EXPLORING THE POTENTIAL OF DYNAMIC FACADE SYSTEMS: AN EXTERIOR SHADING SYSTEM VERSUS A SWITCHABLE WINDOW

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ABSTRACT

Dynamic façade systems can play an important role in the overall performance of the building by adjusting the amount of transmitted solar radiation into the room and responding to environmental conditions. This paper evaluates two types of dynamic facade systems under various control strategies and shows their influences on energy, visual comfort, and thermal comfort in an office building.

This paper looks into the simulated hourly/annual results of venetian blinds versus electrochromic glazing (EC) for an open office room with south-facing window shaded/operated by different control strategies such as manual, radiation-based, illuminance-based, and optimal control scenario, to indicate the overall capabilities and limitations of each shading system.

Finally, results show that a well-engineered automatic control strategy can ensure visual and thermal comfort as well as total site energy savings up to 38% for an EC glazing and up to 49% for external venetian blinds.

INTRODUCTION

Buildings are responsible for a significant portion of total global energy consumption and windows have the most important impact on the energy balance of buildings. By harvesting solar gains, a considerable part of heating demand can be covered in cold winters. Moreover, by using external shading and blocking the sunlight, cooling demand and risk of overheating can be reduced up to 57% (Nikoofard et al. 2014). But protection from disturbing glare in winter decreases the expected solar gains and the reduction of the solar transmittance mostly comes at the cost of poorer daylighting and view obstruction. This makes the control of a dynamic façade system very complex since people prefer windows to provide daylight and view to the outside (Inoue et al. 1985).

Automated venetian blinds can play an important role in the overall performance of the building by redirecting solar radiation. Electrochromic (EC) windows are also capable of adjusting the amount of transmitted solar radiation into the room and responding to environmental conditions. By adjusting incident solar heat flux entering the building, dynamic shadings can improve building energy efficiency significantly for south, west, and east oriented glazed facades (from 8% to 53% for Quebec, Canada), but unremarkably for the north facade (Dussault et al. 2012)

In addition to the orientation, the performance of dynamic shadings highly depends on the control strategy for automation. Precedent experimental studies showed that automated venetian blinds could save 7–15% cooling energy and 19–52% lighting energy in comparison to a fixed shading (45◦ tilted) (Lee et al. 1998 & 2002; Roche, 2002).

Despite all the benefits, many post-occupancy studies reported occupants' dissatisfaction with automated systems (Inkarojrit, 2005). Inkarojrit tried to categorize influential factors that lead to the dissatisfactory performance of an automated shading. It should be noted that besides all signs of progress in high-performance systems and attempts to solve the occupants' dissatisfaction problem, even the most promising control strategies are still limited to one or a small number of sensor-based variables among the separated physical factors (e.g. irradiance, illuminance). Only a few predictive control methods can consider some contextual factors and physiological individual preferences (Dussault et al. 2012; Motamed et al. 2020).

Automated dynamic shadings

Conventional control strategies are mostly incapable of considering multiple variables and all the necessary aspects of energy and comfort required for the selection of the right shading state.

Different rule-based strategies have been applied for windows commonly based on predefined conditions (e.g., "if… then…"). The algorithm switches the state of the shading in response to the difference between measured/simulated and set-point values. Many single variables such as indoor temperature, glare, the illuminance at the workplace and radiation level have been used in precedent studies, while there is only limited research with multiple variable rule-based strategies (Dussault et al. 2012; Firląg et

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al. 2015; Dutta, 2018). Radiation-based control is one of the most used strategies which activates the shading when the single variable of global radiation on vertical façade is greater than 200W/m² (DIN 4108-2) or direct radiation falling on the workplace is greater than 50W/m² (Reinhart, 2004).

These algorithms mainly use only two states of the shading system (shaded or not-shaded) applied on the entire opening area without considering the hight of pulled down blinds or zoning of tinted EC. Daylighting, perception of discomfort glare for individual view directions, and individual thermal comfort is not directly taken into account in these strategies and are mostly overlooked. Improved strategies block the solar transmittance by using multiple shading states (different tilting angles for blinds and different tinting states for EC). The so-called "cut-off" controller avoids diminishing daylighting by adjusting the slat angle of the lamellas according to the actual position of the sun to block the direct sunlight while admitting the diffused part of radiation in the room (Bueno et al. 2015).

Another type of control strategy that gained a lot of interest in the past few years in building applications is Model Predictive Control (MPC) (Dussault et al. 2012). MPC is a type of control algorithm that uses an explicit model of a building to predict its condition over a defined time horizon. At each control time step, the MPC minimizes the cost function (including electricity and discomfort) assuming weather forecast and occupation forecast.

Even though the performance of these predictive algorithms sounds very promising (Gehbauer et al. 2020), setting up a predictive model and calibration process requires extensive skills and knowledge, while the same model is not fully compatible for new conditions (new orientation, room geometry, plan lay-out, …).

Simulation/optimization methods

Available methods/tools for simulation/optimization are incapable of finding the optimal control strategies for application in real buildings. The interaction of the fenestration systems with daylighting, thermal inertia, and HVAC systems is one of the major challenges in simulations and applications. Therefore, investigating the potential of different automated shading systems and control strategies is only possible through a multi-objective approach and considering advanced integrated daylight and thermal simulations (e.g. using BSDF data sets).

By using a weighted penalty function method introduced by authors (Ganji & Hoffmann, 2018 & 2019), this paper evaluates different control strategies for dynamic facade systems and their influence on energy and visual comfort, thermal comfort performance in office buildings. The "optimal scenario", a time series of EC glazing or venetian blinds states over a year were found based on some predefined preferences and priorities. Moreover, the overall performance of shading systems was also compared under various control strategies.

METHODOLOGY

In this paper, advanced simulation methods of integrated daylight and energy simulation were used for an open office room (shared by four users) with a south-facing window. South-facing façade is the most ideal orientation, particularly for an office building, to have commonly large openings where proper shading can increase the potential for energy saving, provide comfort, and keep enough view outside.

Later, this paper looks into the annual/hourly performance of venetian blinds versus electrochromic glazing under different control strategies to understand the behavior of the systems and use this knowledge for finding the investment potential in dynamic shadings and advanced control strategies.

