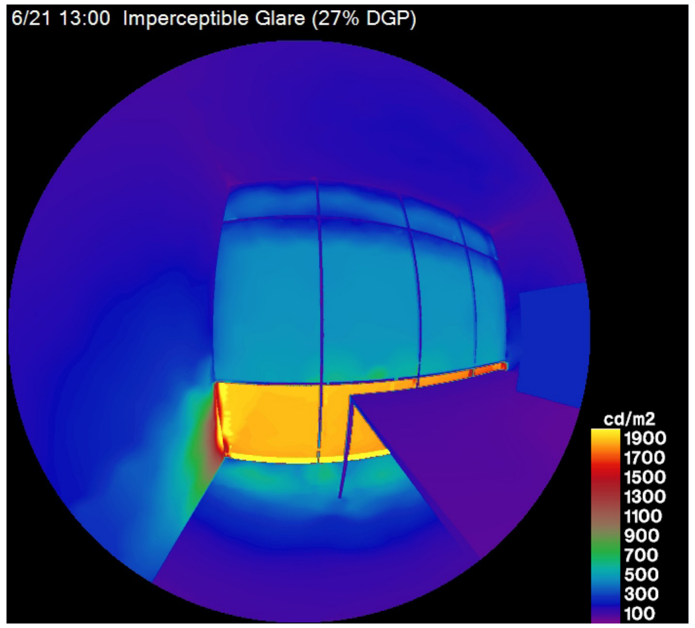

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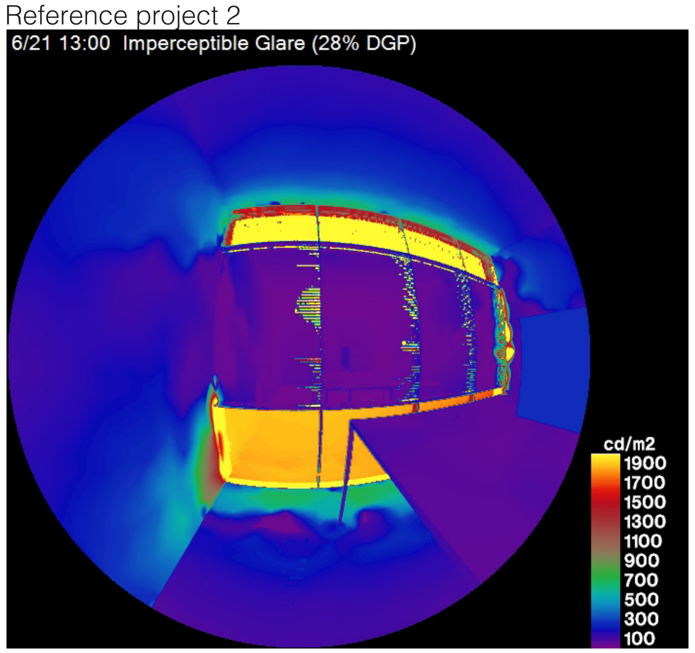

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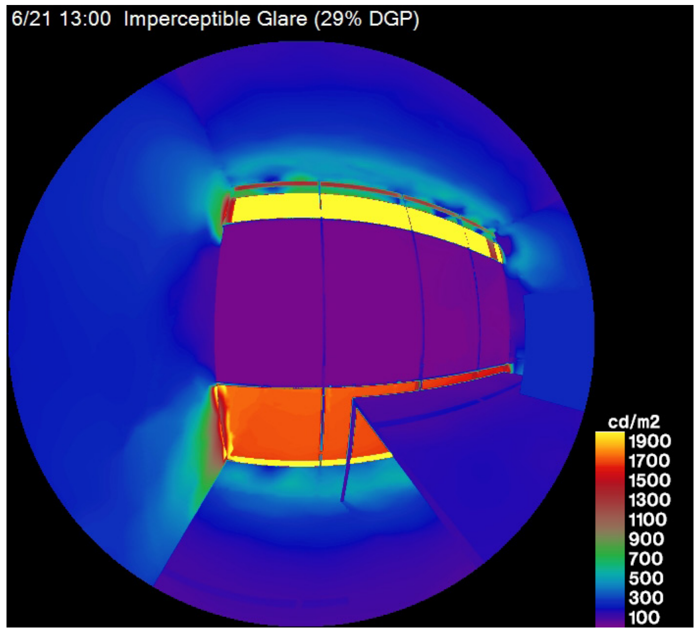

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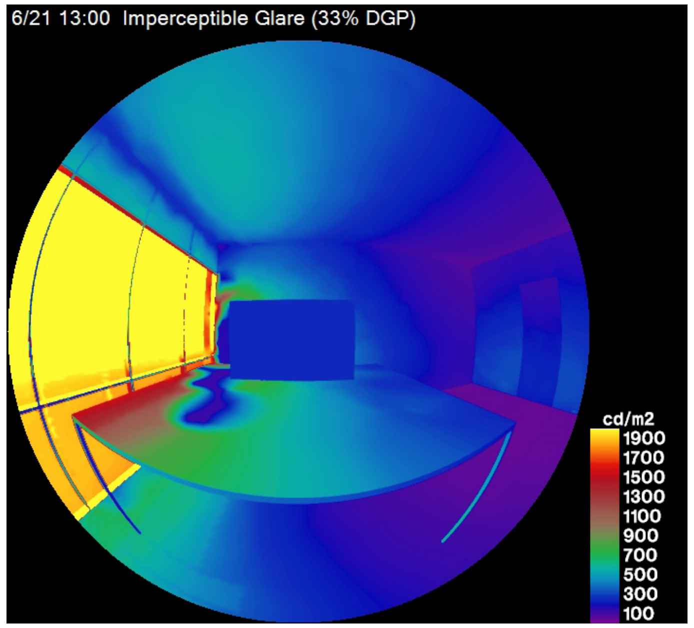

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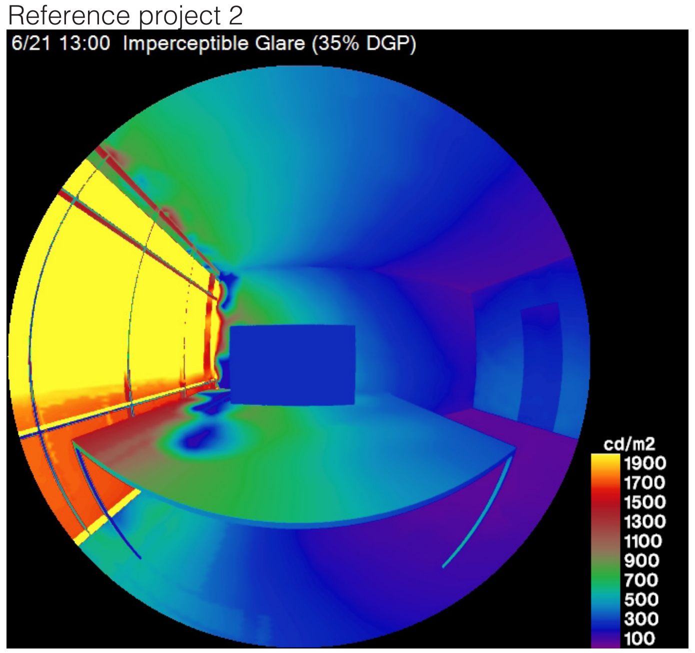

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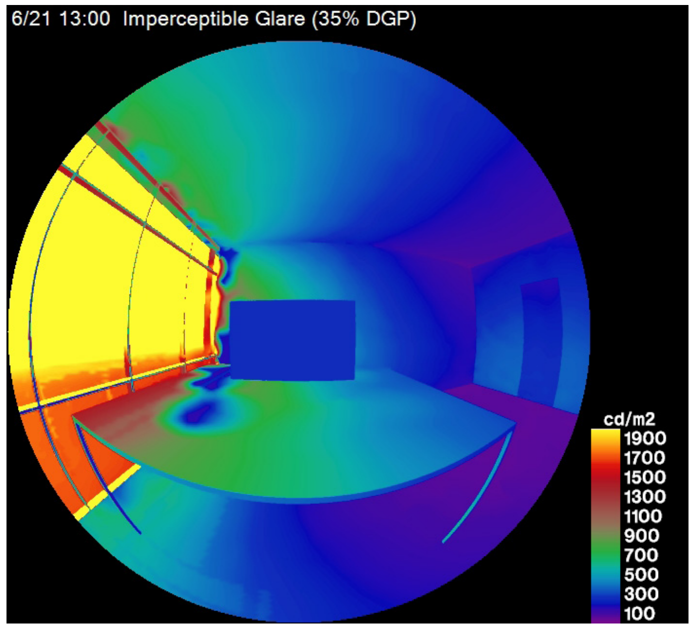
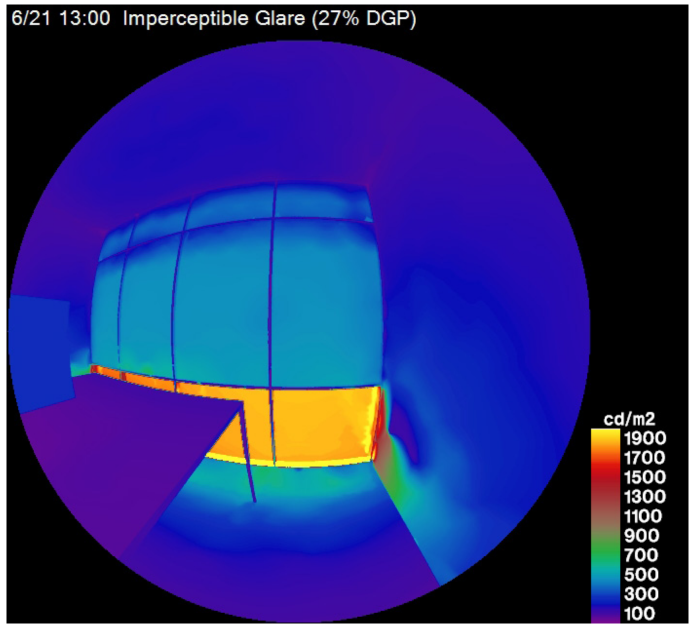


21st June 13:00, User 2, View to the window

Reference project 1



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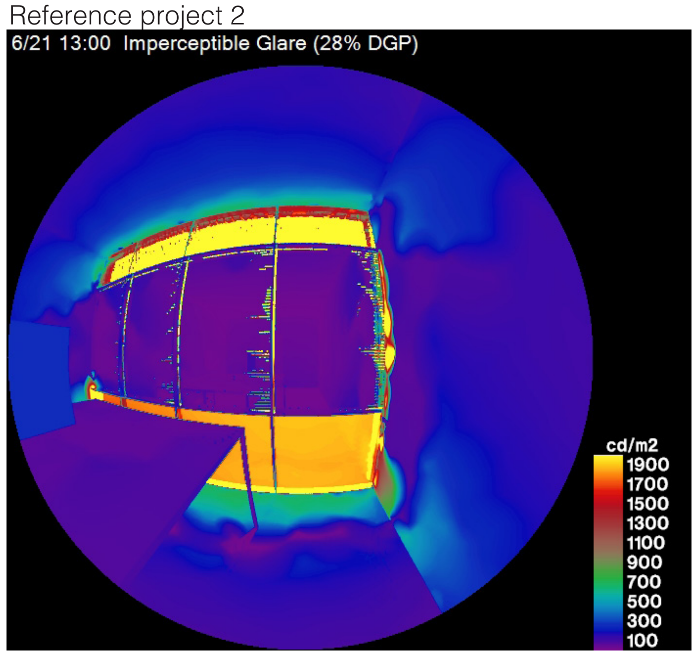

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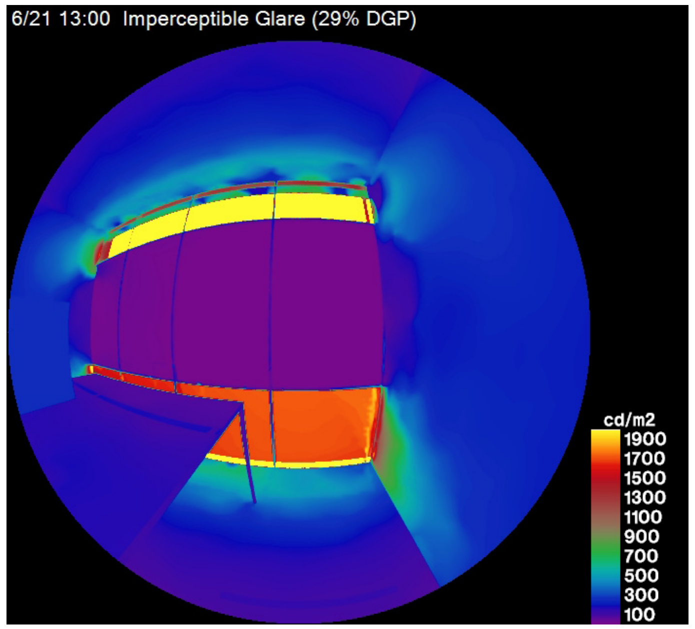

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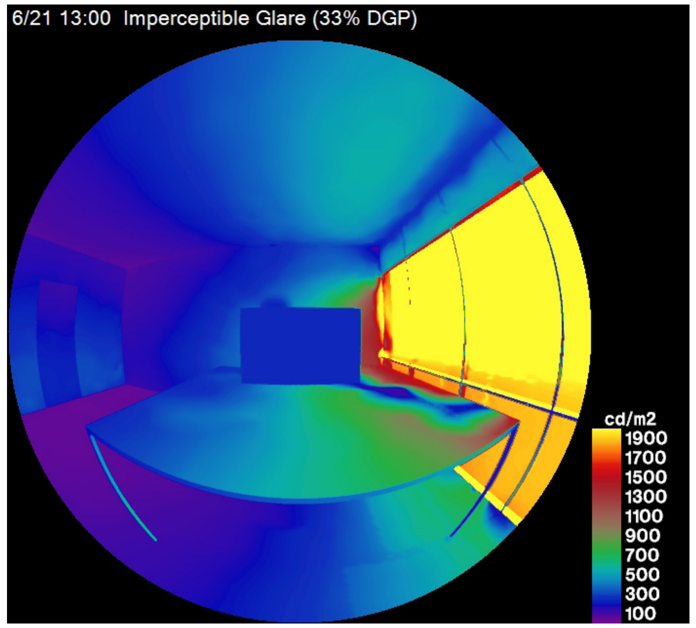

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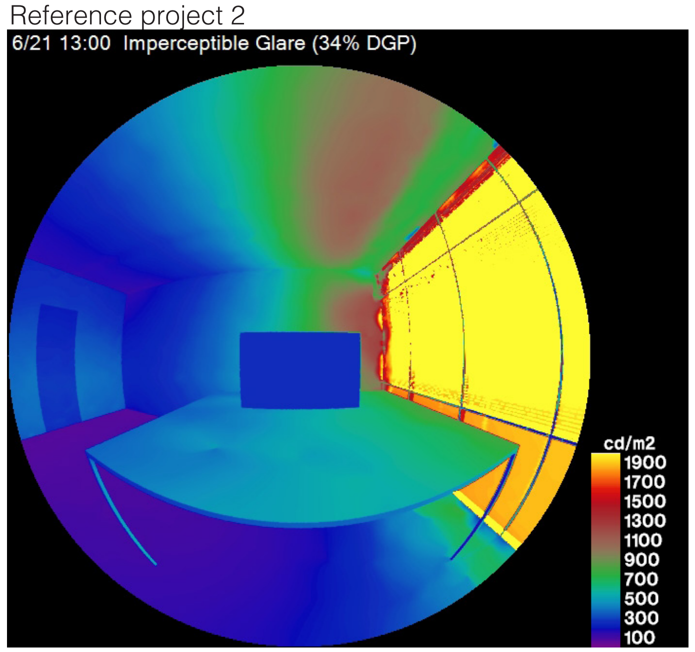

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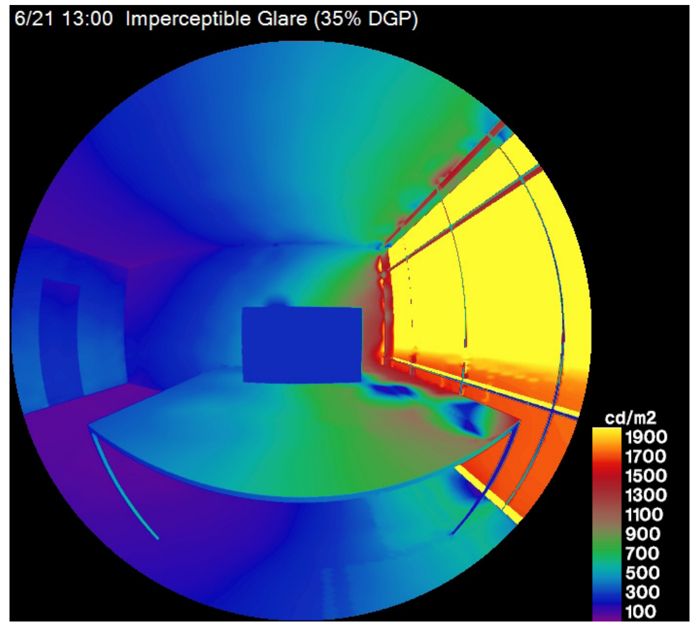

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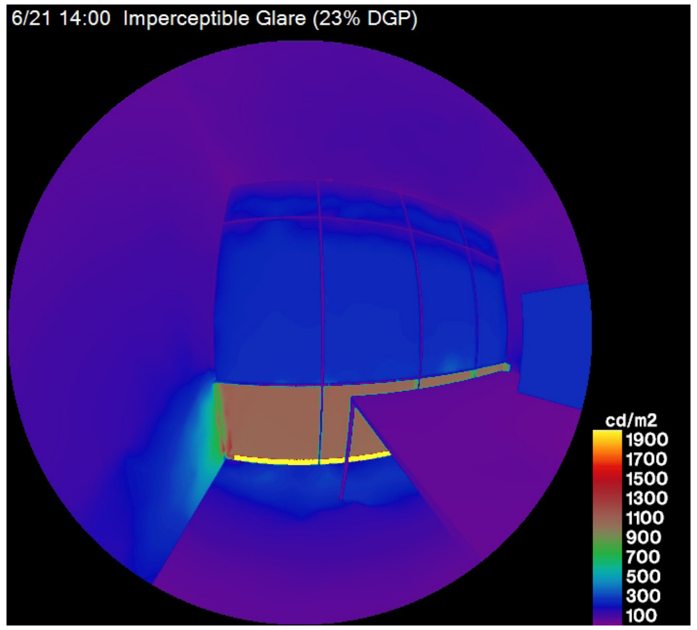

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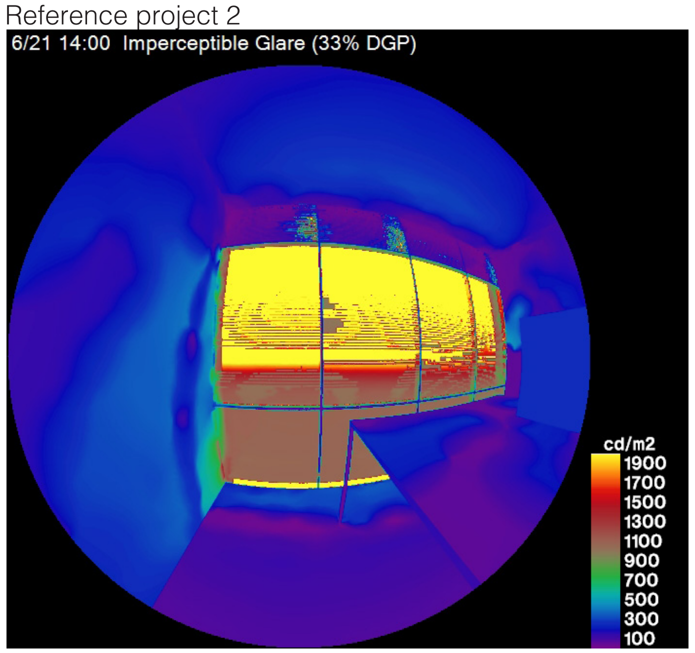

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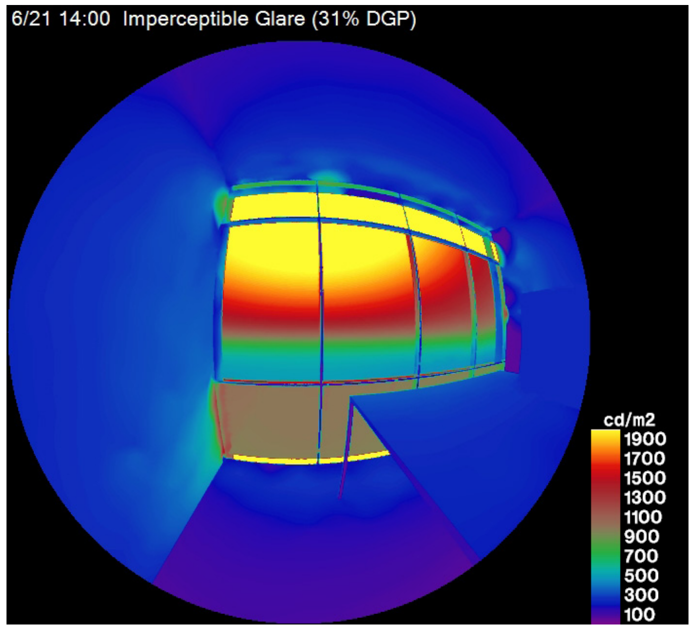

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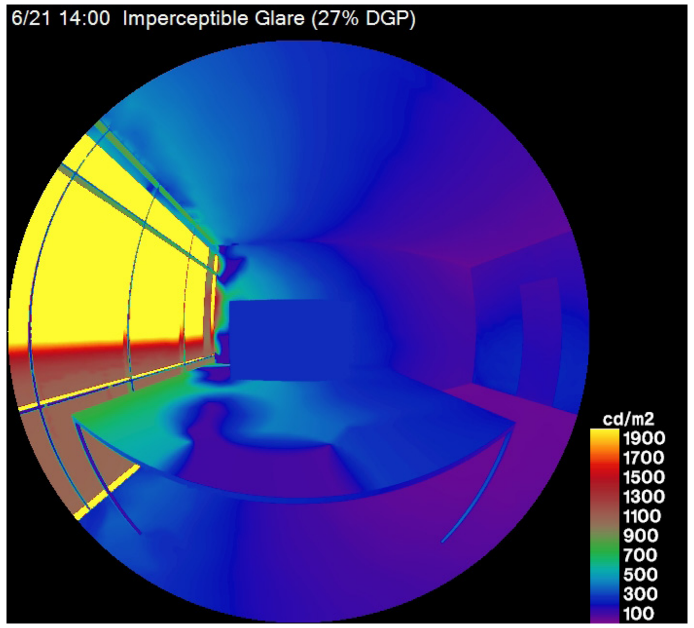

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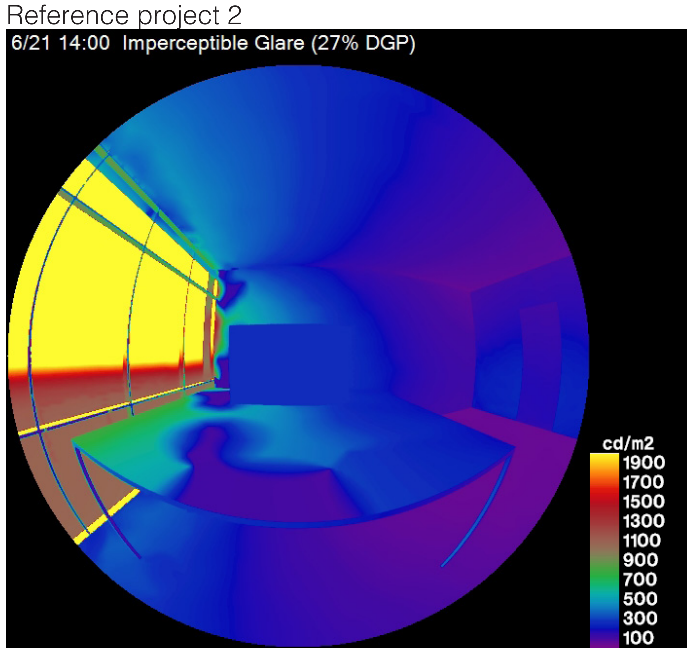

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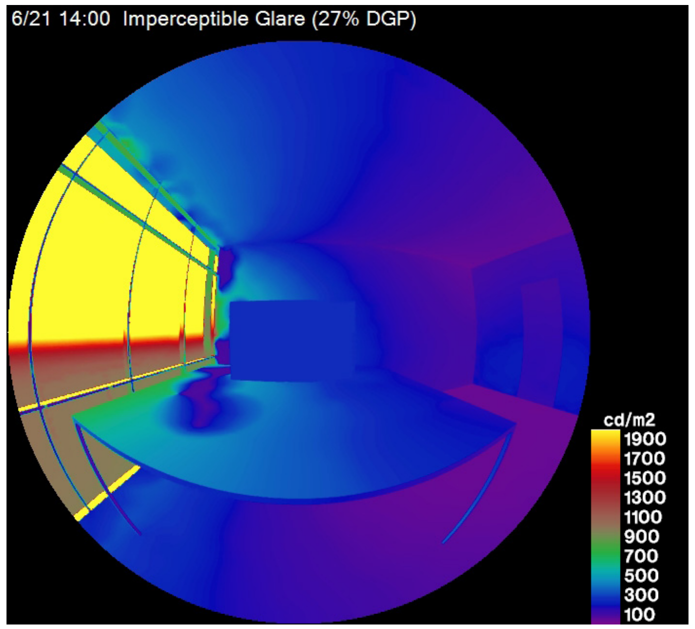

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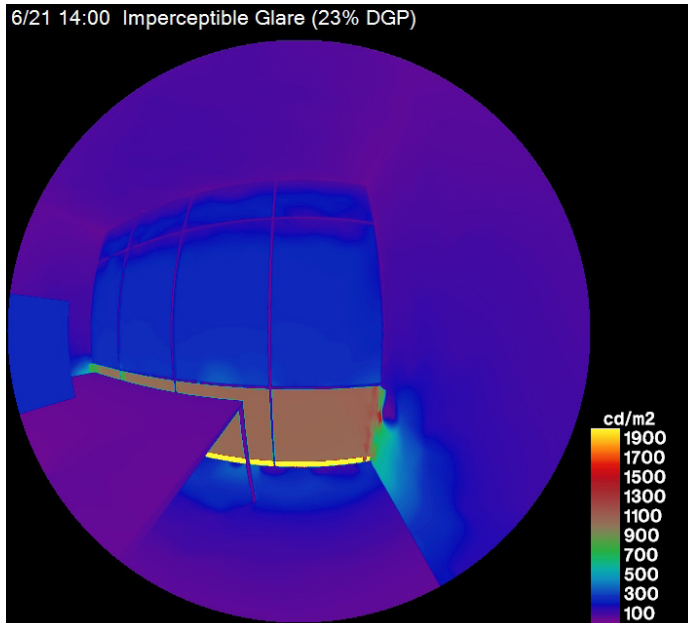

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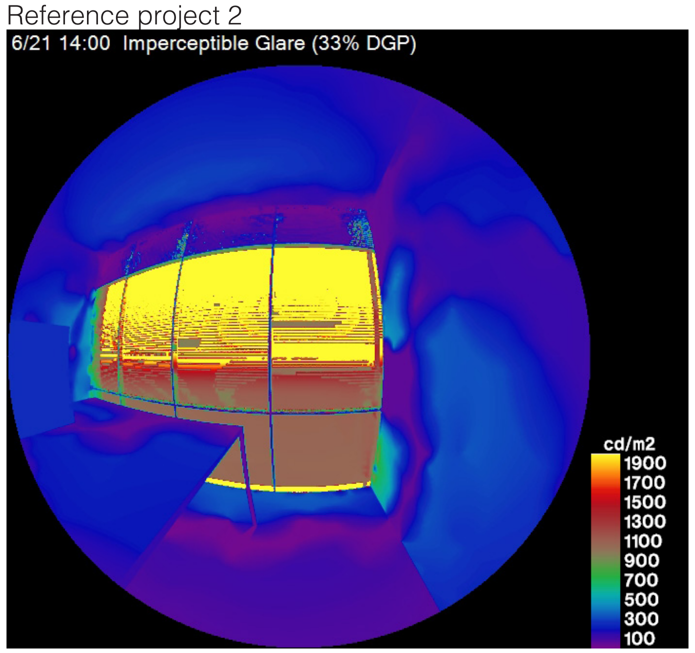

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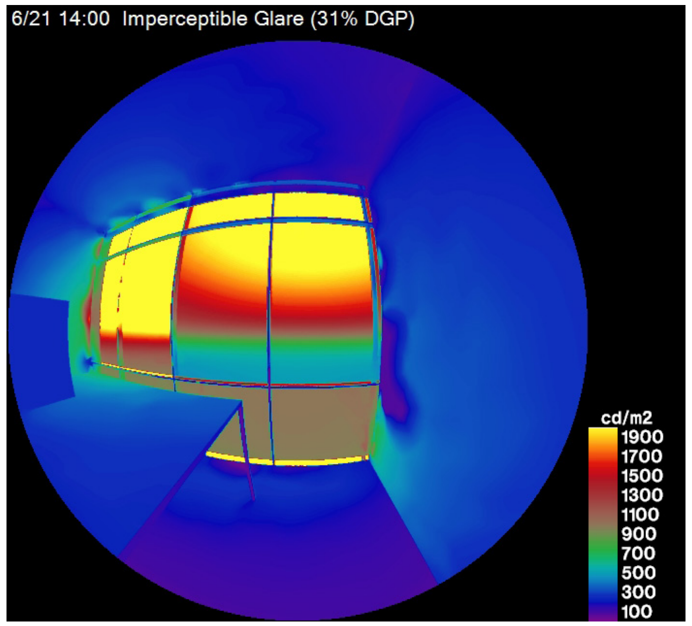

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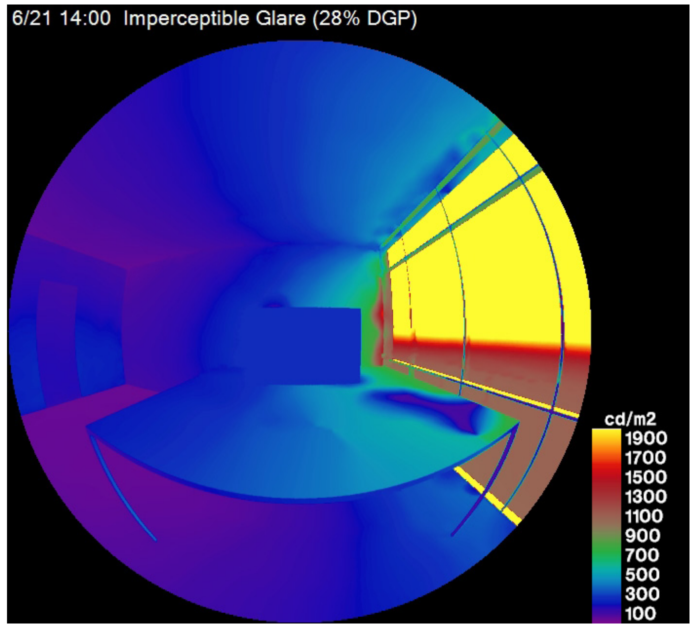

