DAYLIGHT UTILIZATION POTENTIALS OF HIGHLY GLAZED INDIVIDUAL OFFICE SPACES IN BELGRADE CLIMATE CONDITION

by

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Office buildings have high standards for lighting requirements, which greatly contribute to high lighting energy consumption. Daylight utilization is one of the means to reduce it. The goal of this paper is to evaluate daylight utilization potentials in Belgrade climate in order to generate initial design guideline for highly glazed small, individual office spaces. Daylight availability and its lighting energy implications are analyzed using computer simulation tool DIVA for Rhino. Selected individual office space is modelled as a narrow rectangular space, sidelit and highly glazed. Parametric analysis was carried out for: four different glazing ratios (50, 60, 70, and 85%), four glazing types with different visible transmittance properties (80, 72, 62, and 54%), and four different major orientations. Since this analysis is evaluating daylight utilization potentials, no shades or external obstructions were considered. The major results of this study indicate high potential for daylight utilization in office buildings in Belgrade. Daylight utilization in single offices is reaching its maximum in model with 70% window-to-wall ratio for all office orientations except north orientation, where daylight utilization is reaching its maximum at maximum window-to-wall ratio. Also, north orientated spaces have highest benefits from utilization of useful diffuse daylight. Direct sunlight and size and shape of façade aperture above working plane are determining factors for utilization of daylight in office spaces.

Key words: *highly glazed façade, daylight utilization, individual office, computer simulation*

Introduction

Highly glazed façades are often used in contemporary office architecture. The aesthetic of glazed façades was used during 1960s to express modernity and power of companies, but today highly glazed façades also express the openness to the public and business honesty. The meaning and appearance of glazed façades are very suitable to the image of contemporary business, so the transparent façade concept is used very often. Contemporary, high technology glazed façades are also associated with an image of modern organization behind transparent walls, which is responsible to the environment and committed to energy preservation. But such energy preservation responsibility becomes quite questionable if glazed façade is not optimized according to building site and climate.

This paper is evaluating potentials for daylight utilization and lighting energy use in highly glazed individual office spaces in Belgrade climate conditions. The purpose of research

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is to generate initial design guideline for highly glazed small office spaces. The accent in this study is on initial design guidelines, since no shading was applied and consequently visual comfort in such spaces cannot be achieved.

Studies of daylight utilization and its implications on energy use in buildings are very popular in contemporary research. Technology and methodology of simulation process, as well as climate-based daylight metrics, have been rapidly developed during past decade. Many contemporary studies have concluded that daylight utilization in office buildings can highly contribute to lighting savings only or to overall energy savings in buildings [1-3]. Most of these studies are based on integrated approach, assessing interdependence of lighting, cooling and heating energy demands. Contemporary daylight utilization studies show different estimations of lighting energy savings, savings from 20% to 80% [4]. The results differ so much since the results of the studies highly depend on climate and site conditions, used daylight availability metrics and method of daylight availability assessment and performance. The method and metrics of daylight research and their influence on results for lighting or overall energy demand in buildings, is a new research ground. Most of researches in Serbian region are dealing with only cooling and heating energy demand [5, 6], investments in contemporary façades [7, 8], solar potentials in region [9], or policies for low energy buildings [10]. For comparison purpose with this research, no studies of daylight utilization in office buildings for Belgrade climate have been performed or published, to the best of author`s knowledge.

Most of metrics, used in this study for evaluation of daylight utilization potentials in office spaces, is not part of official standards, but it is still well-established climate-based metrics. Three groups of metrics were used: metrics that are evaluating annual daylight availability in space, such as daylight autonomy (*DA*), spatial *DA* ($DA_{500\text{lx}}$[50%]), maximum *DA* ($DA_{\max}$) and main daylight availability [11, 12], metrics that is evaluating the quality of visual comfort in space, such as effective daylight glare probability (*DGP*) [13, 14], and third group of metrics, established as metrics group in Reinhart`s and Wienold`s hibrid deffinition of well daylit space [15], which is evaluating energy demand.

The utilization of daylight is assessed using only one parameter of energy evaluation (assessing only lighting energy implications), since it suites the purpose of this study – to evaluate only potentials for utilization of daylight in small office spaces in Belgrade climate. The goal of this study is not to reach an optimum solution, which would require an integrative approach and a deeper analysis of interdependence of lighting and cooling/heating energy demand.