Model description and simulation setup

The reference model represents a typical open office room with a window divided into three different zones (top, middle, bottom). Figure 1 shows the room geometry and the layout of four workplaces.

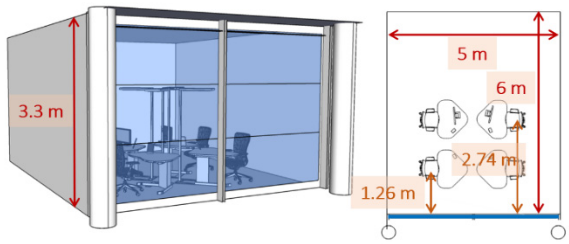

Figure 1: left) 3D model with different window zones (top, middle, bottom), right) the layout of occupants' position in the open office

Verified simulation tools including TRNSYS for energy simulation, Radiance for daylight simulation, and LBNL Window for modeling the glazing and shading systems were used in this study. These tools are all empowered with the BSDF (Bidirectional Scattering Distribution Functions) for the advance calculation of transmitted radiation through complex fenestration systems.

The glazing systems were modeled in LBNL window software (www.windows.lbl.gov) and prepared to be used in Radiance and TRNSYS (via trnBSDF tool) (McDowell et al. 2017). Table 1 shows the overall performance of the glazing and shading systems including solar heat gain coefficient (SHGC), solar transmittance (T_{sol}), and visible transmittance (T_{vis}) calculated using LBNL Window (v 7.6).

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Table 1: Overall performance of glazing and shading

EC glazing	SHGC	T_{sol}	T_{vis}	Shading state
Clear state	0.43	0.29	0.44	S0
Low tinted	0.21	0.07	0.12	S1
Middle tinted	0.16	0.02	0.04	S2
Fully tinted	0.14	0.004	0.007	S3

Venetian blinds	SHGC	T_{sol}	T_{vis}	Shading state
Pulled up* (base-case)	0.61	0.42	0.58	S0
Horizontal: 0 °	0.52	0.35	0.48	S1
30 °	0.29	0.18	0.25	S2
45 °	0.16	0.01	0.13	S3
Closed: 80°	0.03	0.003	0.005	S4

* This window state represents a conventional double glazed window which was used as base-case in this study.

For modeling the exterior blinds, Radiance base tool genBSDF was used to generate the BSDF data sets for each state of the shading. These data sets were combined with the glazing systems (pulled up) in the Window software again. These modeling methods were explained in detail by authors for electrochromic glazing (Ganji & Hoffmann, 2019) and venetian blinds (Ganji & Hoffmann, 2018).

It is worth mentioning that the clear EC glazing (bleached) is less transparent than the clear base-case window (SHGC delta 0.18). Also, fully closed blinds with 80° tilting angle have lower solar heat gain coefficient than fully tinted EC glazing (SHGC delta 0.11), which leads to better solar protection during summer when the use of fully closed shading is needed, particularly for optimal control profile (CtrlOpt).

In this study, the window with no shade (Venetian blinds Pulled up) represents a conventional double glazed window which was used as base-case.

In the next step, the optical properties of the glazing and shading system were applied to the window surface (top, middle, bottom) of the reference room as BSDF data-set (xml format) for every state of shading/tinting. For climate-based annual daylight simulation Radiance three-phase method (Ward & Shakespeare, 2004 & McNeil et al. 2013) was used.

Energy simulation using the “detailed” window model was performed in TRNSYS (v. 18) (Hiller & Schöttl, 2014). Using variable configuration ID (shading states), optical and thermal properties of a window can be adjusted at every time step during TRNSYS simulation.

The daylight availability which was simulated earlier in Radiance for each window combination of EC and venetian blinds (64 and 13 cases respectively) was read to control artificial lighting. Knowing the current state of the window(s) during simulation, corresponding daylight values were read in TRNSYS to calculate the electrical power for supplemental artificial lighting and taking into account that amount of energy as internal gain.

Tables 2 and 3 show the construction properties of the surfaces and some boundary conditions used in simulations.

Table 2: Properties of surfaces in simulations

Construction	Area [m²]	Thickness [m]	U-Value [W/m².K]	Thermal Category	Reflectivity
Floor	30	0.42	0.22	Boundary	0.25
Ceiling	30	0.31	0.58	Boundary	0.9
Int. Wall	36.3	0.13	0.32	Boundary	0.8
Ext. Wall	22.3	0.41	0.19	External	0.8
Overhang	-	-	-	Dummy	0.55
Window (notshaded)	14	0.036	Blind:1.37 EC:1.3	External	BSDF Data sets

Table 3: Dynamic simulation setup & description

Item	Description	
Room geometry	6 m length, 5 m width, and 3.3 m height WWR: 90%	Rhino 3D model
Weather data	49.48° N, 8.46° E (Mannheim, Germany)	.epw file
Schedule	Mon to Fri 8:00-18:00 Sat & Sun Off	office
Internal gains	4 People, light work 4 Computers 2 groups of LED lighting (5 W/m²)	daylight base control 300-500lx
Infiltration	Unoccupied: n = 0.1 [h^{-1}] Occupied: n = 1.45 [h^{-1}]	
Heating Cooling	H_Set-point = 20°C C_Set-point = 27°C	Ideal systems
PMV calculation parameters	Clothing factor: 1 [clo] Metabolic rate: 1 [met] Air velocity: 0.1 [m/s]	Internal calculation in TRNSYS

Control strategies applied in simulations

In this paper, six different control conditions were defined and applied for both electrochromic glazing and external shading simulations.

By applying these control profiles including two static cases (not-controlled), one manual operation, and three dynamic cases (automatic control algorithms) in simulations, the annual energy and comfort performance of an open office room with a south-facing window was simulated for comparison.

Static facade without any control: Indicates the impact of using an automated shading system, these two control cases were used in this study as baseline energy consumption. **No-shade (CtrlClr):** the EC glazing is always in clear state and the blinds are completely pulled up. An office room with “CtrlClr” has minimal heating demand and electrical lighting use. **Always-shaded (CtrlDrk):** the EC glazing is always in a fully tinted state and the blinds are completely pulled down and closed (tilted 80° outward). An office room with “CtrlDrk” has minimal cooling demand, risk of glare, and thermal discomfort.