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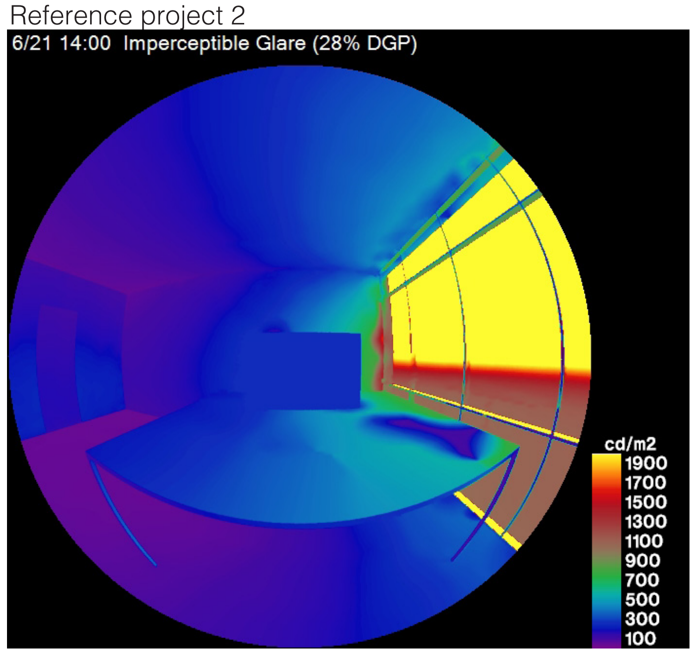

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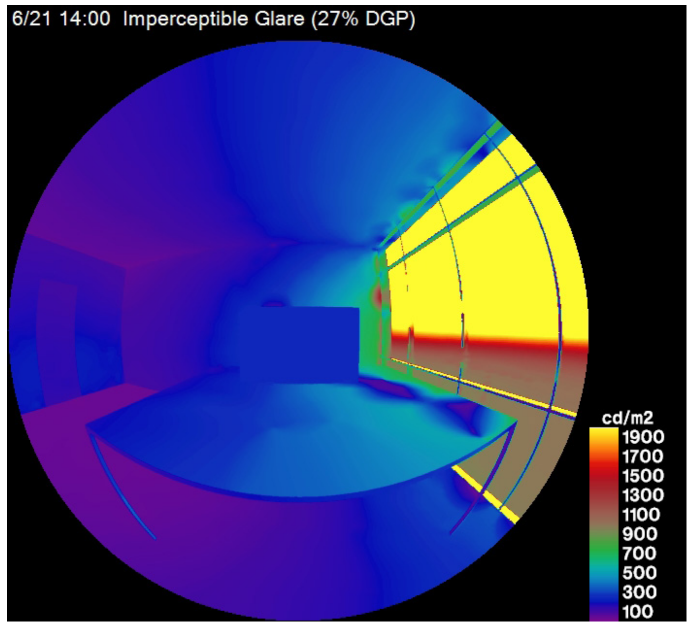

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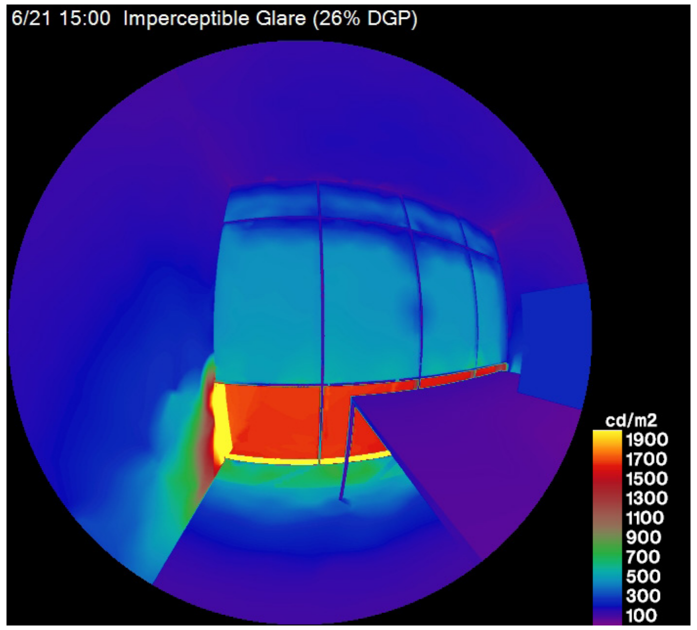

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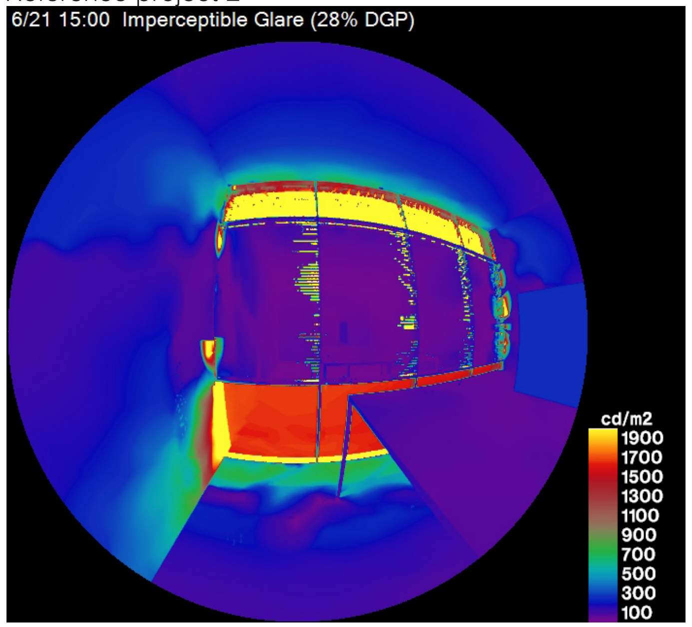

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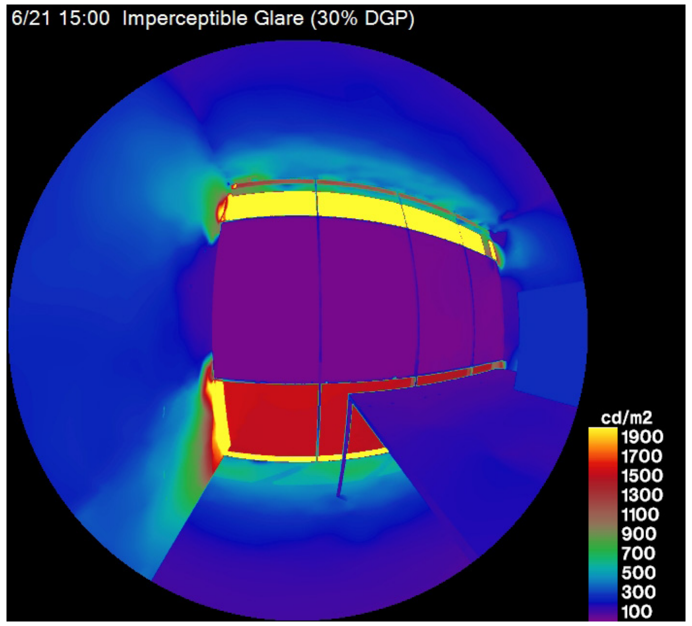

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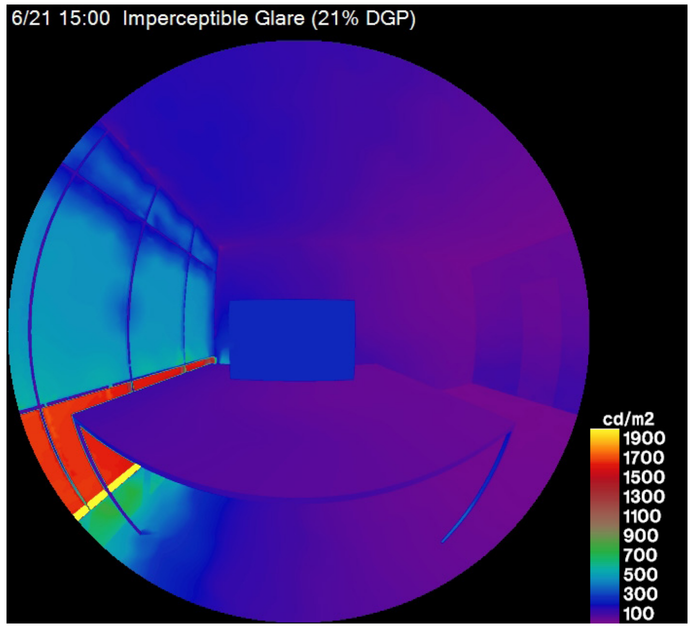

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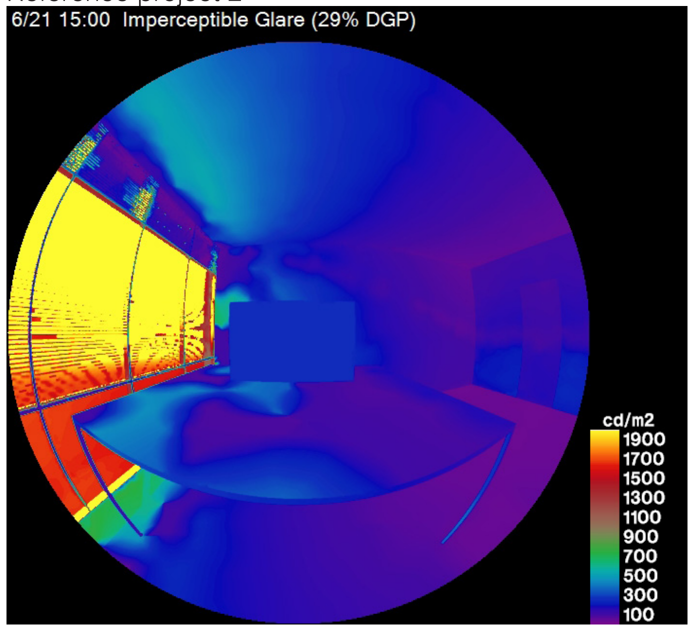

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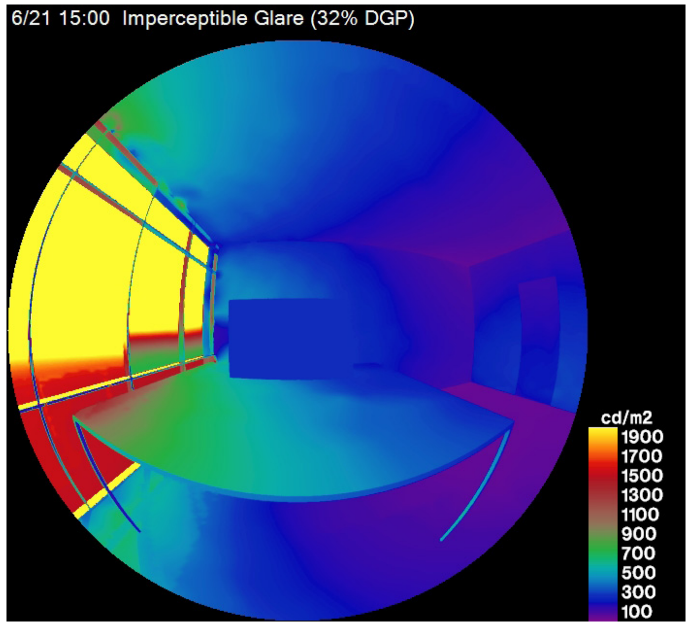

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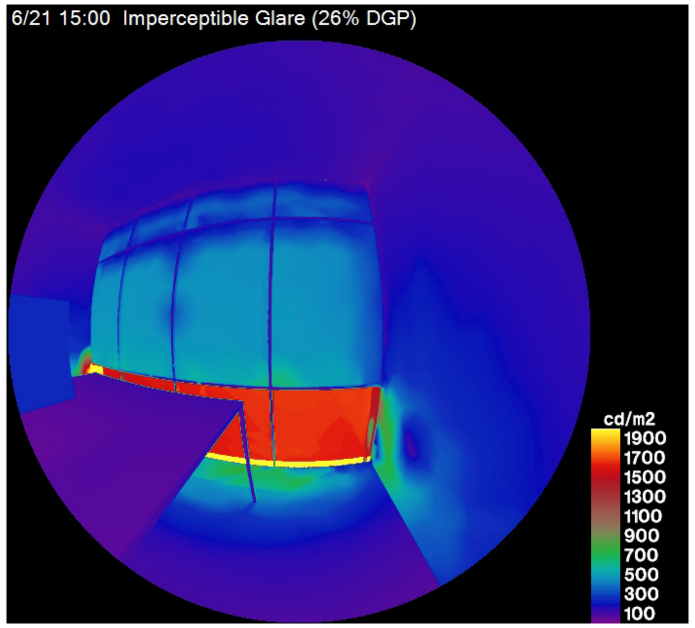

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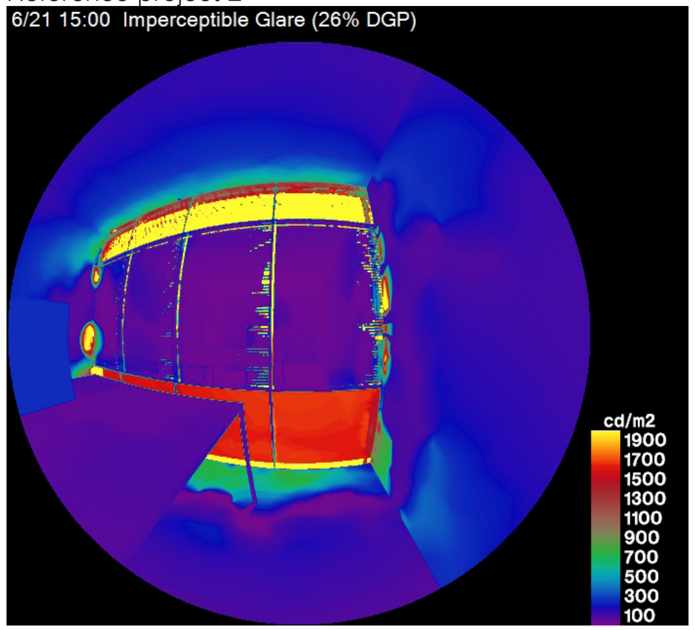

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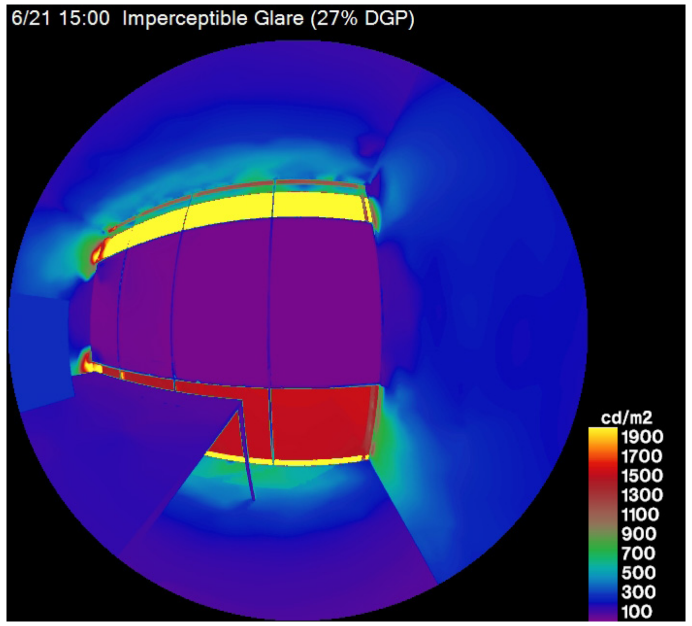

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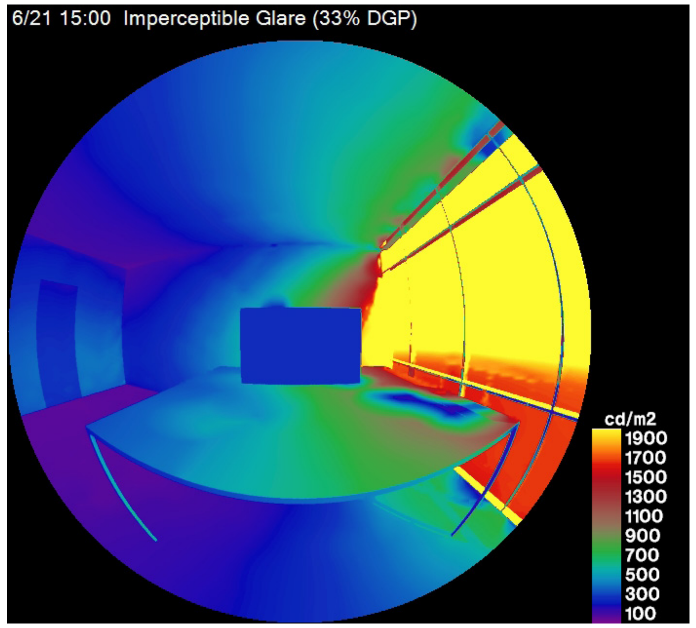

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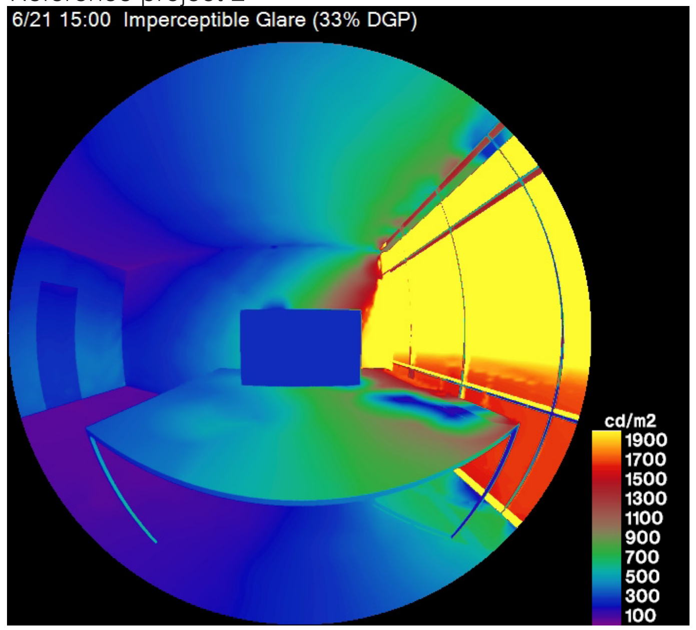

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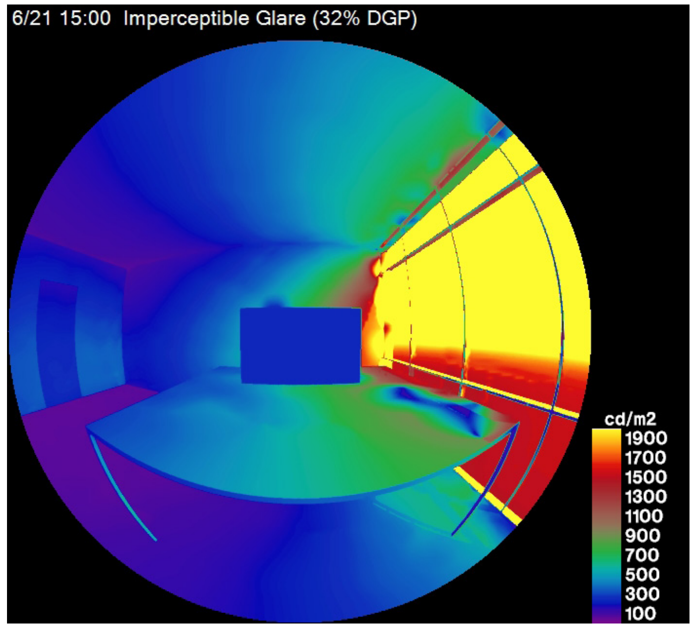

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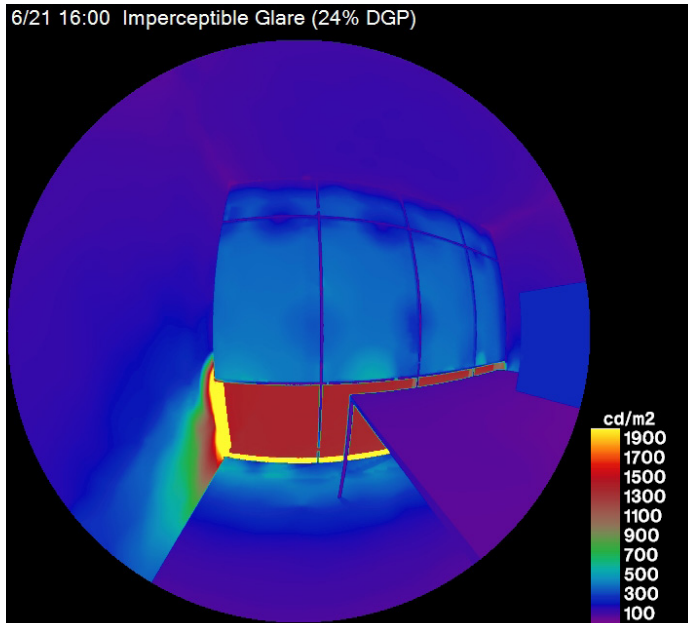

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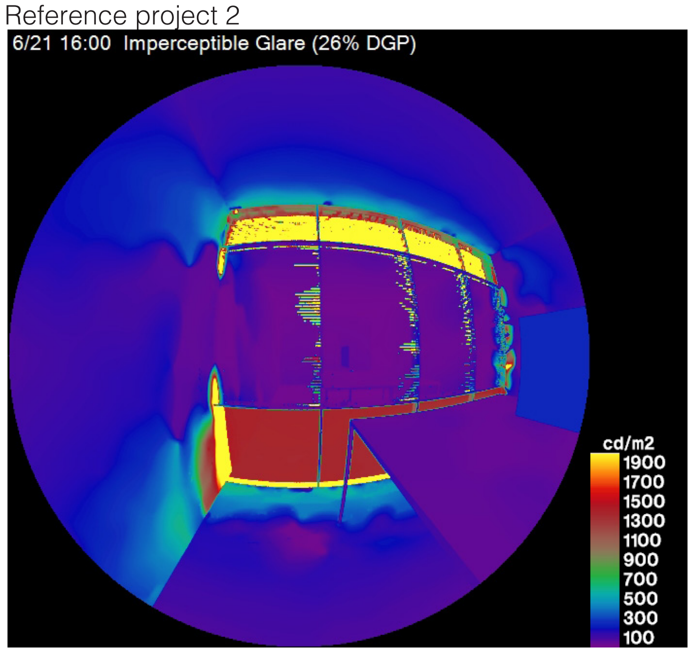

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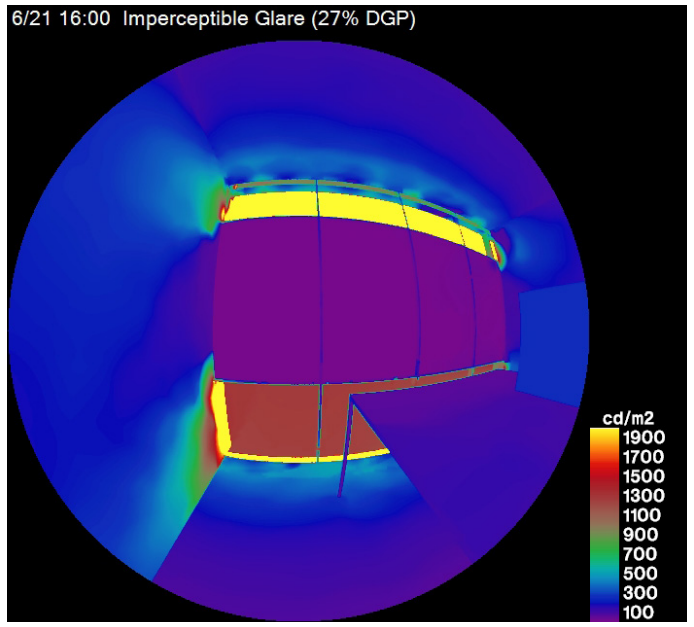

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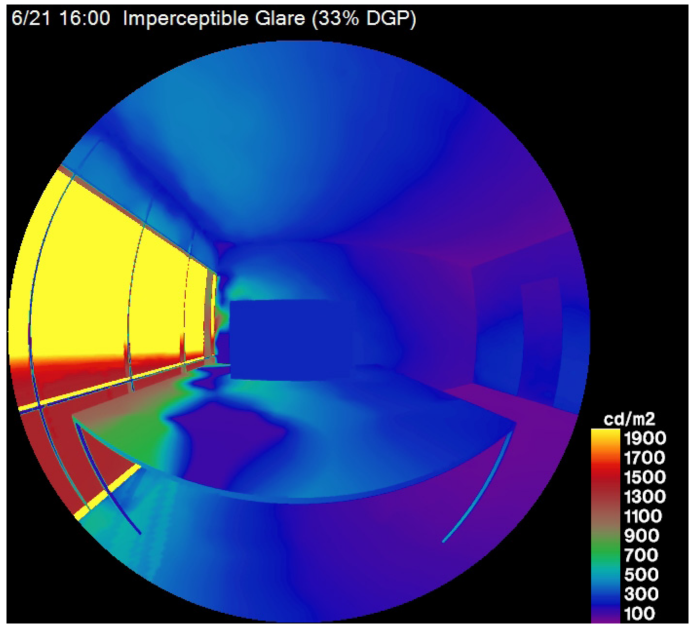

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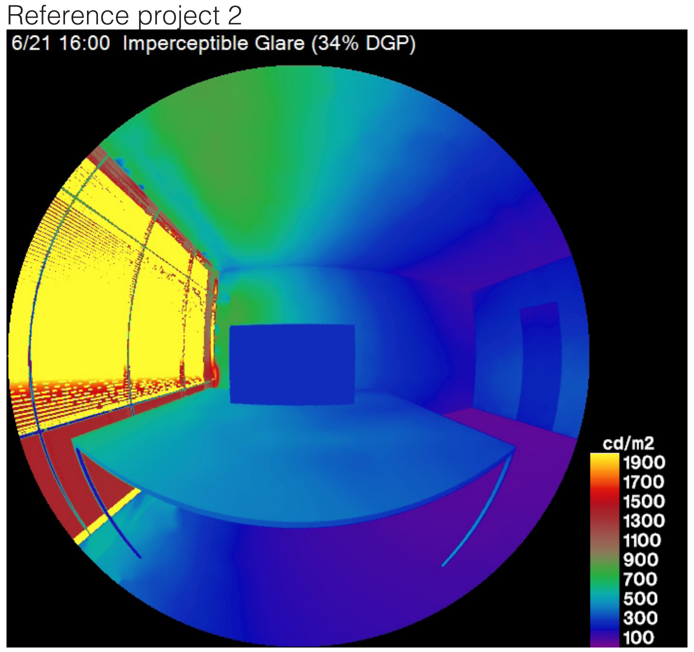

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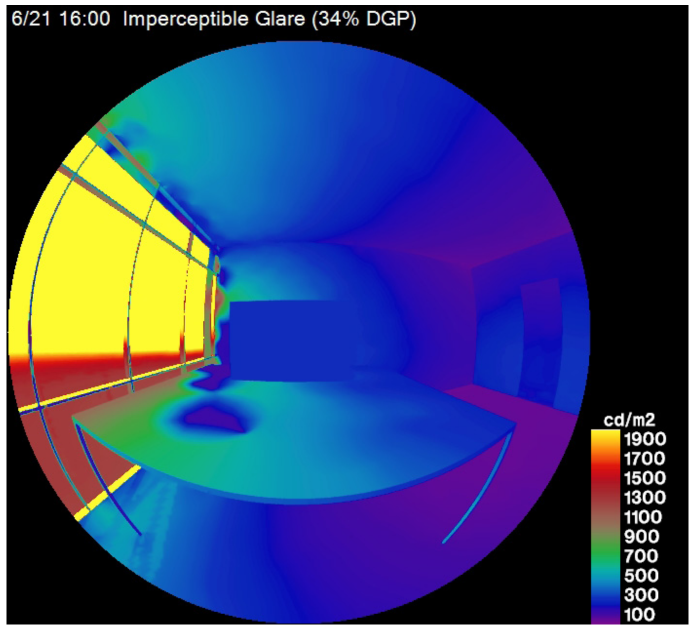

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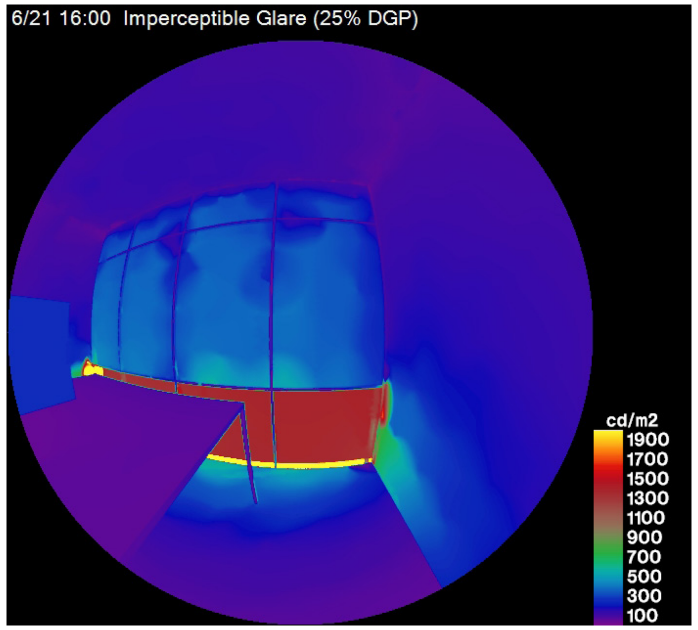

