Coupled design optimization of façade design and automated shading control for improving visual comfort in office buildings

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Coupled design optimization of façade design and automated shading control for improving visual comfort in office buildings

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Summary

Solar shading is an important feature of high-performance building design, as these systems can determine the access of natural daylight illuminance, prevent glare, enable view to outside and have an impact on the energy balance of a building. Research shows that daylight and view to the outside can improve the occupant well-being, workplace productivity and satisfaction by positively influencing various psychological and physical processes. Given that most working adults spend the majority of their time indoors, it is important that we optimize the indoor environmental quality. Appropriate design and control of solar shading systems can play a prominent role in this respect, by finding balanced trade-off solutions among the various competing performance aspects.

Various shading systems have merits and disadvantages. Static shading solutions offer interesting opportunities for architectural integration but they have the drawback that they cannot respond to changing weather conditions. Dynamic shading systems such as verticals blinds or a roller blind, on the other hand, can be adapted to outside conditions and occupant preferences, bringing more flexibility for energy and comfort management during building operation. However, their control can be complex, and dynamic shading system significantly limit the admission of daylight views to outside. Whereas horizontal shading systems can block effectively the summer sun around mid-day, vertical shading is more preferable in the early morning and late noon.

Based on: i) the aspiration to maximize the positive influence of daylight and view, ii) the application-specific strengths and weaknesses of the various shading typologies, and iii) the promising potential of novel automated control strategies, it is hypothesized that the visual comfort in office buildings can be improved through coupled design optimization of façade design and automated shading control. Two simulation studies are performed to evaluate and compare the visual performance of dynamic and static shading, individually and combined. Both studies focus on finding synergies in the combination of horizontal and vertical shading topologies. The first case study regards an interior roller blind and exterior fins. The second case study focuses on interior vertical blinds and an overhang. Both studies are performed for a south-oriented test office building of 27m² area in Amsterdam with a window-to-wall ratio of 80%.

Three performance indicators are considered for evaluation of the visual comfort: Daylight Glare Probability Simplified (DGPs) for glare, spatial Daylight Autonomy (sDA) for daylight utilization and View Fraction for view to the outside. A multi-criteria performance-based control strategy is used by embedding the DGPs, sDA and View Fraction in a penalty function. The most appropriate state of the dynamic shading for each time-step is selected by finding the state with minimum penalties. For evaluation of the results for the different shading solutions, a threshold value for glare is specified to narrow down the solution space and to assist in decision-making trade-offs.

The two case studies show that static shading combined with performance-based controlled dynamic shading has potential to improve visual comfort in comparison to both systems as individual shading solutions. This can be assigned to the fact that blocking of the sun by static shading results in a higher uncovered window fraction for dynamic shading. It leads to a more beneficial daylight performance (16% – 31%) in terms of spatial daylight autonomy in comparison to dynamic shading as individual shading solution. The impact on view depends strongly on: i) the size of view obstruction by the static shading, ii) the improvement of the view through increase of the uncovered window fraction for dynamic shading and the iii) occupant-related assumptions (e.g. occupant position, view direction).

By using a performance-based control strategy in both case studies for concurrent optimization of static shading design and dynamic shading, it was possible to make a tight coupling between façade design and the operational aspect. This leads to more beneficial values for daylight and view performance in comparison with the results for the rule-based control strategy and a larger facade design space with near-optimal performance. This larger design space could offer benefits in terms of performance aspects (e.g. energy use, thermal comfort), which were not explictly addressed in this study. In addition, it leads in one of the case studies to the ability to use a different design solution, which generates number of benefits, such as cost-reduction and material saving.

This study shows the potential of coupled design optimization of static shading and performance-based controlled dynamic shading to improve the visual comfort. Application of this approach in practice asks for a tailored approach from the design team. In the first place, it requires conscious choices regarding the façade as a static element. Therefore, the façade design must result from a careful process in the early phase of an integral design process. Secondly, the use of an advanced control strategy requires an expression of the performance of the shading through a set of clearly defined criteria and also a definition of acceptance thresholds for dynamic evaluations. A final recommendation is to use objective performance information to assist in decision-making trade-offs.

Acknowledgements

I want to thank prof. Jan Hensen, Roel Loonen and Samuel de Vries for their continuous advice and suggestions in the supervision of this project. Their questions, feedback and support were essential for the successful completion of this thesis. I am grateful that you were willing to share your knowledge with me. Samuel, I greatly appreciate your patience and support during the weekly meetings. Your suggestions, enthusiasm and guidance throughout the entire thesis were fundamental for completing my thesis. Roel, thank you very much for sharing you knowledge with me and challenging me with your questions and ideas. Finally, I would like to thank prof. Jan Hensen for the monthly progress meetings. His suggestions and feedback were very helpful for this thesis.

"It's okay to not be perfect.
It's okay to make mistakes.
It's okay to do something that
you wish you hadn't done,
because if we don't do those
things we never grow."

– Dawn Stanyon

Contents

Acronyms

BPS	Building performance simulation
DGP	Daylight glare probability
DGPs	Daylight glare probability simplified
H-sDA	Hourly spatial daylight autonomy
HSA	Horizontal shading angle
IEA	International Energy Agency
PBC	Performance-based control
RBC	Rule-based control
sDA	Spatial daylight autonomy
VB	Vertical blinds
VF	View fraction
VSA	Vertical shading angle
WWR	Window-to-wall ratio

1. Introduction

Effective use of daylight in buildings is an important consideration for minimizing the carbon impacts and for creating an high indoor environment quality. A growing number of studies demonstrate that access to daylight and window view have a range of impacts on health, well-being, productivity and job satisfaction of building occupants. *[Ward, Rockcastle, Kline, & Wymelenberg, 2019; Al Horr, Arif, Mazroei, Katafygiotou, & Elsarrag, 2016; WGBC, 2014]*. The importance of view is increasingly recognized over the last years by the introduction of multiple design guides regarding view by, for example, the Leadership in Energy and Environmental Design (LEED), the Chartered Institution of Building Services Engineers (CIBSE) and New European Daylighting Standard EN 17037. Beside the impact on health, view and daylight also play a significant role in the market price of real estate since people are often willing to pay a premium for attractive views and more daylight *[Turan, Chegut, & Reinhart, 2020; Damigos & Anyfantis, 2011]*.

Solar shading is an important feature of high-performance building design to achieve a good balance between daylight admission, views to outside and solar gains. Especially with the often highly glazed façades nowadays. In terms of visual comfort, an “ideal” façade, would continuously provide: i) sufficient levels of well-distributed daylight illuminance, ii) absence of discomfort glare for all occupants and iii) view to the outside. *[Loonen, 2018; Ruck, et al., 2001]*. In this context, various shading solutions have their merits and disadvantages. Static shading solutions offer interesting opportunities for architectural integration and are able to block the direct sun while keeping daylighting view to the outside (Figure 1)

Figure 1. Examples of façades with static shading: 1) Head office ING Amsterdam [source: Rollecate, 2019]; 2) Office Tower Amsterdam [source: Rafel Viñoly Architects, 2005], 3) Office DUO Groningen [source: UN Studio, 2011], 4) Residential building Amadeus Den Haag [source: BNA, 2019]

Application of static shading results for selective hours in an higher daylight utilization and more view in comparison to dynamic shading. However, static shading has the drawback that it cannot respond to changing weather conditions. Extreme dimensions for fixed solar shading devices may be necessary to prevent discomfort glare all year long. Another disadvantage is that it also limits the exposure to positive aspects of daylight utilization, for example on cloudy days. (Figure 2)

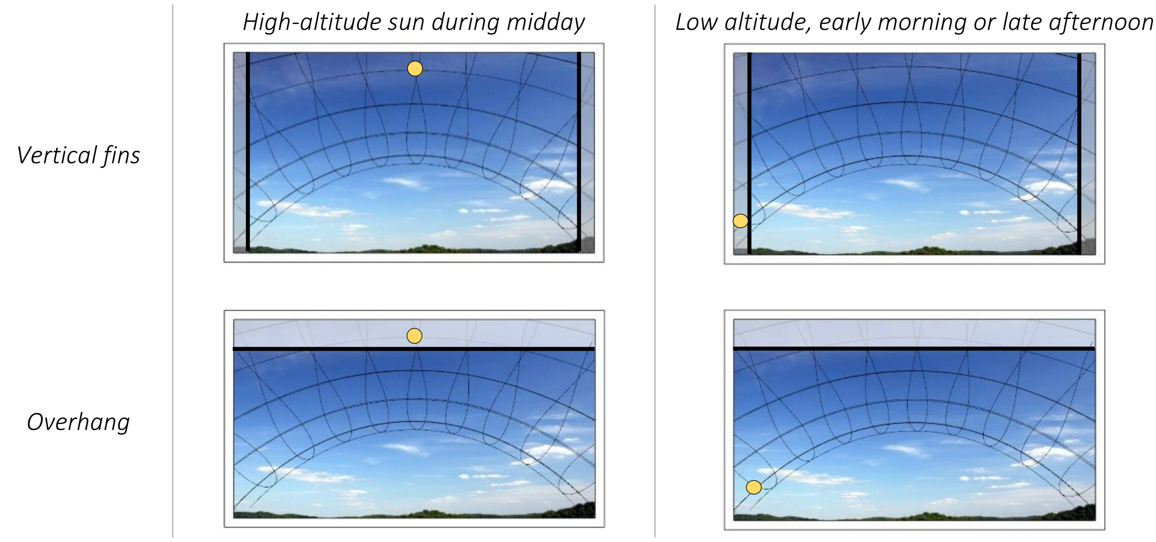


Figure 2. Strength and weakness of static shading systems in relation to the sun position

Dynamic shading systems such as venetian blinds or a roller blind, on the other hand, can be adapted to outside conditions and occupant preferences. However, their control can be complex, and dynamic shading system can significantly limits the admission of daylight views to outside. (Figure 3)

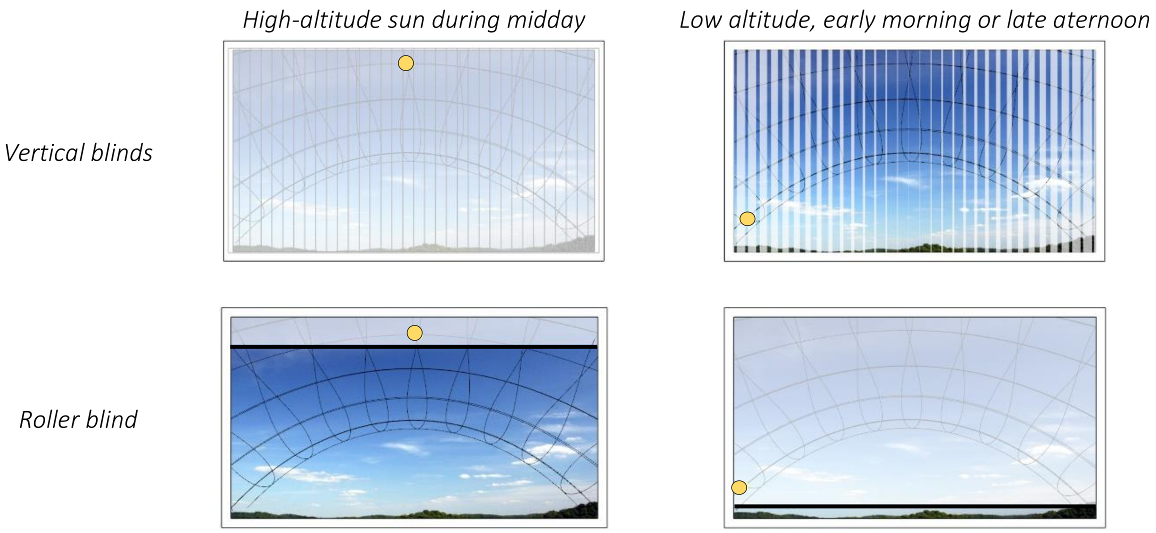


Figure 3. Strength and weakness of dynamic shading systems in relation to the sun position

Horizontal shading is preferable during summer 12h00 (Figure 4). On these moments, vertical fins aren't able to prevent glare and vertical blinds needs to be fully closed. Vertical shading is preferable in the early morning and late afternoon. On these hours, the roller blind needs to be fully lowered to prevent glare and an overhang isn't able to prevent glare.

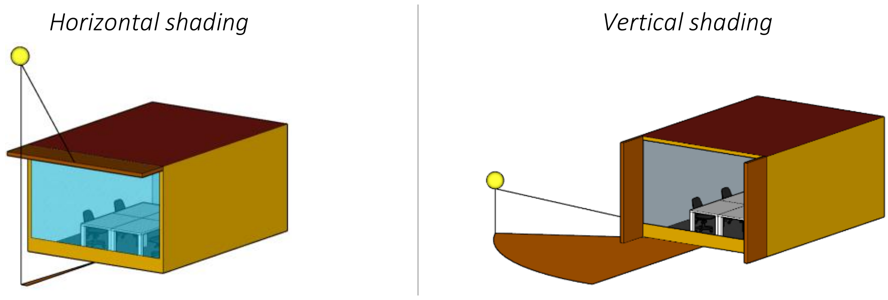


Figure 4. Effectiveness of horizontal (left) and vertical (right) shading in relation the sun position

1.1. Hypothesis

Based on: i) the aspiration to maximize the positive influence of daylight and view, ii) the application-specific strengths and weaknesses of the various shading typologies, and iii) the promising potential of novel automated control strategies, it is hypothesized that the visual comfort in office buildings can be improved through coupled design optimization of façade design and automated shading control.

1.2. Background studies

The number of studies regarding combined static and dynamic shading is limited. Lee and Tavil (2007) considered façade designs with overhangs combined with electrochromic window control strategies and so show the potential for optimization of the energy and comfort by combining dynamic and static shading *[Tavil & Lee, 2006]*.

Over the last years, breakthroughs in material science opened up a range of new possibilities for building designers to influence the conflicting performance goals of visual comfort, daylighting and energy consumption in a more dynamic way. Switchable reflection/ transmission materials, intelligent lighting systems and advanced control strategies are three examples of promising opportunities through their adaptability *[Favoino, Jin, & Overend, 2017; Jeong, Choi, & Sung, 2016; Kheybari & Hoffmann, 2018; Creemers, Loenen, Aarts, Chraibi, & Lashina, 2014; Loonen & Hensen, 2014]*.