The DIVA for Rhino [16], a plug in for RHINOCEROS software, was used as a simulation tool for daylight and energy performance in office space. The software is relatively new, initially developed at Harvard University and presented in 2010. It is validated software for integrated analysis of daylight and thermal performance of buildings. For such purpose DIVA calculation process combines different software algorithms, such as Daysim [17] and Radiance [18] algorithm (for calculation of daylight performance) and EnergyPlus algorithm [19] (for calculation of thermal performance).

Methodology: model of individual office space

Analysis was carried out for typical individual office space with rectangular plan. Individual office space was modeled as narrow space, 3.0 m net wide on façade wall, with unusually elongated space depth of 9.8 m, which corresponds to measure of 3.5 net height of the space, fig. 1(a). The adopted height of the space is 2.8 m, as this height is usual net height used in Serbia for office spaces. Floor area of modelled office space is 29.4 m^2.

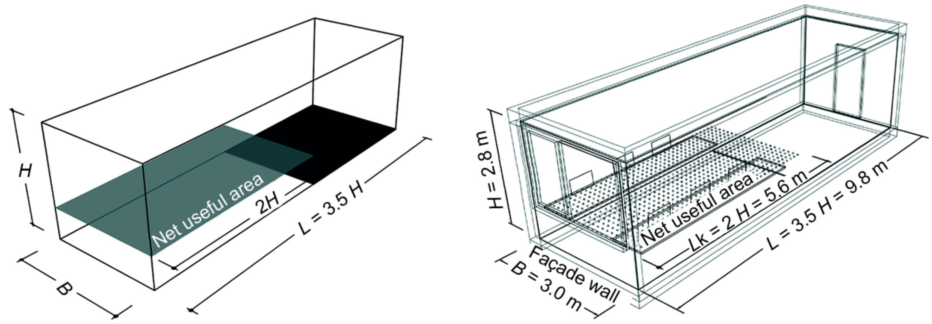


Figure 1. Dimensions and proportions of modeled individual office space

Elongated depth of office space was adopted in order to avoid the influence of back wall reflected daylight on horizontal and vertical illuminance in space. Daylight utilization was analyzed only for 5.6 m depth of space, which represents standard depth of real individual office spaces and correspond to 2 times net space height. This is called *useful* area of the office model. It is located next to façade wall, as shown in fig. 1. Useful net area is 16.8 m^2. Illuminance levels are measured on work plane height, 0.80 m above floor.

Only work desks and monitors are modelled in the interior, fig. 2. Work desks are arranged linearly next to both side walls, so all selected user positions are orientated towards side walls. First user position is set at distance of 1.0 m from façade wall. The distance between all other user positions is 60 cm. Since the office model represents an individual office space, twelve selected user positions represent possible locations of one or two users.

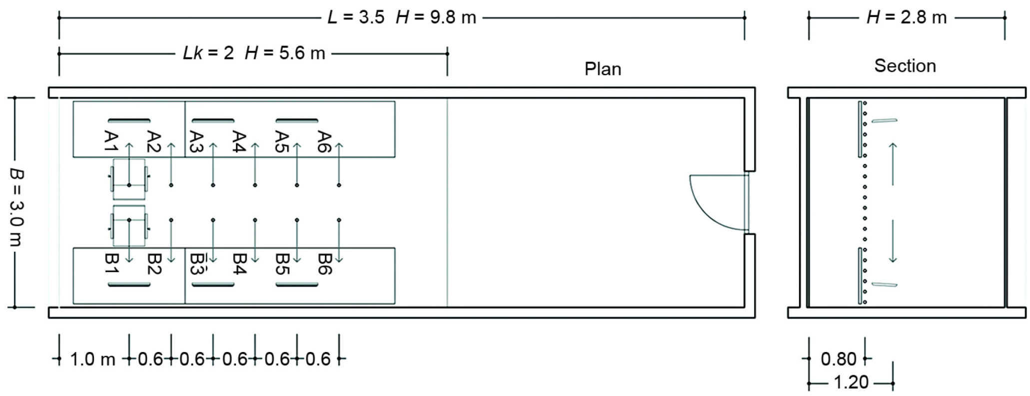
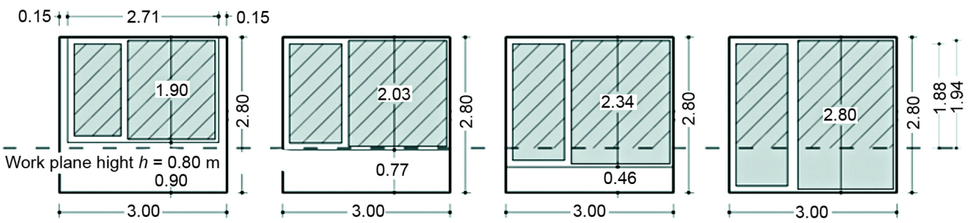