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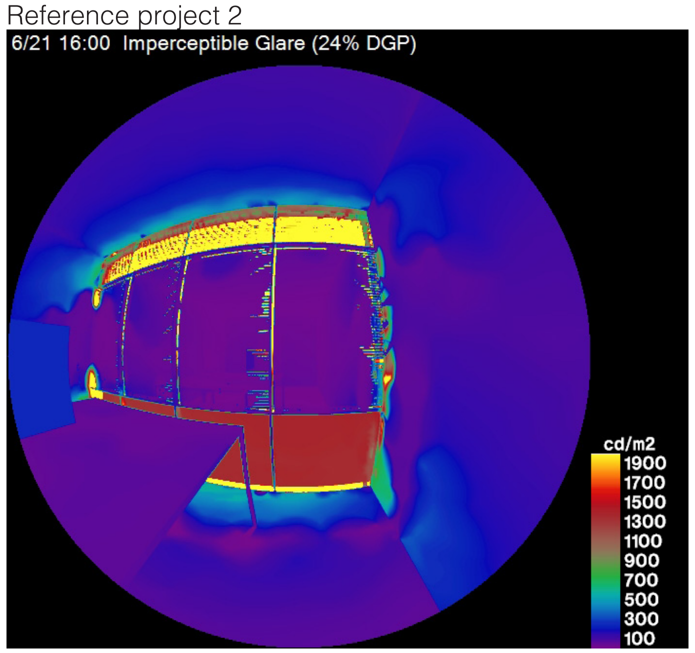

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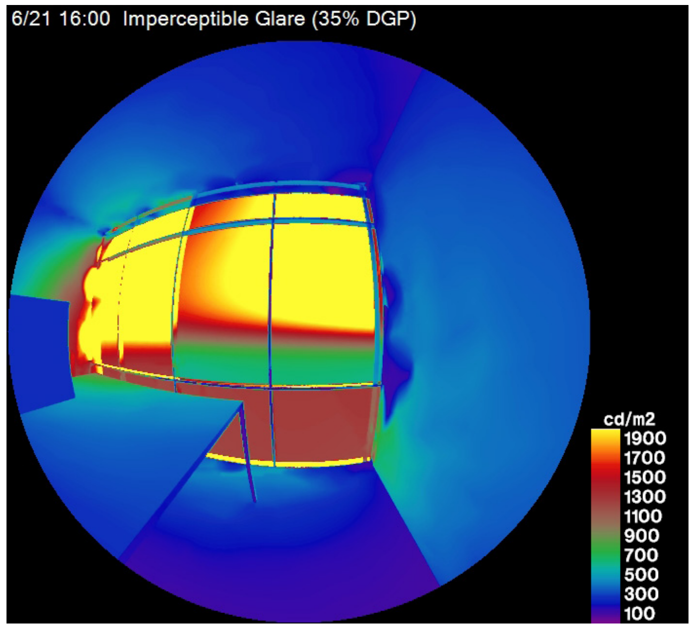

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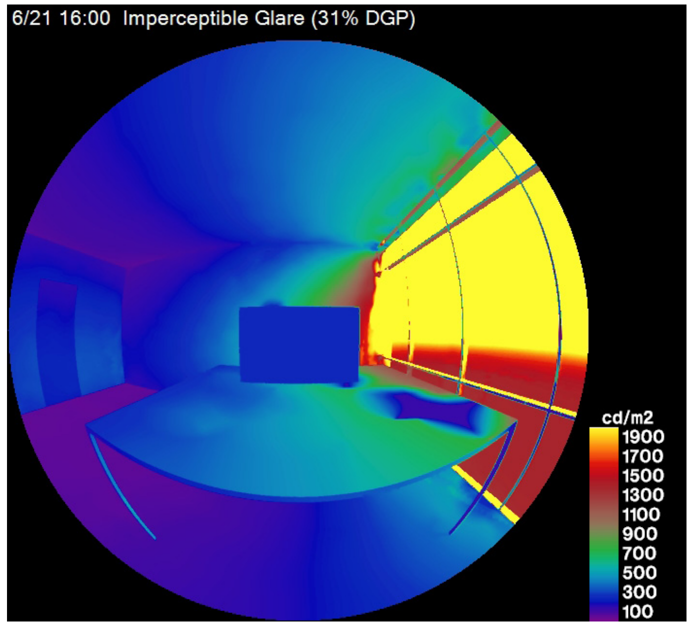

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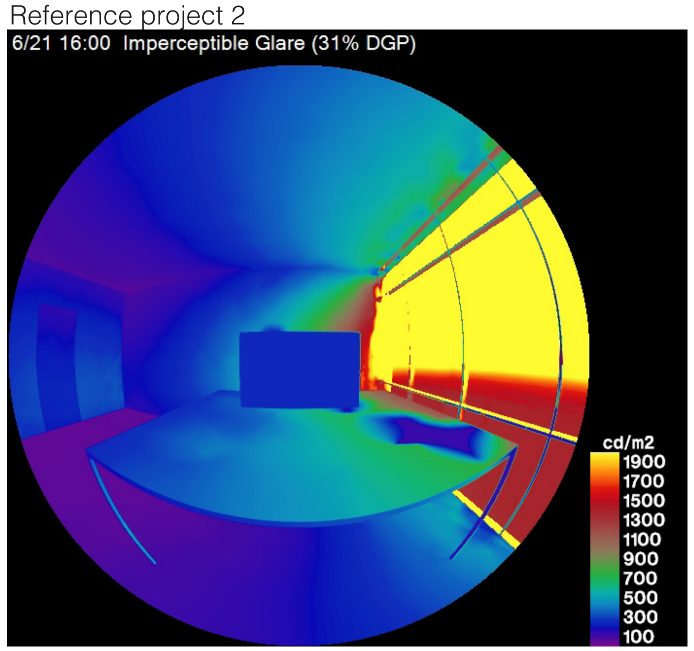

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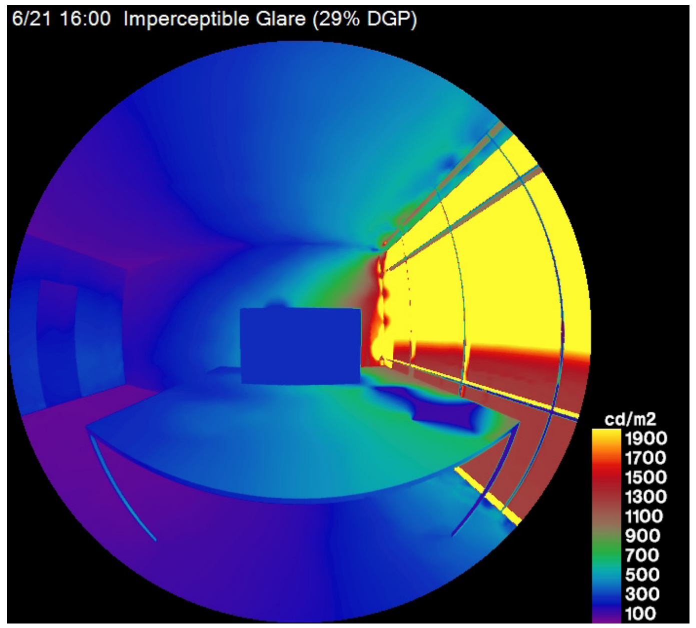

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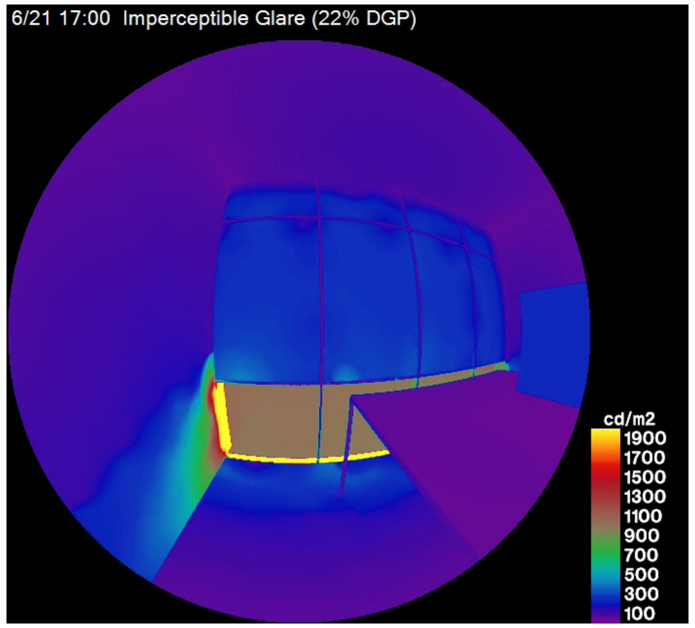

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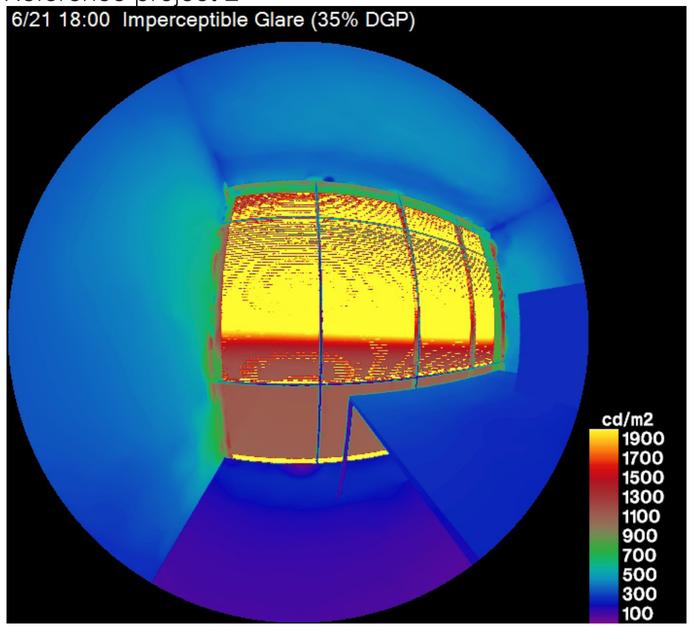

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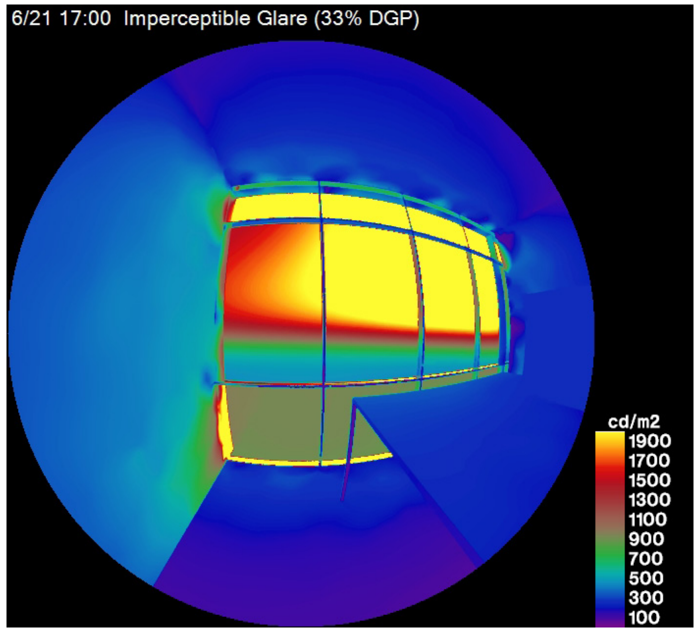

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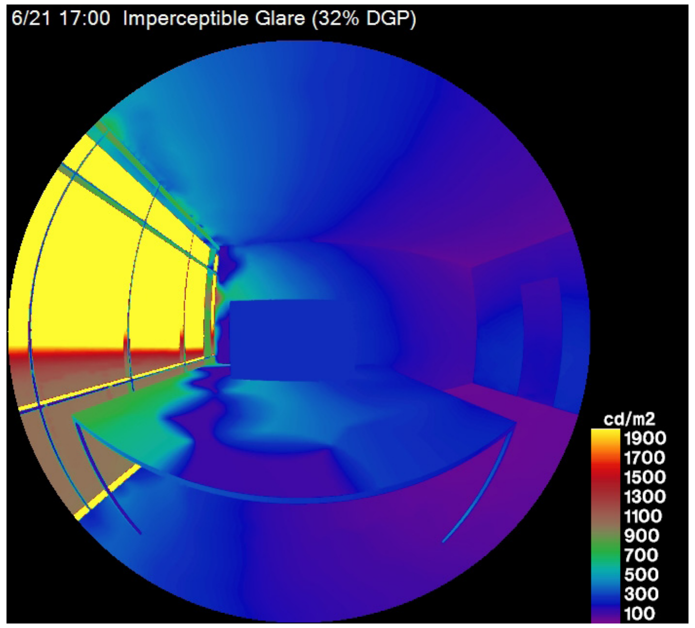

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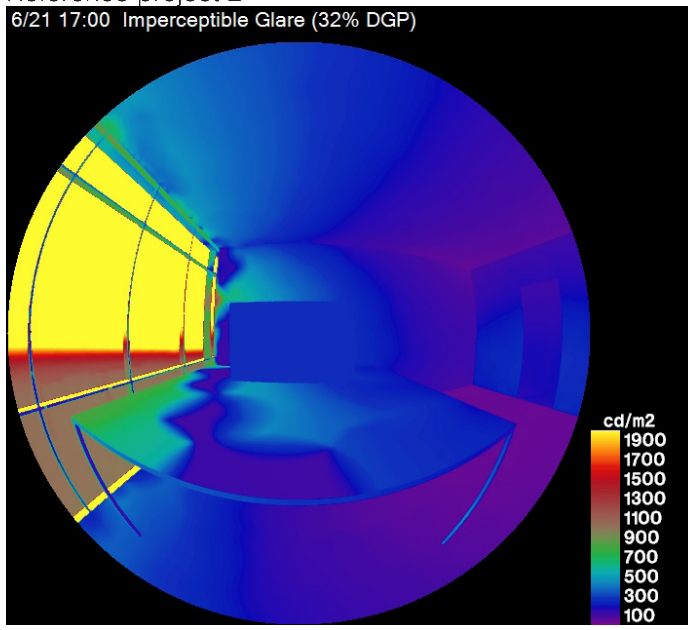

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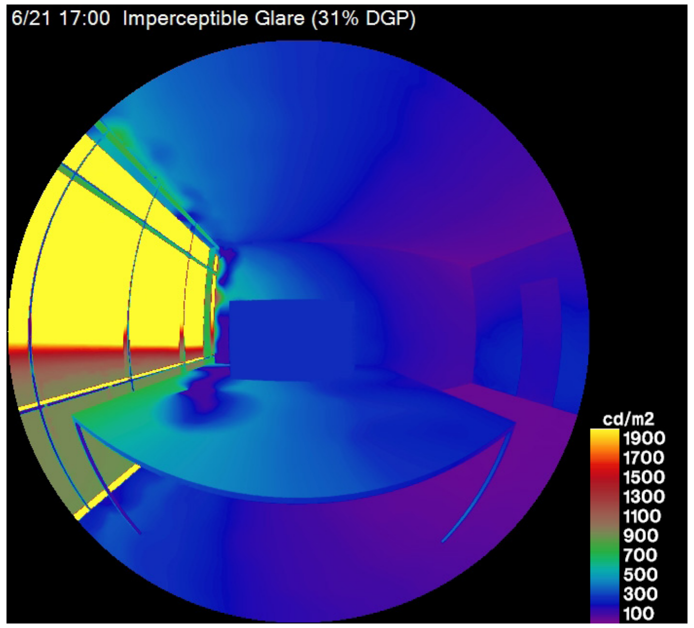

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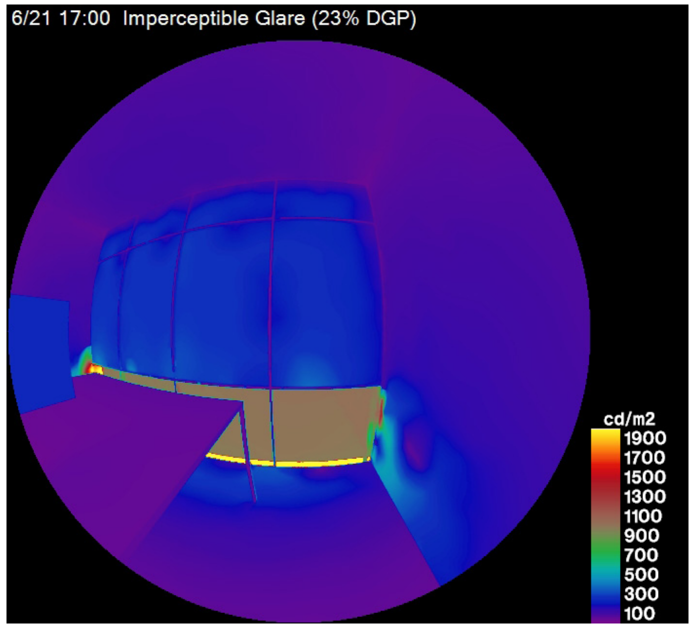

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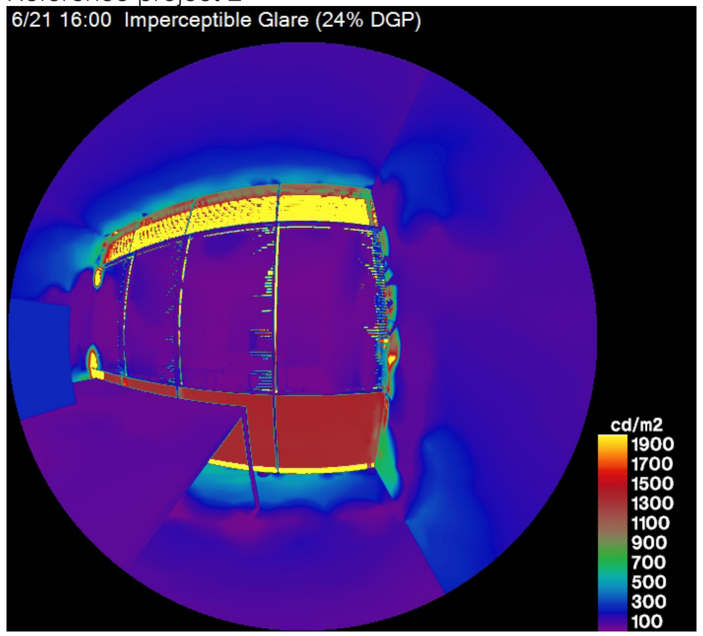

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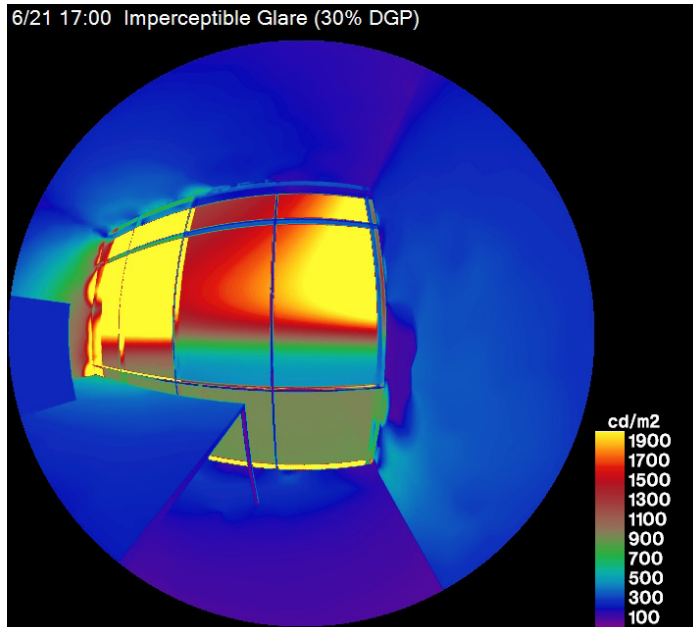

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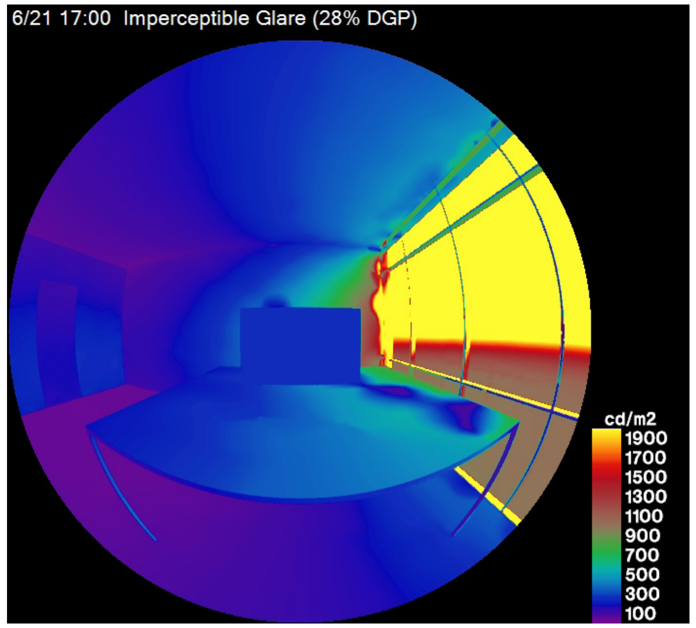

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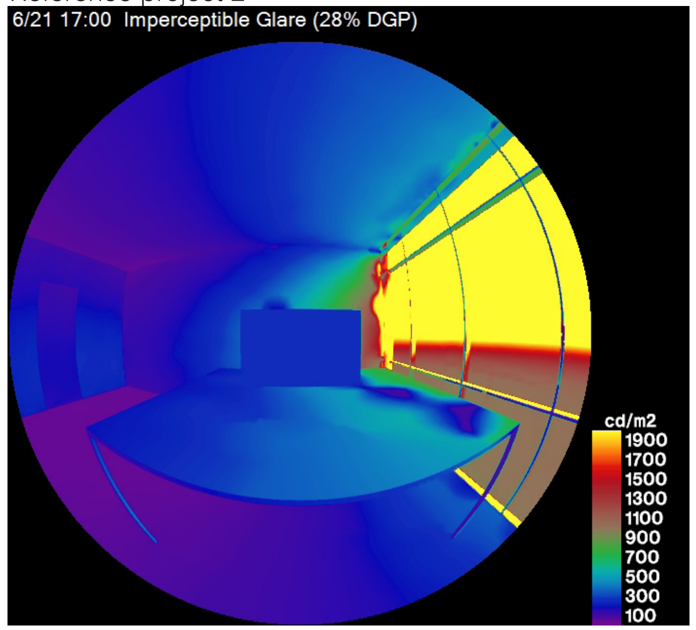

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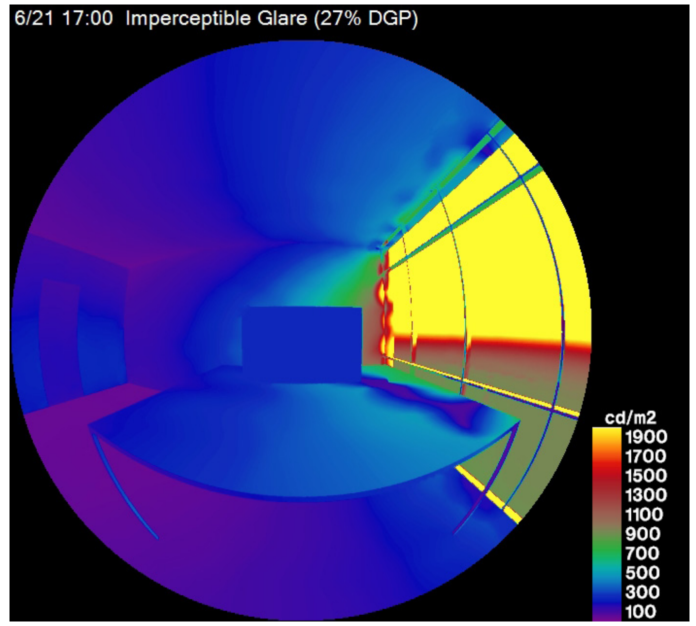

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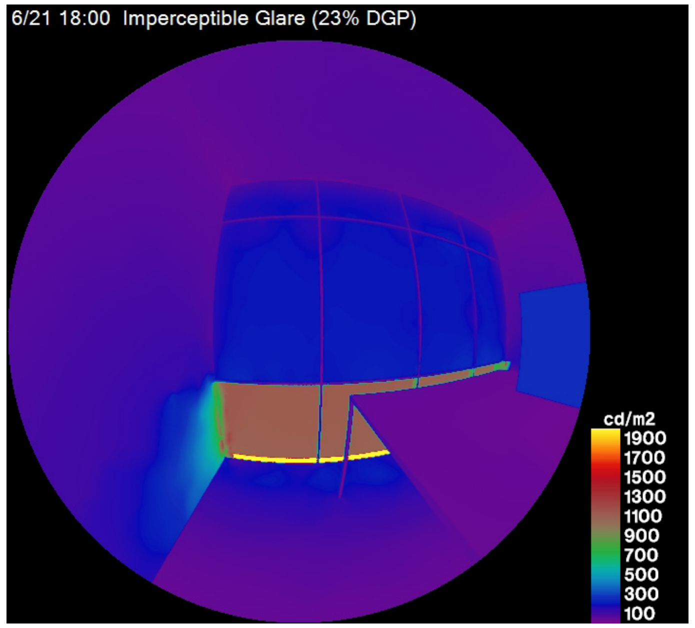

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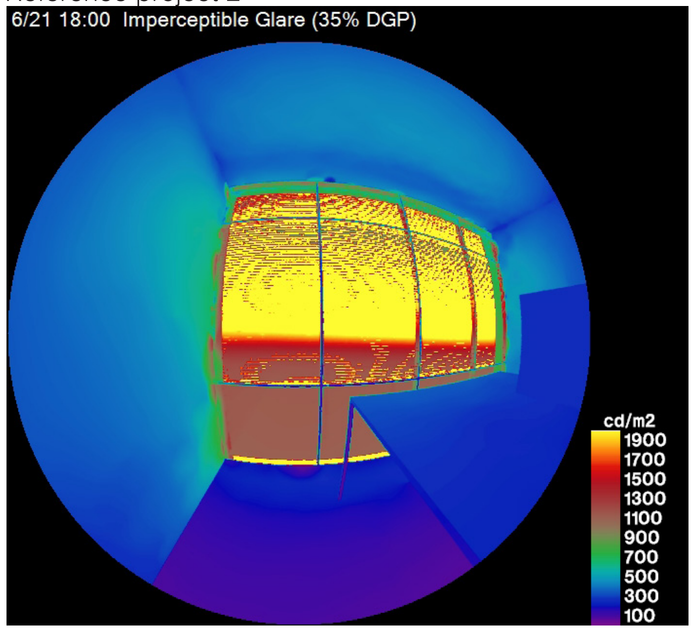

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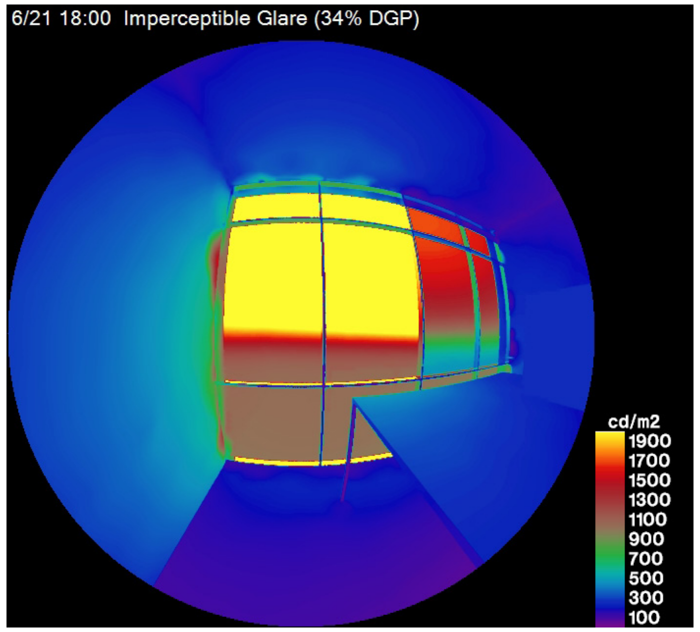

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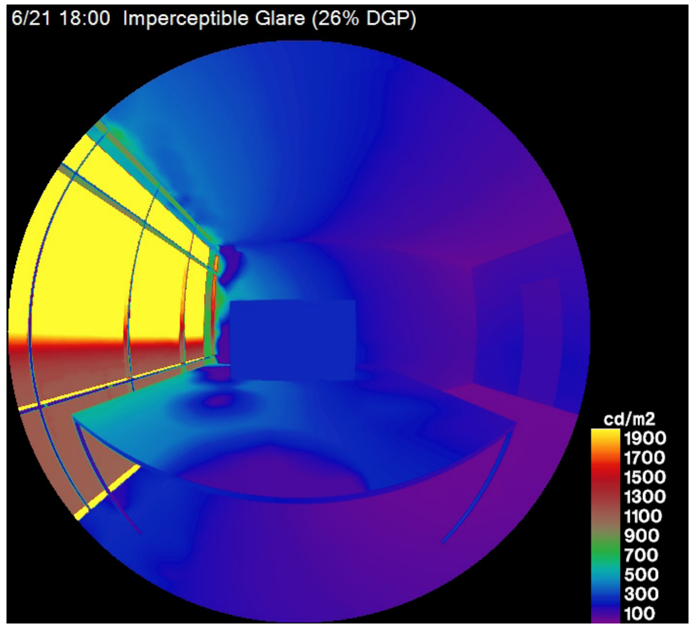

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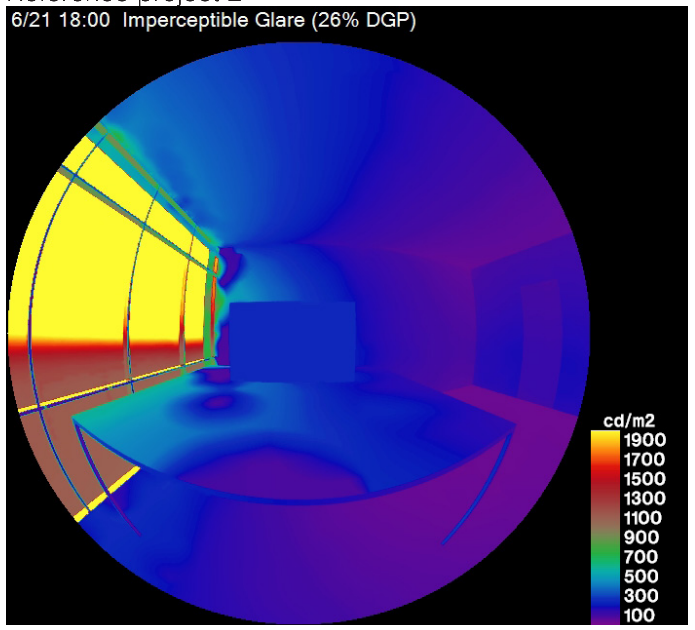