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Manual operation (CtrlMan): Users tend to avoid the direct sunlight on the workplace, but it remains pulled down/tinted until the lunch-time break or next morning upon arrival. Also, occupants may accept intensive irradiance if that gives them a good view outside. The manual control of the shading device has been implemented for blinds and EC similar to the algorithm described by Reinhart (Reinhart, 2004). For low solar altitude angle (≤ 60°), a user activates the shading, if a specific set point for the radiation, illuminance, or glare is exceeded (e.g. $I_{dir} \geq 50$ W/m², Eh ≥ 3000 lx, and DGP ≥ 0.38). While when the solar altitude angle is high (> 60°), the sun is not directly visible to the eyes and users would prefer to keep the view outside unobstructed.

The manual operation was considered in the study to compare it to automatic algorithms.

Automatic rule-based control: The state of the shading system switches in response to the difference between simulated and set-point values of illuminance or radiation:

Illuminance-base control (CtrlIll) checks the amount of available daylight on the horizontal workplaces (horizontal illuminance, E_h) and changes the EC glazing and venetian blinds regarding the predefined conditions. Normally, the range between 300 [lx] and 3000 [lx] is considered as useful daylighting. When Eh is greater than 3000 [lx] there is a high risk of glare or overheating in the space. E_h lower than 300 [lx] is considered as "not enough daylight" and artificial lighting needs to be applied to provide sufficient lighting level on the workplaces during the occupied hours.

In previous studies, a wide range of various global and direct irradiance thresholds have been applied (150-400 [W/m²] and 20-100 [W/m²] respectively) for controlling EC systems. In this study, **Radiation-based control (CtrlRad)** checks the amount of direct radiation on the window surface and activates the EC glazing and venetian blinds accordingly when the direct radiation on the vertical façade is greater than 50 [W/m^2]. Both radiation-based control (CtrlRad) and illuminance-based control (CtrlIll) are sensor-based controllers that have been used commonly in buildings for automating shading systems.

To avoid infeasible cases (all window areas in fully-shaded state) and providing minimum daylighting, the bottom zone of the window was kept always clear for both "CtrlIll" and "CtrlRad".

In the conclusion section, we only compare the results of radiation-based control (CtrlRad) with other types of control strategies for the sake of simplicity.

Optimal automatic control scenario (CtrlOpt)

A "simulation-based optimization" that has been introduced by the authors is used in this study to explore different possible control profiles for shading states. According to the predefined priorities for energy, visual comfort, and thermal comfort, an "optimal" scenario can be generated by exploring pre-calculated hourly results for all possible window combinations to find the top-ranked (optimal hourly) states with minimum penalties (Ganji 2019 & 2018).

Applying the "optimal" scenario in simulation can provide minimum energy demand and maximum thermal and visual comfort over the course of a year as it was prioritized by users. These priorities may vary from one project to the other and should be defined in advance, whether the main objective is e.g. saving energy or providing comfort. Previously the authors have investigated different weighting fractions (ω_i) for each aspect of visual comfort, thermal comfort, and energy (Ganji 2019 & 2018). However, in this paper, the weighting fractions (see Table 4) were decided equally with the same priority in the total penalty function (Equation. 1 & 2). Meaning, the results should show a good trade-off between energy savings and thermal and visual comfort provision.

$$\text{Penalty}_{\text{total}} = \sum \omega_i \times P_i \qquad (1)$$

$$\text{Penalty}_{\text{total}} = (\omega_1 \times P_{dgp} + \omega_2 \times P_{daylight} + \omega_3 \times P_{art.light} + \omega_4 \times P_{pmv} + \omega_5 \times P_{energy}) \qquad (2)$$

Table 4: Weighting fractions used in penalty function for optimal control (CtrlOpt)

Discomfort glare	Daylight quality	Artificial lighting	Thermal comfort	Energy
ω_1	ω_2	ω_3	ω_4	ω_5
0.11	0.11	0.11	0.33	0.33

Table 5 summarizes different control strategies and their criteria for controlling electrochromic glazing (EC) and external venetian blinds.

Table 5: Various control strategies

Ctrl strategies	Condition		Shading state ID [Top, Middle, Bottom] EC state	Blinds state
Static				
CtrlClr	Fixed not-shaded		[0,0,0] Clear	[0,0,0] Up
CtrlDrk	Fixed shaded		[3,3,3] Fully tinted	[4,4,4] 80° tilted
Dynamic				
CtrlMan	$I_{dir} < 25$ W/m²		[0,0,0]	[0,0,0]
	$I_{dir} \geq 50$ W/m²	alt ≤ 60°	[3,3,0] Fully tinted	[4,4,0] 80° tilted
		alt > 60°	[2,0,2] Low tinted	[2,2,0] 30° tilted
CtrlIll	Eh < 300 lx		[0,0,0]	[0,0,0]
	300 ≤ Eh < 3000		[2,2,0] Low tinted	[1,1,0] 0° tilted
	Eh ≥ 3000 lx		[3,3,0] Fully tinted	[3,3,0] 45° tilted
CtrlRad	$I_{dir} < 50$ W/m²		[0,0,0]	[0,0,0]
	$I_{dir} \geq 50$ W/m²		[2,2,0] Low tinted	[3,3,0] 45° tilted
CtrlOpt	Optimal scenario: Penalty function-based algorithm		[var., var., var.] 0,1,2, or 3	[var., var., var.] 0,1,2,3, or 4
			All aspects with same weighting fraction	

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ANALYSIS OF THE RESULTS

This paper evaluates the overall performance of a building with a switchable window (EC glazing) versus external venetian blinds in the following three aspects: energy, visual comfort, and thermal comfort. The hourly results of the simulations for different control strategies were evaluated and compared using the following overall parameter:

- Percentage of occupied hours with visual discomfort, including discomfort glare and not useful daylight
- Percentage of occupied hours with thermal discomfort
- Total energy consumption (site, source energy, and equivalent CO_2 emission)
- Percentage of occupied hours with retracted shades or tinted glazing

Performance indicators

Based on the hourly simulated results (8760 values for each case), some overall performance indices and their acceptance criteria were defined to be used for the evaluation process.