Figure 2. Plan and cross-section of modeled office space

Modeled office space is sidelit. Façade window is modeled as a single aperture, with window head height positioned next to the ceiling (2.8 m height). In this study, highly glazed office spaces are considered to have 50% or more glass area within façade wall. One third of glazed surface is placed within operable windows, so the maximum possible glass surface area for fully glazed façade wall is around 85% of façade wall net area, presented in tab. 1. For this study, four different window-to-wall ratios (WWR) were selected: 50, 60, 70, and 85% (shown in tab.1). The WWR of 80% and 85% had almost identical daylight metrics results, so only fully glazed façade wall was selected in this study.

Table 1. Selected four glazing ratios

Model name	M50	M60	M70	M85
Glazing ratio WWR [%]	50%	60%	70%	84.8%



glazing area; effective glazing area (on work plane illuminance level)

Basic criterion for glazing selection was optical property of glazing. Four different glazing types ware selected for the analysis: visible transmittance, τ_v, is ranging from 54% to 80%, and gradated around 10%, tab. 2. All glazing types have *U*-value of 0.7 W/m^2K^1, except G01 glazing type (*U* = 1.1 W/mK), because triple glazing cannot produce visible transmittance, τ_v, higher than 75%. Selected glazing types do not qualify as selective glazing. Solar factor of glazing was selected according to Belgrade climate, which is climate with predominant heating period.

The space was rotated to face four major orientations: east, south, west, and north.

Since this analysis is evaluating daylight utilization potentials, no shades or external obstructions were considered. Only huge external ground was modeled.

Table 2. Thermal and optical properties of selected glazing

Glazing group	Glazing model name G0x ($\boldsymbol{\tau}.g.U$) [(1)]	Glazing layers[(2)] [mm]	Glazing properties: Visible transmittance [(3)] τ_v [%]	Glazing properties: Solar factor[(3)] g [%]	Glazing properties: *U*-value[(4)] U_g [$Wm^{-2}K^{-1}$]	Selectivity S
1	G01 (**80**.73.1,3)	10-16-6	**80**	73	1.3	1.1
2	G03 (**72**.62.0,7)	10-16-6-16-6	**72**	62	0.7	1.2
3	G05 (**62**.50.0,7)	10-16-6-16-6	**62**	50	0.7	1.3
4	G07 (**54**.48.0,7)	10-16-6-16-6	**54**	48	0.7	1.1

(1) Structure of glazing model name: GlassNumber (visible transmittance. solar factor. *U*-value).
(2) For double glazing: (glass-spacer-glass) thickness; for triple glazing: (glass-spacer-glass-spacer-glass) thickness; spacers: 10% air, 90% argon.
(3) According to EN 410 – 2011.
(4) According to EN 673 – 2011.

Selected working hours are from 7:00 a. m. to 17:00 p. m., every day during year, including weekends, with daylight saving time, which altogether counts space occupancy of 3650 hours per year.

Analysis was carried out for 500 lx illuminance, E_v, level on working plane. Lighting fixtures are LED lamps with dimming function. Lighting controls are automated and whenever daylight levels in work plane control sensors are below 500 lx lighting is deployed to maintain minimum illuminance levels of 500 lx.

Radiance parameters (that control simulation process) and model surface reflectance are shown in tabs. 3 and 4, respectively.