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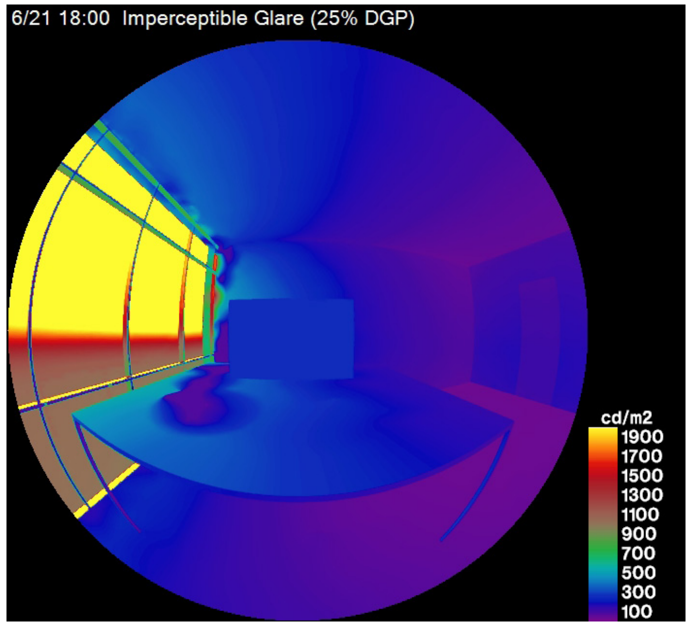

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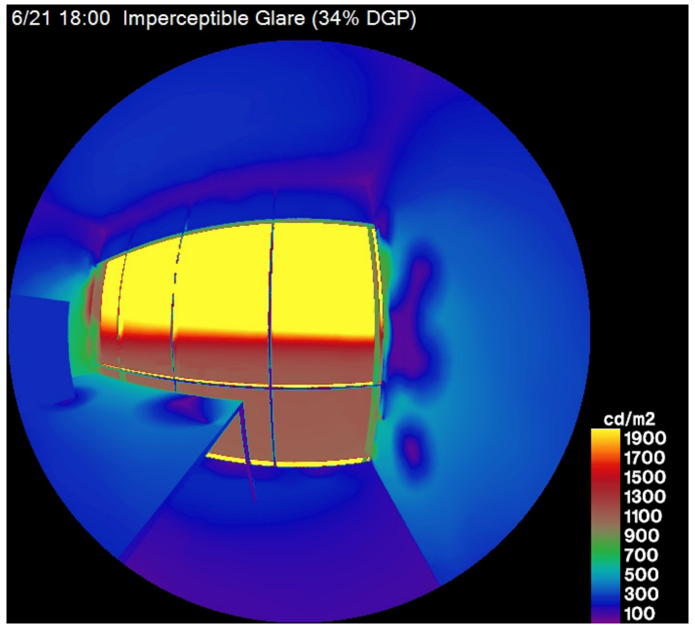

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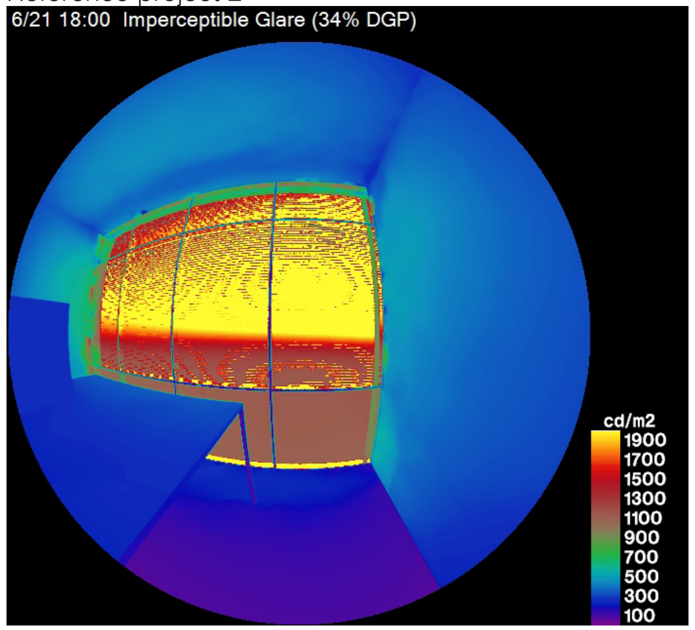

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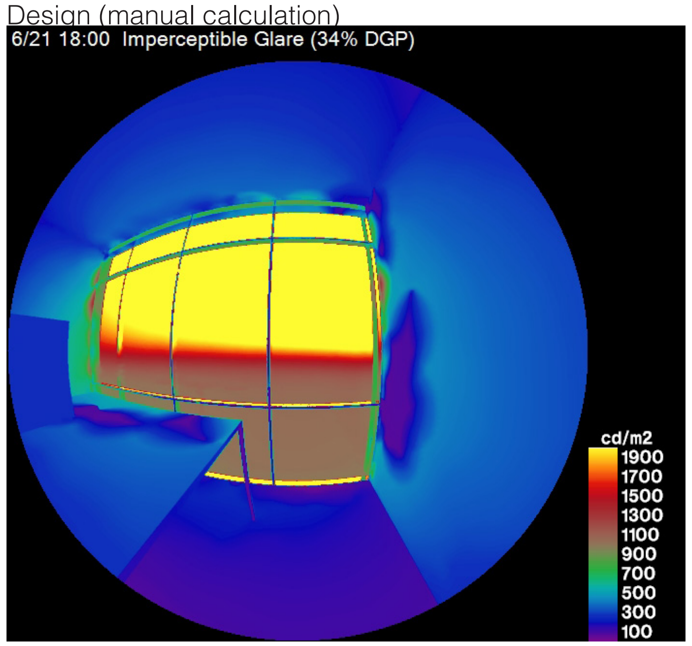

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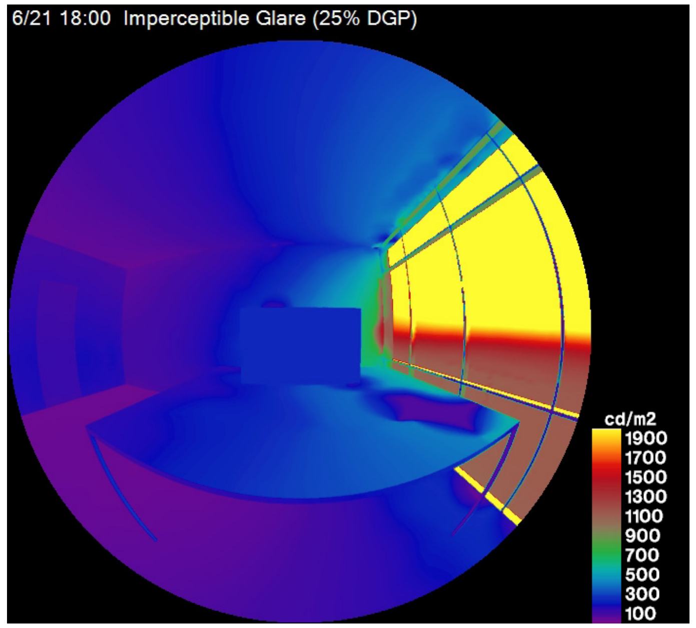

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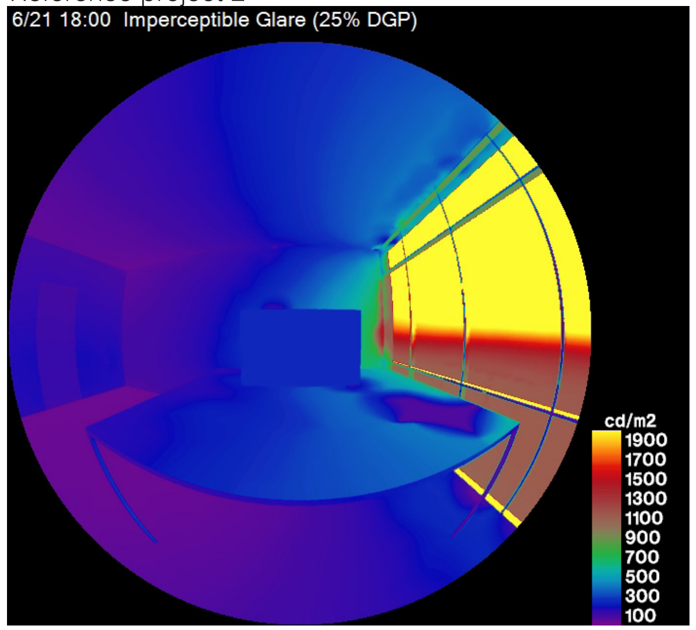

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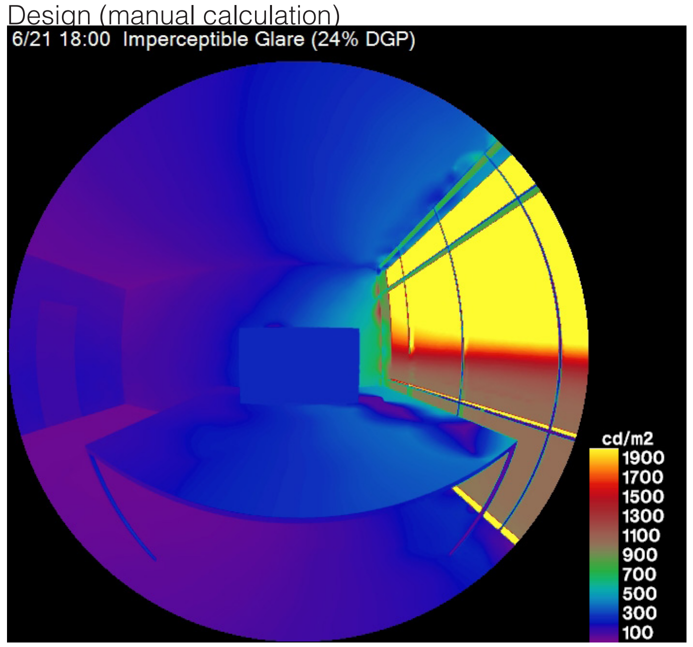

23rd December 9:00, User 1, View to the window

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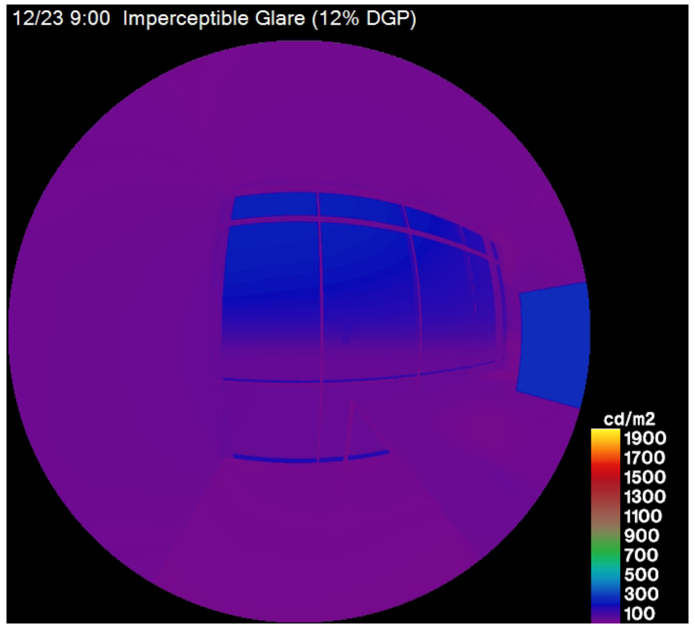

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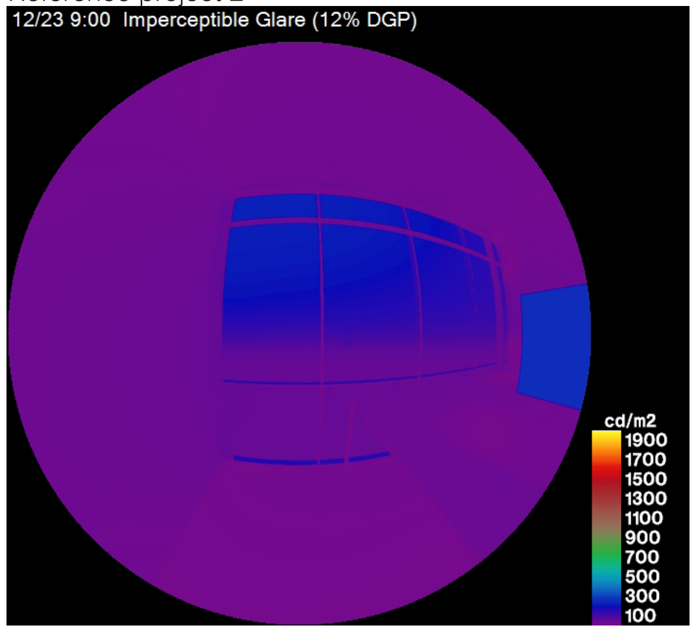

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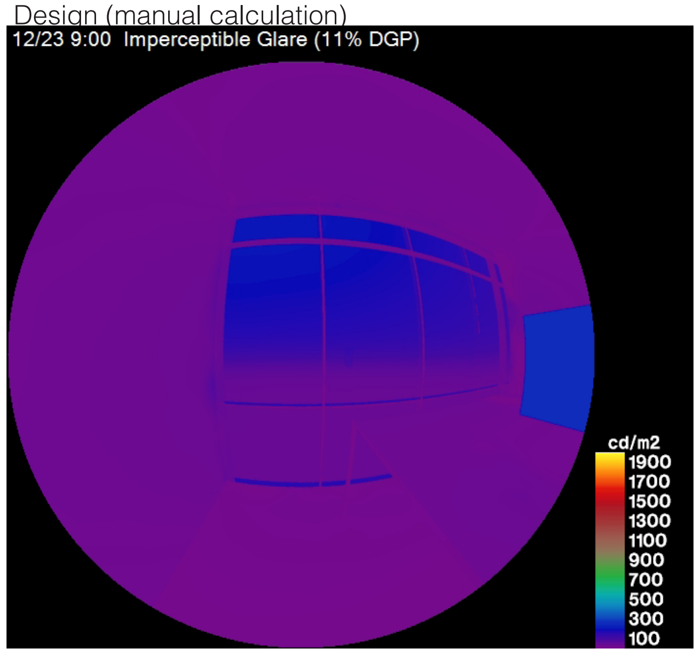

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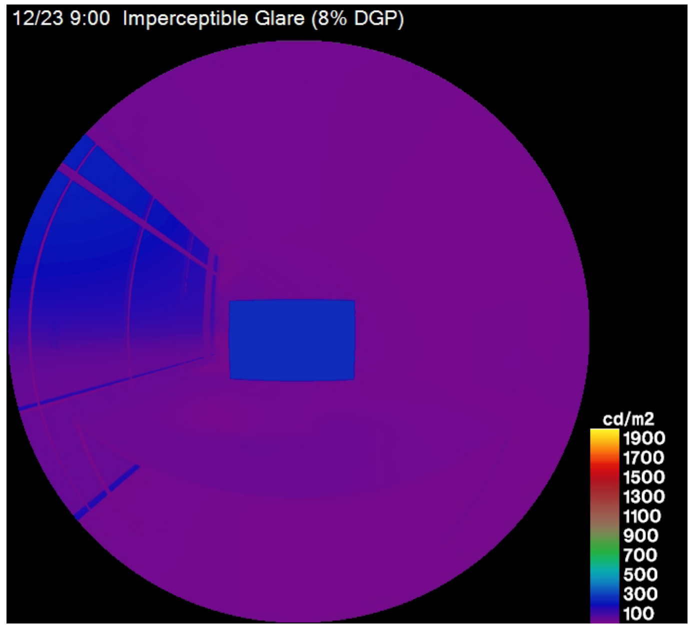

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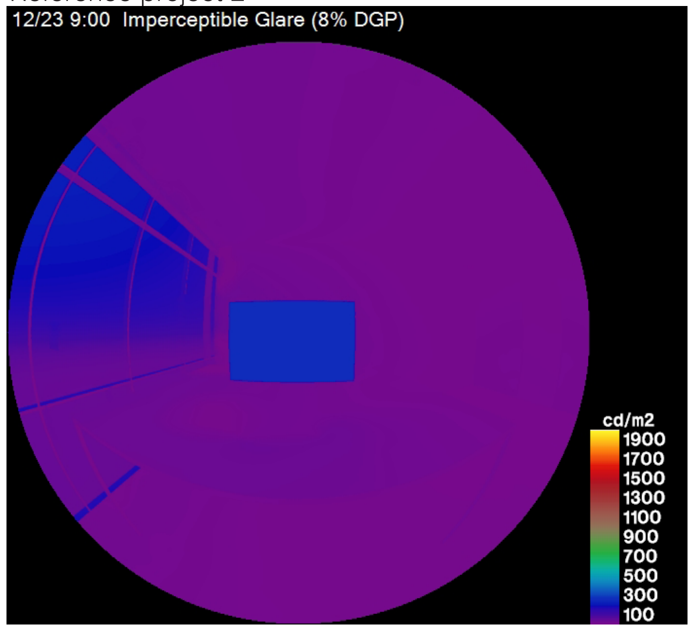

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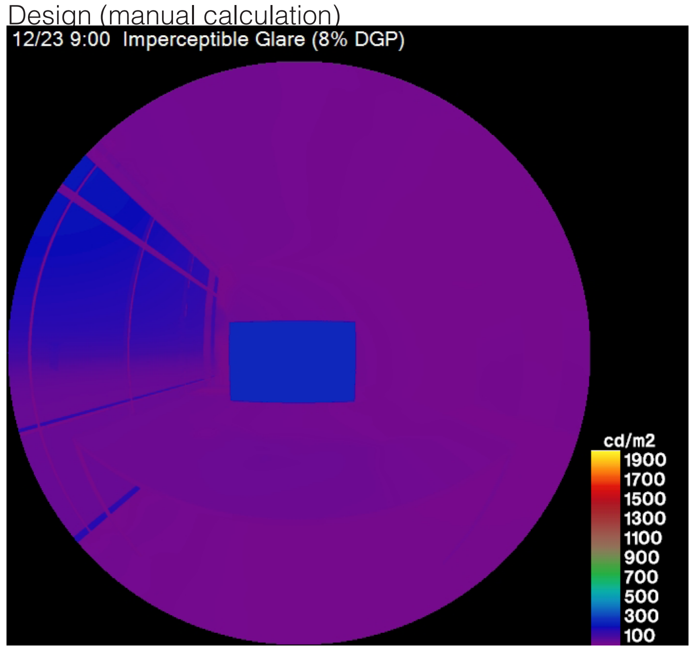

23rd December 9:00, User 2, View to the window

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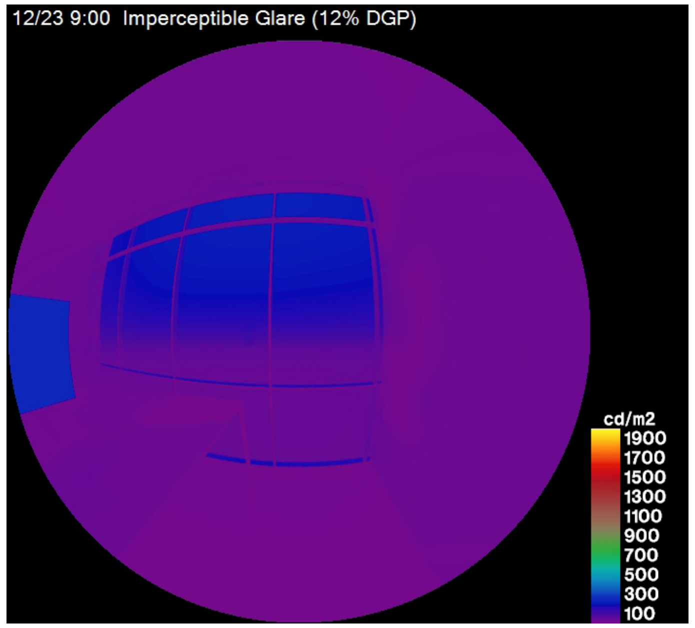

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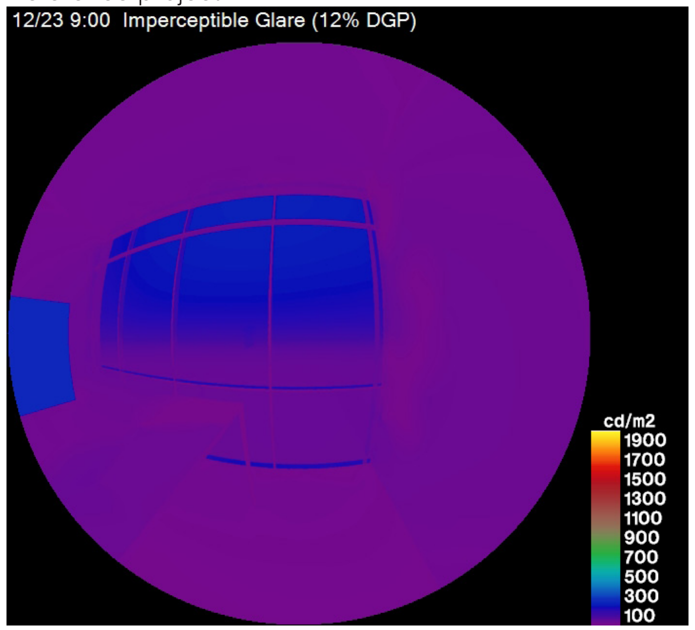

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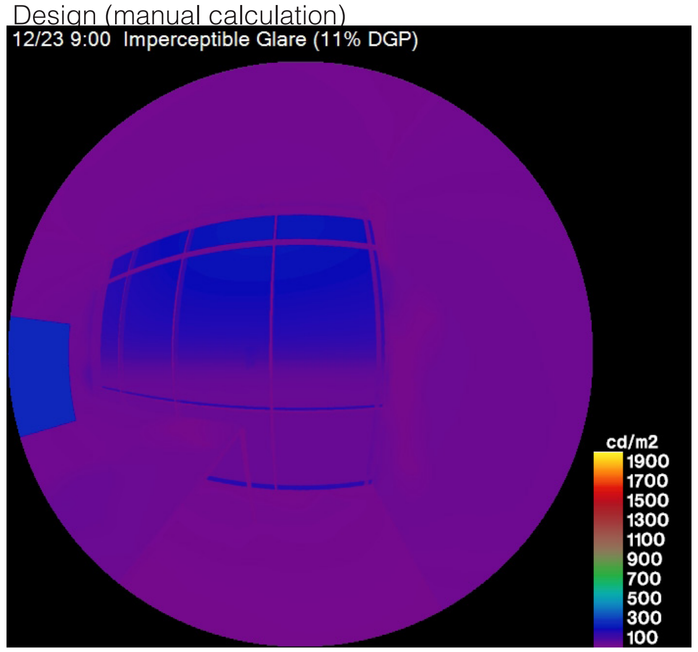

23rd December 9:00, User 2, View to the computer

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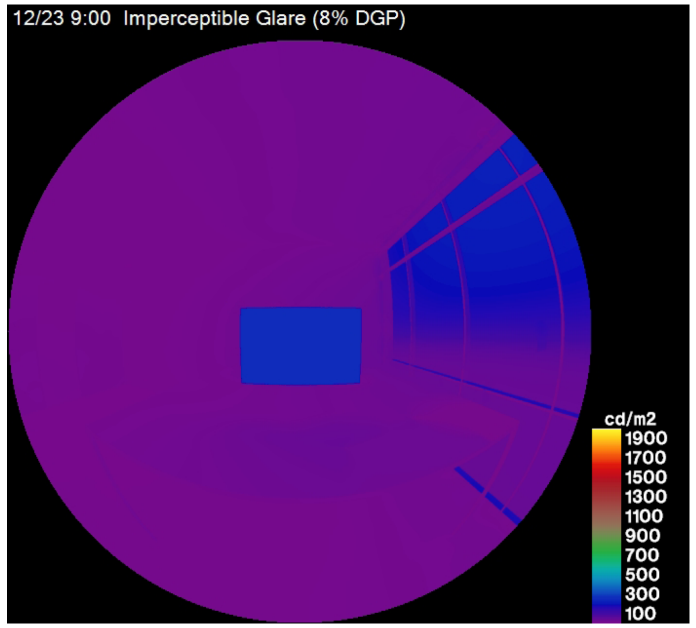

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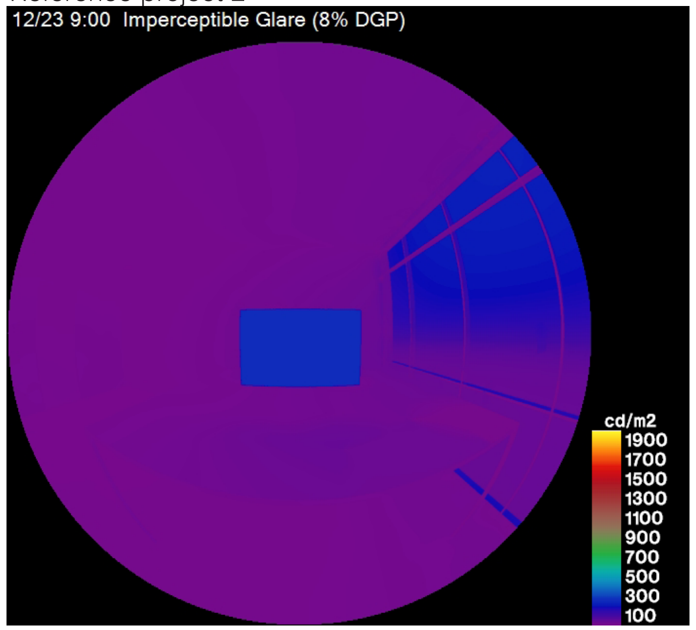

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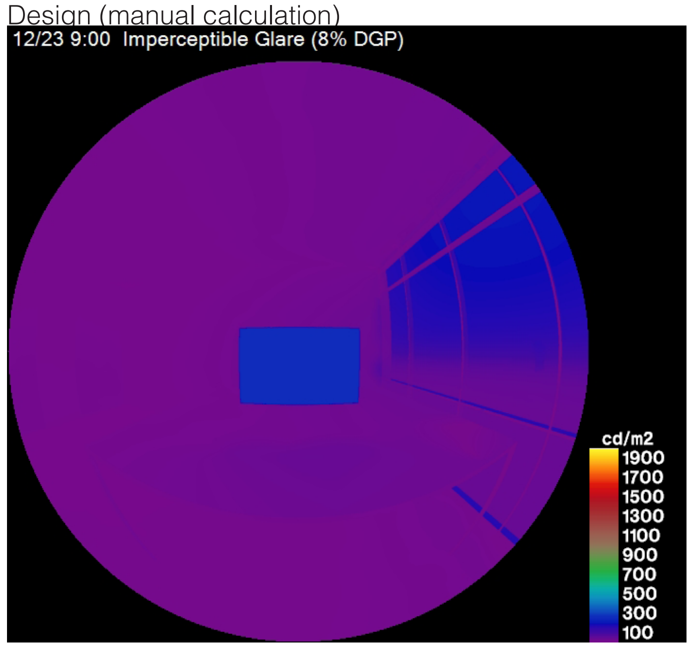

23rd December 10:00, User 1, View to the window

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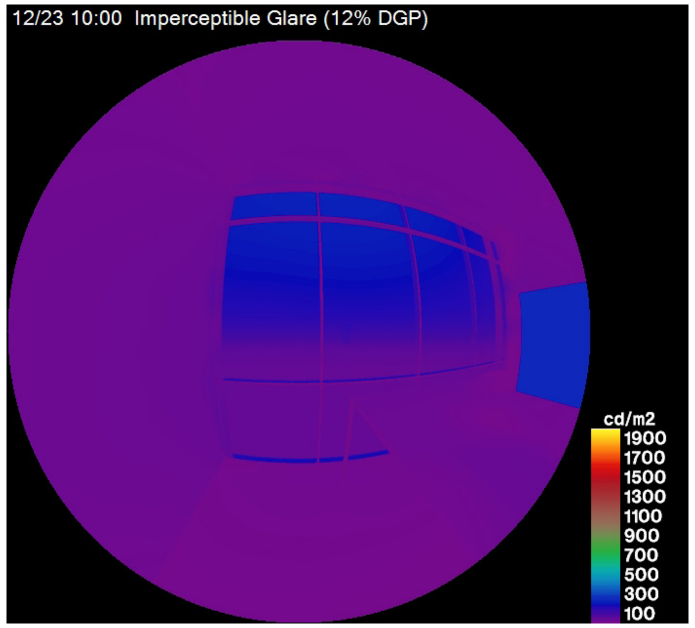

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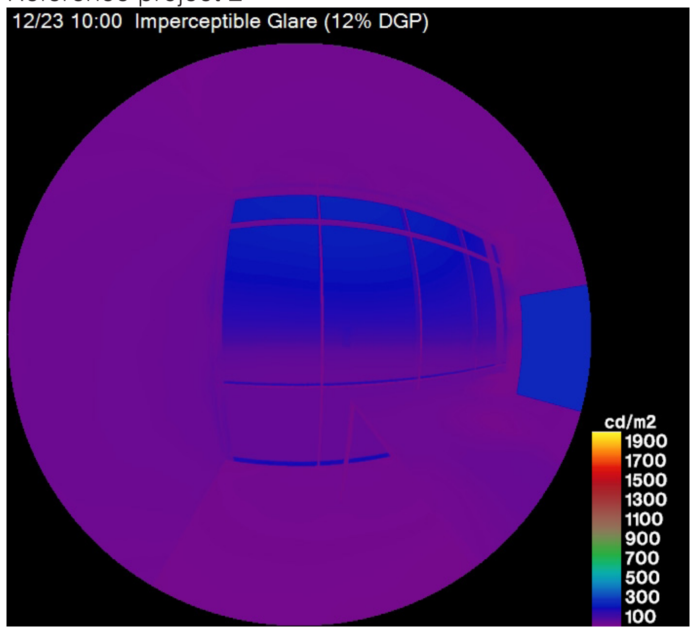

