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Effects of Interior Design on the Daylight Availability in Open Plan Offices

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ABSTRACT

The COPE (cost-effective open plan environments) project investigates the effect of open-plan office design on the indoor environment and on the occupant satisfaction with that environment. COPE is sponsored by a consortium of North American public and private-sector organizations and relies on field, laboratory and simulation studies to address design aspects like acoustics, lighting quality, indoor air quality, operating costs and energy efficiency.

This paper describes the influence of various design variables on the daylight availability and electric lighting requirements in open plan office spaces using the RADIANCE-based annual daylight simulation method DAYSIM. To make simulation results more reliable a manual and an automated blind control strategy have been considered. Five climatic centers which represent the ambient daylight conditions of 186 North American Metropolitan Areas have been identified. For these five climatic centers over 1000 office settings have been investigated which feature varying external shading situations, glazing types, facade orientations ceiling designs and partition arrangements. The daylight performance of the offices was expressed in terms of their daylight autonomy distributions and energy savings for an ideally dimmed lighting system.

The simulation results reveal, that the daylight availability in peripheral offices allows for electric lighting energy savings between 25% and 60% for an ideally commissioned, dimmed lighting system depending on the underlying blind control strategy. 2nd row offices receive considerably less daylight even though a reduced partition height and increased ceiling reflectances can double electric lighting energy savings up to 40%.

Background

Modular open-plan offices consist of an assembly of individual work stations which are in visual and acoustical contact with each other. The first open plan offices were designed by the brothers Schnelles in Germany in the 1960s and were called *Bürolandschaften* (office landscapes). Bürolandschaften were an architectural expression of the human relations movement of the 1950s which promoted 2-way communication between management and employees (Sundstrom 1986). They were non-traditional in appearance, rejecting rigid grid systems in favor of asymmetric spaces and did not include any private offices. By having everyone in the open, the design intended to facilitate communication through the physical availability of co-workers and expressed a more egalitarian attitude than the Tayloristic interpretation of offices as “assembly lines of documents". Over time the original free-form floor concept disappeared and shifted to interlocking, modular furniture systems that are arranged in tighter and highly predictable rectilinear groupings of work stations. Such systems nowadays dominate North American commercial interiors. Organizational trends like *space optimization*, *hotelling* or *hot desking* are putting further pressure on individuals' spaces while –at the same time– work stations have become routinely equipped with phones and VDTs, i.e. they require enhanced acoustic separation and *glare-free* illumination.

It seems obvious that the above described changes to the office landscape have the potential to degrade an office environment and reported problems range from lack of privacy to distraction from other's noise and missing control over the thermal and visual conditions (Leaman & Bordass 2002). It is commonly assumed that declining occupant satisfaction has negative consequences for an organization's bottom line as the financial consequences of a dissatisfied workforce can far outweigh any savings associated with reduced office space.

The COPE project (cost-effective open plan environments; www.nrc.ca/irc/ie/cope) was initiated to provide decision makers with a comprehensive predictive model that describes how changing interior open-plan office design parameters affect the environmental conditions of the indoor environment and the occupant satisfaction with that environment. The scope of the project ranges from literature reviews to field studies, laboratory evaluations, subject studies and computer modeling. Performance indicators cover acoustics, lighting quality, indoor air quality, operating costs and energy efficiency.

This paper concentrates specifically on the annual daylight availability and energy saving potential of a dimmed lighting system in open plan offices. The analysis is based on multiple daylight simulations using the RADIANCE-based dynamic daylight simulation method DAYSIM (Reinhart & Walkenhorst 2001). The paper extends previous research as *annual* daylight simulations have been used in a *systematic* fashion to investigate the impact of design variables which are specific to open plan offices ranging from circumstantial boundary conditions like the geographical site, shading due to external objects and facade orientation to interior design parameters like partition height, workstation reflectivity and ceiling reflectivity. To make simulation results more reliable a manual and an automated blind control strategy have been considered. The following questions are discussed:

- Which design parameters influence the daylight situation in open plan offices?
- What is the relevance of daylight in open plan office spaces?

Daylighting in Open Plan offices

Daylighting can be defined as the conscious usage of *glare-free* natural daylight to light a building's interior. Daylighting advocates claim that it yields significant benefits for a building and its occupants ranging from occupant productivity gains to an enhanced architectural design quality and energy savings. Despite these high hopes daylighting is usually not a high priority design aspect – especially in open plan offices. This indifference of many planners towards daylighting may be the result of

- a lack of informative daylight performance indicators
- overoptimistic energy saving predictions that are rarely met in real buildings

Daylight Performance Indicators

Benefits that are associated with daylight tend to be qualitative in nature and are always –including energy saving benefits– difficult to express in quantitative terms. The resulting lack of meaningful daylight performance indicators usually prevent daylight from being a rigorous design criteria. In fact, the *daylight factor* is still the only commonly used parameter to characterize the daylight situation in a building.