1.3. Research question

The primary objective of this research is to explore the potential of coupled design optimisation of fixed building characteristics, static shading and automated shading control in terms of visual comfort. Thereby, this study focuses on finding synergies in the combination of horizontal and vertical shading topologies, where the one is static, and the other is controlled in a dynamic way. In order to fulfil this objective, the following main question will be answered:

- Could the application of static and automated controlled shading mutually enhance each other, to combine their strengths, while mitigating the weaknesses in terms of visual comfort and daylight performance?

This research addresses the following sub-questions:

- What is the performance gain compared to individual shading solutions?
- What is the impact of the control strategy on the performance?

1.3. Methodology

This research makes use Building Performance Simulation (BPS). Thereby, two case studies will be performed to explore the potential of coupled design optimization of static and dynamic shading systems in comparison to the performance for dynamic and static shading as individual solutions. This research follows the majority of the steps indicated by Loonen et al., who mapped out the different fundamental stages for simulation based support or product development of adaptive building technologies *[Loonen, Singaravel, Trčka, Cóstola, & Hensen, 2014]*. The resulting steps, which add structure to the simulation in this research and to the structure of this report, are:

1. Determining performance indicators
2. Developing an appropriate modelling and simulation strategy
3. Identification of (un)certainties and quality assurance
4. Defining test case models
5. Presenting and discussing the results

1.4. Thesis outline

Figure 5 shows a graphical representation of the way this thesis is structured. Chapter 2 presents the simulation strategy to be used for exploring the potential of coupled design of static shading automated shading control for optimization of visual comfort. This chapter also presents model's assumptions and explains the approach for the advanced-control strategy. The reliability of the simulation model and model's assumptions is examined in chapter 3. Chapter 4 describes the outcomes of the two simulation studies. Finally, chapter 5 concludes with summarizing the findings of the entire study and provides recommendations for future work.

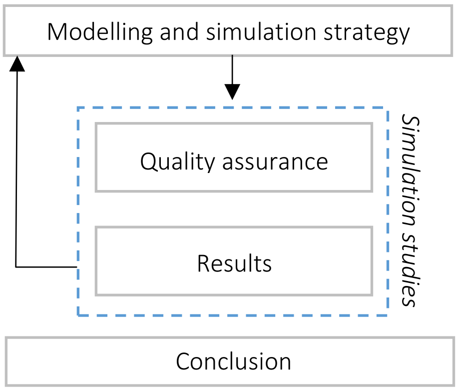


Figure 5. Structure of the thesis

2. Modelling and simulation strategy

In this chapter, the modelling and simulation strategy for the BPS in this research is presented in six steps: 1) performance indicators, 2) building test case model, 3) static shading, 4) dynamic shading, 5) simulation method and 6) shading control.

2.1. Performance indicators

In this research are glare, daylight and view to the outside considered for evaluation of the visual performance.

Glare

The ‘daylight glare probability simplified’ (DGPs) is used as indicator to assess the discomfort glare. *[Wienold, 2009]*. The DGPs indicator is primarily based on vertical illuminance (E_v). In this report, the DGPs has been considered at the four sensor points as shown in Figure 6, whereby the occupants look under an angle of 45 degrees in the direction of the window. The maximum value out of the four sensor points is considered at each timestep. Four different categories according to the classification of *[Wienold, 2009]* are considered: intolerable (DPGs > 0.45), disturbing (0.40 > DGPs ≤ 0.45), perceptible (0.35 > DGPs ≤ 0.40) and imperceptible (DPGs < 0.35). The DGPs 95th percentile is used for the annual glare performance *[Mardaljevic, Andersen, Roy, & Christoffersen, 2012]*.

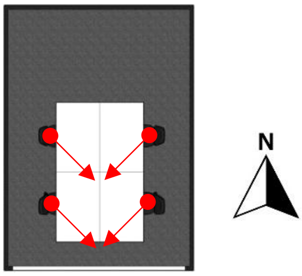


Figure 6. Floor plan with the seating of the four occupants and their view direction

Daylight

Spatial daylight autonomy (sDA) is used as an indicator for the daylight quality. In this report, the $sDA_{300/50\%}$ is defined as the percentage of floor area that receives at least 300 lux for more than 50% of the occupied hours *[Illuminating Engineering Society, 2012]*. The hourly daylight illuminance sufficiency is assessed by the Hourly Spatial Daylight Autonomy ($H\text{-}sDA_{300}$). This is the percentage of the floor area that receives more than 300 lux for a particular point in time *[Wagdy, Fathy, & Altomonte, 2016]*.

View to the outside

There is no standard method or set of metrics to evaluate view. Over the years, researchers have developed multiple methods to evaluate view, based on: vector raytracing in 3D models *[Mardaljevic, 2019; Turan, Reinhart & Kocher 2019]*, answering multiple choice questions about the view content *[Hellinga & Hordijk, 2014]*, geometric quantification of view access *[Pilechiha, Mahdavinejad, & Rahimian, 2020; Konstantzos & Tzempelikos, 2017]* and quantification of the area-weighted occupant’s view preference *[Wenting & Samuelson, 2020]*. An overview with the description of each method is attached as appendix I to this report.

Although the visual perception of the user and the effects on visual performance are difficult to quantify, it is believed that improve of: i) view quantity and ii) the view quality (*what* is seen, *where* and *how* points of interest relate to one another) can affect these aspects in a positive way. The view quantity depends on multiple variables such as the seating position, view direction, window size, glazing type and properties of shading material.

View quality depends on a variety of highly subjective parameters, including scenery, location and the human visual perception. This research focus only on the view quantity. The objective of this research is to quantify and evaluate to what extent the different shading solutions have impact on the view quantity. The view quantity is assessed as the portion of the occupant's visual field (Figure 7) that has a direct line of sight to the exterior. This approach makes the view performance dependent on the shading solution, observers position and view direction. The shading fabrics are assumed to be fully opaque. The Ladybug Grasshopper plug-in is used for vector raytracing in the building model and so calculation of the fraction of rays in the visual field which beam through the window without intersect with the shading system. (Figure 7) *[Sadeghipour Roudsari, Michelle, & Smith, 2013].* The component makes use of the Tregenza sky subdivision, which divides the hemisphere into 145 patches of approximately equal solid angle. The accuracy of this division is increased by dividing up the sky patches (Figure 8).

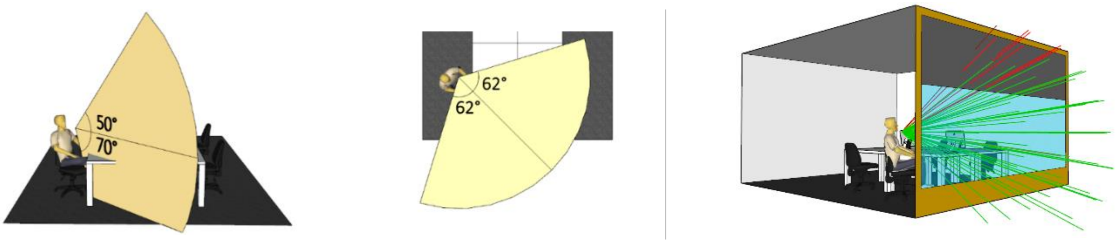


Figure 7. Left: human cone of vision in two directions, horizontally and vertically; Right: Rays cast from position of occupant eye within the human cone of vision for a façade with and without roller blind

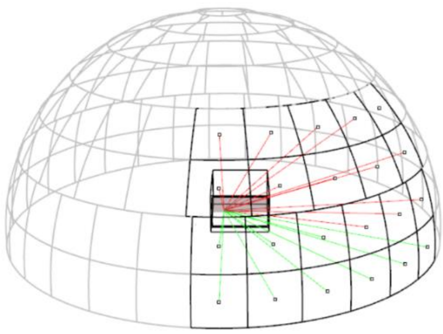


Figure 8. Rays cast from position of occupant eye, within the human cone of vision, to the centre point of the Tregenza sky patches

The occupants are simulated as small grids (0.5 x 0.5m; 25 points) instead of one point to mitigate differences in view at a short distance from the occupant's eye level (Figure 9). This assumption is based on an explorative study which is attached as appendix II to this research. The view quantity is determined for each shading configuration by defining the fraction of rays with unobstructed view to the outside within the vision field. This is called the View Fraction. The average view fraction is taking over the all the grid-points of the four grids.

$$VF = \frac{1}{100} * \frac{1}{N} * \sum_{i=1}^{100} \sum_{j=1}^{N} A_j$$

N: number of rays

$$A: \begin{cases} 1, \text{ if ray intersect with window, but not with shading system } \textit{(green rays)} \\ 0, \text{ else} \end{cases}$$

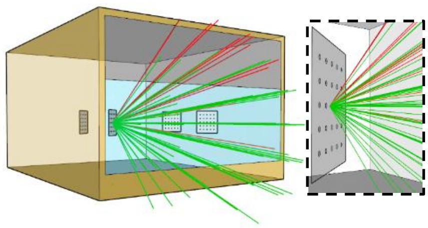


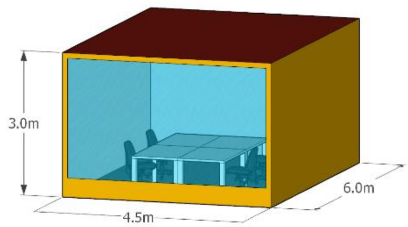
Figure 9. Left: Defining equation for View Fraction (VF); Right: rays cast from position of one of grid points.

2.2. Building test case model

This research used the reference office building for evaluating building integrated solar envelope systems, developed within IEA SHC Task 56 with some minor adjustments *[D'Antoni, Bonato, Geisler-Moroder , Loonen, & Ochs, 2017]*. Details of this south facing perimeter office cell and the associated modelling assumptions are given in Table 1. The office is assumed to be occupied by four persons on working days, which are present from 8:00 to 18:00. The total number of occupied hours in this study is 2860.

Table 1. Reference office building details and modelling assumptions

Geometry	Dimensions	4.5m x 6m x 3m (W x D x H)
	Orientation	South
	Window-to-wall ratio	80%
Fenestration	Type	Low-E double glazing with argon cavity filling
	Glazing	SHGC: 0.637, T_{vis}: 0.785
Separations	Ceiling	r_{vis} = 0.8
	Walls	r_{vis} = 0.5
	Floor	r_{vis} = 0.2
Weather		IWEC, Amsterdam, The Netherlands



2.3. Static shading

The static shading design is in this research specified by using the vertical shading angle (VSA) for the overhang and horizontal shading angle (HSA) for the fins (Figure 10).

$$HSA = \frac{d}{0.5 \cdot w} \qquad VSA = \frac{d}{h}$$

Figure 10. Defining images for the horizontal (left) and vertical (right) shading angle

The design of static shading with the HSA and VSA gives the possibility to freely change between different shading device typologies. Many configurations, shapes, and sizes are possible for exterior shading systems. One large or several small static shading elements may give the same shading angle (Figure 11). This study uses an abstraction, where only a simple horizontal overhang at the top of the window opening and two simples vertical fins on both sides of the window are considered. The intention is that it can be used to extract general design principles. These can then be used as input for architectural design concepts that may (or may not) have more geometric complexitiy and asethetic appeal that the test solutions.

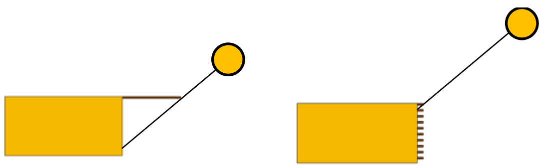
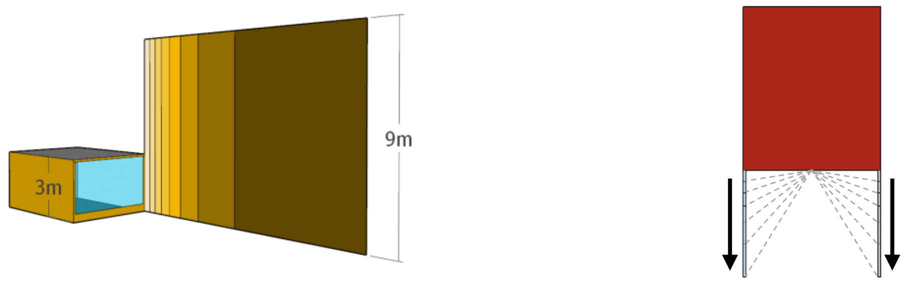


Figure 11. Different shading designs for the same shading angle

Different designs for the overhang and fins are generated by increasing the shading angle with steps of 10°. The shading angle is increasing by increasing the depth of the shading device. Multiple small shading devices in combination with the imprecise representation of the direct sun component through averaging over relatively large sky solid angles could lead to blurry and featureless interior shadows *[Ward, Mistrick, & Lee, 2011]*.

Simulation of fins

The fins are is modelled as two vertical surfaces on each side of the window and with a reflection value of 0.2. Eight different designs are generated by assuming a discrete possible range of vertical shading angles (10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°) (Figure 12). The height of the fins is assumed to be equal to three times the office height. This assumption will be explained in section 3.

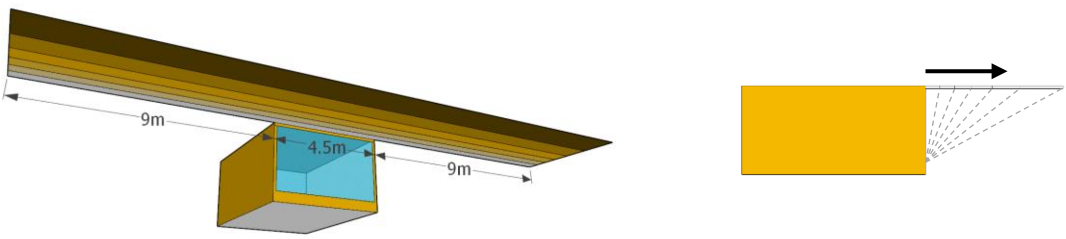


HSA	10°	20°	30°	40°	50°	60°	70°	80°
Fin depth [m]	0.40	0.82	1.30	1.89	2.68	3.90	6.18	12.76

Figure 12. The eight façade designs for fins, characterised by their HSA, fin depth and visualized with colours

Simulation of overhang

The overhang is modelled as one horizontal surface with a reflection value of 0.2 on top of the window. Six different designs are generated by assuming a discrete possible range of vertical shading angles (10°, 20°, 30°, 40°, 50°, 60°). (Figure 13). The extrusion for the overhang is assumed to be equal to two times the office width. This assumption will be explained in section 3.