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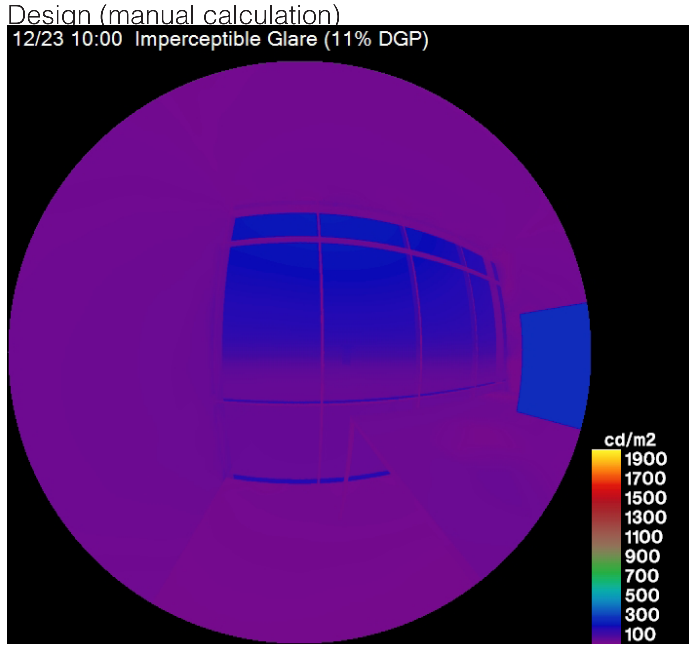

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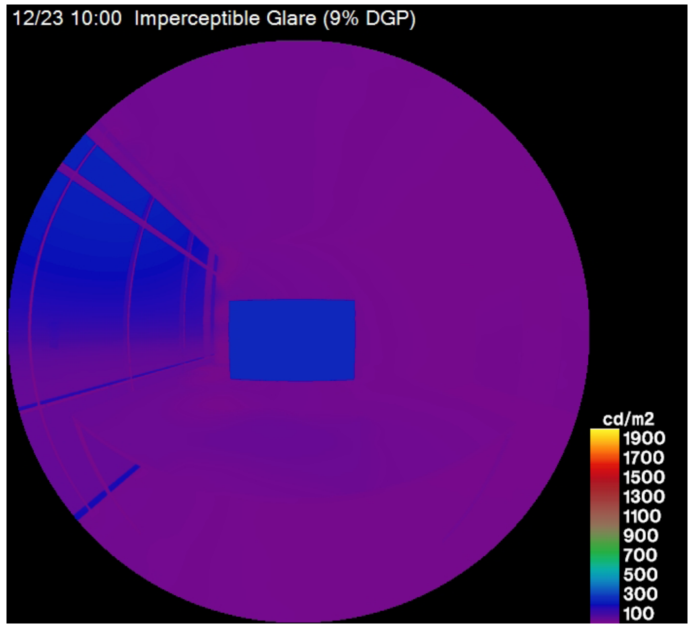

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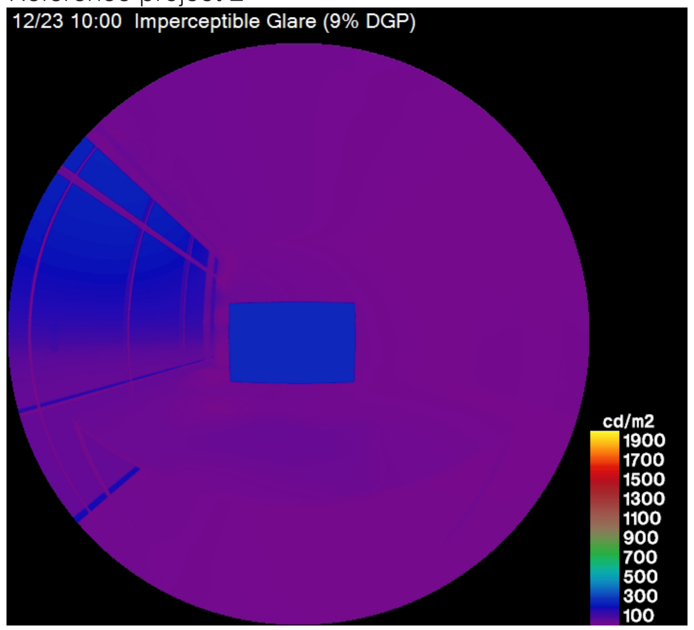

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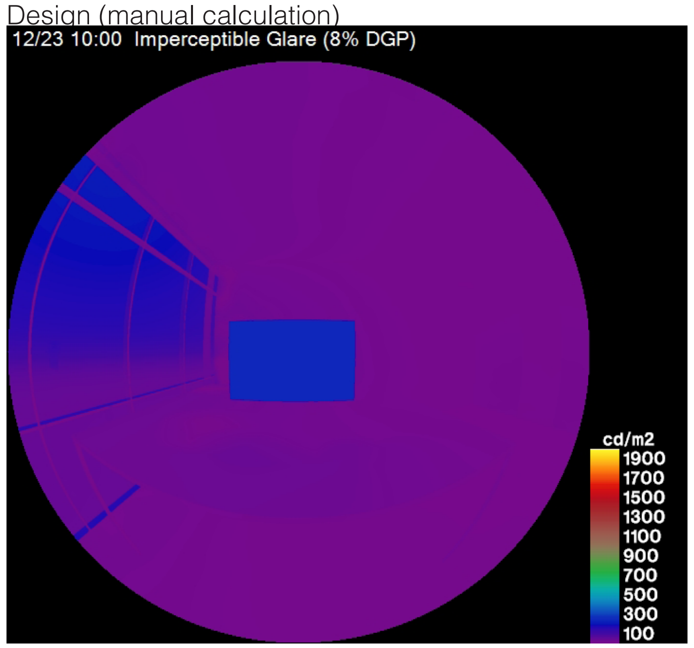

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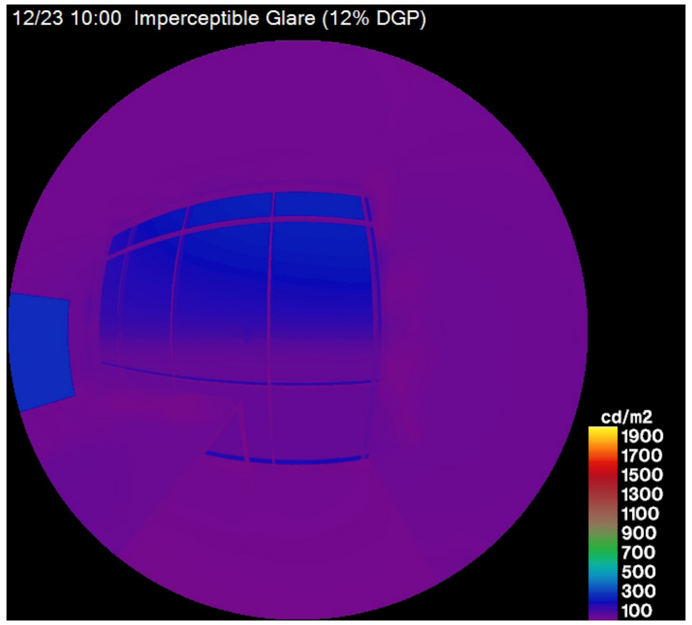

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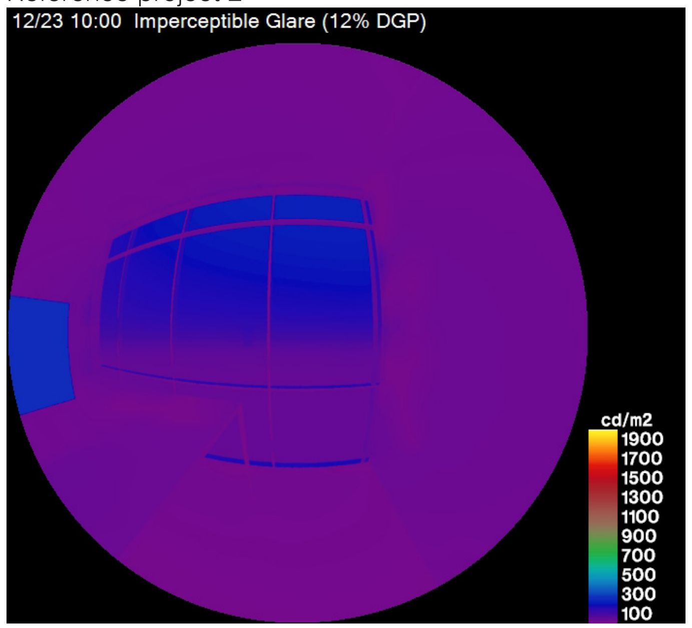

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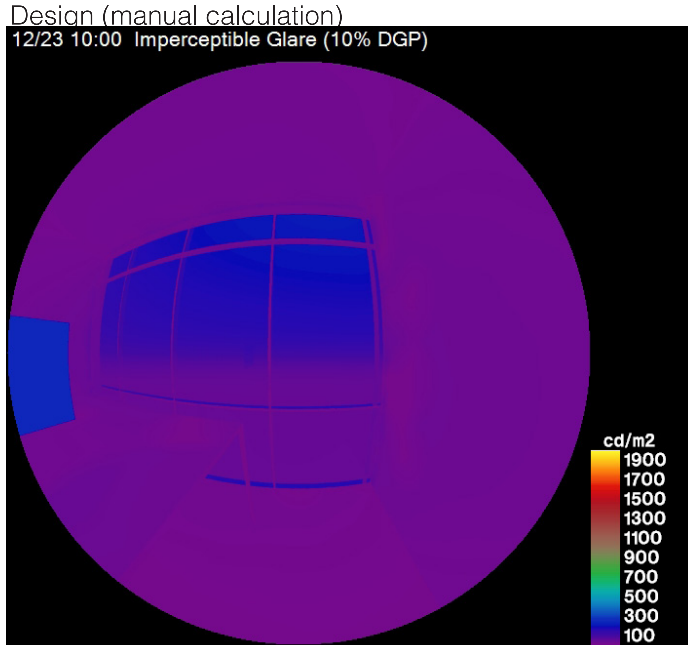

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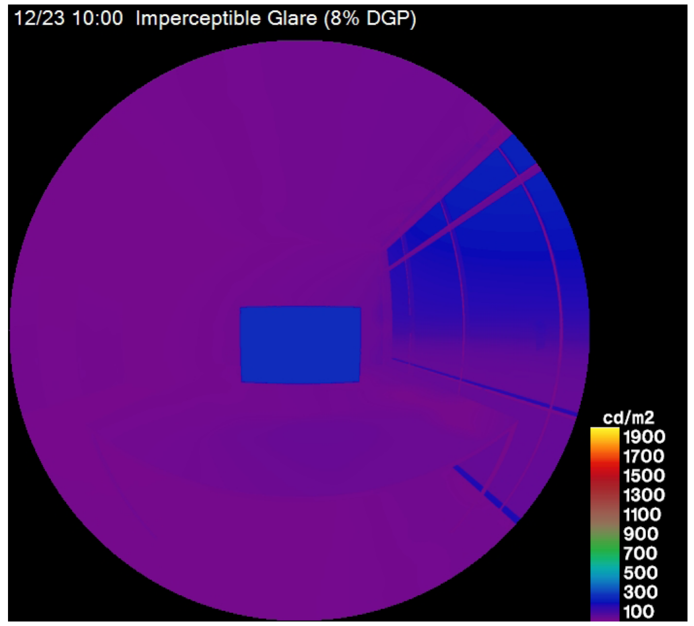

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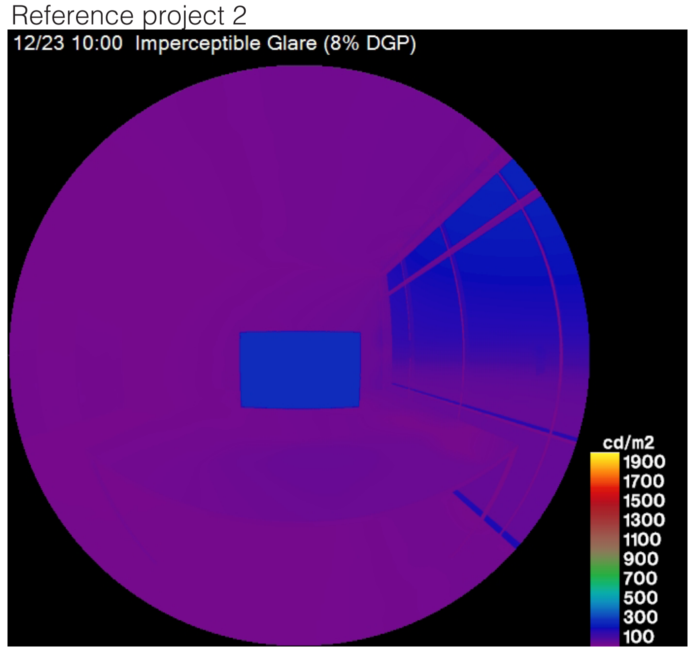

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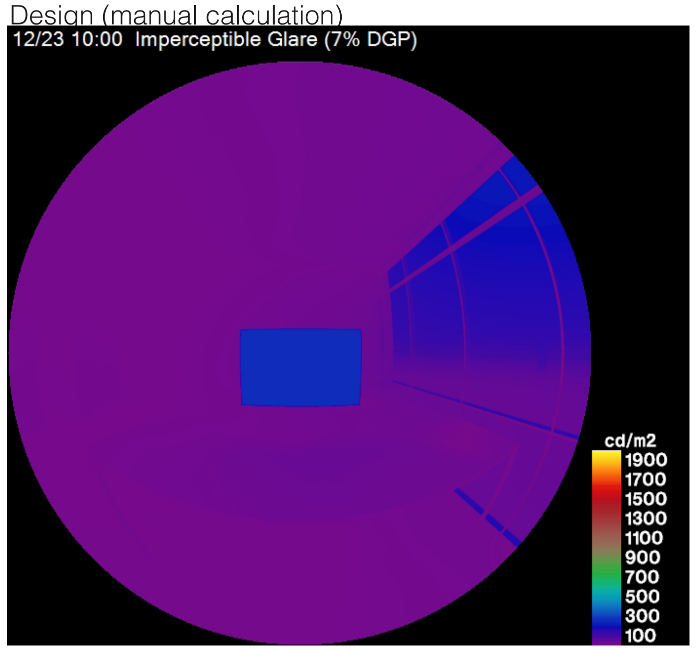

23rd December 11:00, User 1, View to the window

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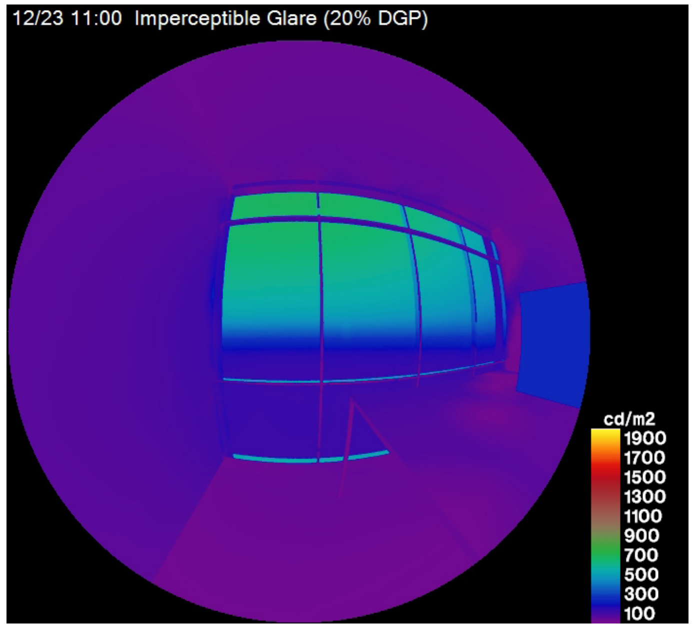

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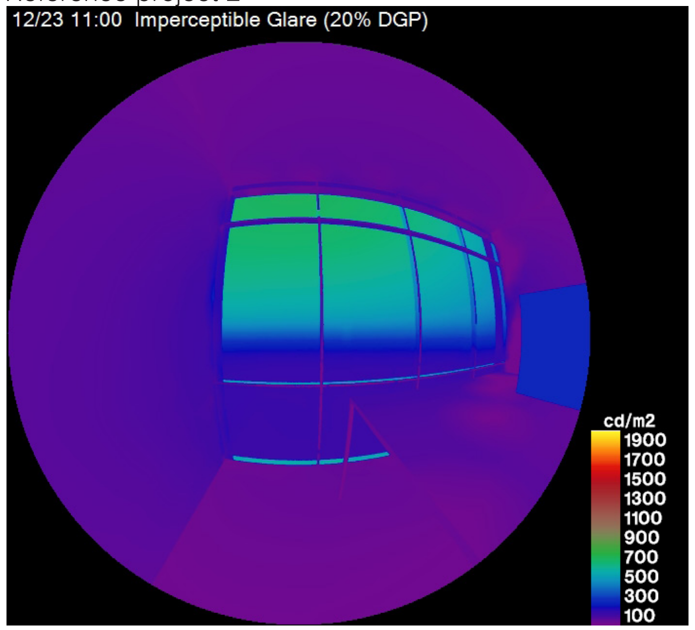

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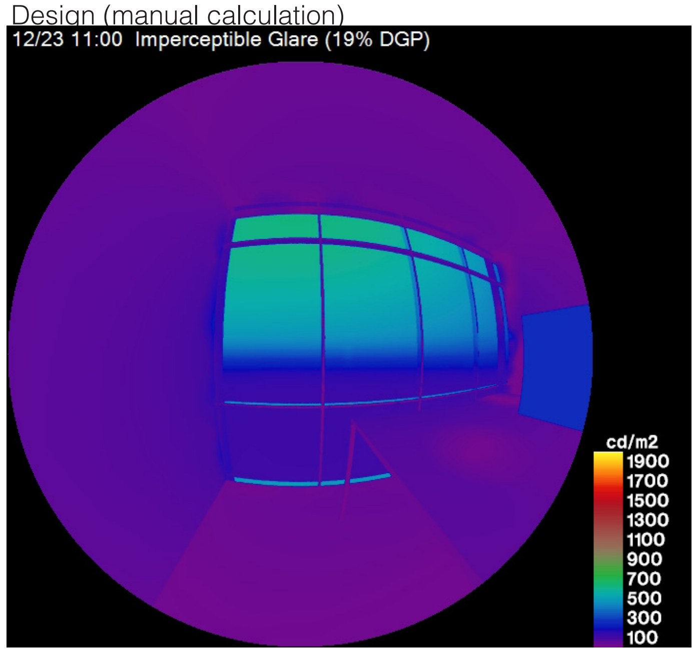

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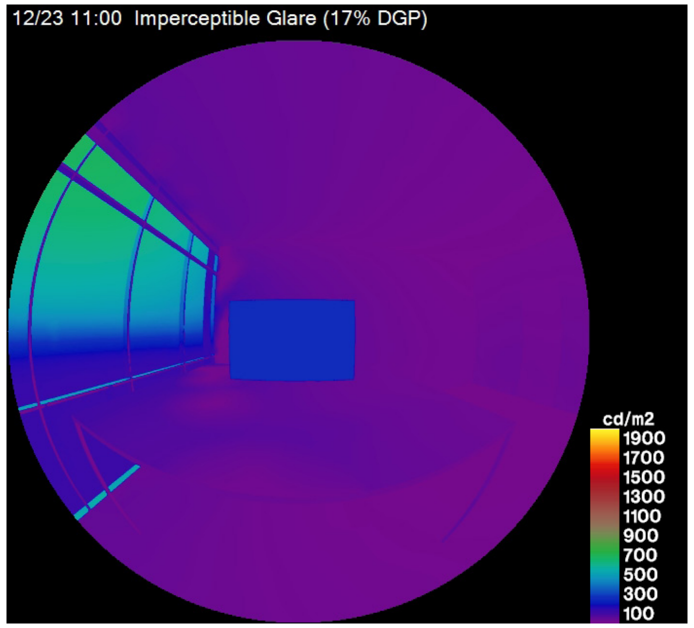

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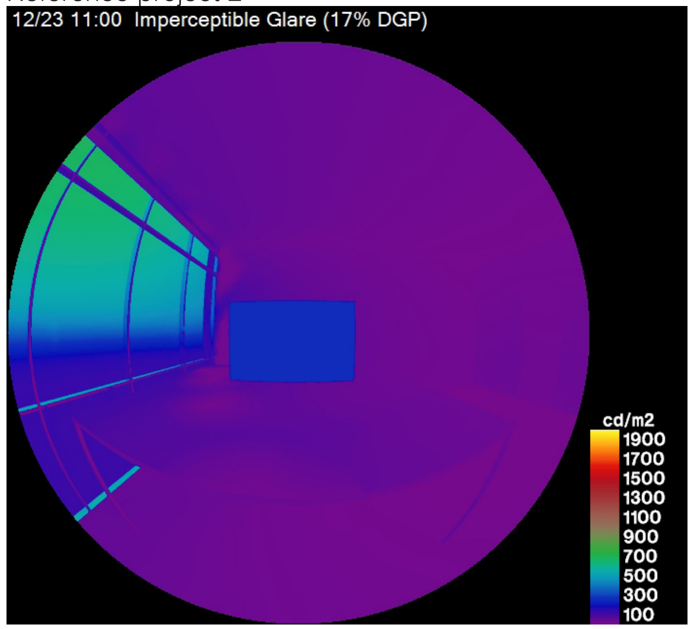

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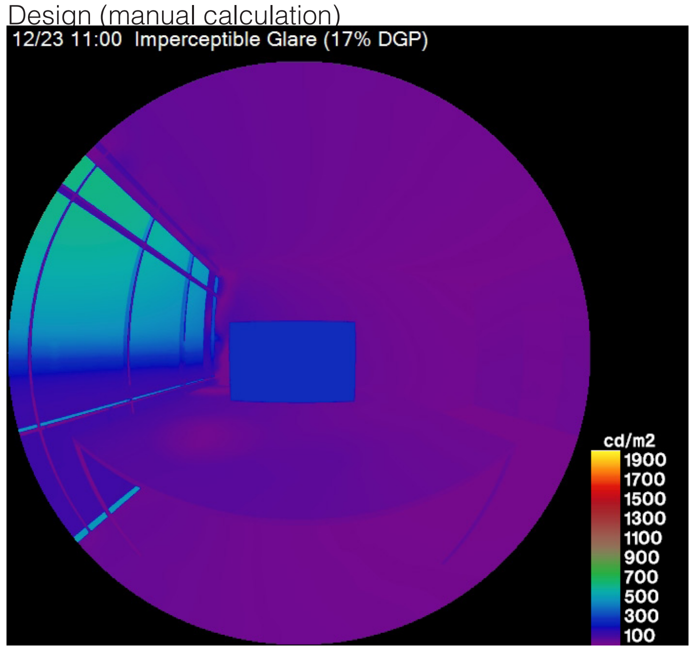

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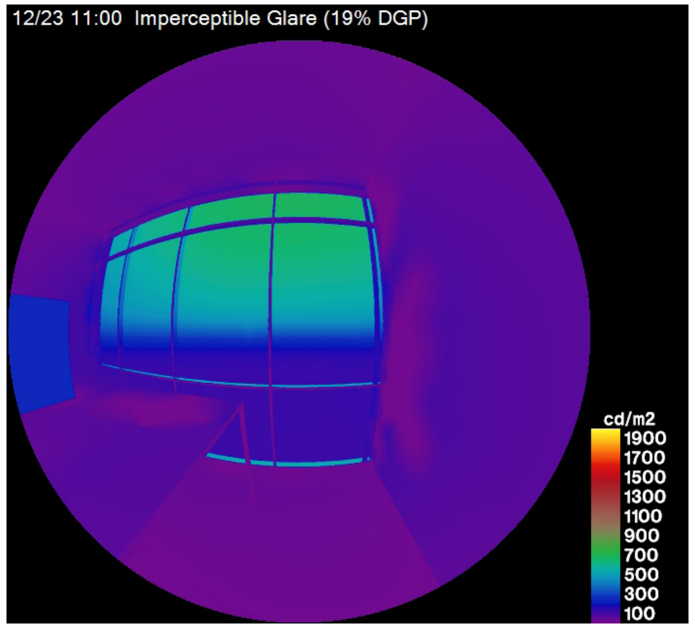

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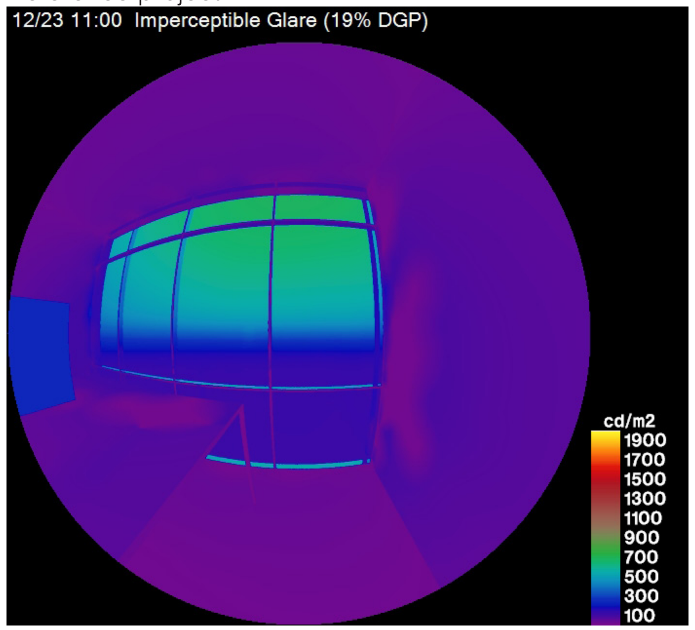

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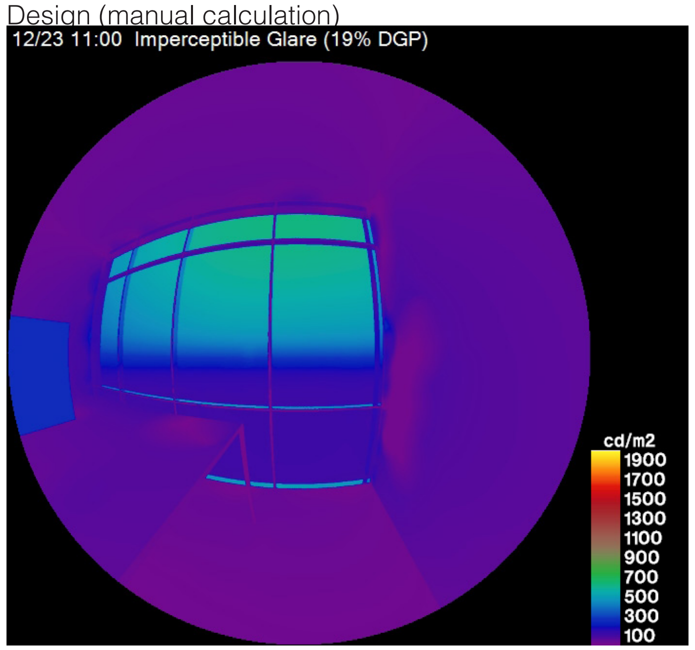

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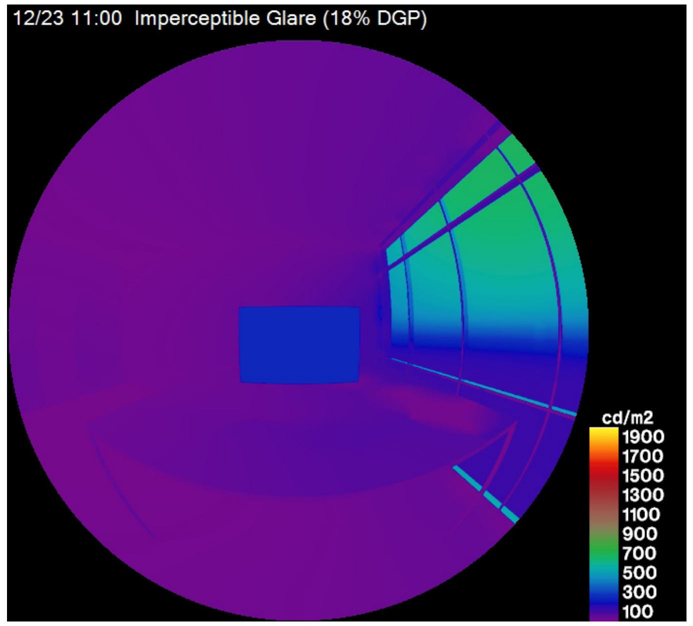

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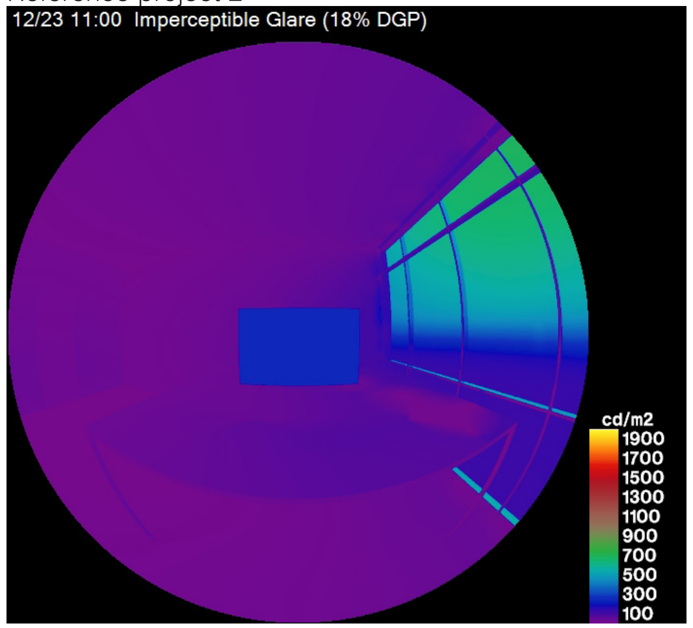

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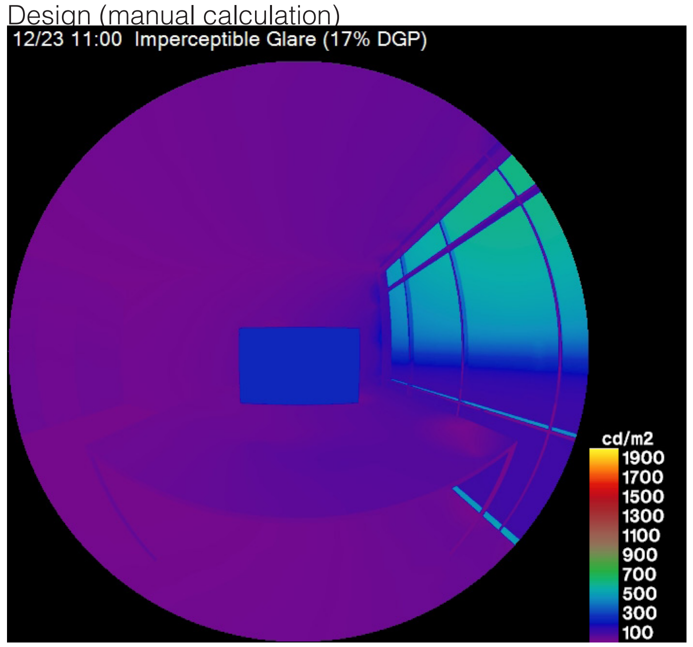