Table 3. Radiance parameters

Radiance parameters	*-ab*	*-ad*	*-as*	*-ar*	*-aa*
Value	7	1500	20	300	0.05

Table 4. Surface reflectance in modeled space

Surface	Reflectance
Interior walls, furniture, and door	50%
Ceiling	80%
Floor, outside ground	20%

Results and discussion: Daylight metrics and daylit zones

The results of this study divide net useful area into three zones: *daylit area* – a zone where *DA* value is equal to or higher than 50% of its maximum value [20], which means that target illuminance level is reached more than half of occupancy time; *partially daylit area* – a zone with daylight metric values below half of its maximum value, but still close to target illuminance, and the third zone is *overlit zone* – a zone with oversupply of daylight. In this study, for illuminance target of 500 lx at work plane level, oversupply of daylight is considered as sensors` illuminance values above 5000 lx for more than 5% of occupied hours [21].

Daylight metrics results for all model variants show that office façade models with WWR above 50% have very similar results. Only results for M50 model (50% WWR) differ substantially from results of models with higher glazing ratio. This façade model has smaller dimensions of façade aperture (both horizontally and vertically), and aperture lower edge is positioned slightly above work plane height (at which illuminance levels are measured) (see schematic figures in tab. 1). The rest of façade models have identical transparent area above work plane, so the daylight metrics results (*DA* and $DA_{500\text{lx}}$ [50%]) show difference within only 1% to 5% range within the same space orientation, figs. 3 and 4.

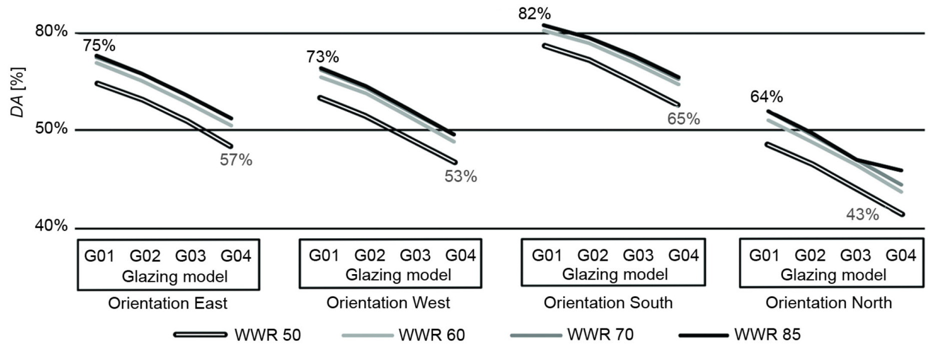


Figure 3. Change of main *DA* for all model variants, as function of glazing visible transmittance change

As glass visible transmittance is decreasing, *DA* and daylit work plane area (DA_{500lx} [50%]) are being reduced for all WWR and façade orientations, figs. 3 and 4.

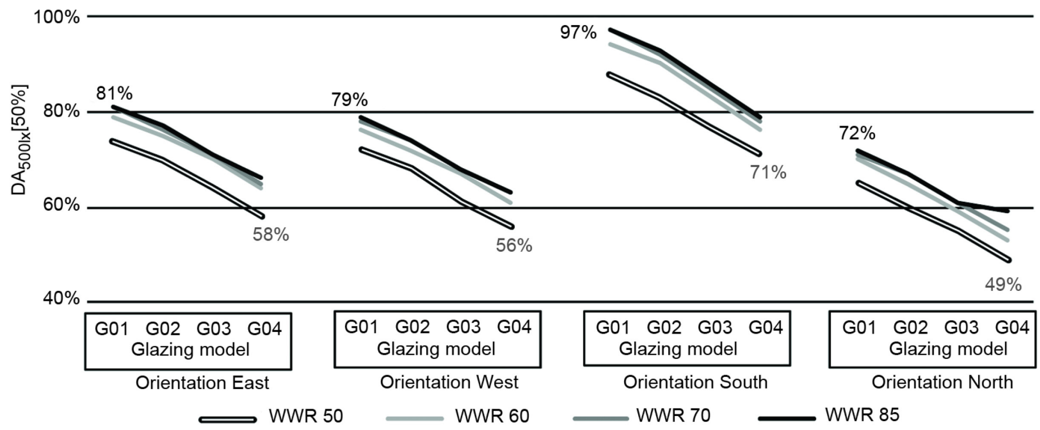


Figure 4. Change in percentage of work plane area with DA larger than 50% (DA_{500lx} [50%]) (for 500 lx illuminance threshold at work plane level), as a function of glazing visible transmittance change

Very close results of *DA* and DA_{500lx} [50%] for M70 and M85 façade model (for all types of glazing) indicate that daylight saturation in modeled office space is reaching its maximum at 70% WWR. Daylight saturation in modeled space with 70% glazed façade also can be seen from prediction of lighting energy use: after 70% WWR there is no further reduction of lighting energy demand, fig. 5.