VSA	10°	20°	30°	40°	50°	60°
Overhang depth [m]	0.44	0.91	1.44	2.09	2.97	4.31

Figure 13. The six façade designs for an overhang, characterised by their VSA, overhang depth and visualized with colours

2.4. Dynamic shading

Vertical blinds and roller blind, as dynamic shading systems in this research, are modelled by assuming a range of discrete shading states for both shading systems.

Roller blind

The roller blind is assumed as dense shade with a visible reflection outside of 0.74, light transmission of 4% and an openness factor of 2%. The roller blind shading system is modelled by dividing the window into ten horizontally oriented equal segments which are either fully shaded or unshaded. This resulted in eleven shading states as shown in Figure 14.

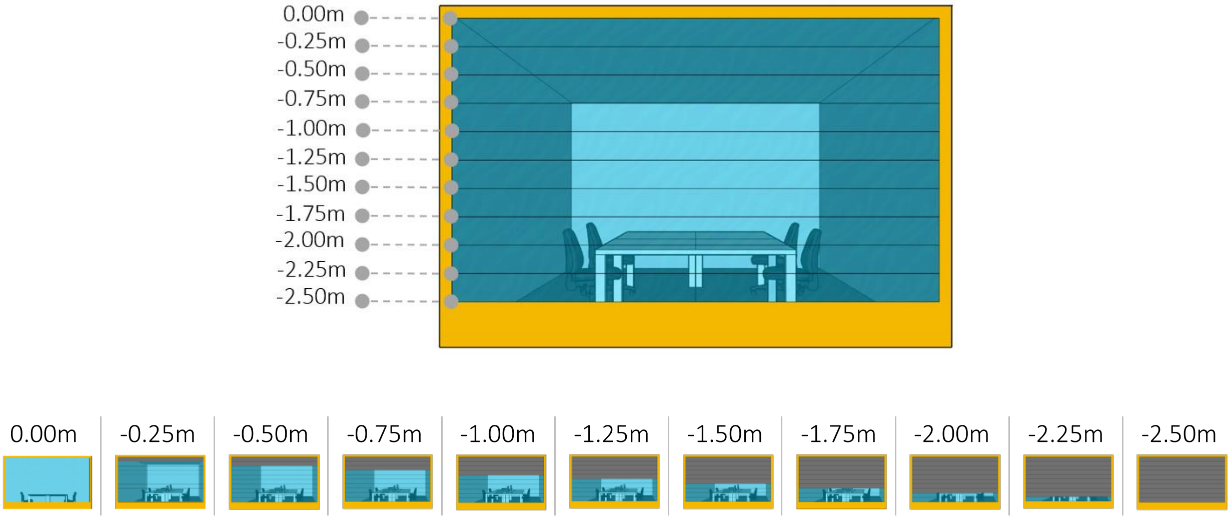


Figure 14. The eleven modelled shading states for the roller blind with their shade height

Vertical blinds

Vertical blinds are assumed as flat slats (slat width: 127mm, spacing: 127 mm) with a solar reflection value of 0.75 (front) and 0.50 (back) . The variable slat angle of the blinds is assumed as the discrete possible range of eight different angles (-67.5°, -45°, -22.5°, 0°, 22.5°, 45°, 67.5°, 90°). The slat angle α is defined as the angle between the glazing outward normal and the slat outwards normal, where the outwards normal points away from the front of the slat. The different slat angles for the vertical blinds are visualized in (Figure 15).

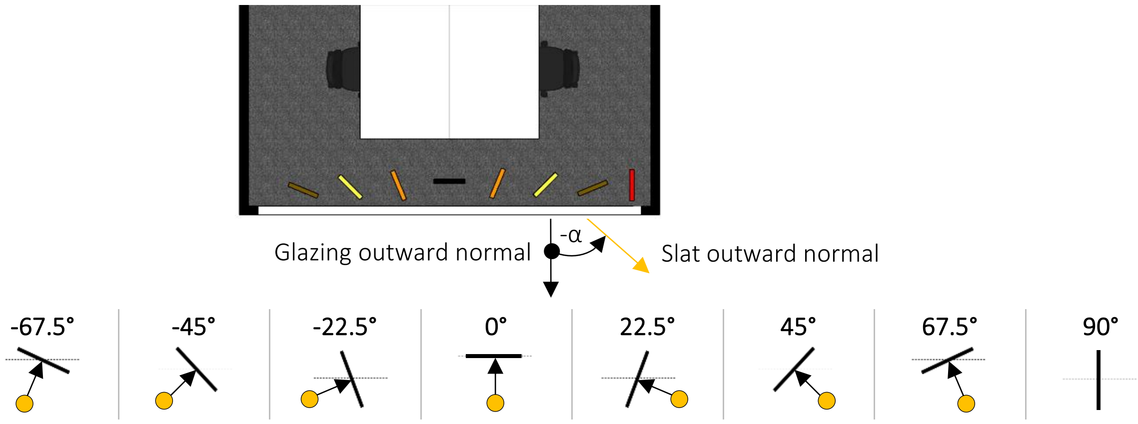
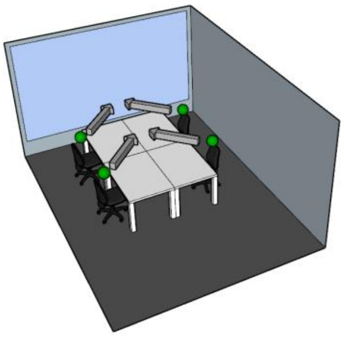


Figure 15. The eight slat angles for the vertical blinds

2.5. Simulation method

The Radiance three-phase method is used for daylighting and glare performance assessments. This validated method separates light transport between the sky and the sensor points into three phases: exterior transport (sky matrix), fenestration transmission (transmission matrix) and interior transport (view matrix). Each phase of light transport is simulated independently and stored in a matrix form. The resulting climate-based indoor illumination is obtained using matrix multiplication *[McNeil & Lee, 2013]*. The main reason for using the three-phase method in this research is the possibility for analysing the dynamic performance of multiple shading configuration in a quick, yet accurate way. The shading state can be changed without simulating the entire light path, simply by substituting a new fenestration transmission matrix *[Subramaniam, 2018]*. The spatial daylight autonomy in the office is determined by modelling a grid of 70-sensor points on work plane height (Figure 16). The vertical illuminance at the eye of the observer is modelled by modelling four sensors at the position of the observer with the view direction facing the window at 45° to assess glare probability.



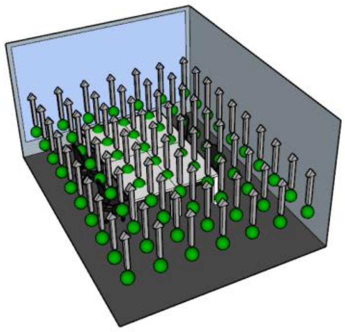


Figure 16. Four points grid for glare and daylight (left) and seventy points sensor grid for daylight (right)

2.6. Shading control

The control strategy is very important for the performance of dynamic shading during operation. This research makes use of different control strategies which are elaborated below.

Rule-based control strategies

Rule-based control (RBC) strategies connect measurements by sensors to actions via rules of the kind "*if* condition *then* action" *[Loonen, 2018]*. Two different RBC strategies are used in this research to control the roller blind and vertical blinds. The roller blind is controlled using an outdoor global horizontal irradiance sensor on the roof of the office where the shade is either fully raised or lowered in response to a threshold of 200 W/m². The vertical blinds are controlled by using sun tracking behaviour. In this strategy, the cut-off angle of the slats is determined in relation to the sun's position (azimuth angle) to exclude direct sunlight from entering the office.

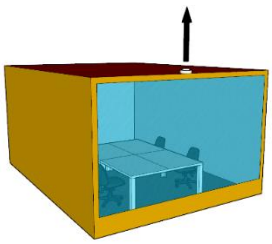


Figure 17. Office with outdoor global horizontal irradiance sensor on the roof

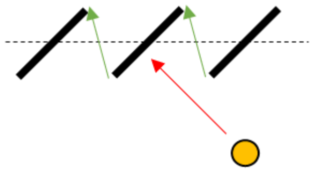


Figure 18. Vertical blind "cut-off" angle

Performance-based control strategy

The control actions for the performance-based control (PBC) strategy in this research follows from comparing the visual performance for the different dynamic shading states for each time-step and selecting the best state. The selection of the best shading state is driven by an optimization function that ranks the visual performance for each shading state. This strategy couples the façade design with the operational aspects of the dynamic shading and so allow coupled-design optimization.

This strategy consists of three steps:

1. Simulation of all possible states of the shading system to get the hourly values for daylight, glare and view

2. Evaluation of the performance of all possible shading states by using weighted penalty functions. When the required criteria are not achieved, the unacceptable cases are rejected by applying penalties for the different components: DGPs (P_{glare}), H-sDA$_{300}$($P_{daylight}$) and view (P_{view}). The threshold values for glare, daylight and view are indicated in (Figure 19). The priority of daylight, glare and view can be set separately by different weighting factors (W_{glare}, $W_{daylight}$, W_{view}).

Main penalty function: $P_{total} = W_{glare} \times P_{glare} + W_{daylight} \times P_{daylight} + W_{view} \times P_{view}$

3. Selection of the most appropriate shading state at every time-step by selecting for every timestep the shading state with the minimum main penalty (P_{total}). The outcome is a schedule which contains the shading states with the best performance at every timestep.

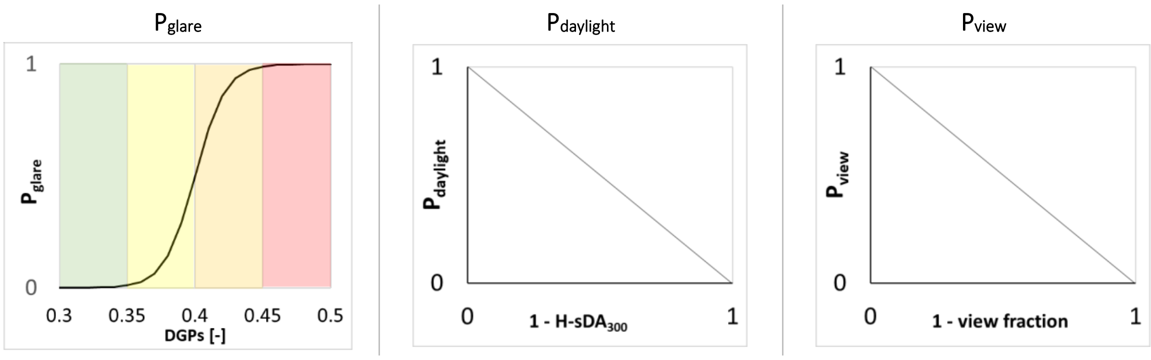


Figure 19. Penalty functions for glare, daylight and view

The weights (W_{glare}, $W_{daylight}$, W_{view}) represent the relative importance of glare, daylight and view. Multiple test runs are performed to evaluate the impact of different penalty functions on daylight performance. This resulted in five different penalty functions by making different assumptions for the weighting factors W_{glare}, $W_{daylight}$ and W_{view} (Table 2**Fout! Verwijzingsbron niet gevonden.**).

Table 2. Five penalty functions

Function	W_{glare}	$W_{daylight}$	W_{view}
P1	0.33	0.33	0.33
P2	0.44	0.56	0.00
P3	0.56	0.33	0.11
P4	0.67	0.33	0.00
P5	0.95	0.05	0.001

These five penalty functions are developed based on two sets of criteria. The first criteria is that the annual glare performance, in the form of 95th percentile, is divided over the different glare classes (see appendix III). The second criteria is that sometimes (e.g. low illuminance), glare and daylight are not sufficient for the control to make a meaningful decision. In this context, the role of view differs between the five penalty function by giving the weighting factor an value of 0 for P2 and P4 and an value larger than zero for P1 and P3. P5 is a preconditioned penalty function whereby view to the outside is only of interest after the performance criteria for glare (DPGs ≤ 0.35) has been met. By giving view a relatively low weight, the penalty function tends to select solutions that maximize openness of the façade while not compromising on glare discomfort and daylight illuminance (Figure 20**Fout! Verwijzingsbron niet gevonden.**).

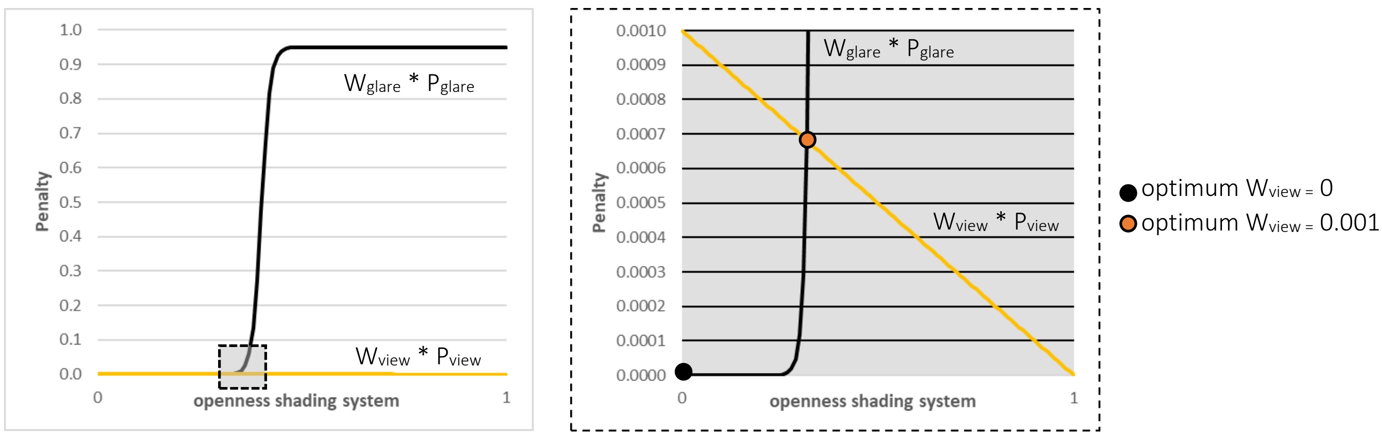


Figure 20. A relatively low weight for Wview leads to nudging of solution towards a solution that maximize openness of the shading system while not compromising on glare

As summary of the performance-based control strategy is given in (Figure 21).