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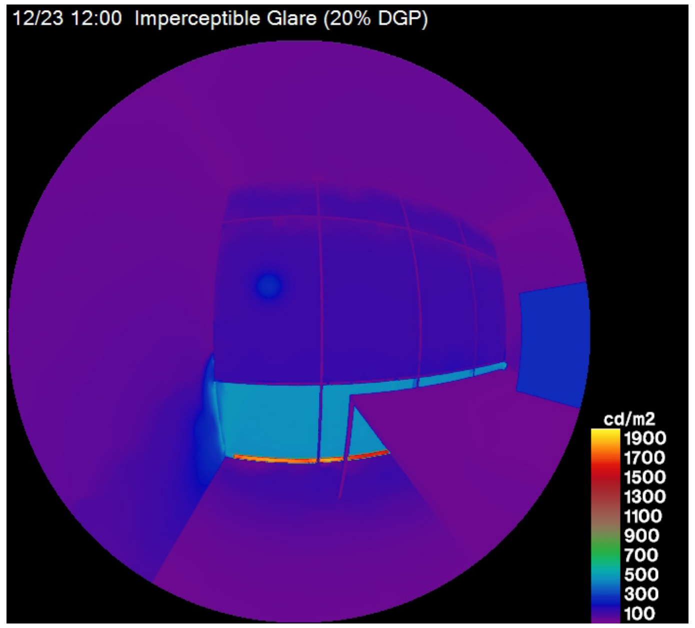

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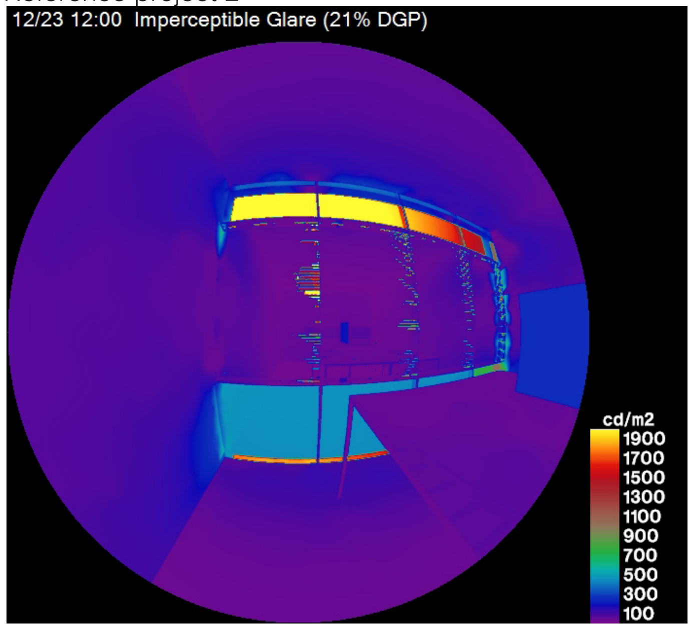

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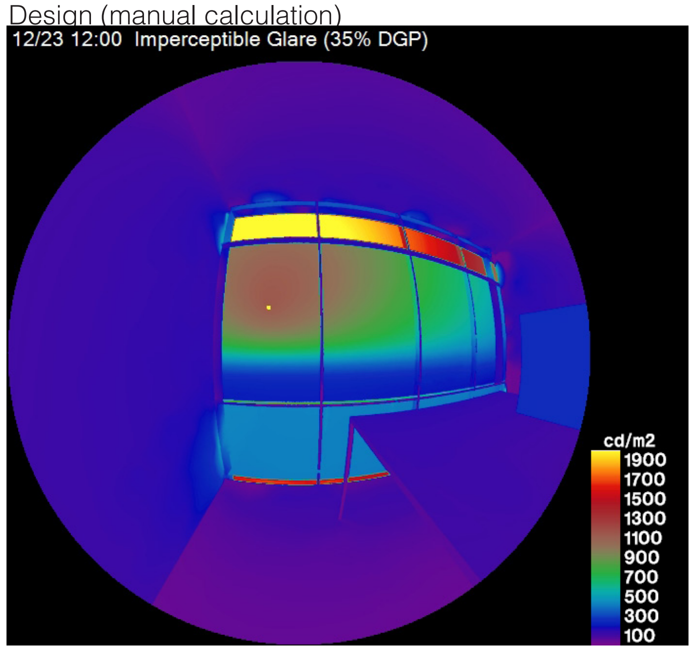

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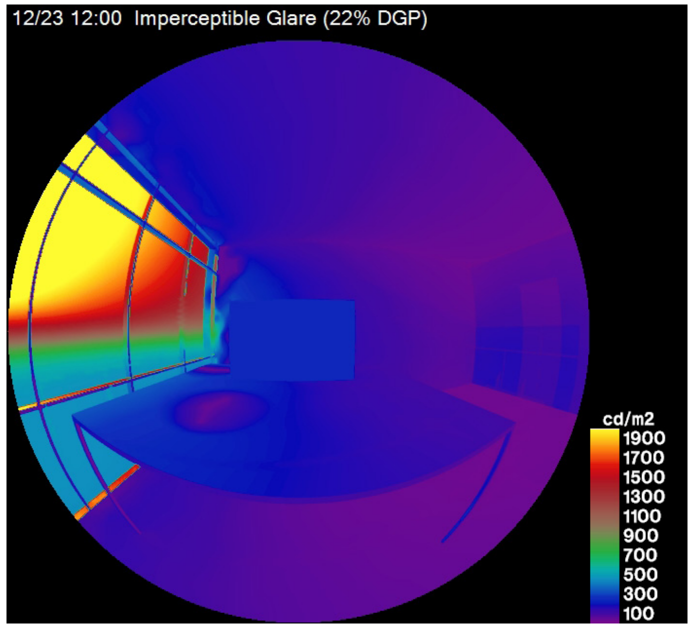

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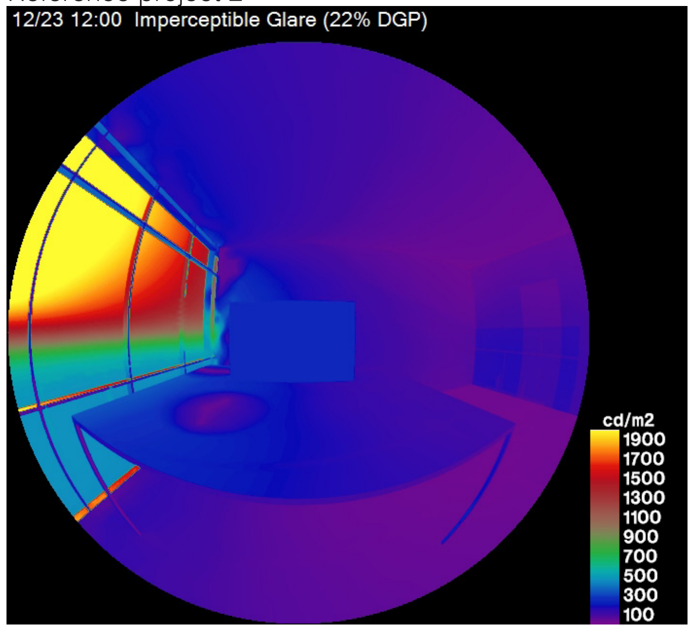

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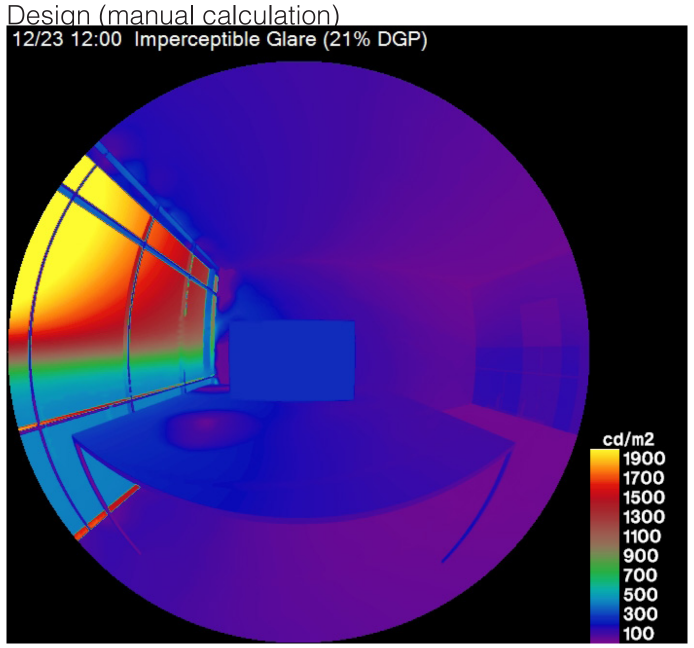

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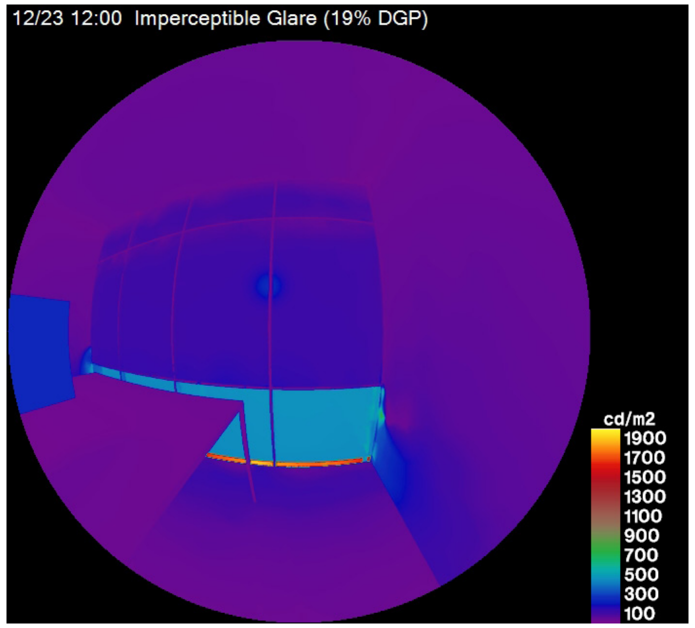

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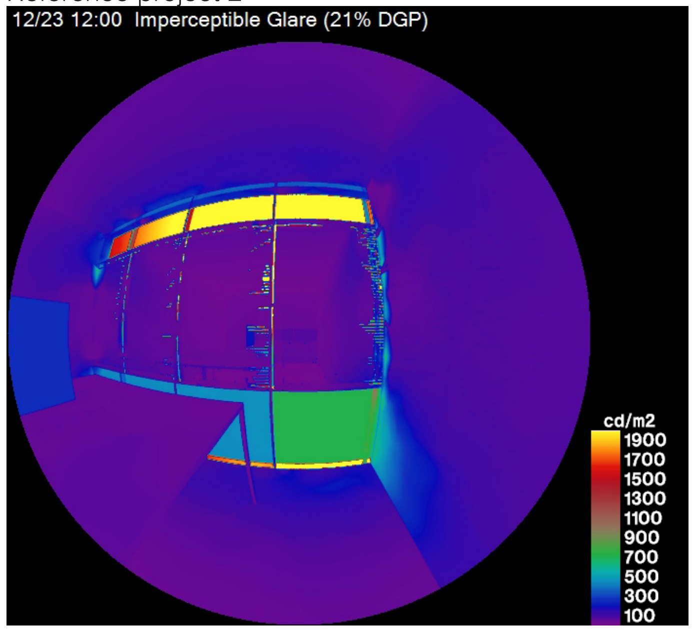

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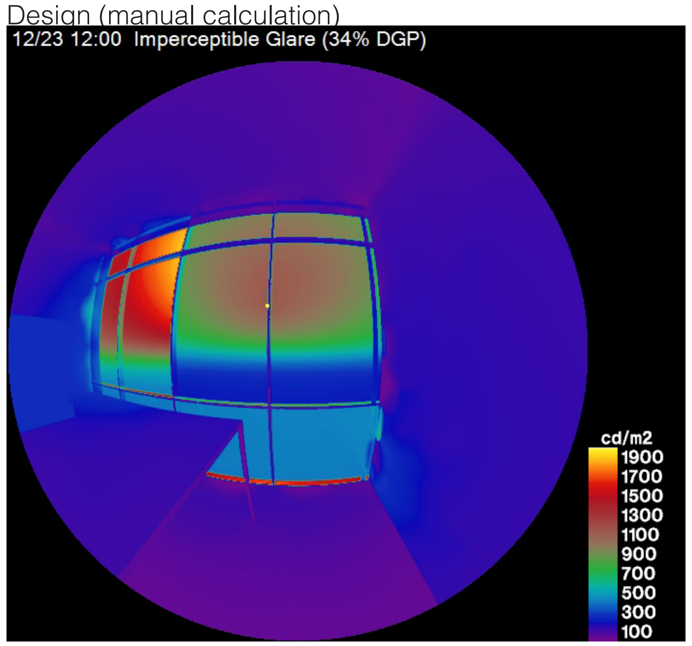

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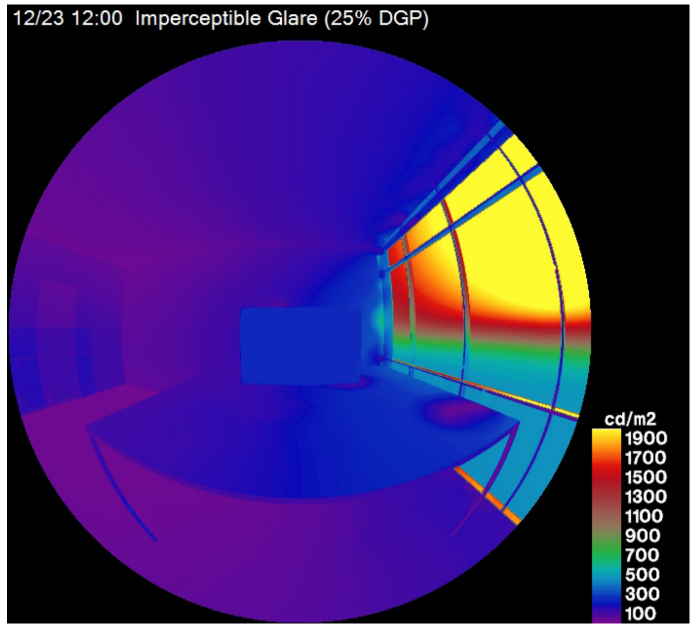

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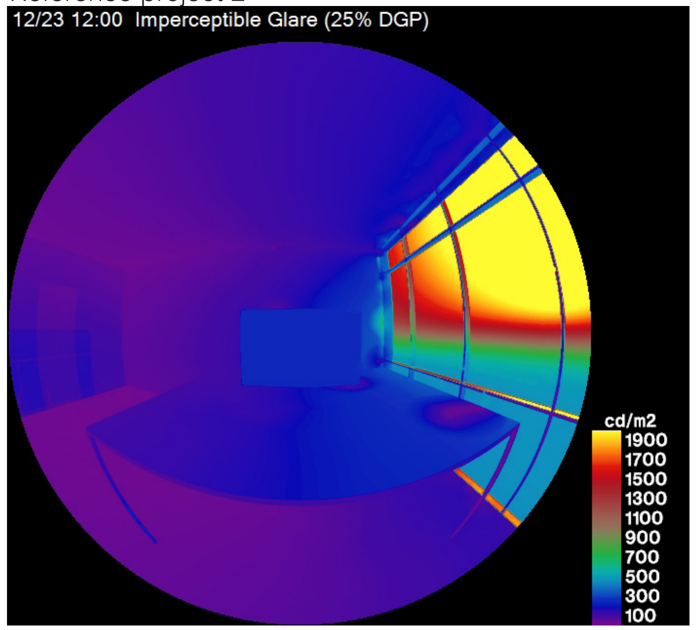

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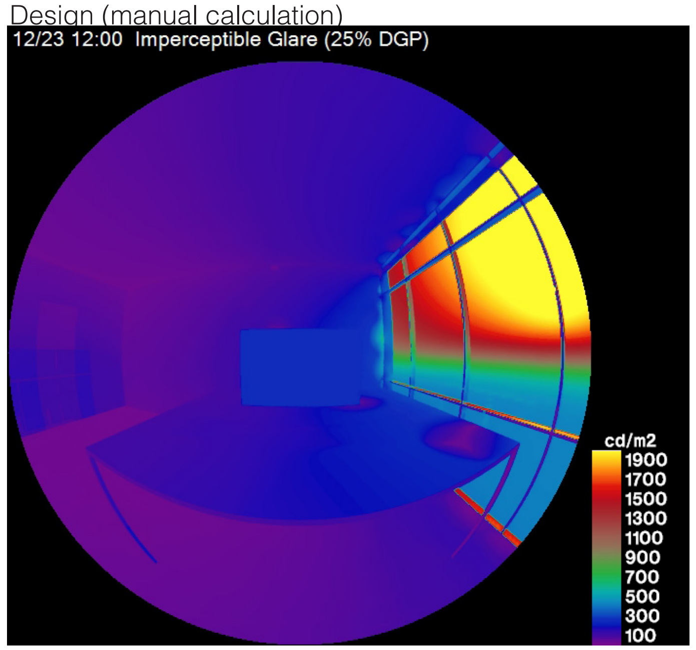

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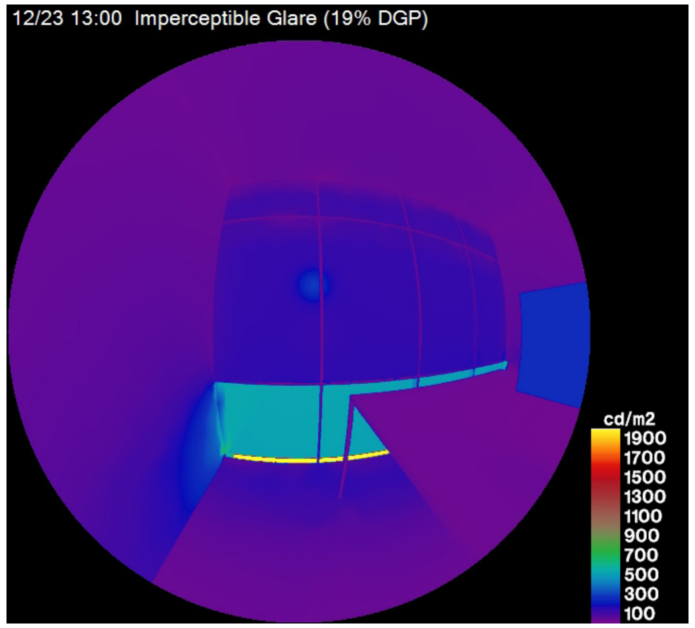

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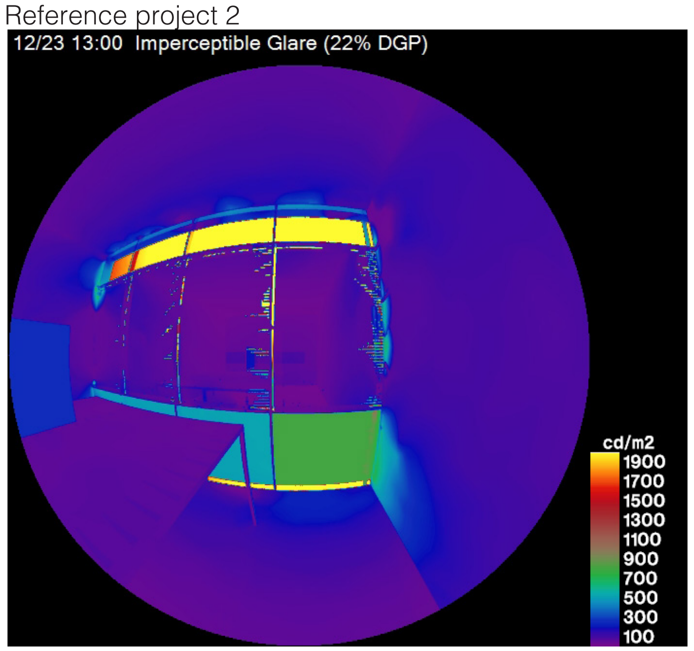

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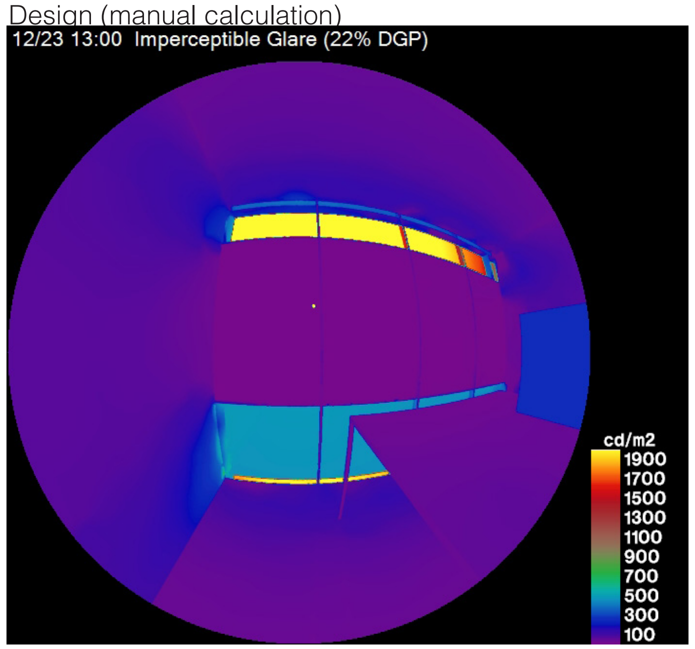

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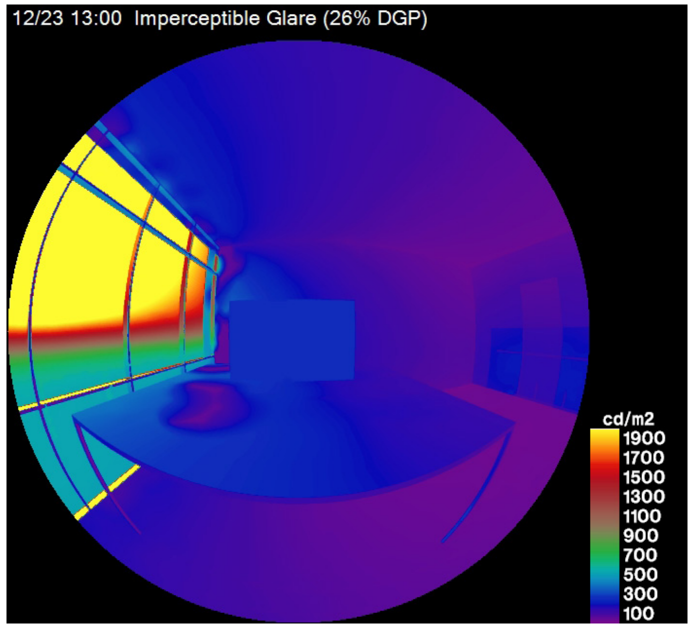

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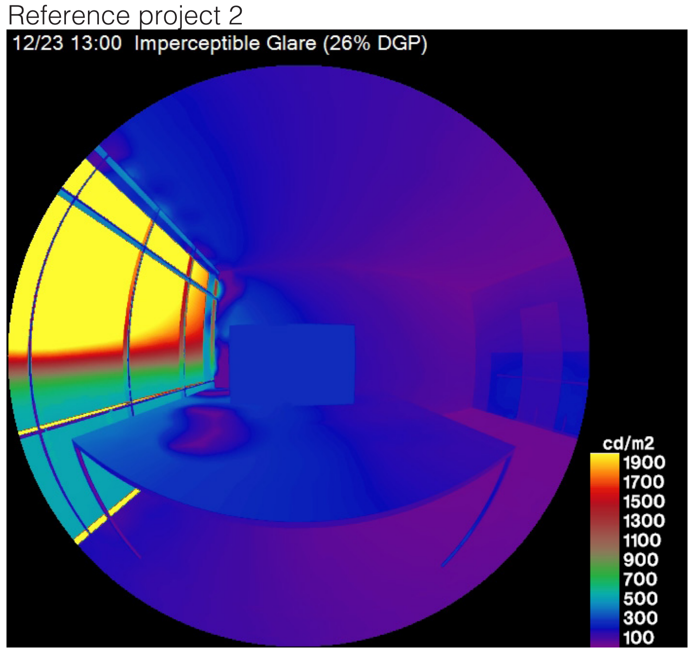

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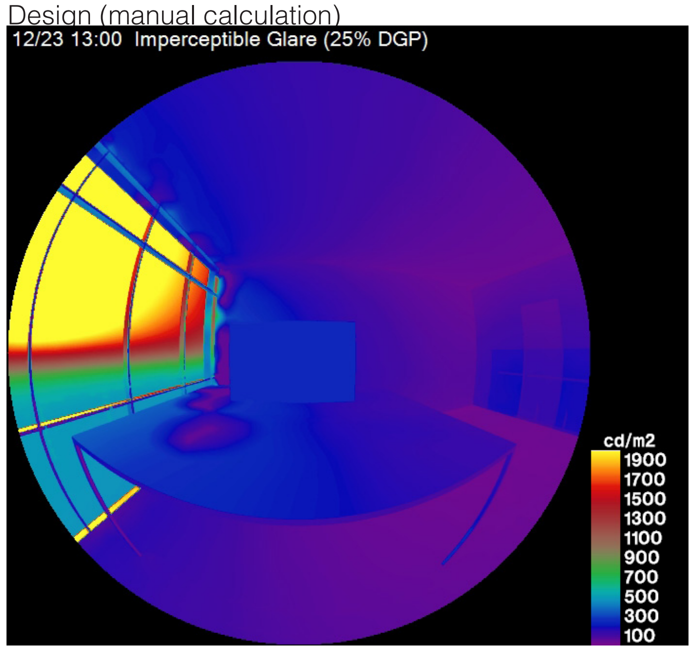

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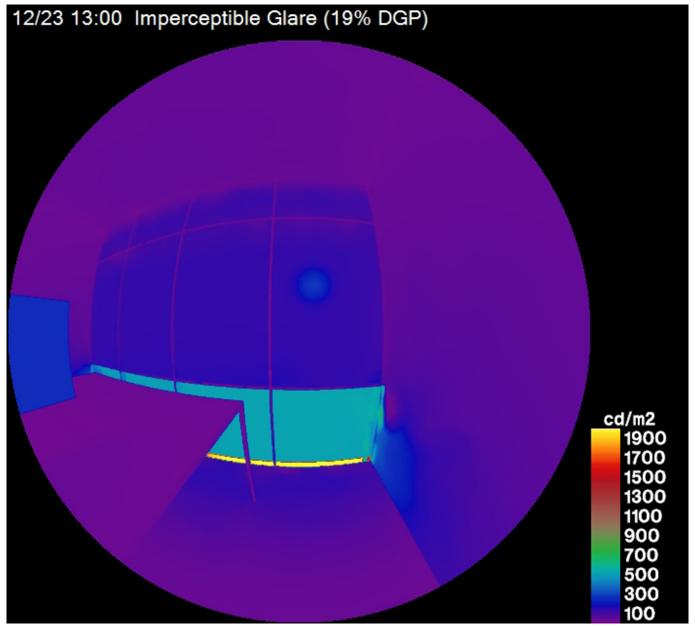

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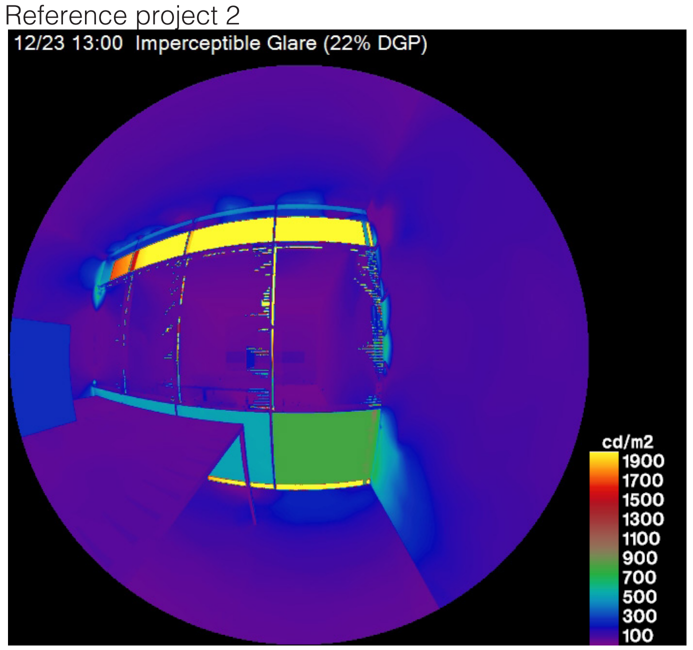

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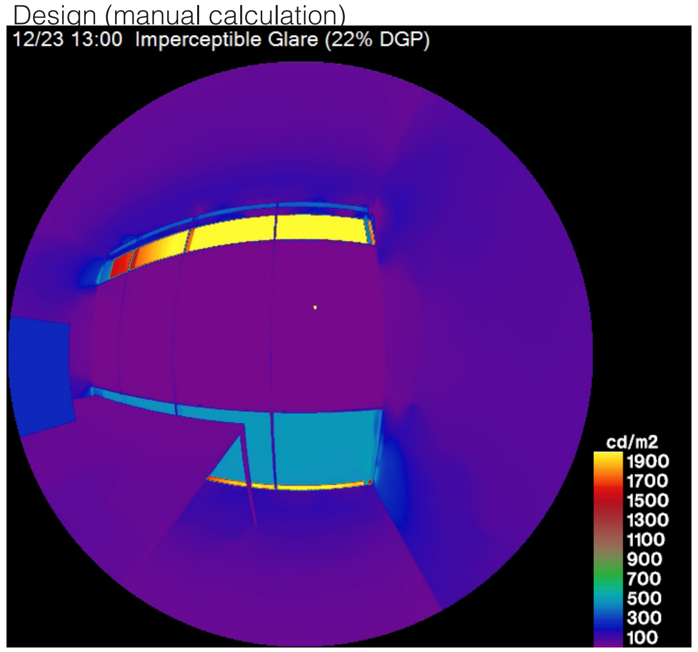