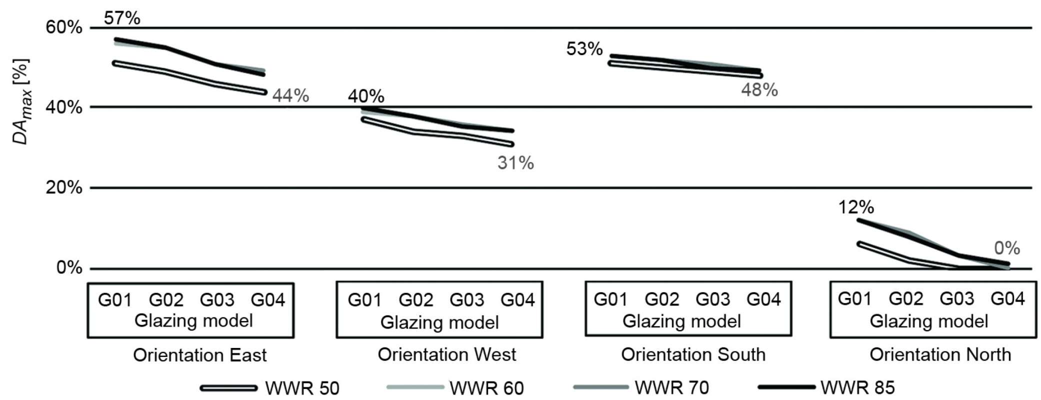


Figure 5. Change of predicted annual lighting energy demand for all model combinations, presented as a function of glazing visible transmittance change

High potential for daylight utilization in modeled office space can be seen from results of *DA* and DA_{500lx} [50%], figs. 3 and 4. East and west orientated models have similar results. Daylit work plane area for east orientated models is between 58% and 81%, while west oriented models have similar daylit work plane area – between 56% and 79%. Also values of

DA for east and west orientated models are similar. South orientated models have highest potential for daylight utilization – occupied hours when space is adequately daylit only by daylight are within range from 65% to 82% of occupied hours and work plane area that is daylit more than 50% of occupied time is ranging from 71% to 97% of work plane area. Judging by results of standard *DA* and spatial *DA* (DA_{500lx} [50%]), north orientated spaces have lowest potential for daylight utilization (ranging from 43% to 64% of occupied time and 49% to 72% of work plane area).

Although east and west oriented models show similar *DA* and DA_{500lx} [50%] results, east orientated models have considerably higher presence of DA_{max} during occupied time (44% to 57% of occupied hours comparing to 31% to 40% for west orientated models), fig. 6. The presence of DA_{max} is usually indicating the presence of direct sunlight in control sensors, which causes high illuminance levels and thus glare problems for occupants.

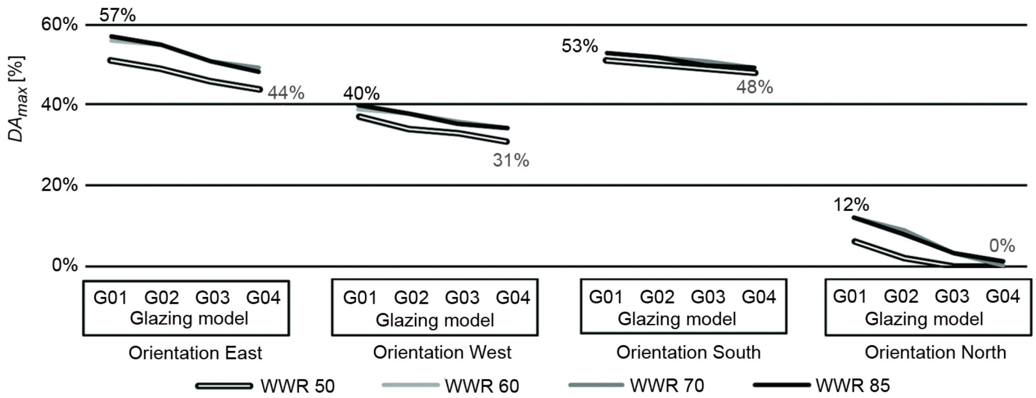


Figure 6. Change of DA_{max} for all model variants, presented as a function of glazing visible transmittance change

In this study, glare was analyzed for model M85 (fully glazed façade wall) combined with glazing type G01 (maximum visible transmittance), as a worst case scenario for glare. Results are shown in tab. 5. Only model oriented towards north does not have effective glare present in space. The highest value of occupied hours when effective glare is present is in south oriented model (55% of occupied time). East and west oriented models have effective glare present during 30.8% and 25.4% of occupied hours, respectively.