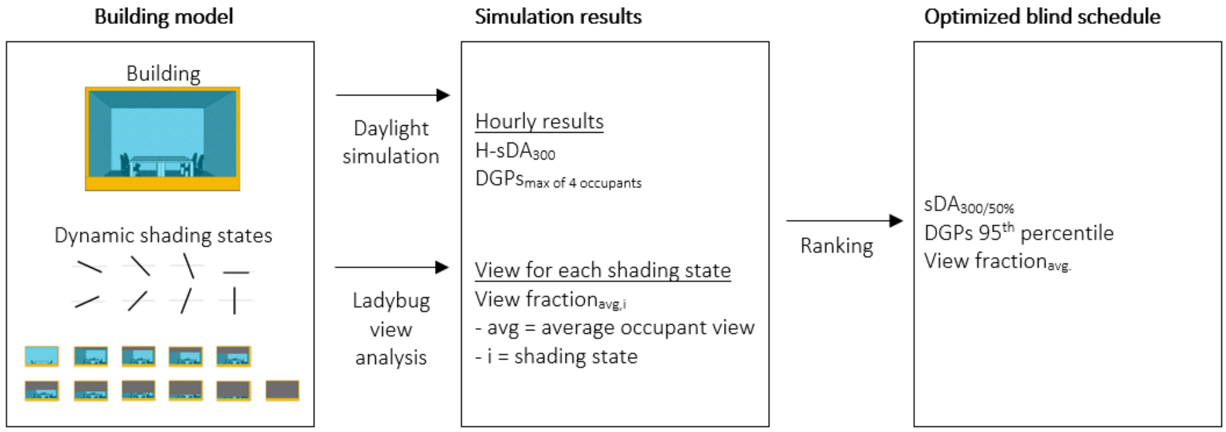


Figure 21. Summary of the PBC strategy

3. Quality assurance

It is important to examine whether the simulation model behaves in a manner - like a real building. Due to unavailability of measurement and experiment data it is not possible to perform empirical validation, but only to increase the level of confidence *[Hensen & Lamberts, 2019]*. This chapter examines the reliability of simulation-based predictions by:

1. Testing assumptions that are made regarding static shading by performing sensitivity analysis
2. Comparing the computer predictions of shading behaviour with expectations
3. Comparing the simulation results with data from comparable studies

3.1. Sensitivity analysis

Effect of fin height

A simulation study is performed to explore the impact of the extrusion for static fins on the annual glare performance, whereby the geometry is changed by setting the height of the exterior fins equal to one, two and three times the office height. The results show a minimum impact on glare for a fins with an extrusion of two times the office height. See appendix IV for more information about this study (Figure 22). This situation is representative for an office cell which is part of a larger building, whereby static shading devices of upper neighboring cells result in additional shading.

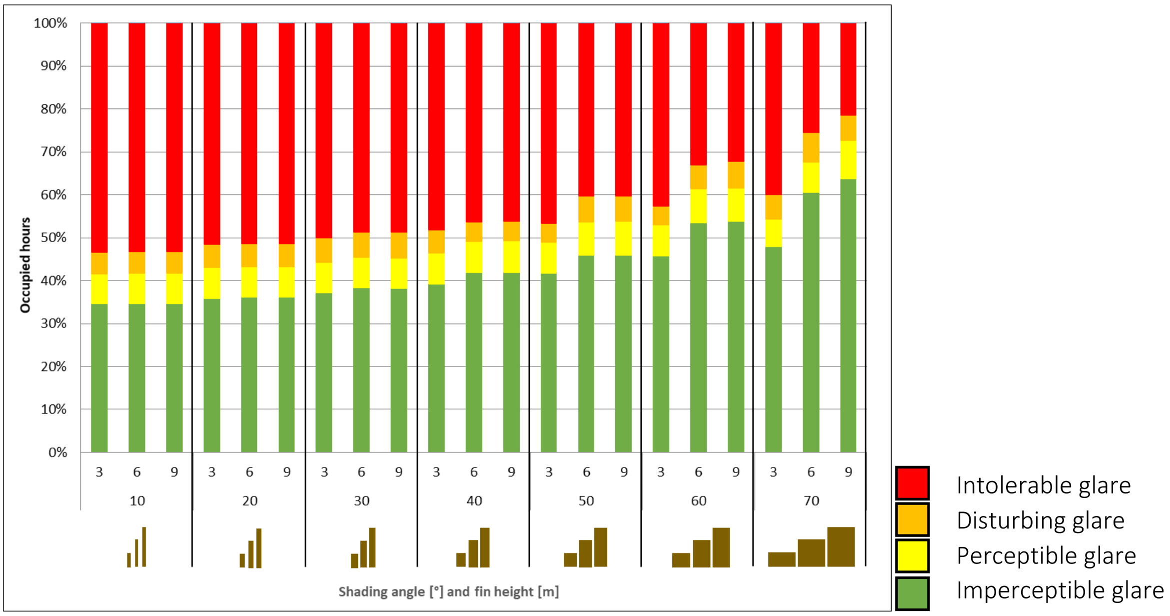


Figure 22. Difference in annual glare performance for fins with one(3) , two (6) or three times (9) the reference office height (for more see appendix IV)

Effect of number of overhangs, reflection value and ground reflection

A simulation study is performed for the overhang to explore the impact of: i) the number of horizontal devices, ii) the reflection value and iii) the ground reflection on the annual glare performance when it is combined with vertical blinds. Whereas the impact of the number of fins is minimal, increase of the reflection value results in an increase of glare (see appendix V). The ground reflection as a surface doesn't seem to have much impact on the results for visual comfort (Figure 23).

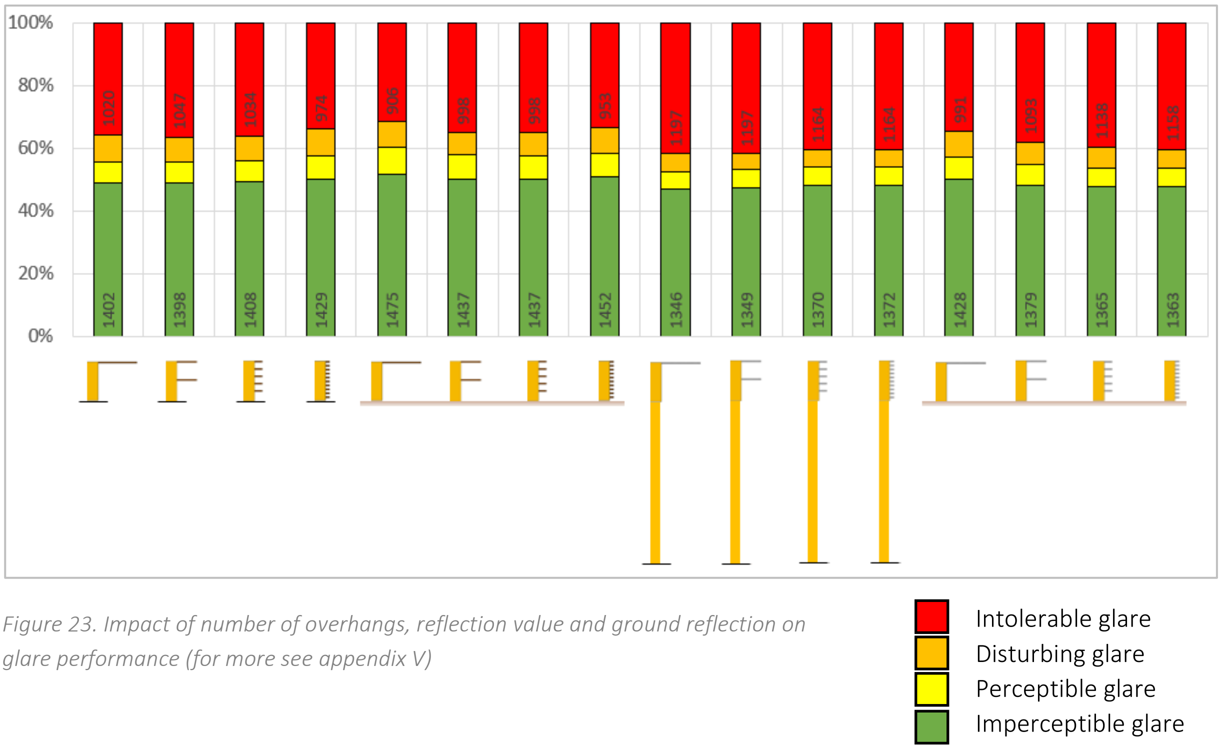


Figure 23. Impact of number of overhangs, reflection value and ground reflection on glare performance (for more see appendix V)

3.2. Model testing

Model testing is performed to see if the results for the modelled shading systems are in line with the expectations. To put this into practice, the impact of the different static shading designs, for both the overhang and fins, and dynamic shading states, for both the VB and roller blind, on the spatial illuminance distribution over the work plane is analysed. The hourly spatial illuminance results for all the different shading states (dynamic shading) and static shading designs for all the occupied hours are gathered for a clear sunny day (31 March). The expectations and results for each of the four shading systems in this research will be discussed below together with three spatial maps. All the spatial maps are attached as appendix VI to this report.

Roller blind

A roller blind controls daylight by varying the effective window aperture and so changing the luminous flux through the window. In case of dense shade material (2% openness), the majority of the diffuse daylight is blocked when the roller blind is deployed. Lowering of the roller blind results in reduction of the daylight penetration in the back of the office. The spatial maps show that pulling down of the roller blind leads to initially to an area with less daylight than desirable back in the room. Further lowering of the roller blind results in an increase of this area to the front of the office. Figure 24 gives an impression of the reduction of the penetration depth by lowering the roller blind.

12h00 (azimuth: 177°, altitude: 41°)

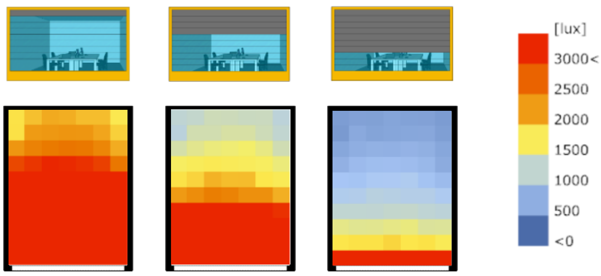


Figure 24. Spatial maps with the illuminance distribution on the work plane for three roller blind states

Vertical blinds

Vertical blinds block direct sunlight, while redirecting diffuse light and maintaining daylight performance within the space. Elimination of direct sunlight and view over a wide range of annual sun angles and sky conditions requires intermittently adjusting of the slat angles and may result in blinds that are rotated to a closed state, thus eliminating daylight and view along with glare. Figure 25 shows the spatial maps for the vertical blinds (VB) at 15h00 and confirms the relation between the redirecting behaviour of the slats, the openness of the slats and the illuminance distribution over the work plane.

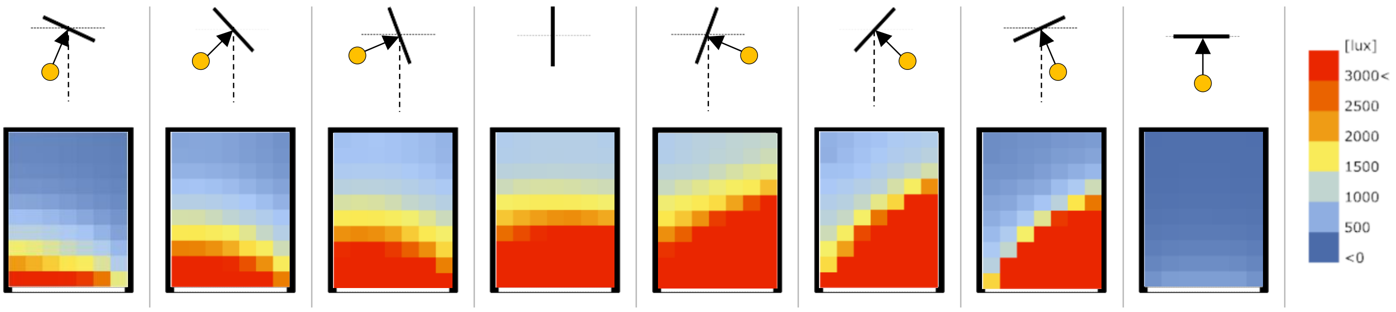


Figure 25. Spatial maps with the illuminance distribution on the work plane for different slat angles

Overhang

An horizontal surface on top of the window blocks the direct solar radiation from entering the window in case of high altitude sun. Diffuse radiation will partially be blocked. The amount of daylight in the back of the room will be decreased by increasing the depth of shading device. The simulation results for the different overhang geometries for 12h00 are shown in Figure 26. These spatial maps show that application of an overhang, with an reflection value of 0.2, results initially in reduction of the daylight penetration in the back of the office. Increase of the overhang depth results in an enlargement of this area to the front of the office.

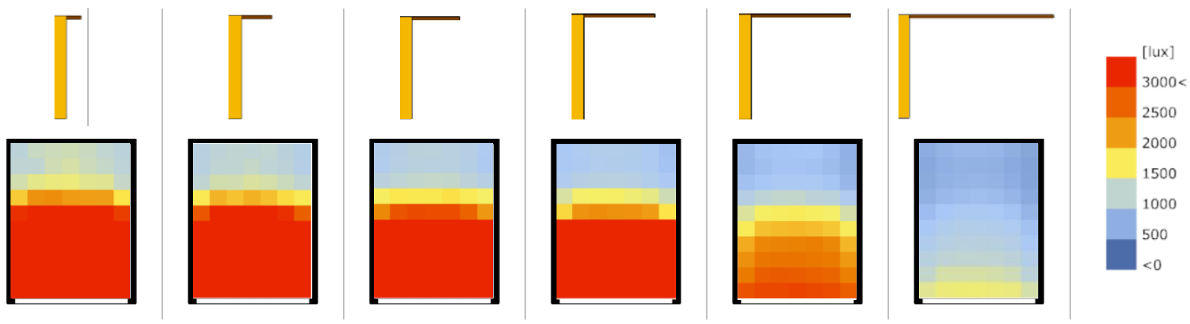


Figure 26. Spatial maps with the illuminance distribution on the work plane for six overhang depths

Fins

Vertical exterior fins are most effective at blocking sun positions with a high surface-solar azimuth and low altitude. The deeper the fins, the longer they are able to block sun in the morning and the earlier the sun in the afternoon. But fins are not able to block the sun when it is positioned perpendicular to the south-oriented window during noon, the moment of the day when solar irradiation is often highest. The simulated spatial maps confirm the blocking of the early morning and late evening sun. The results, for fins with an reflection value of 0.2, show also a decrease of the daylight penetration depth by increasing the fin depth. In comparison with the overhang, a larger shading angle for the fins is necessary to lower the maximum illuminance on the work plane (Figure 27).