Glare: To predict glare experience, the enhanced simplified method was implemented by simulating vertical eye illuminance (E_v) and rendering fisheye HDR images (when a direct sunray hits the observer's eye) (Wienold et al. 2004) for every view direction (at 120 cm height) and window combination in Radiance. For a complete year, the percentage of occupied hours when DGP value(s) exceeded the threshold (here is 0.4) is calculated as DGPe. This annual parameter is recommended to be kept below 5% for a "good-class" glare protection (DIN EN 17037:2019). Since the office was shared between four users with different view directions, in this study when any individual's DGP value went above 0.4, that occupied hour was assumed with discomfort glare probability (maximum hourly DGP).

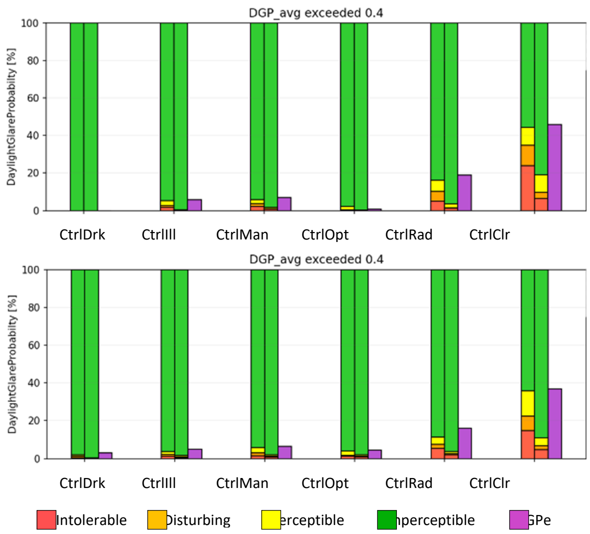

Figure 2: The overall performance of the systems for glare protection, top: blinds, bottom: EC

Figure 2 (also see Table A-1 and B-1 in Appendix) shows the overall results of glare probability as a triple color-coded bar for each control case (green: imperceptible, yellow: perceptible, orange: disturbing, and red: intolerable). For each control case, the left bar shows glare for the two users sitting closer to the window (G1) and the middle bar shows the results for the other two users positioned farther away from the façade (G2). The right bar shows the exceeded values, DGPe (purple).

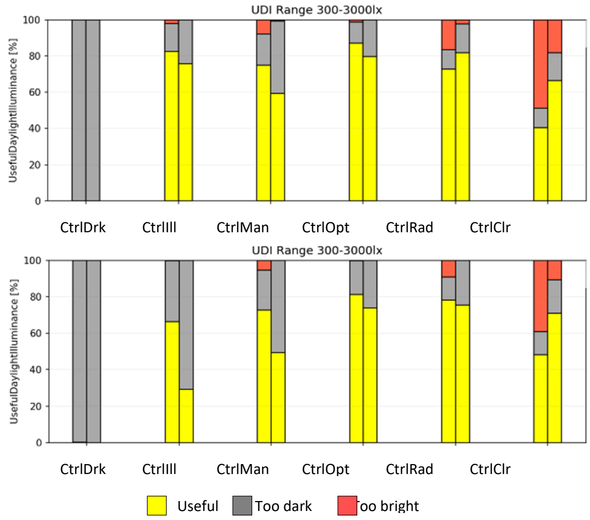

Figure 3: The overall performance of the systems for daylighting, top: blinds, bottom: EC

Available daylight: Since there is a significant risk of glare or overheating when the illuminance values on the workplace are above 3000 [lx], the hourly horizontal illuminance (E_h) for all four workplaces was simulated at the height of 75 cm above the floor. Useful Daylight Illuminance (UDI) is the percentage of occupied hours when the average E_h lies in the range between 300 [lx] and 3000 [lx] (Nabil & Mardaljevic 2005). This annual parameter shows how much daylight can be available by applying dynamic shading for a complete year.

Figure 3 (also see Table A-1 and B-1 in Appendix) shows the overall results of UDI percentage as a double color-coded bar for each case (red: too bright ($E_h \geq 3000$), gray: too dark ($E_h < 300$), and yellow: useful daylight) for groups G1 and G2.

Thermal comfort: Assuming that a satisfying thermal condition (feeling neutral) can be achieved when the predicted mean vote temperature (PMV) stays between -1 and +1 (ASHRAE 55: Class IV), simulated hourly results of individual local PMV (based on users' position) from TRNSYS were post-processed over a complete year.

Figure 4 (also see Table A-2 and B-2 in Appendix) shows the overall percentage of occupied hours with thermal discomfort when PMV value lies below -1 (blue: cold) or above +1 (red: warm) for groups G1 and G2.

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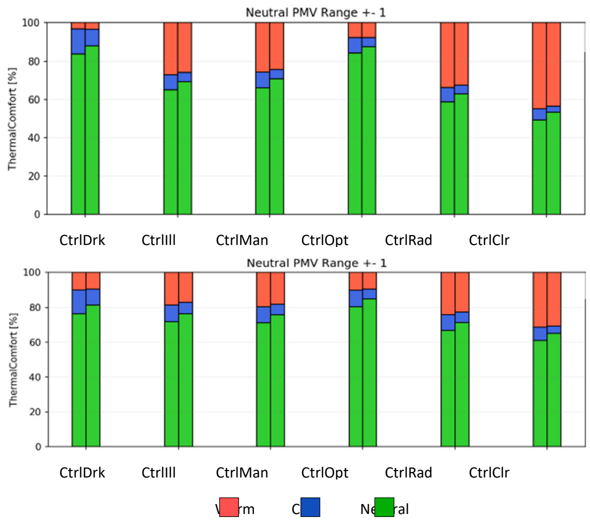

Figure 4: The overall performance of the systems for thermal comfort, top: blinds, bottom: EC

Energy and carbon footprint: Based on the set-point temperatures assigned in thermal simulation for the ideal heating and cooling (respectively 20°C and 27°C and later 21°C and 25°C), hourly energy demands for heating and cooling were simulated. This dead-band was defined quite loose in order to magnify the impact of shading systems. Later, the second dead-band was applied for heating and cooling systems (respectively 21°C and 25°C) to provide 100% thermal comfort in the room under all control conditions).