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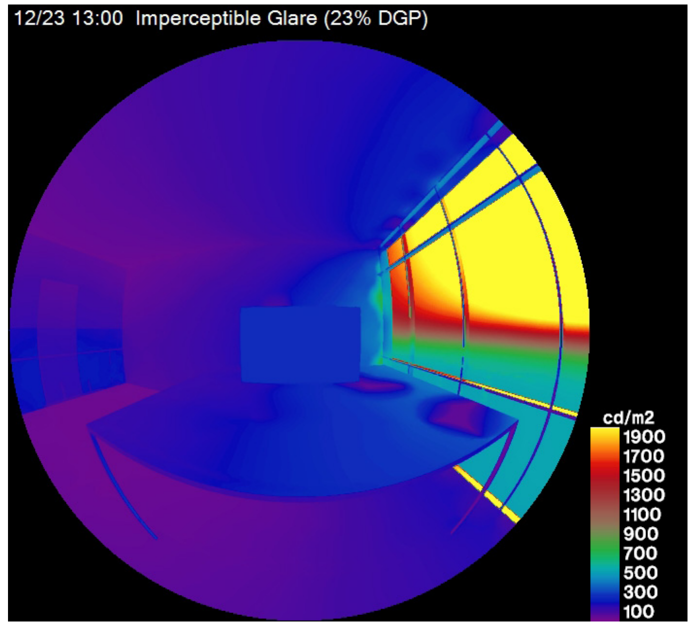

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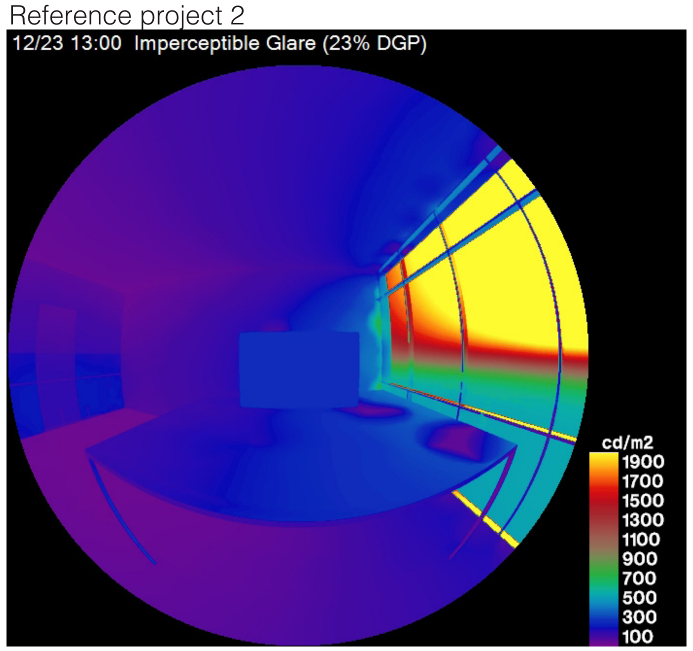

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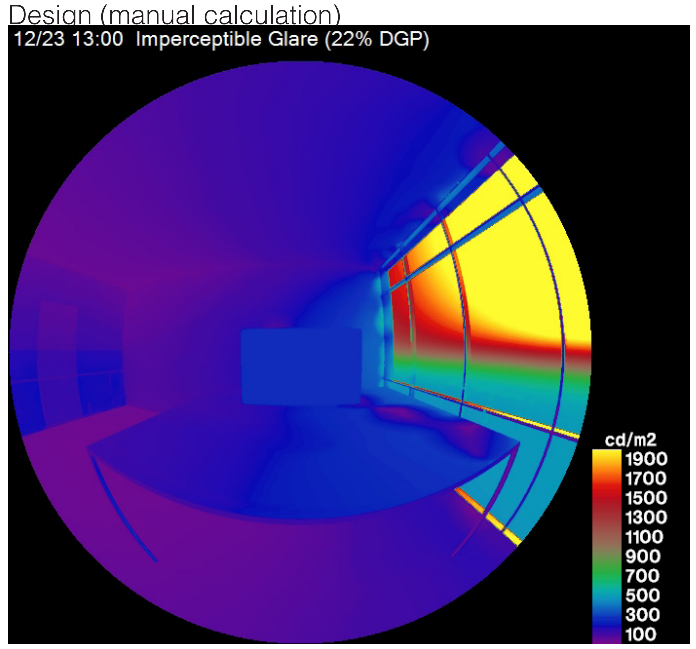

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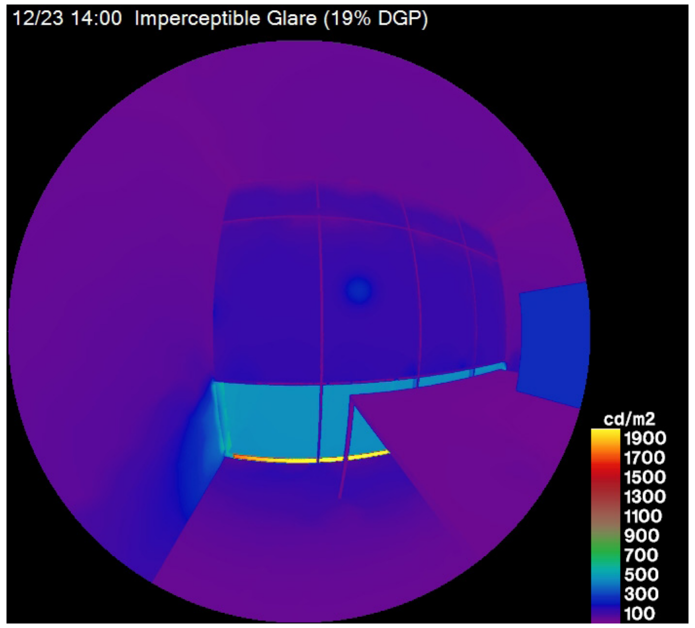

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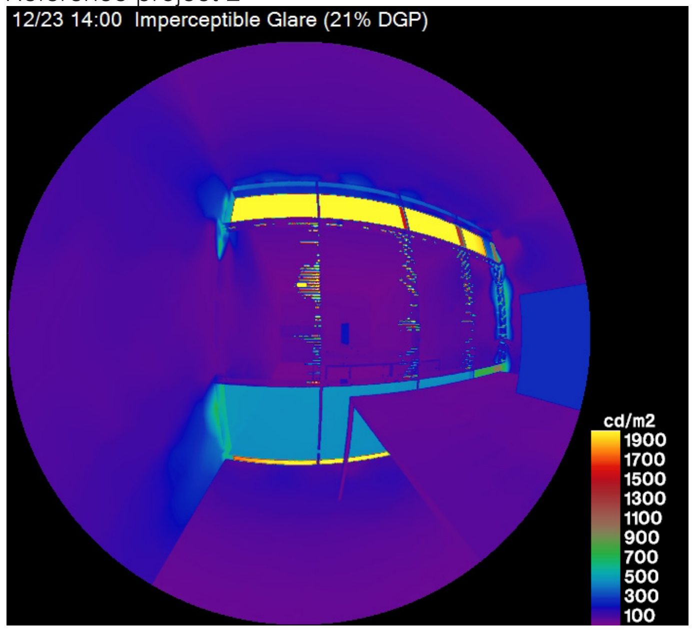

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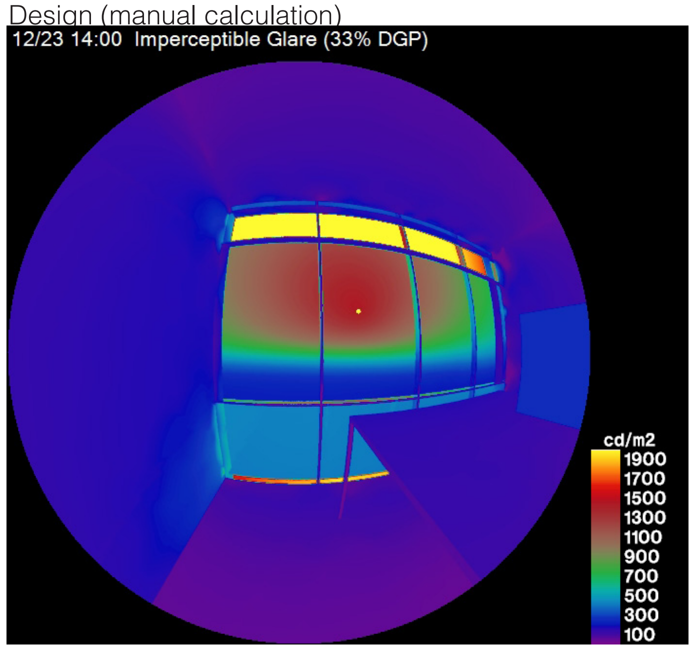

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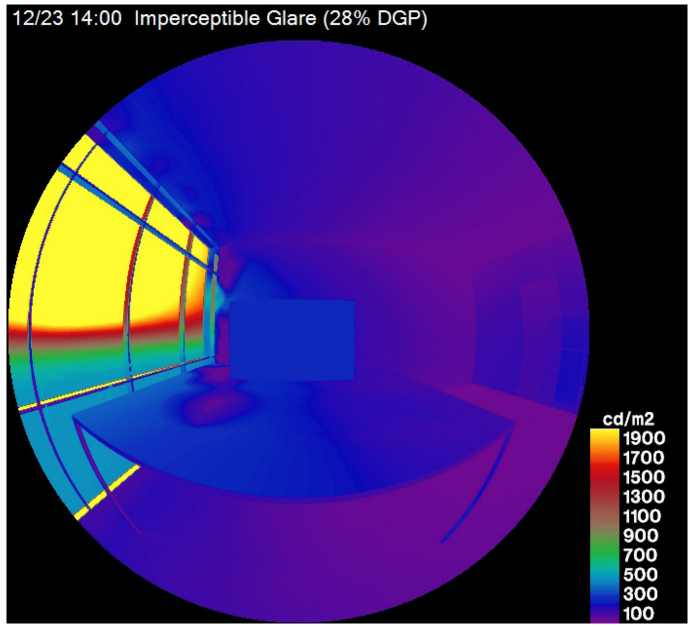

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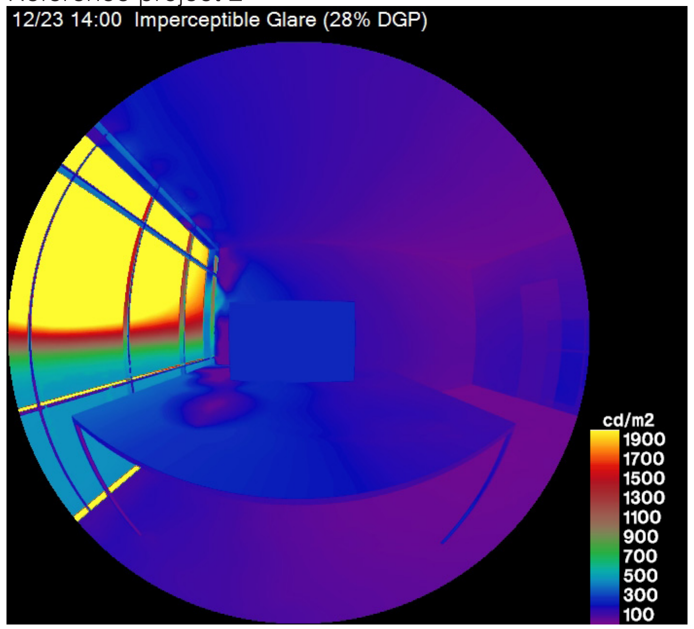

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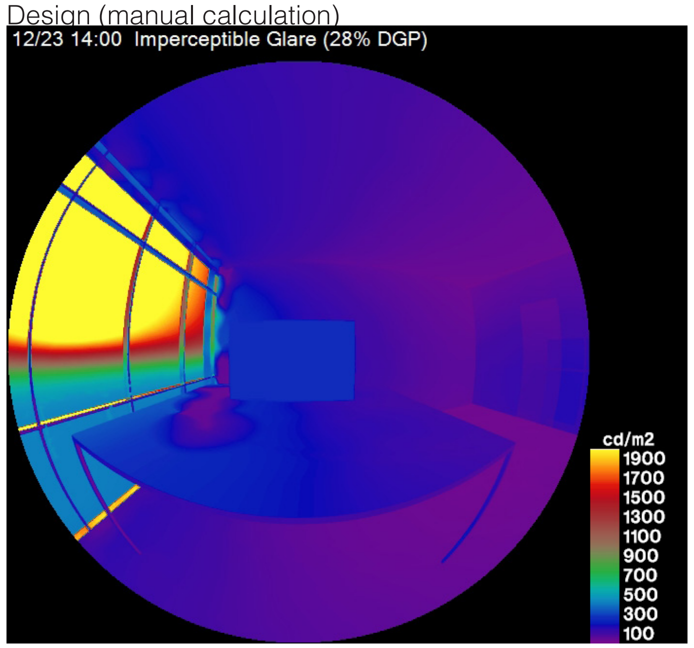

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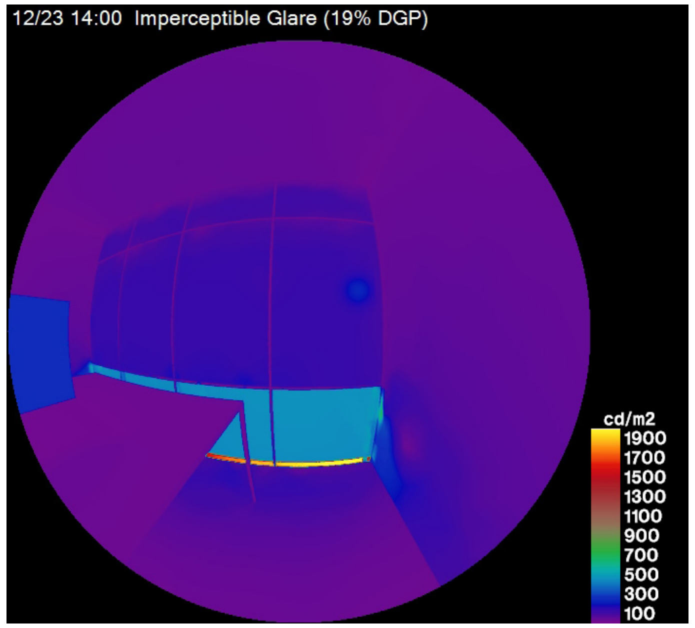

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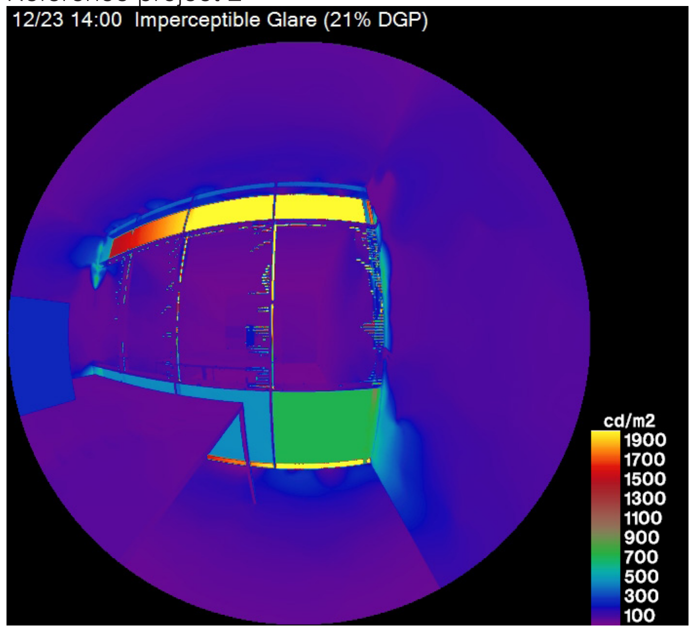

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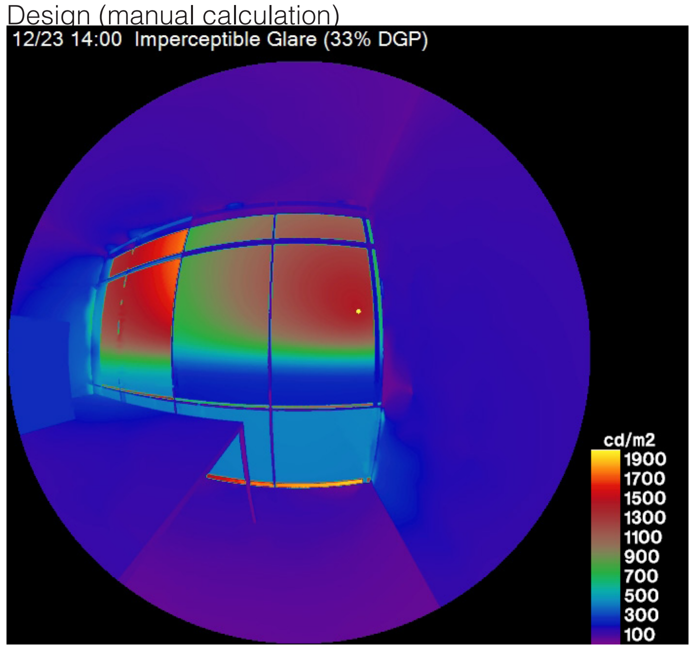

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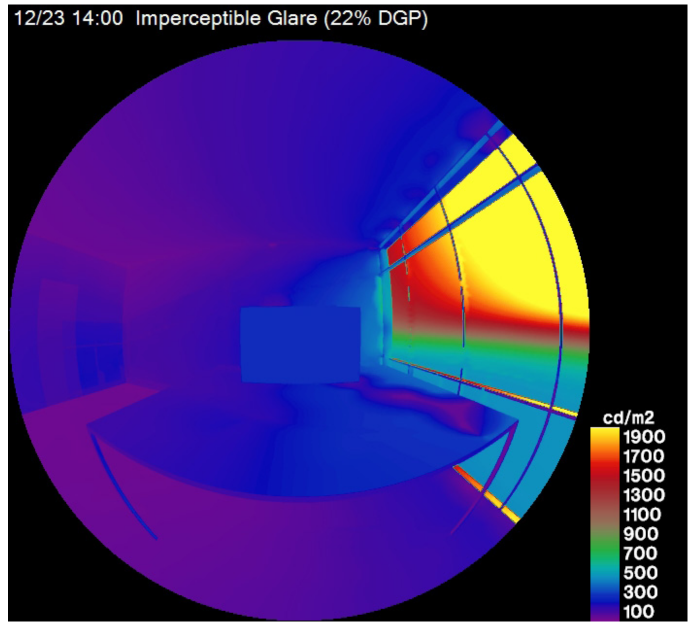

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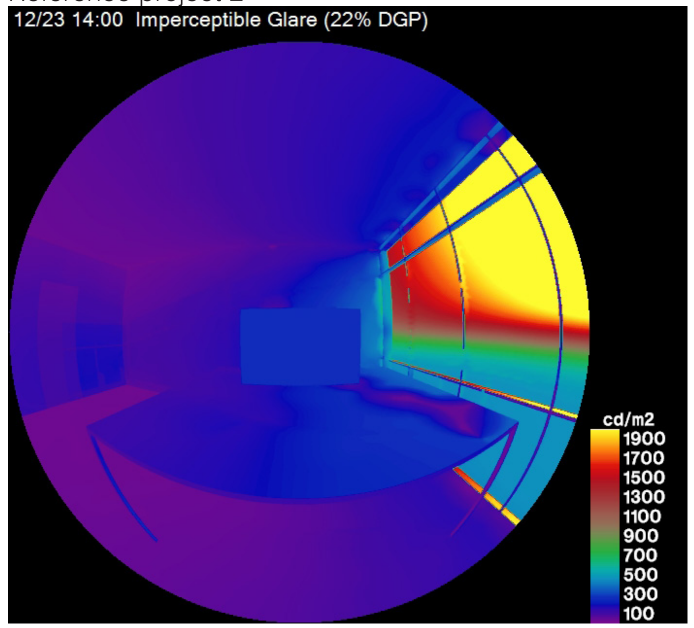

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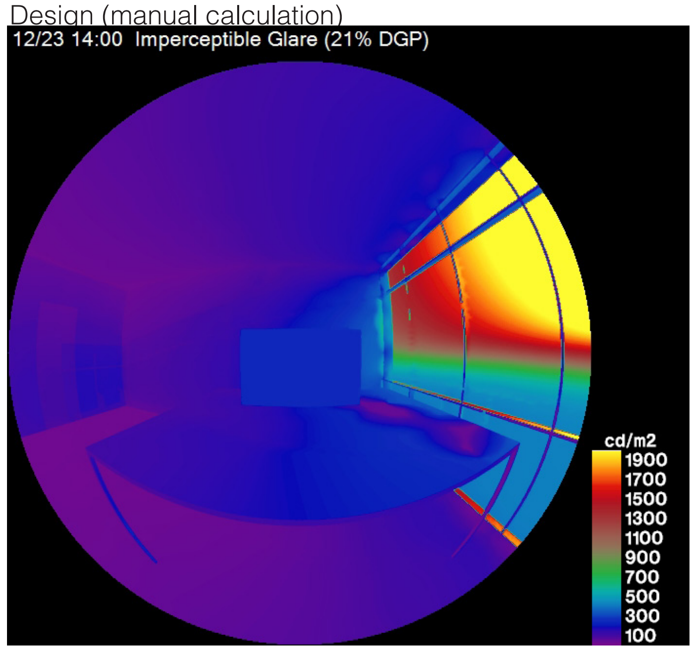

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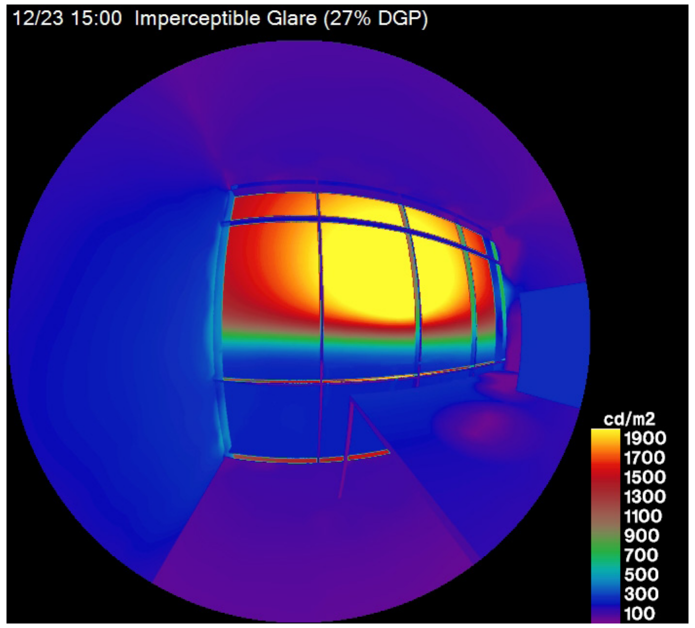

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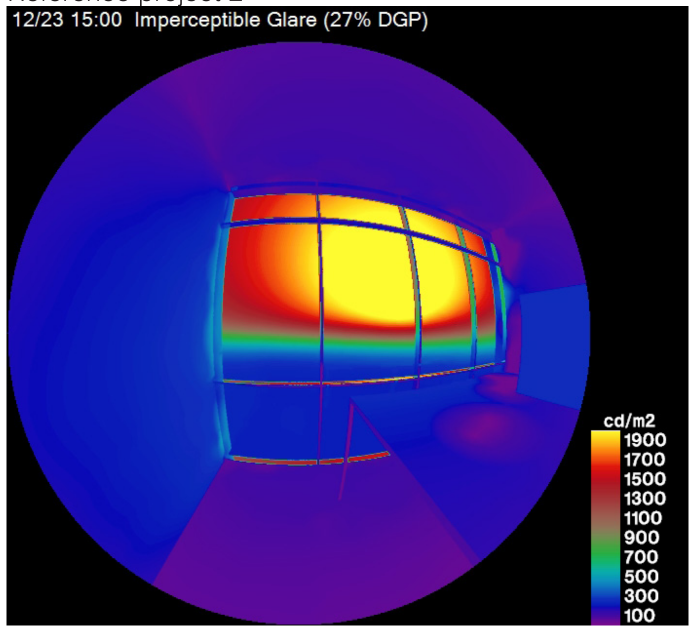

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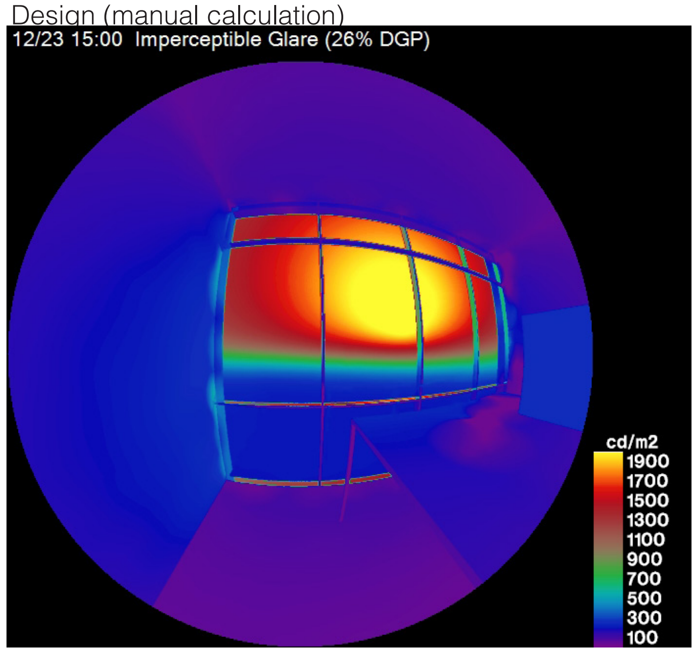
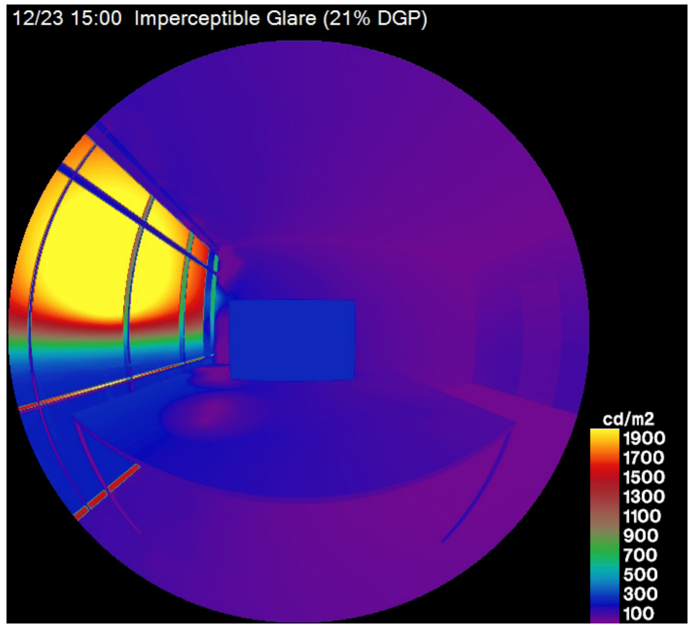
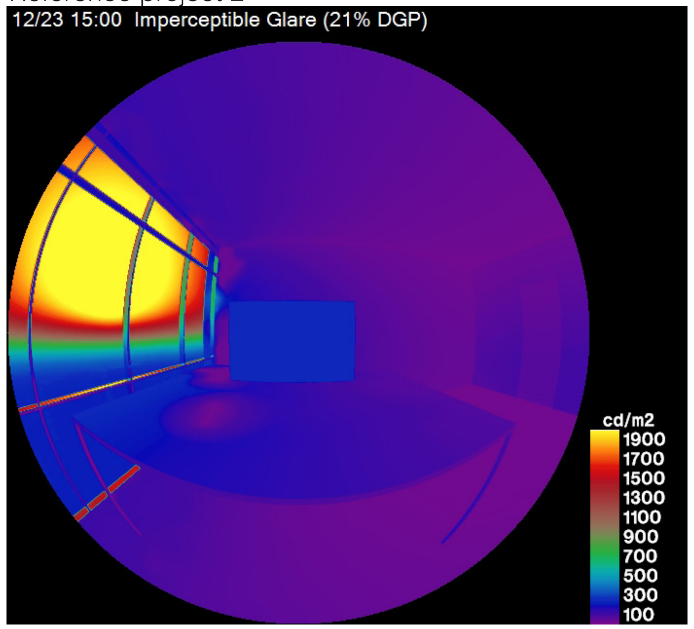


23rd December 15:00, User 1, View to the computer

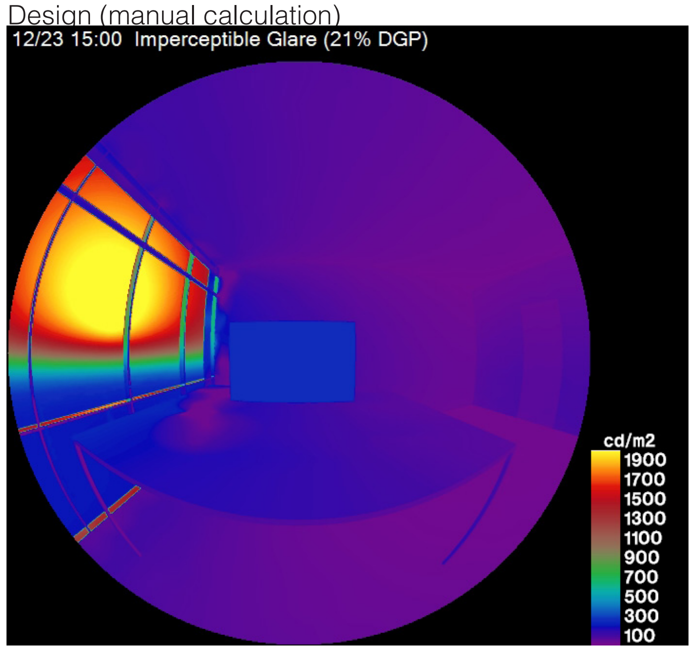
Reference project 1



Reference project 2



Design (manual calculation)



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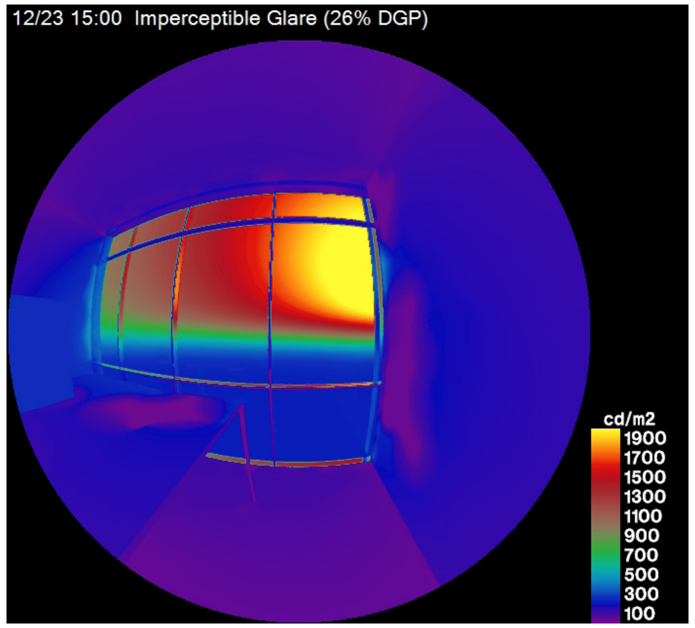