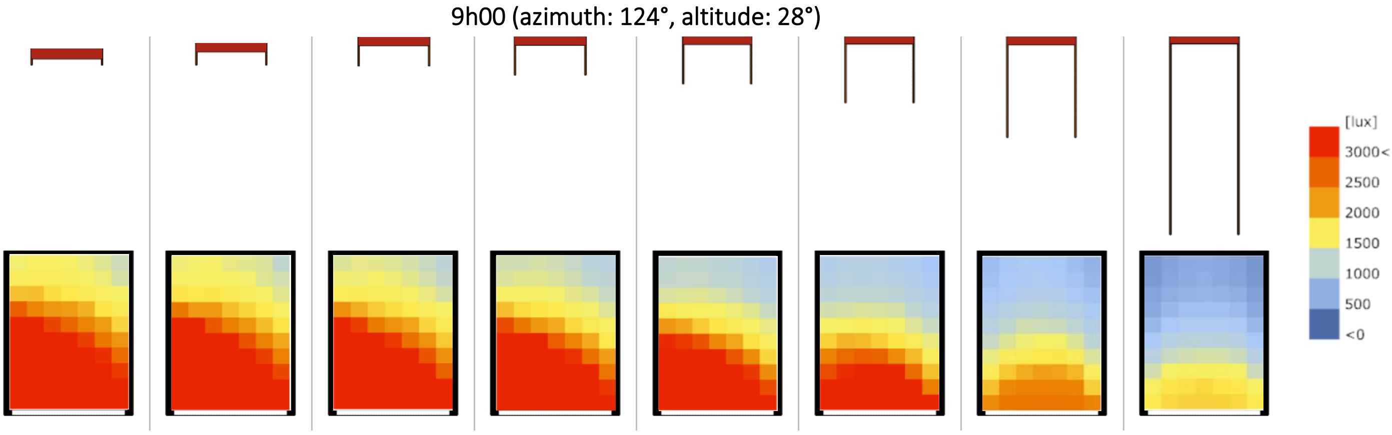


Figure 27. Spatial maps with the illuminance distribution on the work plane for eight fin depths

3.3. Comparative validation

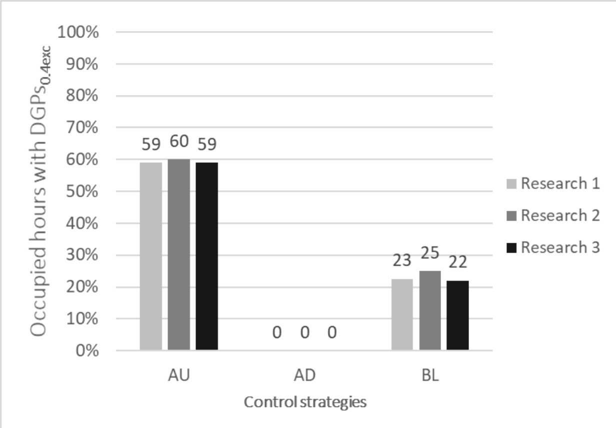
The results of daylight simulations for the reference office with interior roller blind are compared with simulation data, obtained from one published and one yet-to-be-published research article *[de Vries, Loonen, & Hensen, 2019; de Vries, Loonen, & Hensen]*. The two studies also make use of IEA SHC Task 56. Also Radiance three-phase method is used for simulation. Table 3 shows the details of this reference space and the associated modelling assumptions for the two studies, whereby the titles of the studies are:

- **Research 1 - title:** Sensor selection and control strategy development support for automated solar shading systems using building performance simulation
- **Research 2 - title:** A screening method for sensor selection and control strategy development of automated solar shading systems using building performance simulation

Table 3. Comparative overview with the simulation details and modelling assumptions for the two studies and this research

		Research 1	Research 2	This study
Geometry	Dimensions	4.5m x 6m x 3m	4.5m x 6m x 3m	4.5m x 6m x 3m
	WTW-ratio	85%	80%	80%
Fenestration	Type	Low-E double glazing with argon cavity filling	Low-E double glazing with argon cavity filling	Low-E double glazing with argon cavity filling
	Glazing	SHGC: 0.62, T_{vis}: 0.82	SHGC: 0.62, T_{vis}: 0.82	SHGC: 0.64, T_{vis}: 0.79
	Shade	Indoor roller blind OF: 0.04	Indoor roller blind OF:0.008	Indoor roller blind OF: 0.04
Visible reflection	Ceiling	0.8	0.8	0.8
	Walls	0.5	0.5	0.5
	floor	0.2	0.2	0.2
Weather		IWEC, Amsterdam	IWEC, Amsterdam	IWEC, Amsterdam

Three control scenarios are discussed. A situation where the roller blind is always up (AU), a situation where the shades are always down (AD) and control strategy where roller blind is controlled using an outdoor sensor where the shade is either fully raised or lowered in response to a threshold of 200 W/m² (BL).



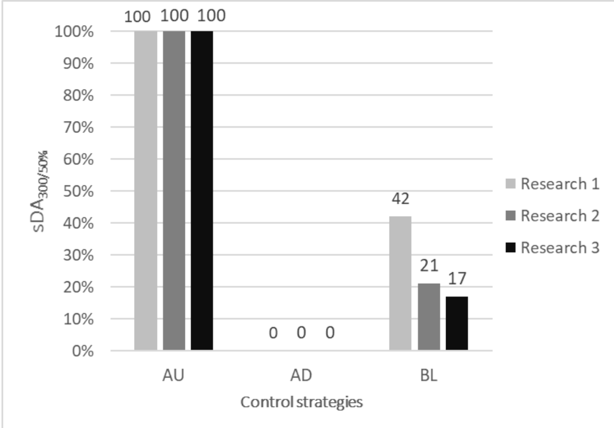


Figure 28. Summary of glare (left) and daylight (right) performance for the three researches and the three strategies. AU: always up, AD: always down, BL: Baseline E-ig; 200 W/m².

Figure 28 shows a building performance summary comparing the AU, AD and BL strategies as well as the glare and daylight performance for all the three researches. Glare performance is shown as the percentage of occupied hours that a DGPs of 0.40 is exceeded using the maximum of the view directions. Daylight performance is presented as the $sDA_{300/50\%}$. Figure 28 shows that the difference between all the three studies for both glare and daylight are very equal. Regarding daylight performance, the BL strategy shows the biggest discrepancies between the studies, especially between this study and research study 1. An explanation for this difference could be the different orientation of the shading control sensor. Overall, the simulations results of this study are very comparable with the results of the other two studies.

4. Results

This chapter presents two case studies to explore the potential of coupled design optimisation of fixed building characteristics, static shading and automated shading control in terms of visual comfort. In the first case study, we make use of a roller blind as interior, horizontal, dynamic shading solution and exterior vertical fins in the façade. For the second case study, an overhang is assumed in the façade and vertical blinds as interior dynamic shading system. In both studies, the visual performance for different static façade solutions and dynamic shading, both individually and in combination, are tested. Each case study can be divided into 3 parts (a-c):

a) **Static shading**: testing the visual performance for different static façade solutions
b) **Dynamic shading**: testing the visual performance for the dynamic shading system and evaluate the effect of using different control strategies
c) **Static and dynamic shading**: testing the visual performance for the different combinations between the static façade solutions and the different control strategies for dynamic shading

Table 4 presents the structure for the performed simulation studies and represents also the structure in this chapter.

Table 4. Structure of the two case studies

			Horizontal shading	Vertical shading
Case study 1	a:	Static shading		Fins
	b:	Dynamic shading	Roller blind	
	c:	Static and dynamic shading	Roller blind	Fins
Case study 2	a:	Static shading	Overhang	
	b:	Dynamic shading		Vertical blinds
	c:	Static and dynamic shading	Overhang	Vertical blinds

The comparison of the visual performance for the different shading solutions and the optimization process for visual comfort seeks to improve three performance aspects at the same time; glare, daylight and view. In this study, the performance for the different shading solutions is explored by analysing the trade-offs between glare and daylight and glare and view. Thereby, a DGP 95th percentile of maximum 0.35 (perceptible glare) is assumed as a constraint and indicated with a dashed line ($DGPs_{thr.}$) in the different scatter plots in this chapter.

4.1. Case 1 - Roller blind combined and fins

4.1.1. Case 1A - Fins

Figure 29 shows the trade-offs between glare and daylight for fins with different shading angles. Even though the $sDA_{300/50\%}$ levels are high, vertical fins lead to a high risk of intolerable glare discomfort. If we assume a DGP 95th percentile of max. 0.35, all the static shading solutions for the fins are clearly unacceptable. Only the application of 80°-fins lead to a small reduction in glare, contrary to the other dots which are all positioned under each other in the right-upper corner of the plot. Blocking of direct sunlight for all the annual occupied hours will lead to extremely large shading systems. To create visual comfort, an additional shading solution needs to be applied.

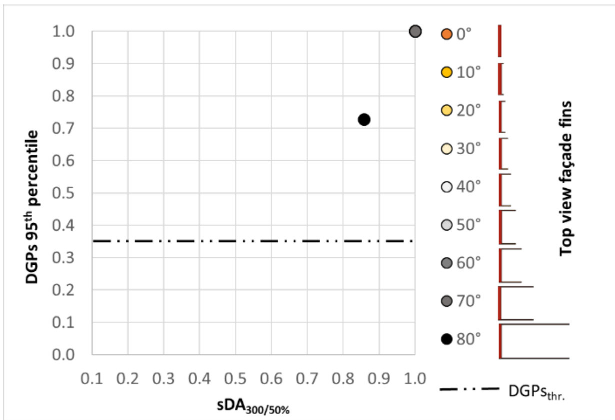


Figure 29. The trade-offs between the annual glare and daylight performance for the fins with different shading angles.

4.1.2. Case 1B - Roller blind

Figure 30 and Figure 31 show the annual performance of the roller blind in case of different control strategies. The dots represent the five penalty functions. The diamond is representative for the RBC strategy, which is based on a control sensor with a threshold of 200 W/m² positioned on the roof of the office. The figures show that:

- RBC *(diamonds)* strategy for the roller blind leads to a high risk of intolerable glare discomfort. That can be assigned to the fact that the roller blind is either fully raised or lowered in response to a threshold of 200 W/m². The advanced strategy has the possibility to control the roller blind in way that best responds to the dynamically changing conditions and is able to find a more beneficial balance between the glare, daylight and view. This makes the PBC strategy controlled roller blind able to prevent glare all year long.
- Application of PBC strategy results a 41 - 47% reduction of the DGP 95th percentile value compared to the RBC strategy
- If a maximum DGP 95th percentile of 0.35 is assumed, P5 gives the most beneficial trade-off between glare and daylight and between glare and view. Glare could be reduced further, but always at the expense of view and daylight.
- P1 – P5 contain different weights for glare, daylight and view and so have different priorities for glare, daylight and view. This results in a different order of the five dots between the two plots below.

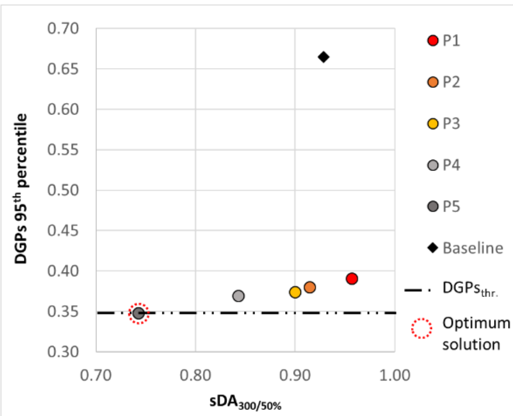


Figure 30. The trade-offs between the annual glare and daylight performance for the roller blind with different control strategies.

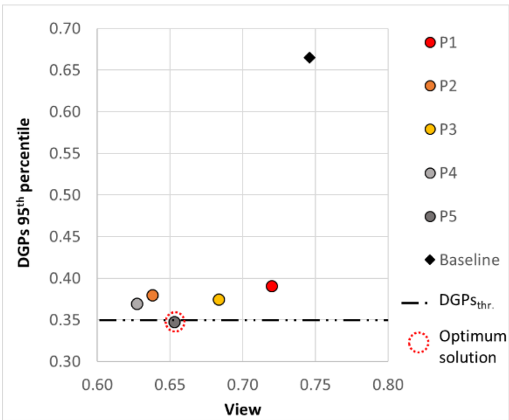


Figure 31. The trade-offs between the annual glare and view performance for the roller blind with different control strategies.

4.1.3. Case 1C - Roller blind with fins

Glare and view performance

Figure 32 shows a scatter plot with the annual performance for glare and view for all the possible combinations between the static fin designs (i.e. façade designs) and the different control strategies for the roller blind as dynamic shading system. The orange-grey colour gradient is based on the value for the shading angle of the overhang. Figure 33 zooms in on the trade-offs in case of a performance-based control strategy. The 5 penalty functions (P1-P5) together with 9 overhang angles (0° - 80°) provide 45 dots. The figures show that:

- The addition of static fins in the façade doesn't lead to a more beneficial trade-off between glare and view fraction for both control strategies, RBC *(diamonds)* and PBC (*dots*).
- If a maximum DGP 95th percentile of 0.35 is assumed, the optimum design in case of an RBC-strategy is 70° fins. A façade without fins is the optimum design in case of a PBC control strategy.