Electricity demand for supplementary artificial lighting was also calculated based on the integrated daylight-based control in TRNSYS considering the amount of available daylight on workplaces. This controller (Type4) has a continuous dimming function and on/off with the 1st illuminance setpoint: 500 [lx] and 2nd illuminance setpoint: 300 [lx].

Since the use of heat-pump based systems in buildings is growing significantly, to convert energy demand into site energy (end-use energy) a heat-pump and a chiller system were assumed for heating and cooling in this study. Therefore, the annual average of seasonal performance factor (SPF) was considered 4.2 for heating and 4 for cooling. In order to convert site-energy to source-energy (primary) constant primary energy factor (f_P) equal to 3.31 was assumed for electricity (EN 15603).

Finally, the total annual carbon dioxide emission was estimated in this study by considering the specific CO_2 emission factor equal to 0.469 [$KgCO_2e/kWh$] for electricity production mix factor in Germany (carbonfootprint.com).

Figure 5 (also see Table A-3 and B-3 in Appendix) shows the annual energy impact as a double color-coded bar for each case of control condition. The left bar shows the annual end-energy [$kWh/m^2.a$] (blue: cooling, red: heating, and yellow: electricity) and the right bar indicates the annual carbon footprint [$KgCO_2e/kWh$] (gray).

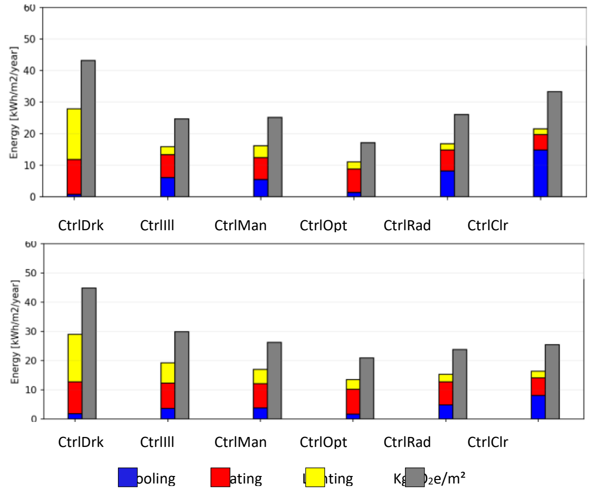

Figure 5: The annual energy consumption and CO_2 emission for each shading system, top: blinds, bottom: EC (set-point temp. 20-27°C)

Shading usage: The total percentage of each shading state occurrence during the occupied hours can indicate how the users' visual connection to the outside is impacted by the use of shading.

It is assumed that the clear state (light cyan color, S0: pulled up for blinds and clear (bleached) for EC glazing) can deliver sufficient view to outdoors and should be provided to users whenever it is not causing discomfort glare or overheating.

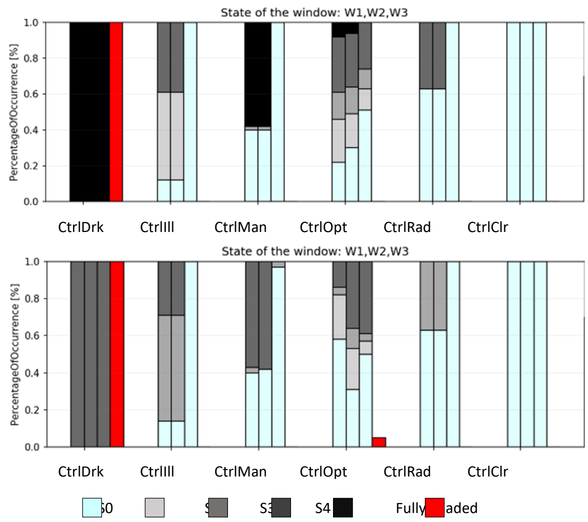

Figure 6: The total percentage of each state occurrence in different window zones, top: blinds, bottom: EC

Figure 6 (also see Table A-4 and B-4 in Appendix) shows the total percentage of occurrence as a triple color-coded bar for each window zone (top, middle, and bottom: from left to right).

Besides, the final red bar indicates the percentage of occurrence when all three window zones were completely shaded at the same time (pulled down and 80° tilted: S4 for blinds and fully tinted: S3 for EC glazing). This incident has been reported annoying by the users and should be avoided as

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much as possible. Avoiding this incident ensures the acceptable quality of light in the room with an electrochromic window since the color rendering index (CRI) stays above 80 as long as the three zones are not fully tinted at the same time.

All the results shown in this section (as Figures 2 to 6) can be also found in appendix for both venetian blinds (Tables A-1 to A-4) and electrochromic glazing (Tables B-1 to B-4).

DISCUSSION

The overall performance of a shading system can be assessed by comparing the annual simulated results for each performance indicator (e.g. glare, daylight, thermal comfort, and energy) and predefined acceptance criteria.

In this section, firstly, the overall potential of applying two different types of automated dynamic shading (blinds versus EC) was thoroughly compared by considering a conventional double glazing window without any sun protection as a base-case (see table 1, SHGC=0.61, and T_{sol}=0.42).

Secondly, the impact of using a control strategy is investigated by showing the improvement percentages considering the reference control strategies in three steps:

a) The clear window with no shade (CtrlClr) is used as a reference. Comparing other strategies to this reference case shows us clearly the impact of using shading for an office with a south-facing window.

b) The manual operation (CtrlMan) is used as a reference to show the importance of using an automatic controller for dynamic shading systems.

c) The radiation-based control (CtrlRad) is considered as a reference to explore the full potential of optimal automatic control (CtrlOpt) which may be achieved by applying a well-engineered heuristic or predictive model.

Glare protection: By comparing the performance of two shading systems, (EC vs. blinds), one can see that EC glazing with the clear state (bleached) has lower visible transmissivity (T_{vis}) which leads to better glare protection.