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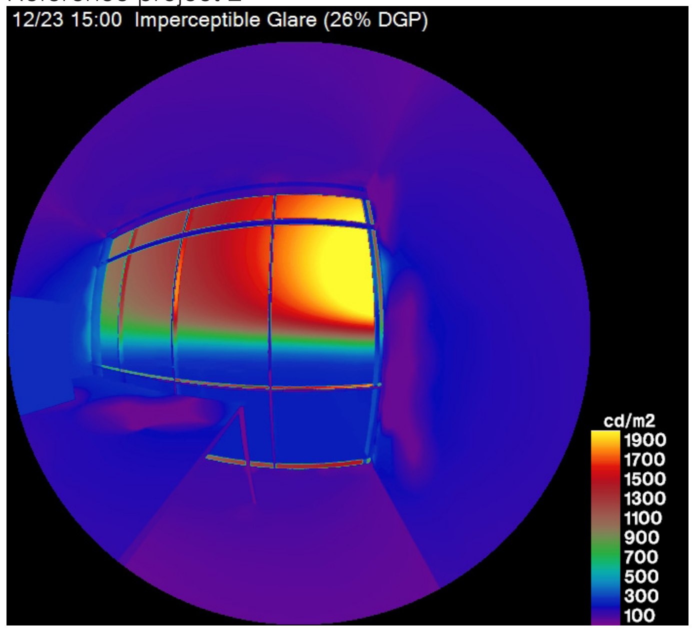

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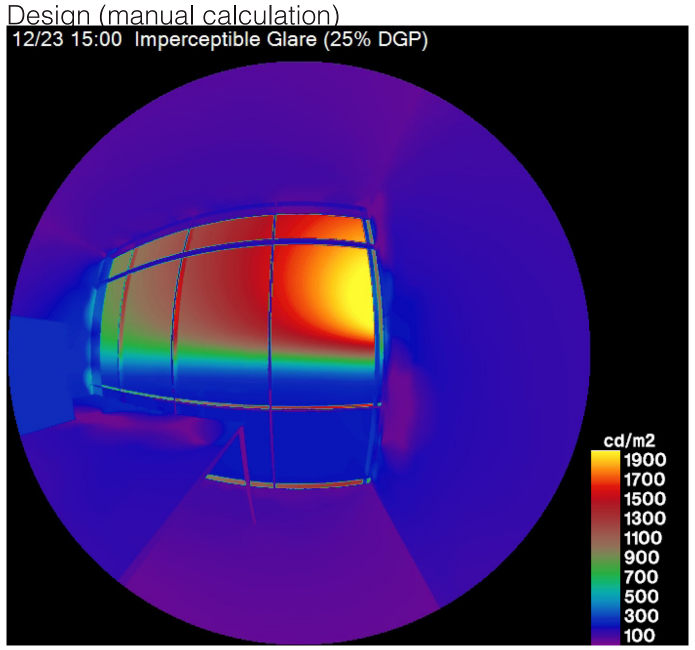

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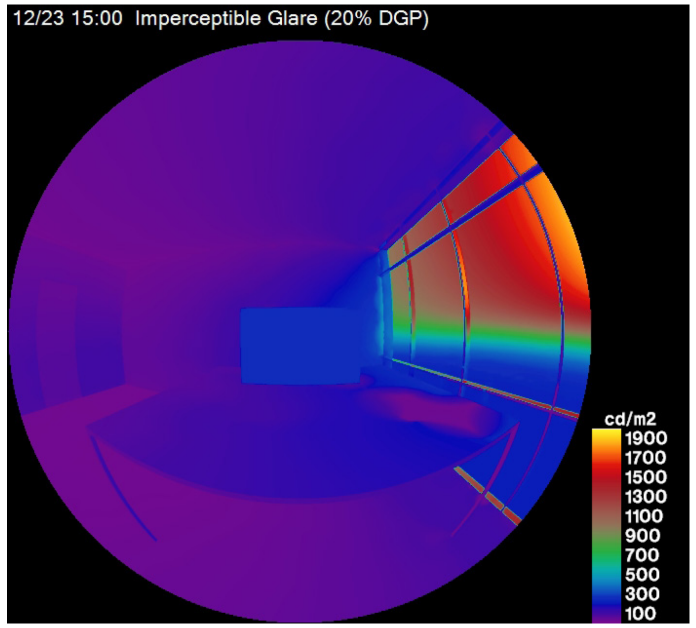

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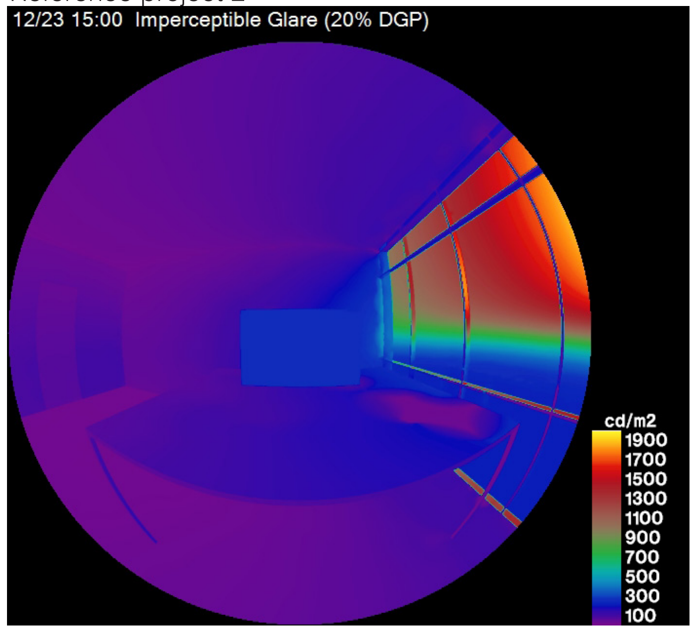

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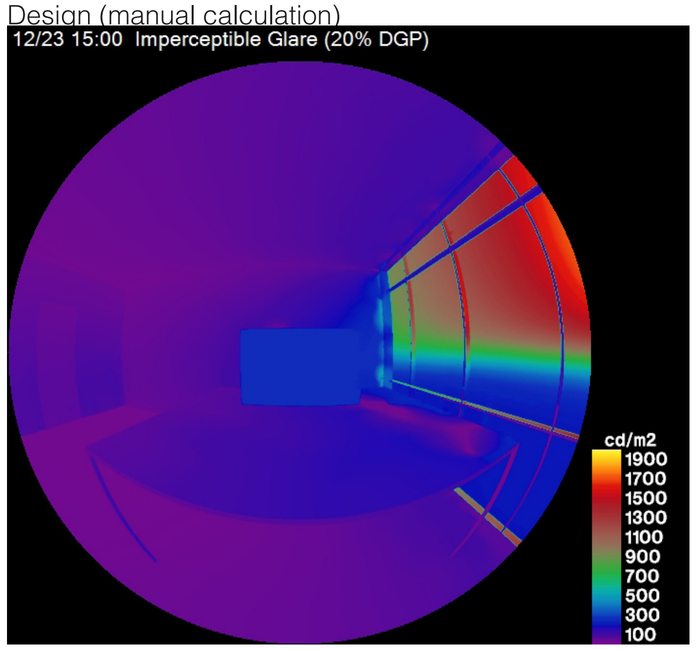
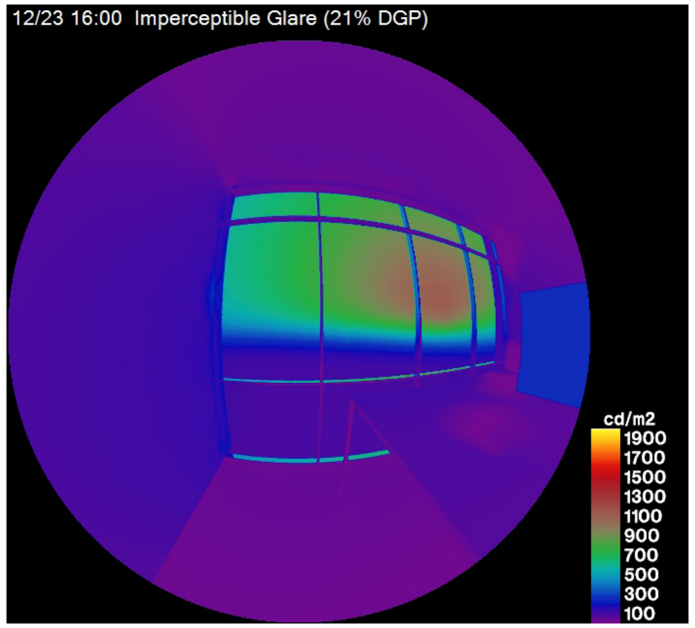


23rd December 16:00, User 1, View to the window

Reference project 1



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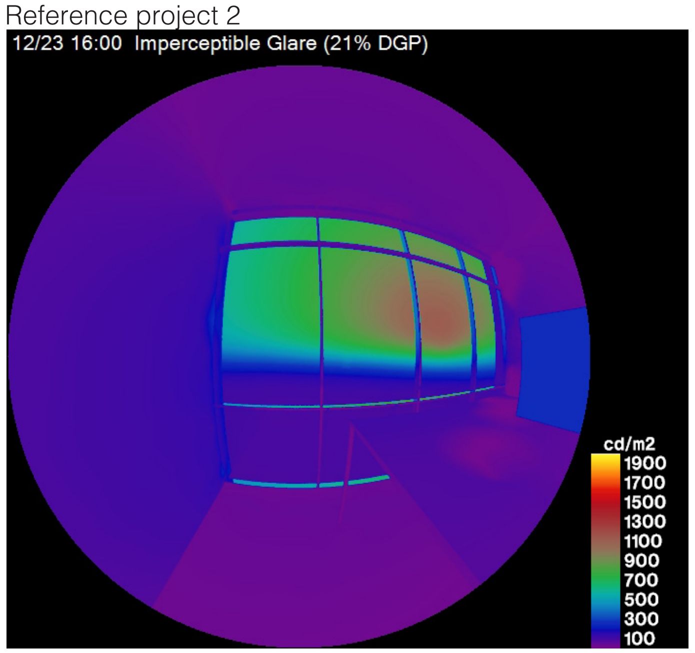

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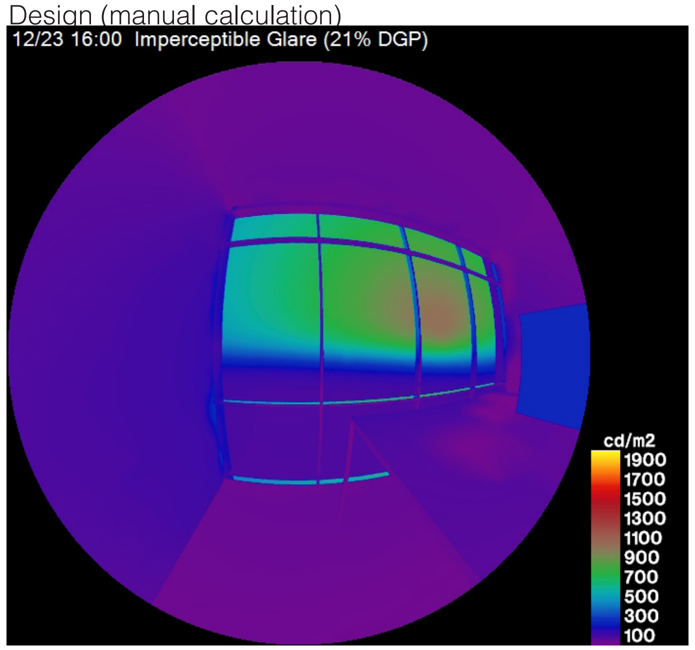

23rd December 16:00, User 1, View to the computer

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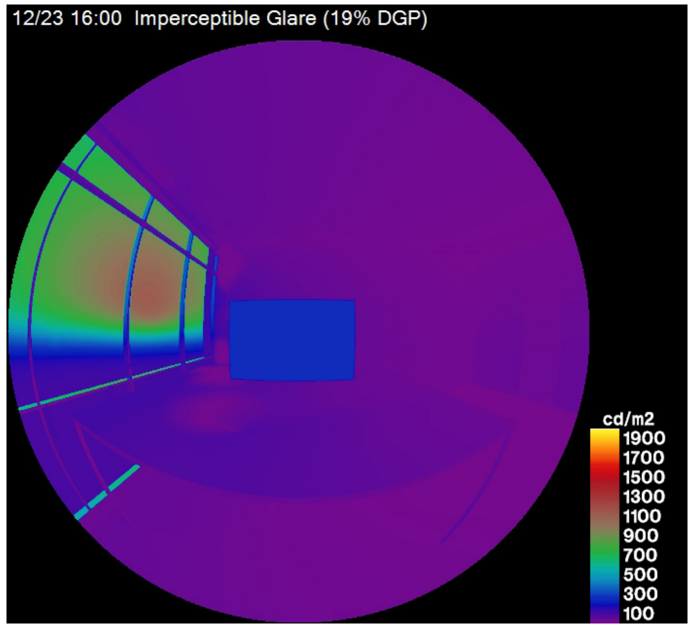

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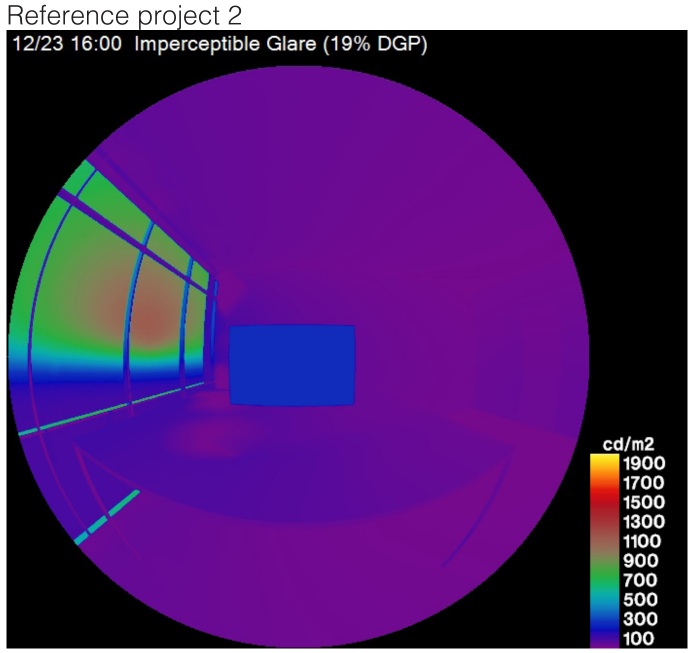
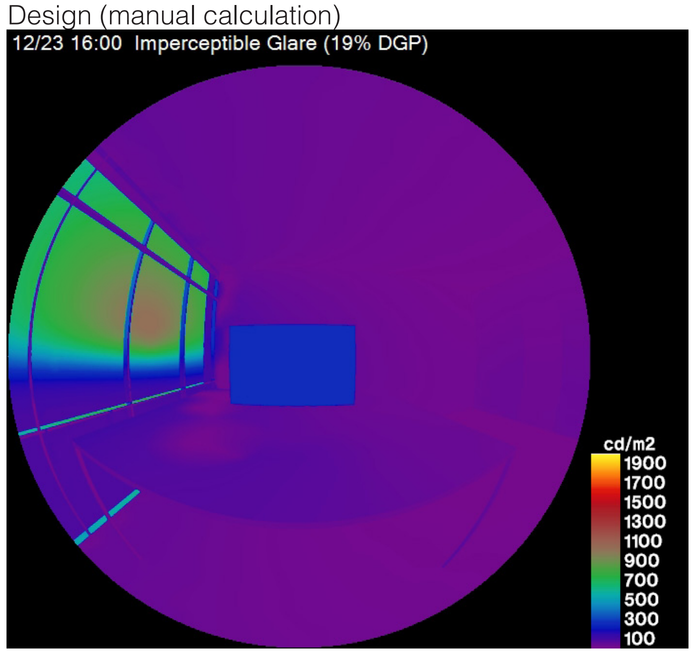
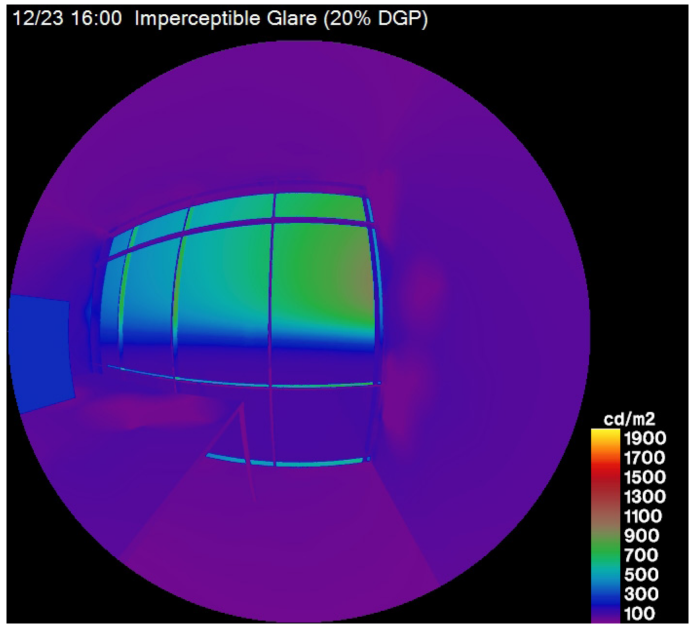


Design (manual calculation)



23rd December 16:00, User 2, View to the window

Reference project 1



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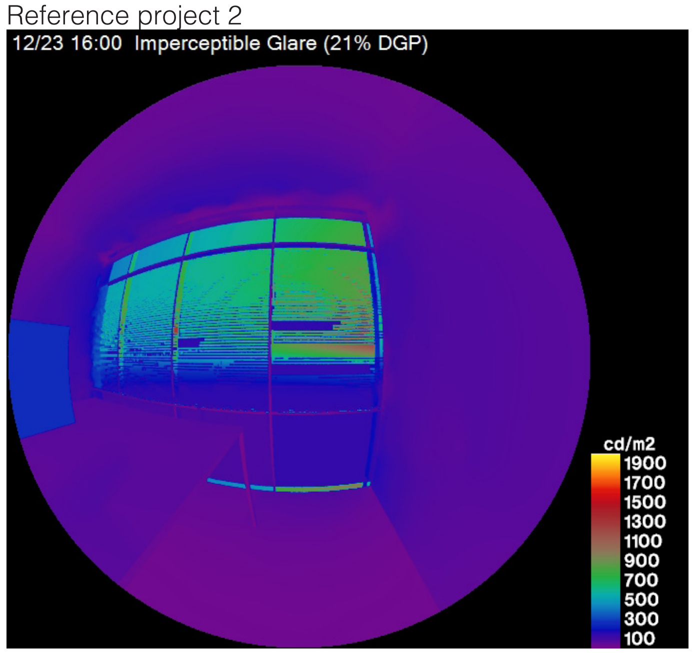

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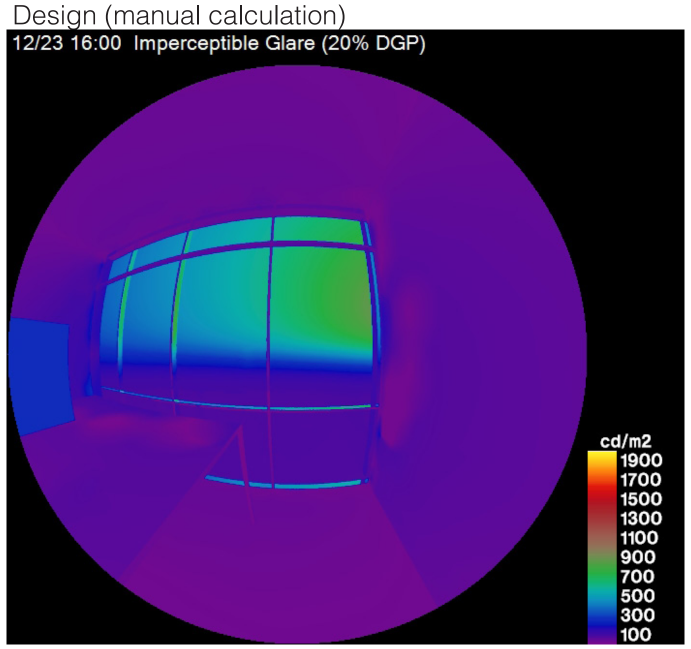
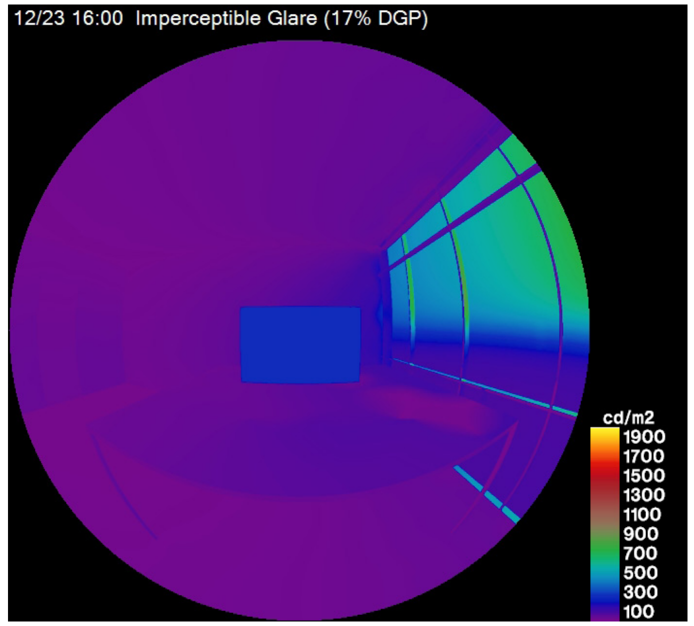


23rd December 16:00, User 2, View to the computer

Reference project 1



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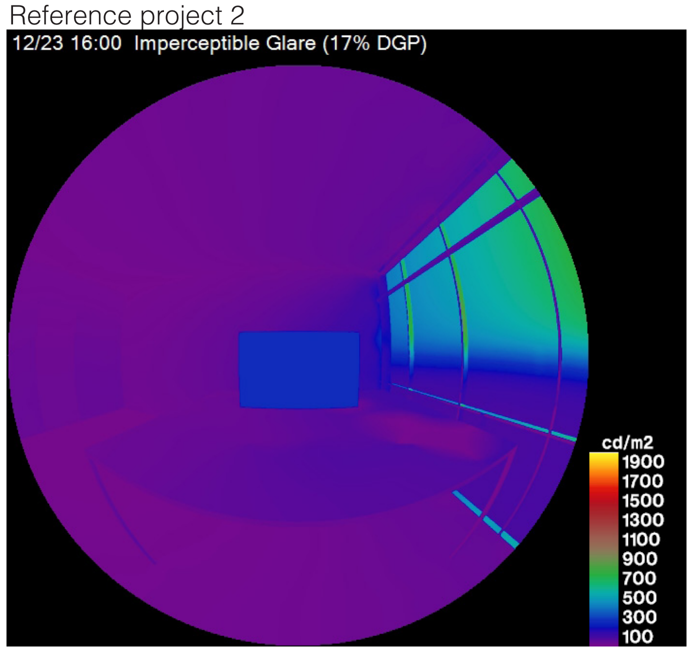

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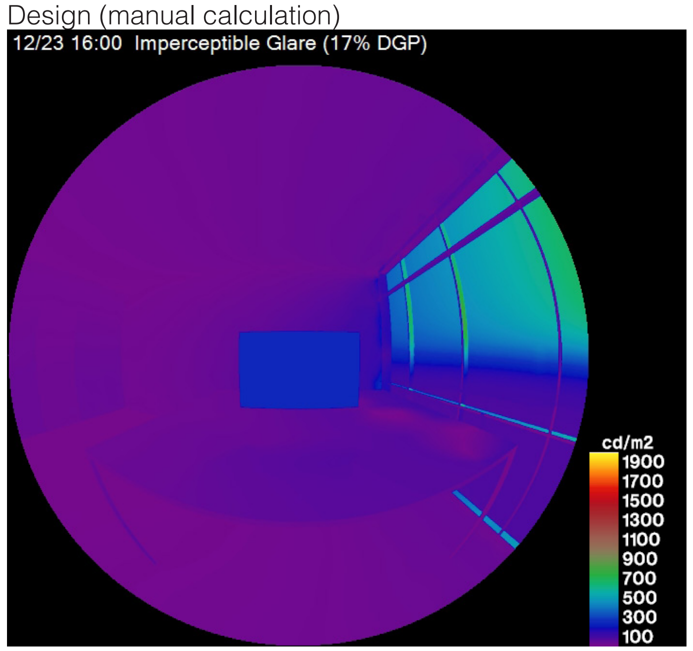

Thermal comfort - Design Builder

Monthly average temperature for each model

T [C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LC switchable	22	22	24	25	26	26	26	26	26	24	22	21
Ch-LC 0%	22	22	24	24	24	25	25	25	24	24	23	22
Ch-LC 50%	22	23	26	26	27	27	27	27	27	26	23	22
Ch-LC 100%	21	22	24	24	25	25	25	25	25	23	22	21
Ch-LC 0% + LC clear	22	23	25	25	26	26	26	26	26	25	22	21
Ch-LC 50% + LC clear	22	22	24	25	26	26	26	26	25	24	22	21
Ch-LC 100% + LC clear	21	22	23	23	24	25	25	25	24	23	22	21
Ch-LC 0% + LC tint	20	21	21	22	23	24	25	25	24	22	21	20
Ch-LC 50% + LC tint	20	21	21	21	23	24	24	25	24	22	21	20
Ch-LC 100% + LC tint	20	21	21	21	23	23	24	24	23	21	21	20
T [C]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference project 1 (Roller shading)	22	23	26	26	27	27	26	27	26	25	22	21
Reference project 2 (Venetian blinds)	22	23	25	25	26	26	26	26	26	25	22	21
LC + Ch-LC	21	22	23	23	24	25	25	25	24	23	22	21

Monthly energy consumption for heating for each model

Energy consumption Heating	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LC switchable	43,89	14,89	2,96	0,19	0	0	0	0	0	1,06	15,56	60,42
Ch-LC 0%	32	9,24	0,44	0	0	0	0	0	0	0	8,08	44,83
Ch-LC 50%	31,45	8,98	0,41	0	0	0	0	0	0	0	7,53	44,24
Ch-LC 100%	42,89	15,37	4,05	0,58	0,16	0	0	0	0	1,75	14,89	53,77
Ch-LC 0% + LC clear	37,85	12,26	1,2	0	0	0	0	0	0	0,19	11,75	50,22
Ch-LC 50% + LC clear	41,7	14,33	3,32	0,28	0	0	0	0	0	0,95	14,44	53,45
Ch-LC 100% + LC clear	45,91	20,91	10,23	1,94	0,71	0	0	0	0,06	4,95	19,73	57
Ch-LC 0% + LC tint	90,55	64,97	51,2	29,07	9,77	1,34	0,22	0	0,4	19,7	53,41	91,75
Ch-LC 50% + LC tint	90,55	64,97	52,35	30,21	10,63	1,58	0,29	0	1,14	20,25	53,8	91,75
Ch-LC 100% + LC tint	90,55	64,97	54,05	32,52	12,49	2,64	0,46	0,5	3,2	22,39	55,27	91,75
Energy consumption Heating	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference project 1 (Roller shading)	37,09	12,2	0,78	0	0	0	0	0	0	0	10,67	55,61
Reference project 2 (Venetian blinds)	39,61	13,48	1,36	0	0	0	0	0	0	0,24	12,47	55,91
LC + Ch-LC	45,91	20,91	10,23	1,94	0,71	0	0	0	0,06	4,95	19,73	57

Monthly energy consumption for cooling for each model

Energy consumption Cooling	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LC switchable	26,22	56,99	114,59	130,98	196,42	187,22	230,02	236,37	178,82	83,12	34,86	14,67
Ch-LC 0%	57,79	144,91	264,28	265,38	370,46	346,75	405,91	403,91	305,73	185,93	82,87	31,23
Ch-LC 50%	59,74	147,92	274,02	273,35	378,55	352,57	409,83	408,36	312,55	195,12	89,41	32,42
Ch-LC 100%	27,19	37,88	63,39	69,37	84,22	86,99	106,87	106,41	67,14	46,77	30,59	18,64
Ch-LC 0% + LC clear	45,64	106,38	195,85	196,78	290,47	273,02	323,86	322,41	243,33	146,78	65,32	26,14
Ch-LC 50% + LC clear	31,89	67,11	123,6	125,51	190,69	185,12	225,45	224,08	162,01	94,92	43,41	19,09
Ch-LC 100% + LC clear	21,35	28,56	53,72	57,17	73,88	75,53	92,02	93,47	61,11	42,96	26,23	14,73
Ch-LC 0% + LC tint	0	0	19,24	35,33	107,71	142,31	181,52	187,52	118,24	14,61	4,16	0
Ch-LC 50% + LC tint	6,52	10,63	32,69	39,16	92,19	107,71	137,72	142,87	92,66	31,88	13,38	4,48
Ch-LC 100% + LC tint	6,52	10,63	22,86	22	44,95	50,87	63,02	66,73	40,09	24,61	11,22	4,48
Energy consumption Heat	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Reference project 1 (Rolle	41,17	105,2	220,59	216,54	303,1	283,43	340,7	350,51	271,45	148,22	53,56	20,83
Reference project 2 (Ven	45,95	108,67	193,63	181,09	257,11	240,39	291,93	303,77	238,13	138,06	62,66	26,79
LC + Ch-LC	21,35	28,56	53,72	57,17	73,88	75,53	92,02	93,47	61,11	42,96	26,23	14,73

Monthly energy consumption for heating + cooling

Heating + Cooling	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(Roller shading)	78,26	117,4	221,37	216,54	303,1	283,43	340,7	350,51	271,45	148,22	64,23	76,44
(Venetian blinds)	85,56	122,15	194,99	181,09	257,11	240,39	291,93	303,77	238,13	138,3	75,13	82,7
Ch-LC 100% + LC clear	67,26	49,47	63,95	59,11	74,59	75,53	92,02	93,47	61,17	47,91	45,96	71,73