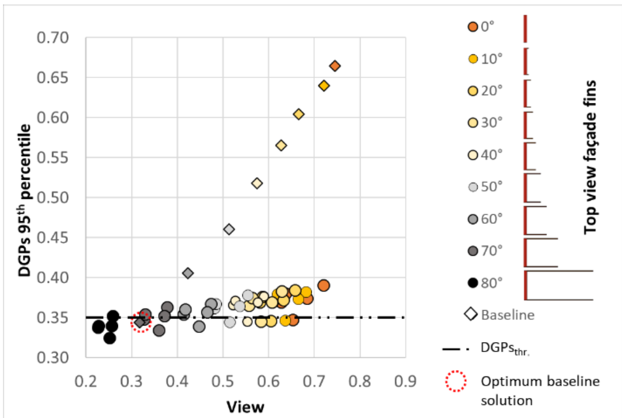


Figure 32. The trade-offs between the annual glare and view performance for the different combinations between façade designs and the roller blind..

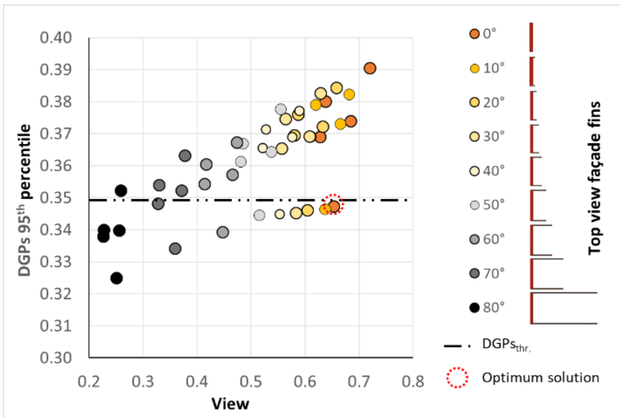


Figure 33. The trade-offs between the annual glare and view performance for the different combinations between façade designs and the PBC controlled roller blind.

Glare and daylight performance

Figure 34 shows a scatter plot with the annual performance for glare and daylight for all the possible combinations between the static fins angles (i.e. façade designs) and the different control strategies for the roller blind as dynamic shading system. Figure 35 zooms in the trade-offs in case of a performance-based control strategy. The figures show that:

- Application of the RBC *(diamonds)* strategy results in decrease of $sDA_{300/50\%}$ by increase of fin depth.
- PBC *(diamonds)* strategy shows potential for coupled optimization.
- The larger spread of the diamonds in comparison to the dots indicates that the RBC is more sensitive to the choices in the early design phase regarding the static façade design than the PBC. This results in more freedom for the designers in comparison to the RBC-strategy in case of an assumed glare requirement.
- If a maximum DGP 95th percentile of 0.35 is assumed, optimization in the early design phase with the RBC or PBC not will lead to different façade solutions. For both, the optimum design contains 70°-fins in the façade. Note that in case of 0.37 or 0.38 as maximum for glare would lead to other façade design.
- The difference between the PBC and RBC-strategy for daylight is large. This finding could probably lead to different design decisions if other performance aspects (e.g. energy use, thermal comfort) and design parameters are taken into account in the comparison.

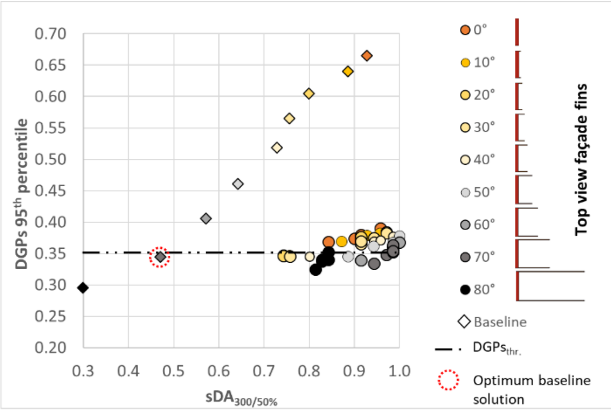


Figure 34. Scatter plot with performance for glare and daylight for the different combinations between façade designs and the roller blind. The colours are based on the value for the shading angle

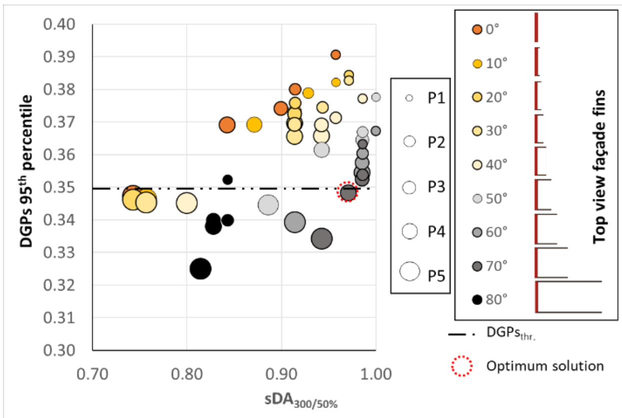


Figure 35. The trade-offs between the annual glare and view performance for the different combinations between façade designs and the PBC controlled roller blind.

The optimum in Figure 35 contains 70°-fins in the façade and shows an increase of the $sDA_{300/50\%}$ with 31% (from 0.74 to 0.97) compared to the optimum controlled roller blind and an increase of more than 100% (from 0.47 to 0.97) compared to the optimum conventional controlled roller blind combined with 70°-fins. This improvement in daylight performance can be assigned to an higher uncovered window fraction for the roller blind. (Figure 36)

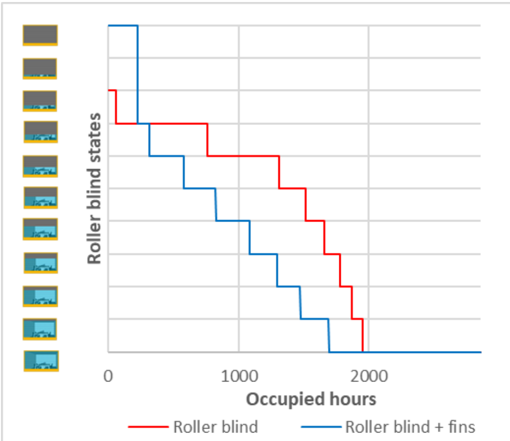


Figure 36. The openness duration curve for the optimum controlled roller blind as individual shading solution and with the addition of 70°-fins

Figure 38 shows the difference in roller blind states for the optimum controlled roller blind as individual shading solution and with 70°-fins. The hours with a large decrease of the roller blind are the consequence of the characteristics of the penalty function P4. This function excludes view from the penalty function by $W_{view} = 0$ with the consequence that P4 tends to select solutions with the minimum glare during hours with minimum daylight. The largest increase of the roller blind is in the early morning and late afternoon, when the fins are most effective. The associated impact on daylight and view is shown in Figure 39 and Figure 40.

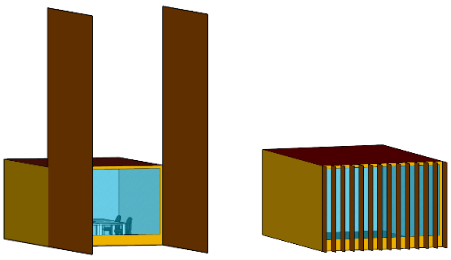


Figure 37. Simulated façade (left) and a variant design (right) for a façade with 70°-fins

The three maps together show a clear relationship between the impact of the fins, the change in roller blind state and the impact on the daylight. Figure 39 shows that the visual obstruction due to the fins does not outweigh the increase of the roller blind with as result a decrease of the VF for the majority of the occupied hours. The assumed fixed view positions and directions for occupants make that only for a couple of hours in the early morning and late afternoon, when Δ state is very high, a small increase of the VF is visible.

Increase roller blind = roller blind height$_{\text{roller blind;opt.}}$ – roller blind height$_{\text{roller blind+overhang;optimum}}$

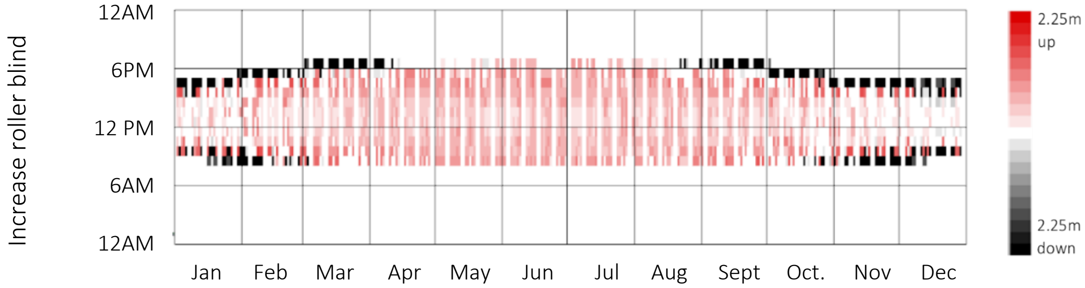


Figure 38. Difference in roller blind state between PBC controlled roller blind with and without 70°-fins

Δ VF = VF$_{\text{roller blind+fins;optimum}}$ - VF$_{\text{roller blind;opt.}}$

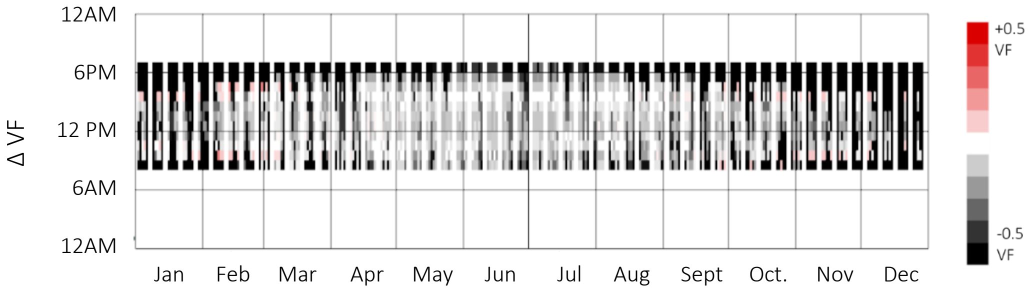


Figure 39. Difference in value for VF between PBC controlled roller blind with and without 70°-fins

ΔH-sDA$_{300lx}$ = H-sDA$_{300lx;\text{roller blind+fins;optimum}}$ - H-sDA$_{300lx;\text{roller blind;opt.}}$

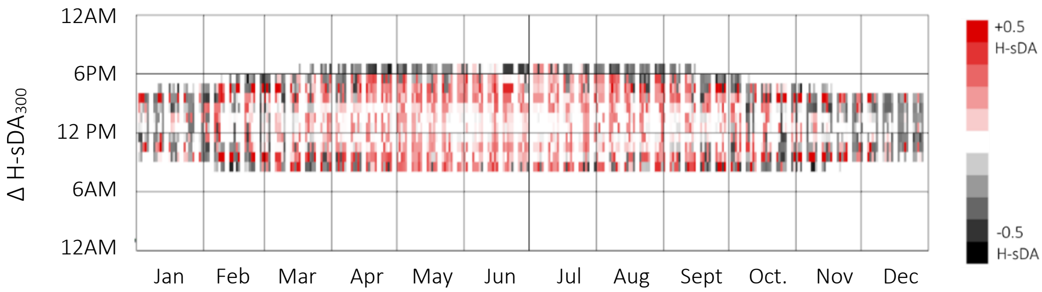


Figure 40. Difference in value for VF between PBC roller blind with and without 70°-fins

Figure 40 shows that the large increase of the roller blind in the early morning and late afternoon also results in a large increase of the H-sDA. See appendix VII for a more explorative analysis. The addition of fins is not beneficial for all occupied hours, because of their angular selectivity in blocking of the direct radiation and restriction of the daylight access during overcast sky conditions. During cloudy hours, for example, it is desired to allow solar radiation in to the office as much as possible. In the maps, such hours show a decrease of the H-sDA. The positive and negative impact of the fins is further analysed by zooming on a representative spring week in Figure 41.

On sunny days, the application of fins results in an increase of the roller blind between the 1 and 2 metres with as result an increase of the H-sDA (from acceptable to high). The view fraction as indicator for view shows small increase for a couple of these hours, but overall the presence of fins is at the expense of the view fraction. During the morning and evening hours on overcast days, the presence of fins does not change the roller blind height with an decrease of the H-sDA (from high to acceptable) and view as result.

For all the five days, the penalty function suggests a small increase of the roller blind height during noon. Dependent of the weather conditions, this results in a positive or negative impact on the daylight utilization. A possible explanation for this phenomenon is the choice of DGPs as glare indicator which is based on the vertical illuminance.