Both manual operation and rule-based controls avoided discomfort glare quite similarly.

The optimal control (CtrlOpt) was successful to keep annual DGPe below 4% with EC glazing and below 1% with venetian blinds system (see Figure 2). This can be explained by the possibility of blocking direct sun exposure to the eye when blinds are pulled down and closed (80° tilted), while even in the fully tinted state, EC glazing cannot completely block glare and direct sunlight (Clear, R. et al. 2006).

Table 6 shows the improvement in avoiding discomfort glare (when the DGP value is exceeded from the threshold) as a positive percentage relative to the reference control strategies.

For EC glazing, the optimal control (CtrlOpt) improved the glare protection condition by 88%, 33%, and 73% relative to no shade, manual control, and radiation-base control respectively. This shows that a manual control for EC may be adequate in terms of glare protection and daylight improvement, and optimal automatic control can only improve it by 33%.

Applying optimal control for external blinds, discomfort glare condition is also improved by 99%, 91%, and 97% relative to no shade, manual control, and radiation-base control respectively.

Table 6: Visual comfort improvements by applying a shading system with different control strategies

	relative to CtrlClr		relative to CtrlMan		relative to CtrlRad	
	Glare	Day-light	Glare	Day-light	Glare	Day-light
EC						
CtrlMan	82%	47%	-	-	59%	-26%
CtrlOpt	**88%**	**64%**	**33%**	**31%**	**73%**	**13%**
CtrlRad	56%	58%	-145%	21%	-	-
CtrlClr	-	-	-457%	-89%	-128%	-139%
Blinds						
CtrlMan	85%	58%	-	-	63%	9%
CtrlOpt	**99%**	**78%**	**91%**	**48%**	**97%**	**53%**
CtrlRad	59%	54%	-171%	-10%	-	-
CtrlClr	-	-	-560%	-140%	-144%	-118%

Available daylight: Similar to glare protection, EC glazing with the clear state (bleached) may avoid too-bright conditions; but it makes space darker compared to blinds (shades all up), due to lower visible transmissivity (T_{vis}).

Both manual and rule-based controls improved the useful daylight availability for workplaces close (G1) and farther away from the window (G2); however external venetian blinds performed more effectively by redirecting the daylight deeper into space for users G2 (see Figure 3).

Considering the impact of automatic controls, table 6 also shows the improvement in providing useful daylight relative to the references.

For EC glazing, the optimal control (CtrlOpt) improved the daylighting by 64%, 31%, and only 13% relative to no shade, manual control, and radiation-based control respectively. This means that the improvement by using optimal control for switchable windows is very minor (only 13%), while the potential of applying an optimal automatic controller for blinds is more significant (53%).

In general, improving the control algorithm from simple radiation-based to optimal control is more promising in providing visual comfort for venetian blinds than EC glazing.

Thermal comfort: The EC glazing system prevented more dissatisfying warm conditions due to lower solar transmittance (T_{sol}) and solar heat gain coefficient (SHGC) for a clear window with no shade (CtrlClr) in comparison to the clear window when venetian blinds are completely pulled up (see Table 1).

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One can see that manual operation for both EC and blinds works more effectively to reduce thermal discomfort in comparison to radiation-based control (see Figure 4).

By applying optimal automated external venetian blinds, avoiding more dissatisfying warm conditions is possible. This can be explained by the lower SHGC of the pulled down blinds in comparison to the fully tinted state of EC glazing (see Table 1).

It is also clear that by using an optimal control (CtrlOpt) providing thermal comfort is achievable only to some extent (up to 80% for EC and 84% for blinds) when the dead-band temperature for heating and cooling is 20°C and 27°C respectively (see Figure 4).

By considering the not-controlled cases (no-shade and always shaded), it can be pointed out that part of this cold discomfort can not be avoided even by opening the shadings (6% for blinds and 7.5% for EC). Similarly, part of warm discomfort can not be diminished even by completely closing the shadings (3% for blinds and 10% for EC).

Of course by using active heating and cooling systems more often thermal comfort can be provided for all occupied hours, but this comes at the cost of higher energy consumption.

Table 7 shows the improvement in avoiding thermal discomfort by applying various types of controls (set-point range: 20–27°C).

While manual shading was very successful for avoiding glare, providing thermal comfort is not achieved significantly; and the improvement due to the use of manual shading is only 26% for EC and 33% for blinds relative to no shade (CtrlClr).

For the EC glazing system, compared to radiation base control the optimal control (CtrlOpt) worsened the thermal comfort condition slightly (6%). This incident happened because the optimal control tries to improve all aspects of energy along with visual and thermal comfort. So, by sacrificing a little in thermal comfort, the optimal control may save a larger amount of energy.

Table 7: Thermal Comfort improvements by applying a shading system with different control strategies

	relative to CtrlClr	relative to CtrlMan	relative to CtrlRad
EC			
CtrlMan	26%	-	-106%
CtrlOpt	**50%**	**33%**	**-6%**
CtrlRad	15%	-15%	-
CtrlClr	-	-35%	-18%
Blinds			
CtrlMan	33%	-	18%
CtrlOpt	**69%**	**53%**	**62%**
CtrlRad	18%	-22%	-
CtrlClr	-	-49%	-23%

Energy consumption: The results of simulations clearly show the impact of dynamic shading systems on the reduction of overall end-use energy, particularly by using optimal automatic control. Considering a conventional double glazing window without any sun protection (see table 1 base-case, SHGC=0.61, and T_{sol}=0.42), applying an EC glazing saves 38-39%, while an external shading saves 49-48% of total annual end-use energy (respectively set-points 20-27°C and 21-25°C). The same reduction ratio can be expected in terms of total primary energy and CO_2 emission which shows significant potential in reducing global warming issues.

Comparing blinds to EC, one can also see that the automated blinds system was able to reduce cooling energy by 26%, heating energy by 13%, and electricity for lighting by 52% regarding automated EC glazing system (see Figure 5).