Table 5. Presence of effective glare during occupied hours (*WWR* = 85%, τ_v = 0.8)

Façade orientation:	East	South	West	North
Presence of effective glare during occupied hours – *effective DGP*:	30.8%	55.0%	25.4%	0.0%

High percentage of occupied hours when glare is present in east oriented model is a result of diurnal space occupancy and diurnal insolation presence on façade. East oriented façade is insolated from early morning hours to noon. Applying daylight saving time in Belgrade latitude, east orientated façade is insolated during summer period around five to six hours. Sun position is low, so direct Sun beams are penetrating deep into space (3.1-3.6 m into space, fig. 7). West orientated façade is diurnally insolated during summer period around three to four hours within the limits of working time (from 7:00 to 17:00). This, almost twice shorter period of diurnal insolation, compared to east orientation, is causing a lot less presence of glare in west orientated model. Also, during working hours, Sun position in western celestial hemisphere is much higher and penetration of direct sunlight into space is not so deep as in east orientated spaces (between 2.2 m and 2.5 m from façade wall, fig. 7).

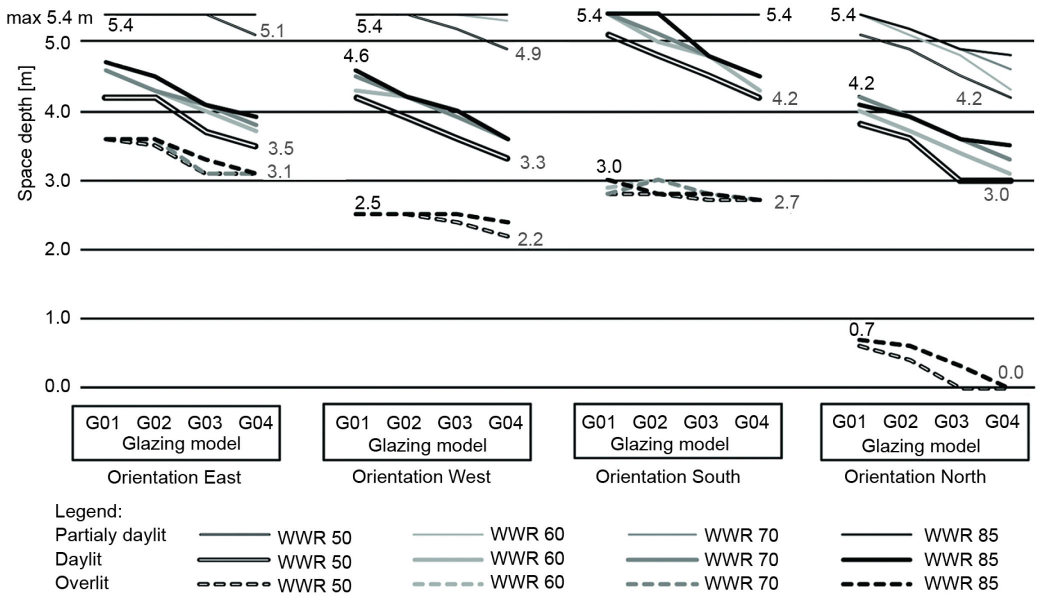


Figure 7. The depth of daylit, partially daylit and overlit zone for all model combinations and four major orientations

South orientated models annually have high presence of overlit hours (48% to 53% of occupied hours, fig. 7), because south facing office spaces in Belgrade have direct sunlight present on façade almost during entire occupancy hours. But still, DA_{max} is lower than in east orientated spaces. The reason lies in high Sun positions on southern celestial hemisphere. Deep penetration of direct sunlight into space is present only during winter period, when Sun positions are predominantly low.