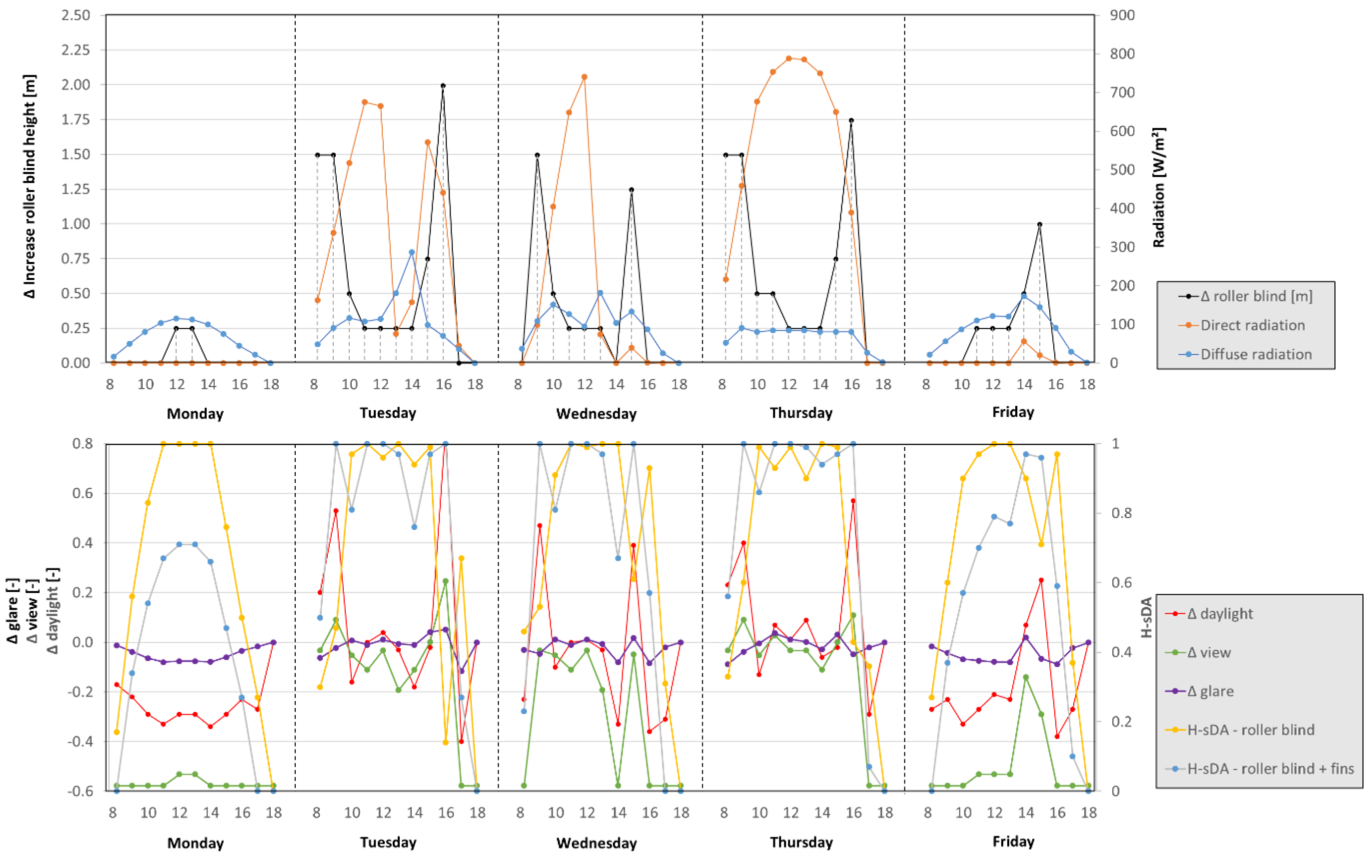


Figure 41. Up: Increase of roller blind after application of fins (70°) in the façade for a spring week together with the direct and diffuse radiation [W/m²]. Down: Impact of application of fins (70°) on glare, daylight(H-sDA$_{300}$) and view.

4.2. Case 2 - Vertical blinds and overhang

4.2.1. Case 2A - Overhang

Figure 42 shows the trade-off between glare and daylight for an overhang with different shading angles. Even though the $sDA_{300/50\%}$ levels are high, overhangs lead to a high risk of intolerable glare discomfort. Only the extreme case (80°-overhang) leads to a small reduction. All cases are clearly unacceptable. Blocking of direct sunlight for all the annual occupied hours will lead to extremely large shading systems. To create visual comfort, an additional shading solution needs to be applied.

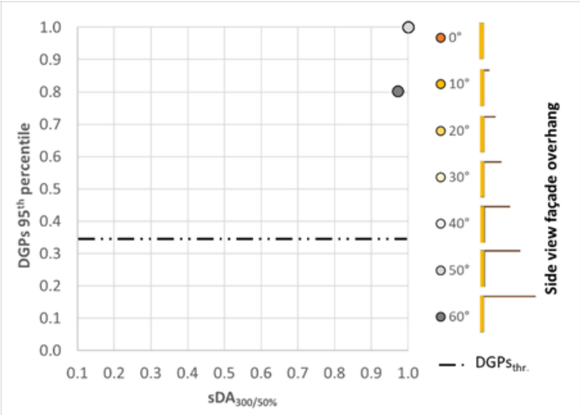


Figure 42. The trade-offs between the annual glare and daylight performance for the overhang with different shading angles.

4.2.2. Case 2B - Vertical blinds

Figure 43 and Figure 44 show the annual performance of the vertical blinds (VB) in case of different control strategies. The dots represent the five penalty functions. The diamond is representative for the RBC strategy, using a sun-tracking control strategy. The figures show that:

- Application of the RBC *(diamonds)* strategy leads to a high risk of intolerable glare discomfort. This can be assigned to that fact that such a sun-tracking control approach does not necessarily eliminate all occurrences of glare. For example, during moment with bright sky conditions.
- Performance-based controlled VB are able to prevent glare.
- In terms of glare, application of a PBC leads to 25 - 35% reduction compared to a conventional control strategy.

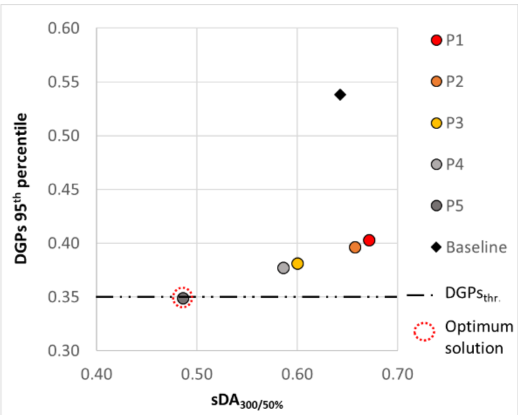


Figure 43. The trade-offs between the annual glare and daylight performance for the VB with different control strategies.

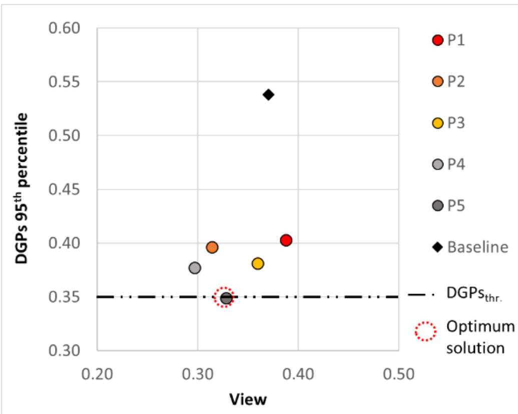


Figure 44. The trade-offs between the annual glare and view performance for the VB with different control strategies.

- If a maximum DGP 95th percentile of 0.35 is assumed, P5 gives the most beneficial trade-off between glare and daylight and between glare and view. Glare could be reduced further, but always at the expense of view and daylight.
- P1 – P5 contain different weights for glare, daylight and view and so have different priorities for glare, daylight and view. This results in a different order of the five dots by comparison Figure 43 and *Figure 44*.

4.2.3. Case 2C - Vertical blinds with overhang

Glare and view performance

Figure 45 shows a scatter plot with the annual performance for glare and view for all the possible combinations between the static overhang designs (i.e. façade designs) and the different control strategies for the VB as dynamic shading system. The orange-grey colour gradient is based on the value for the shading angle of the overhang. Figure 46 zooms in on in the trade-offs in case of a performance-based control strategy. The 5 penalty functions (P1-P5) in combination with 7 overhang angles (0° - 60°) provide 35 dots. The figures show that:

- Application of the RBC *(diamonds)* strategy results in a decrease of view by increase of overhang depth
- If a maximum DGP 95th percentile of 0.35 is assumed, the optimum façade design for a RBC-strategy contains a 50°-overhang
- If a maximum DGP 95th percentile of 0.35 is assumed, the optimum façade design for PBC contains a 30°-overhang. Important to note is that the difference in view performance with no overhang is small (±0.02 VF)
- The two groups (Figure 46) of dots are formed as result of the weights for view in the five penalty function. The left group (*blue dotted circle*) contains the trade-offs for the penalty function with a W_{view} of 0 (P2, P4) The right group (*red dotted circle*) contains the trade-offs for the other three penalty functions

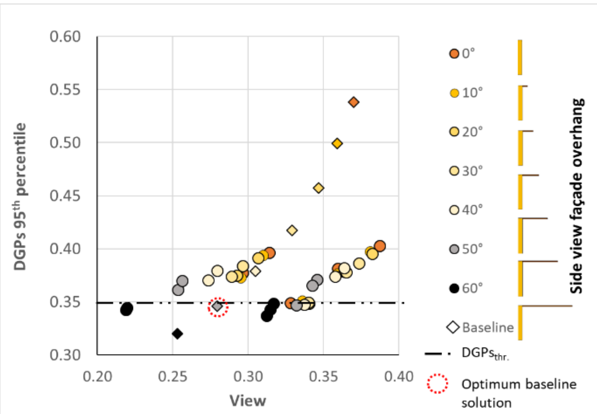


Figure 45. The trade-offs between the annual glare and view performance for the different combinations between façade designs and the VB

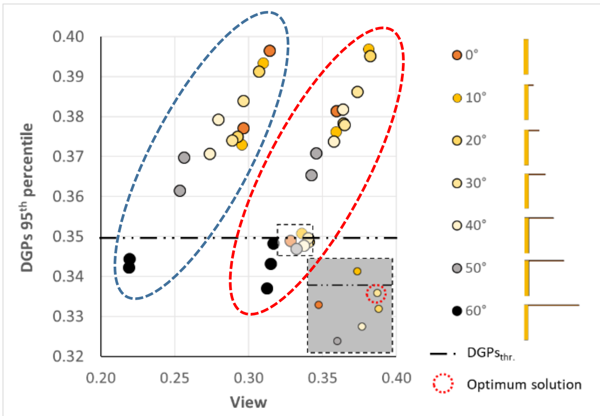


Figure 46. The trade-offs between the annual glare and view performance for the different combinations between façade designs and the performance-based controlled VB.

Glare and daylight performance

Figure 47 shows a scatter plot with the annual performance for glare and daylight for all the possible combinations between the shading angles for the overhang (i.e. façade designs) and the different control strategies for the VB as dynamic shading system. Figure 48 zooms in on in the trade-offs in case of a performance-based control strategy. The figures show that:

- Application of the RBC *(diamonds)* strategy results in decrease of daylight by increase of overhang depth.
- The PBC *(diamonds)* strategy shows potential for coupled optimization.
- The larger spread of the diamonds in comparison to the dots indicates that the RBC is more sensitive to the choices in the early design phase regarding the static façade design than the PBC. This gives more freedom for the designers in comparison to the RBC-strategy in case of an assumed glare requirement.

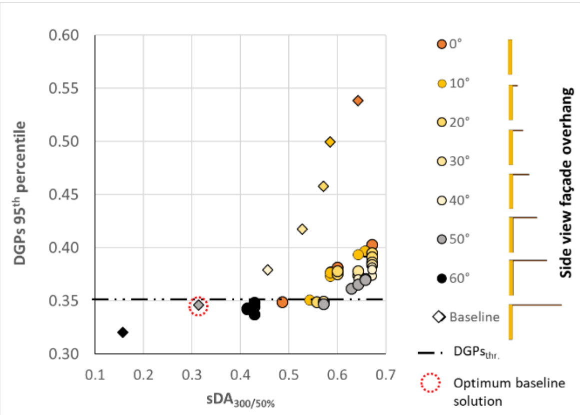


Figure 47. Scatter plot with performance for glare and daylight for the different combinations between façade designs and the VB.

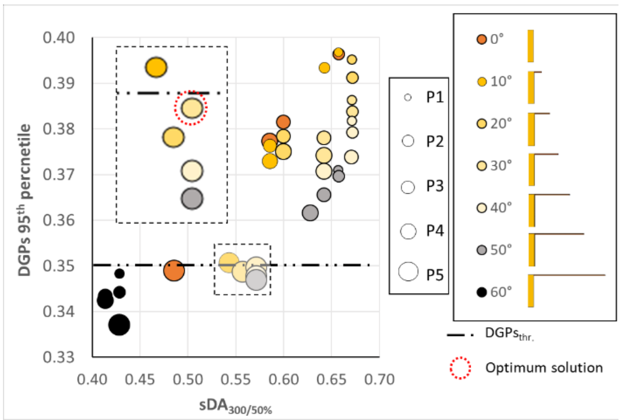


Figure 48. The trade-offs between the annual glare and daylight performance for the different combinations between façade designs and the performance-based controlled VB.

- If a maximum DGP 95th percentile of 0.35 is assumed, the optimum façade design for a RBC-strategy contains a 50°-overhang. In case on PBC strategy, the most optimal design range is an overhang with a shading angle of 20°-50°.
- Optimization of the façade in the early design phase with the RBC (50°-overhang) will lead to minimal differences in annual performance for daylight (±0%) and view (1-2%) if later PBC is installed.
- Optimization of the façade in the early design phase with the RBC will lead to a façade design with an 20°- or 30°-overhang. Application of this design instead of the 50°-overhang (based on RBC optimization) can lead to benefits as cost-reduction and material saving.
- The difference between the PBC and RBC-strategy for view (±8%) and daylight (±25%) is large. This finding could probably lead to different design decisions if other performance aspects (e.g. energy use, thermal comfort) and design parameters are taken into account in the comparison. For example, the benefits for the PBC strategy could lead to a change in window size.

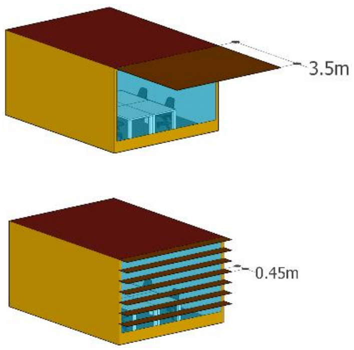


Figure 49. Simulated façade (up) and a variant design (down) for a façade with 50°-fins

Combined shading with an overhang in the range of 20°-50° results in an increase of the $sDA_{300/50\%}$ with 16% (from 0.49 to 0.77) compared to the optimum controlled VB and an increase of 84% (from 0.31 to 0.57) compared to the optimum conventional controlled VB. This improvement in daylight performance can be assigned to an higher uncovered window fraction for the vertical blinds Figure 50.