Table 8: Total end-use energy savings potentials by applying a shading system with different strategies

	relative to CtrlClr	relative to CtrlMan	relative to CtrlRad
Set-points	20° - 27°C		
EC			
CtrlMan	-3%	-	-10%
CtrlOpt	**18%**	**21%**	**12%**
CtrlRad	6%	9%	-
CtrlClr	-	3%	-7%
Blinds			
CtrlMan	25%	-	4%
CtrlOpt	**49%**	**32%**	**35%**
CtrlRad	22%	-4%	-
CtrlClr	-	-33%	-28%

Table 8 shows the impact of automatic controls on saving total end-use energy. By improving the control strategy from no shade to optimal control, 18% and 49% of total end-use energy can be reduced by EC glazing and blinds system respectively. Besides, from radiation-based to optimal control the total end-use energy can be reduced by 12% for EC, but 35% for blinds.

In terms of hourly electricity demand, automated shading systems can avoid critical peak demands for electricity. The results show that the optimal automatic control can reduce peak demand for cooling by 47% for EC and by 63% for blinds relative to the no-shade case; while the heating demands are increased slightly (about 13%).

Furthermore, using the optimal control, peak demand for cooling can be reduced by 26% for EC and by 33% for blinds relative to the manual controller case. In relation to radiation-based control, the reduction reaches 29% for EC and 40% for blinds.

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CONCLUSION

This paper proposes a simulation-based framework to evaluate the performance of shading systems and the impact of different control strategies on energy, visual comfort (glare, daylight availability, and view), and thermal comfort.

Integrated daylight and thermal simulations by using state of the art methods of modeling complex fenestration systems make predicting the behavior of shading systems more dependable.

This study shows that, despite the complexity of dynamic shading behavior concerning the energy and comfort requirements, a well-engineered control strategy can successfully regard all aspects of visual and thermal comfort as well as saving energy. The results clearly show that firstly, applying a rule-based controller can reduce cooling demand and critical peaks. Secondly, developing more advanced strategies, such as predictive control, has a significant impact on not only energy savings and reduction of environmental impacts, but also on visual and thermal comfort provided in office spaces.

During the very early stage of design, information about the full potential of shading systems may help climate consultancies/designers to convince clients for this profitable investment in applying shading systems and developing an automatic control strategy.

The results showed that: (a) in comparison to the base-case window, use of an automated dynamic shading can reduce the total annual end-use energy by about 38% for EC glazing and by nearly 49% for external shading; (b) similarly in regard to primary energy and CO_2 emission, an automatic shading is able to reduce a significant amount of the environmental impacts, (b) the differences between two types of shading systems in regard to providing visual and thermal comfort are not noticeable when an optimal control strategy is applied, however, an external venetian blind may perform more effectively than electrochromic glazing in avoiding discomfort glare, (c) the differences between manual operation and simple rule-based algorithms regarding energy and thermal comfort are noticeable, (d) the control algorithms have a strong influence on users connectivity to outside (view/privacy) and lighting quality (e.g. color rendering) which should not be overlooked during the development of control algorithms.

Despite all the studies that have been done for making the anticipated benefits of a dynamic façade true, the application of these methods in a real building is still limited to affordable sensor-based solutions. Due to the high level of complexity in integrated daylight and thermal model, the level of uncertainty in weather forecasting, rapid changes in sky condition, user behavior, and individual preference; methods of developing new control algorithms need to be further investigated.

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APPENDIX

Overall performance of an open office south-facing window with venetian blinds

Table A-1: Percentage of occupied hours with visual discomfort, including discomfort glare and not useful daylight

	DGPe[%] ≥ 0.4	DGP [%]								UDI[%]					
		Acceptable		Perceptible		Disturbing		Intolerable		Useful		Bright		Dark	
CtrlsName	**DGP max**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**
CtrlDrk	0%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%
CtrlIll	6%	95%	100%	3%	0%	1%	0%	2%	0%	82%	76%	2%	0%	15%	24%
CtrlMan	7%	94%	98%	2%	1%	2%	0%	2%	1%	75%	59%	8%	1%	17%	40%
CtrlOpt	**1%**	**98%**	**100%**	**2%**	**0%**	**0%**	**0%**	**0%**	**0%**	**87%**	**80%**	**1%**	**0%**	**12%**	**20%**
CtrlRad	19%	84%	97%	6%	2%	5%	0%	5%	1%	73%	82%	16%	2%	11%	16%
CtrlClr	46%	56%	81%	10%	9%	11%	3%	24%	6%	40%	66%	49%	18%	11%	15%

Table A-2: Percentage of occupied hours with thermal discomfort, including cold (PMV<-1) or warm (PMV>+1)

	ThermalComfort[%]					
	Neutral		Warm		Cold	
CtrlsName	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**
CtrlDrk	84%	88%	3%	3%	13%	9%
CtrlIll	65%	69%	27%	26%	8%	5%
CtrlMan	66%	71%	26%	24%	8%	5%
CtrlOpt	**84%**	**88%**	**8%**	**8%**	**8%**	**5%**
CtrlRad	59%	63%	34%	32%	8%	5%
CtrlClr	49%	54%	45%	44%	6%	3%

Table A-3: Total annual energy consumption (site and source energy) and annual carbon emission

	PrimaryEnergy		CarbonEmission		EndUseEnergy[kWh/m2/a]						PeakDemand[Wh/m2]			
Set-point	**20-27**	**21-25**	**20-27**	**21-25**	**20-27**			**21-25**			**20-27**		**21-25**	
CtrlsName	**[kWh/m2/a]**		**[KgCO2e/m2]**		**Cooling**	**Heating**	**Lighting**	**Cooling**	**Heating**	**Lighting**	**Cooling**	**Heating**	**Cooling**	**Heating**
CtrlDrk	92.2	102.7	43.2	48.2	0.8	11.0	16.1	2.0	12.9	16.1	8.0	10.6	9.8	11.2
CtrlIll	52.7	67.1	24.7	31.5	6.1	7.2	2.6	8.8	8.8	2.6	16.2	10.8	17.6	11.5
CtrlMan	53.5	67.9	25.1	31.8	5.4	7.0	3.8	8.2	8.5	3.8	14.7	10.9	16.2	11.6
CtrlOpt	**36.4**	**47.2**	**17.1**	**22.2**	**1.3**	**7.5**	**2.2**	**2.8**	**9.3**	**2.2**	**9.8**	**10.4**	**12.4**	**11.1**
CtrlRad	55.7	70.6	26.1	33.1	8.1	6.8	1.9	11.2	8.2	1.9	16.3	10.8	17.7	11.5
CtrlClr (Base-case)	71.2	90.5	33.4	42.5	14.9	4.7	1.9	19.1	6.3	1.9	26.2	9.1	27.8	10.3