North orientated spaces also have DA_{max} present, but penetration of direct sunlight is reaching depth of only 0.7 m, fig. 7. Potential first position of a user is defined to be at 1.0 m away from façade wall, so direct sunlight is not present on user`s working area and, thus, no glare problems are occurring in north orientated spaces (tab. 5 – effective *DGP* is 0% of occupied time).

As *DA* metric is indicating percentage of occupied hours when use of electric lighting is not necessary, *daylight availability* metric is indicating the same, but excludes sensors where DA_{max} is present. For reasons previously mentioned (long period of insolation, low Sun positions and high glare presence), east orientated spaces have lowest *mean daylight availability* (19% to 24% of occupied time), fig. 8 (compared to other space orientations). The depth of daylit zone, that is adequately daylit for office spaces (minimum 500 lx) and without presence of overlit area next to façade aperture, is between 3.6 m and 4.7 m for glazing type with highest visible transmittance, $\tau_v = 0.8$, and between 3.1 m and 3.9 m for glazing type with lowest visible transmittance, $\tau_v = 0.5$, fig. 8. Spaces orientated to west have higher *mean daylight availability* (27% to 36% of occupied time) than east orientated spaces, because depth of overlit zone is shorter (2.2 m to 2.5 m) and daylit zone depth is similar to east orientated spaces (3.3 m to 3.6 m). For south orientated spaces, *mean daylight availability* is between 23% and 33% of occupied time. Penetration of direct sunlight in south orientated spaces is a little deeper than in west orientated spaces (from 2.7 m to 3.0 m), so more sensors are excluded from calculation of daylit zone. North orientated spaces have highest *mean daylight availability*, thus indicating, contrarily to *DA* and DA_{500lx} [50%] results, highest potential for diffuse daylight utilization, which is favorable in office environments.

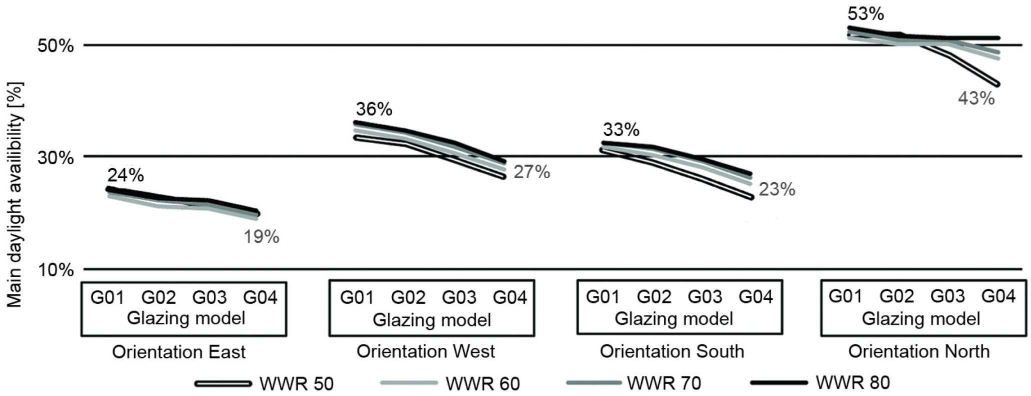


Figure 8. Change of *main daylight availability* for all model variants, presented as a function of glazing visible transmittance change

Table 6. Depth of work plane daylit zone expressed as function of window head height above floor

	Orientation							
	East		West		South		North	
	Glazing type							
	G01	G04	G01	G04	G01	G04	G01	G04
model	($\tau = 0.8$)	($\tau = 0.5$)	($\tau = 0.8$)	($\tau = 0.5$)	($\tau = 0.8$)	($\tau = 0.5$)	($\tau = 0.8$)	($\tau = 0.5$)
M50	1.5	1.3	1.5	1.2	1.8	1.5	1.4	1.1
M85	1.7	1.4	1.6	1.3	1.9	1.6	1.5	1.3

Considering adopted space net height of 2.8 m, highest possible position of window head height and illuminance threshold of 500 lx on work plane, daylit zone in single office spaces in Belgrade latitude and climate is never reaching the depth of two times window head height above the floor, tab. 6. Only south orientated spaces, with 80% visible transmittance of glazing, has penetration of daylit zone close to two times window head height above the floor. The depth of the daylit zone for the rest of glazing-WWR-orientation combinations is around 1.5 times of window head height above the floor.