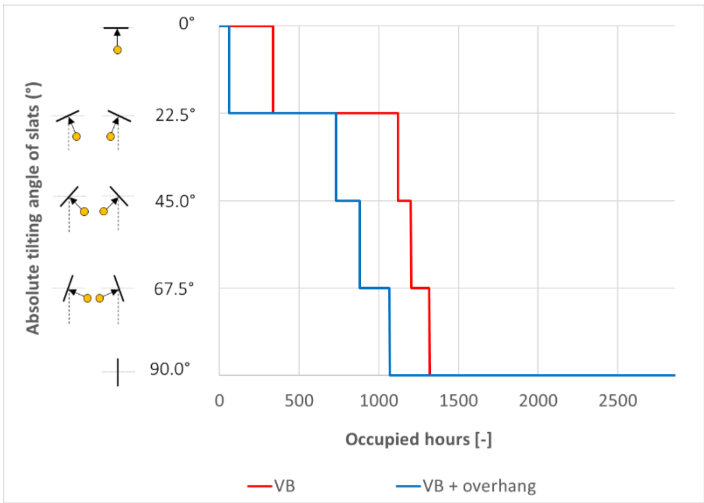


Figure 50. Openness duration curve for optimum controlled VB with and without addition of 30°-overhang

The openness duration curves show that combined shading leads to a more open state for the VB. Increase of the shading angle for the overhang from 30° to 50° results in a rotation of the slats to a more open position, especially during midday when the overhang is most effective (Figure 51). The associate impact on daylight and view is shown in Figure 52 and Figure 53. The three maps together show a clear relationship between the impact of the overhang, the change in slat position and the associated impact on daylight and view. See appendix VIII for more information.

The addition of the overhang is very beneficial for daylight and view during midday in summer, but has also negative consequences. The overhang causes restriction of the daylight access during overcast sky conditions, but this effect is limited in comparison to the previous case study. This result for a small number of hours even a rotation of the slats to a more close position, caused by the low daylight utilization in combination with the sigmoid curve for P_{glare}. Also the VF decreases for the hours when the slats do not rotate to a more open position.

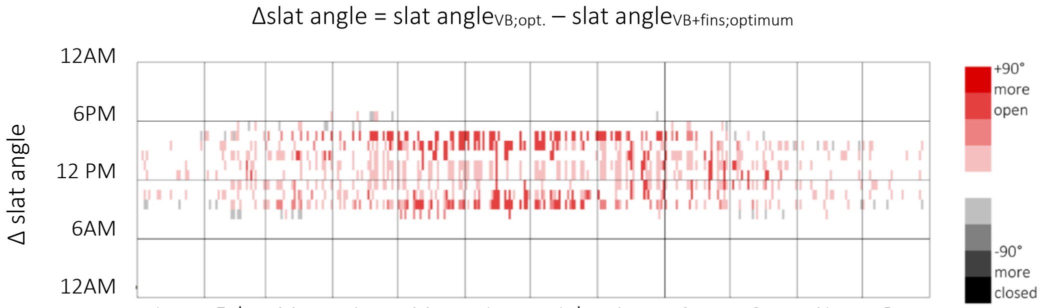


Figure 51. Difference in VB between performance-based controlled VB with and without 30°-overhang

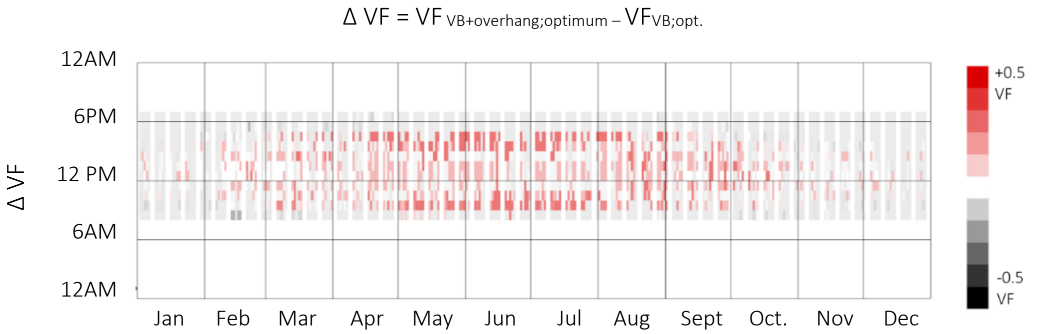


Figure 52. Difference in value for VF between performance-based controlled VB with and without 30°-overhang

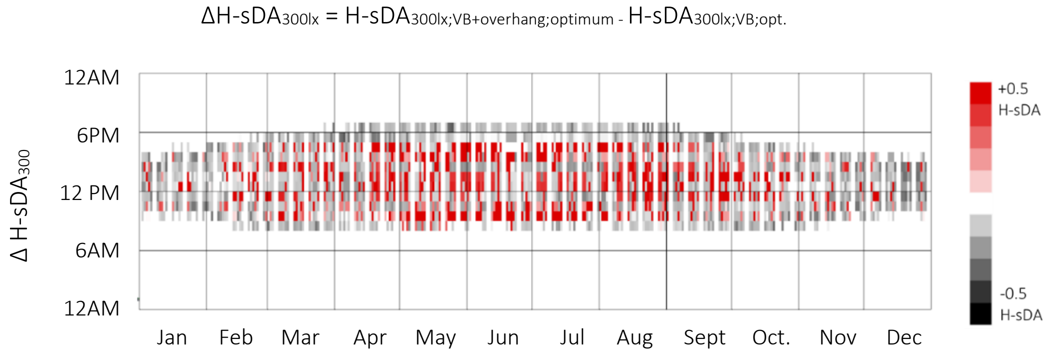


Figure 53. Difference in value for H-sDA$_{300}$ between performance-based controlled VB with and without 30°-overhang

The relationship between façade design, shading control and daylight performance is further analysed by zooming in on a summer week which contains hours with increase and decrease of H-sDA$_{300}$ after application of the overhang (30°). Remarkable is that the largest positive change in slat position happens for just before and after 12h00 in the summer. It is expected, that the biggest increase of the VB-slats and the associated visual comfort would occur at 12h00. However, the results for combined shading with an 50°-overhang are more in line with the expectations and so show the largest positive rotation of the slats during 12h00. The reason for this phenomenon could be the choice of DGPs as glare indicator in combination with the penalty function. The larger overhang results in a lower vertical illuminance at glare sensors which, in combination with the sigmoid function for P_{glare}, results in a significant more open state for the VB. (see matrices, appendix VIII).

Figure 54 shows that application of 30°-fins results in a large rotation of the slats in the morning and afternoon. These hours show also large improvements for daylight utilization and view. At 12h00, the rotation is relative small with 22.5° but on the other hand, the associated impact on daylight and view is relative large, especially on Tuesday. During overcast hours, the presence of overhang doesn't change the slat angle, but is responsible for a decrease of H-sDA$_{300}$ and view as result. The hourly spatial daylight autonomy change on these hours from high to acceptable.

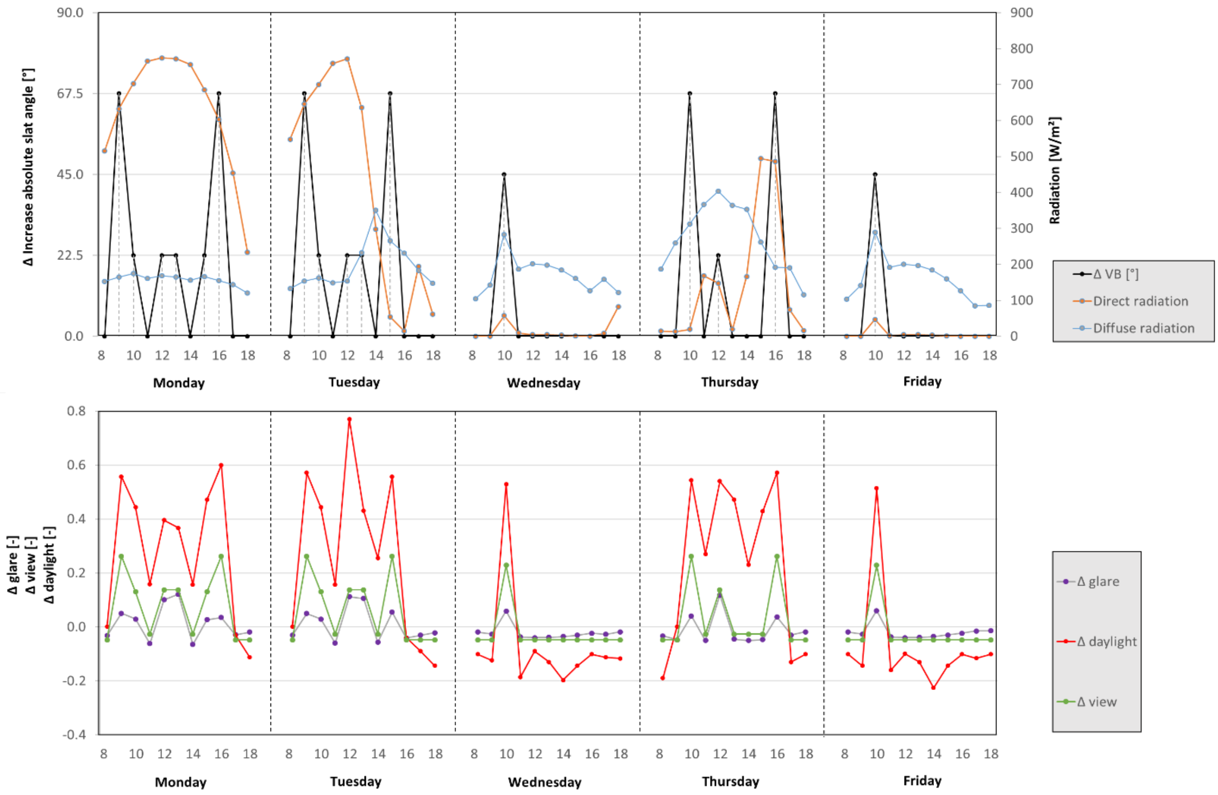


Figure 54. Up: increase of openness of VB after application of 30°-overhang in the façade for a summer week together with the direct and diffuse radiation [W/m²]. Down: the impact of on glare, daylight(H-sDA$_{300}$) and view

5. Discussion and conclusion

This chapter discusses limitations of this work, provides directions for future research and summarizes the main outcomes of this study.

5.1. Limitations and future work

- Three-phase method + DGPs as glare indicator: An identified drawback of the 3-phase method is the imprecise representation of the direct sun component through averaging over relatively large sky solid angles. The DGPs as illuminance baed metric for the assessment of the glare performance is less reliable in predicting contrast glare when there is direct sunlight in the field of view. *[Wienold, et al., 2019; Konstantzos, Tzempelikos, Murchison, & Proctor, 2016]*. The three phase-method in combination with the choice for DGPs as glare indicator might lead to an underestimation of glare. The consequence is that the performance-based controlled dynamic shading chooses a position which is too open with as result an overestimation of the daylight performance.

- Time-step: the case studies are performed with an hour as time-step of recording. A limitation for a smaller time-step is the hourly weather data. Actual outdoor daylight conditions show much more sub-hourly variability than what is represented by the used weather data. Nevertheless, a smaller timestep will drastically increases the computational time.

- Limited scope: the selection of shading systems, the use of simple architectural shading devices, weather condition and orientation are examples of the multiple scope limiting assumptions that are made in the simulation approach of this research. All these factors have influence on the performance. The potential of combined shading is application-specific and context dependent, which makes the scope of the two case studies very limited. In addition, this study is only limited to the visual performance. Coupled design optimization of façade design and automated shading control has also consequences for other performance aspects (e.g. energy use, thermal comfort), which were not explictly addressed in this study. For example, the increase of daylight utilization will probably lead to decrease of the energy demand for artificial lighting.

- Modelling resolution of dynamic shading: that the dynamic shading systems are modelled with a limited resolution. For example, the roller blind is modelled by dividing the fenestration system into ten horizontally oriented segments which are eater fully shaded or unshaded. The sensitivity analysis of de Vries et. al (2019) showed that performance is sensitive to these assumption

- View: Given the benefits and preference for daylight and view, there is interest in understanding and evaluating them. Yet, there is also no standard method or set of metrics to evaluate view. This research used the view fraction as indicator to quantify view. This indicator has his drawbacks and is very dependent on the assumptions regarding the view direction and position of the occupants. More research is also necessary to:
    - fully understand the relationship between daylight, view and health
    - to get more insight in the relationship between view content variables and landscape preference variables and their impact on view quality in a way which can be operationalised for the development of control strategies for façade design.

5.2. Practical implementation

- Multiple studies have shown that performance-based control strategies can offer an improved building performance. Their implication in practice however is complicated. More research and development is necessary to develop practical design solution in this direction to bridge the gap between research and practice.

- It is questionable if the performance benefits of coupled design-optimization in relation to a dynamic shading as individual shadings solution during operation might outweigh the costs. After all, the purchase of an extra shading system is necessary.

5.3. Conclusions

It is hypothesized that the visual comfort in office buildings can be improved through coupled design optimization of façade design and automated shading control. The previous chapters presented two simulation studies for a south-oriented test office building in the Netherlands to explore this potential. The analysis of both studies leads to the following conclusions:

- Static shading combined with performance-based controlled dynamic shading has potential to improve visual comfort in comparison to both systems as individual shading solutions. This can be assigned to the fact that blocking of the sun by static shading results in an higher uncovered window fraction for dynamic shading. The associated impact on the visual comfort is:
  - Significant improvement of the daylight performance in terms of spatial daylight autonomy
  - Contradictory impact on view. Whereas the uncovered window fraction for dynamic shading increases, static shading obstructs the view. The view performance depends strongly on:
    - the size of view obstruction by the static shading
    - the improvement of the view through increase of the uncovered window fraction for dynamic shading
    - occupant-related assumptions (e.g. occupant position, view direction).

- Concurrent optimization of static shading design and dynamic shading control could lead to different design decision if other aspects (e.g. energy use, thermal comfort) are taken in to account and/or to a number of benefits, such as cost-reductions and material-saving.

- Performance-based control integrates the façade design to the control of the dynamic shading and so is an important requirement for concurrent optimization. The benefits are:
  - more beneficial values for daylight and view performance in comparison the results for the rule-based control strategy
  - A larger facade design space with near-optimal performance. This larger design space could offer benefits in terms of performance aspects which were not explictly addressed in this study.

Application of combined shading in practice asks for a tailored approach from the design team. In the first place, it requires conscious choices regarding the façade as a static element. Therefore, the façade design must result from a careful process in the early phase of an integral design process. In addition, an advanced control strategy for dynamic shading is required. Thereby it is recommended to beforehand express the performance of the shading through a set of clearly defined criteria which can be used in dynamic evaluations and define acceptance thresholds for dynamic evaluations. Finally, it is recommended to use objective performance information to assist in decision-making trade-offs.

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Appendices