Table A-4: Percentage of occupied hours with retracted shades or tinted glazing on each window zone

	Occurrence in W1 [%]					Occurrence in W2 [%]					Occurrence in W3 [%]					All
CtrlsName	**S0**	**S1**	**S2**	**S3**	**S4**	**S0**	**S1**	**S2**	**S3**	**S4**	**S0**	**S1**	**S2**	**S3**	**S4**	**Fully Shaded**
CtrlDrk	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	100%
CtrlIll	12%	49%	0%	39%	0%	12%	49%	0%	39%	0%	100%	0%	0%	0%	0%	0%
CtrlMan	40%	0%	3%	-1%	58%	40%	0%	3%	-1%	58%	100%	0%	0%	0%	0%	0%
CtrlOpt	**22%**	**24%**	**15%**	**31%**	**8%**	**30%**	**19%**	**15%**	**30%**	**6%**	**51%**	**12%**	**11%**	**26%**	**0%**	**0%**
CtrlRad	63%	0%	0%	37%	0%	63%	0%	0%	37%	0%	100%	0%	0%	0%	0%	0%
CtrlClr	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%

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Overall performance of an open office south-facing window with electrochromic glazing (EC)

Table B-1: Percentage of occupied hours with visual discomfort, including discomfort glare and not useful daylight

	DGPe[%] ≥ 0.4	DGP [%]								UDI[%]					
		Acceptable		Perceptible		Disturbing		Intolerable		Useful		Bright		Dark	
CtrlsName	**DGP max**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**
CtrlDrk	3%	98%	100%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	100%	100%
CtrlIll	5%	96%	98%	2%	1%	1%	0%	1%	0%	66%	29%	0%	0%	33%	71%
CtrlMan	7%	94%	98%	3%	1%	1%	0%	2%	1%	73%	49%	5%	0%	22%	51%
CtrlOpt	**4%**	**96%**	**98%**	**2%**	**1%**	**1%**	**0%**	**1%**	**1%**	**81%**	**74%**	**0%**	**0%**	**18%**	**26%**
CtrlRad	16%	89%	96%	4%	1%	2%	1%	5%	2%	78%	75%	9%	0%	13%	25%
CtrlClr	37%	64%	89%	13%	4%	7%	2%	15%	5%	48%	71%	39%	11%	13%	18%

Table B-2: Percentage of occupied hours with thermal discomfort, including cold (PMV<-1) or warm (PMV>+1)

	ThermalComfort[%]					
	Neutral		Warm		Cold	
CtrlsName	**G1**	**G2**	**G1**	**G2**	**G1**	**G2**
CtrlDrk	76%	81%	10%	9%	14%	9%
CtrlIll	72%	76%	18%	17%	10%	7%
CtrlMan	71%	76%	20%	18%	9%	6%
CtrlOpt	**80%**	**85%**	**10%**	**9%**	**9%**	**6%**
CtrlRad	67%	71%	24%	23%	9%	6%
CtrlClr	61%	65%	32%	31%	7%	4%

Table B-3: Total annual energy consumption (site and source energy) and annual carbon emission

	PrimaryEnergy		CarbonEmission		EndUseEnergy[kWh/m2/a]						PeakDemand[Wh/m2]			
Set-point	**20-27**	**21-25**	**20-27**	**21-25**	**20-27**			**21-25**			**20-27**		**21-25**	
CtrlsName	**[kWh/m2/a]**		**[KgCO2e/m2]**		**Cooling**	**Heating**	**Lighting**	**Cooling**	**Heating**	**Lighting**	**Cooling**	**Heating**	**Cooling**	**Heating**
CtrlDrk	95.7	107.1	44.9	50.2	1.8	10.9	16.2	3.4	12.8	16.2	10.3	11.7	12.1	12.4
CtrlIll	63.6	76.5	29.8	35.9	3.7	8.6	6.9	5.9	10.3	6.9	13.2	11.3	14.8	12.0
CtrlMan	56.0	69.3	26.3	32.5	3.8	8.2	4.9	6.2	9.9	4.9	13.2	11.3	14.8	12.0
CtrlOpt	**44.5**	**55.4**	**20.9**	**26.0**	**1.6**	**8.5**	**3.3**	**3.1**	**10.3**	**3.3**	**9.8**	**11.1**	**11.6**	**11.7**
CtrlRad	50.8	64.4	23.8	30.2	4.8	7.9	2.6	7.4	9.5	2.6	13.8	11.1	15.3	11.8
CtrlClr	54.1	70.3	25.4	32.9	8.0	6.1	2.3	11.3	7.6	2.3	18.4	9.8	20.2	10.8

Table B-4: Percentage of occupied hours with retracted shades or tinted glazing on each window zone

	Occurrence in W1 [%]					Occurrence in W2 [%]					Occurrence in W3 [%]					All
CtrlsName	**S0**	**S1**	**S2**	**S3**	**S4**	**S0**	**S1**	**S2**	**S3**	**S4**	**S0**	**S1**	**S2**	**S3**	**S4**	**Fully Tinted**
CtrlDrk	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	100%
CtrlIll	14%	0%	57%	29%	0%	14%	0%	57%	29%	0%	100%	0%	0%	0%	0%	0%
CtrlMan	40%	0%	3%	57%	0%	42%	0%	0%	58%	0%	97%	0%	3%	0%	0%	0%
CtrlOpt	**58%**	**24%**	**4%**	**14%**	**0%**	**31%**	**22%**	**11%**	**36%**	**0%**	**50%**	**7%**	**4%**	**39%**	**0%**	**5%**
CtrlRad	63%	0%	37%	0%	0%	63%	0%	37%	0%	0%	100%	0%	0%	0%	0%	0%
CtrlClr	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%

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