Conclusion

General conclusion for daylight utilization in office buildings is that the size and shape of façade aperture above work plane has a strong impact on level of daylight utilization. If size and shape of façade aperture above working plane are not changing with glazing ratio rise, the difference in daylight utilization is negligibly small, but energy demand for cooling and heating might significantly rise. Also, as work plane areas with high direct sunlight occurrences (causing glare) is rising within the office space, the utilization of daylighting potentials is getting lower. Avoiding user positions in such areas might ensure higher utilization of daylighting potentials.

For single office space in Belgrade latitude and climate, higher glazing ratios are resulting in higher percentage of time and area that is considered to be daylit. But the difference in daylight utilization potential between glazing apertures that cover entire façade surface above work plane (in this case: 60, 70, and 85% glazing ratio) is extremely small. In this analysis, after 70% glazing ratio there is no further daylight utilization within office space (except for north orientation), since there are no further lighting energy savings.

In Belgrade latitude and climate, the highest potential for daylight utilization is occurring in spaces oriented to north. North orientated spaces are utilizing diffuse daylight almost during whole selected working time. It is recommended to use glazing with high light transmittance and high WWR. West facing single office spaces, like north facing spaces, also have high percentage of hours for utilization of diffuse daylight. Although direct sunlight is present for very short time diurnally, low Sun positions during winter are causing deep penetration of direct sunlight into space and high illuminance levels. Potential for daylight utilization is thus greatly reduced compared to north orientated spaces. South and east orientated office spaces show very high illuminance values for longer time in areas close to façade wall, which indicates high percentage of time when direct sunlight is present. The space orientation that most often has high illuminance levels near façade is south oriented space. In order to ensure high daylight utilization it is necessary to reduce illuminance levels by application of glazing with low light transmittance, thus ensuring lower percentage of time when shading would be needed. East orientated office spaces have lowest potential for daylight utilization. Presence of direct sunlight during more than half of working hours and low Sun positions are causing high illuminance levels in over half of occupied time. The daylight availability and potential for utilizing daylight are greatly reduced.

For utilization of diffuse daylight in Belgrade latitude and similar geographic locations with similar climate, the ideal position of a user in an individual office without any shading, is located within distance between (around) 1 and 1.5 window head height. This daylit area limits prevail for all space orientations except for north orientated office, where all area of work plane, deep up to around 1.5 window head height, potentially enables high utilization of useful diffuse daylight. The exception in daylit area limit exists also in south orientated space, which has a deeper daylit limit (up to 1.9 window head height depth for glazing with high visible transmittance).

Positioning the user within these limits for each space orientation is ensuring highest potential for utilization of diffuse daylight. These useful daylit area limits for each office orientation also potentially enable the lowest percentage of occupied time when some kind of shading would be needed in order to control visual comfort. High illuminance values in overlit areas are the consequence of direct sunlight, which also carries its energy component, providing solar gains that have to be controlled, depending on weather solar gains are beneficial for building`s energy demand or not. Low percentage of time when some kind of shading is needed in order to control visual comfort, at the same time, provides beneficial solar gains during winter period and have positive influence on heating energy demand. The control of unwonted solar gains during summer period would inevitably lead to higher demand for shading, even in cases when no shading is necessary to control visual comfort. Therefore, if user position is ensuring minimal percentage of time when shading is needed to control visual comfort and, at the same time, is ensuring beneficial solar gains during winter period, shading strategy should be based on summer conditions, placing shading externally, as a measure that could provide highest poslible utilization of usefull daylight and lowest energy demand for cooling and heating.

Nomenclature

B – width, [m]
DA – main daylight autonomy, [%]
DA_{500lx} [50%] – main spatial daylight autonomy, [%]
DA_{max} – maximum daylight autonomy, [%]
DGP – daylight glare probability, [%]
E_v – illuminance, [lx]
g – solar factor, [%]
H – height, [m]
L – length, [m]
S – selectivity, [–]
U – U-value, thermal transmittance, [$Wm^{-2}K^{-1}$]
WWR – window to wall ratio, [%]

Greek symbol

τ_v – visible transmittance, [%]

Radiance parameters

-ab – ambient bounces, [–]
-ad – ambient division, [–]
-as – ambient sampling, [–]
-ar – ambient resolution, [–]
-aa – ambient accuracy, [–]

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