The daylight factor. This corresponds to the normalized indoor illuminance distribution under a overcast CIE sky and can be estimated using a simple spread sheet formula or computer simulations (IESNA 2000). A recent British survey related occupant satisfaction with daylight factors and concluded that satisfaction can be maximized for average daylight levels between 2% and 5% (Roche, Dewey & Littlefair 2000). This finding is in line with recommendations of the British Standards Institution (BSI 1992). On the other hand, the study also acknowledged that satisfaction varied among offices with the same average daylight factor, indicating that other design factors such as "orientation and the effectiveness of blinds are also important".

In this study simulations of the daylight factor distribution in over 1000 open plan office geometries (described further below) yielded, that for a high visual transmittance glazing of 75% the mean daylight factor lay around 15% for a work station adjacent to a facade with a window aperture of 60% (Fig. 1). For a glazing with a visual transmittance of 35% the daylight factor fell to 7%, i.e. it lay just above the recommended range. The average daylight factor for interior workstations never reached 1% even for interior partition heights as low of 48". This analysis suggested that open plan offices are unsuitable for daylighting as work places are either too bright or too dark – a conclusion that justifies current design practices for open plan offices which neglect daylight and favor low transmittance glazings and electric lighting zones that extend over many work stations. In the following a further-going analysis based on dynamic daylight simulations is presented.

Dynamic daylight simulations. The inherent limitations of the daylight factor as a holistic daylighting parameter have triggered the development of *dynamic daylight simulation methods* which can reliably and efficiently model indoor illuminance distributions in complex building geometries under arbitrary sky conditions e.g. (Janak 1997; Mardaljevic 2001; Reinhart & Walkenhorst 2001). These methods combine the backward-raytracer RADIANCE (Ward & Rubinstein 1988) with a daylight coefficient approach (Tregenza 1980) and the Perez sky model (Perez *et al.* 1993). All simulations in this study have been carried out with the DAYSIM method (www.nrc.ca/irc/ie/light/daysim.html) which uses a stochastic model to predict the short-time-step development of direct and diffuse irradiances based on hourly means (Walkenhorst *et al.* 2002). All simulations in this study are based on 5min time steps. A difficult task is to translate the paramount amount of data resulting from an annual daylight simulation into a meaningful measure. The following two indices have been used in this study:

1. Daylight Autonomy. The Canadian Labor Code (CLC 1991) states that for task positions in offices where "continuous reading or writing is performed" the minimum illuminance shall not be less than 500lx (~50footcandles). Based on these legal requirements, the *daylight autonomy* at a work place is defined as the percentage of the occupied times per year when the average desktop illuminance lies above 500lx. The quantity informs how often an occupant could *in principal* work by daylight alone without suggesting how often the electric lighting is *actually* switched off. The main advantage of the daylight autonomy over the daylight factor is that it takes facade orientation and user occupancy profiles into account and considers all possible sky conditions throughout the year.
2. The energy saving potential of a lighting strategy is an informative quantity that can be translated into dollars and payback times. In this study an ideally commissioned, dimmed lighting system that maintains a minimum desktop illuminance of 500lx is considered. The system is activated during operational office hours (Mo-Fr: 8-18), has a minimum electric power demand of 10% at zero lighting output and an installed electric lighting power of $15Wm^{-2}$ (electronic ballast $=0.75Wm^{-2}$). A mixed task-ambient lighting design option which might yield additional savings has not been considered here. While the annual energy demand of this system can be reliably calculated using dynamic daylight simulations, energy savings can only be expressed if a meaningful reference lighting system is identified. For the investigated open plan offices a single-zone lighting system that is permanently activated during working hours has been chosen as it reflects common practice. All energy saving predictions are based on this extremely wasteful system[1]. The resulting energy saving might still be too high as commissioning issues have not been considered (Love 1995).

Blind Usage

Another error source for overoptimistic energy savings predictions is the treatment of blinds. It is often assumed that blinds are retracted all year round (maximum daylight availability) while the lighting is always activated during office hours. Compared to this reference scenario a dimmed lighting system promises unrealistically high energy savings as the lighting sensor responds to the available daylight whereas the occupant does not. To provide more realistic results, four different blind control strategies have been considered:

1. blinds fully opened all year round: unrealistic scenario that defines an upper limit of the annual daylight availability.
2. automatic blinds: blinds are automatically fully lowered with a slat angle of 45^o facing out downwards as soon as outside direct solar irradiance above 50 Wm^{-2} hits the work station adjacent to the facade[2,3]. The blinds are fully opened otherwise.

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1 In private offices a manually controlled on/off lighting system would be a more appropriate choice. For such a system the *manual lighting control model* that has been proposed by the author (Reinhart 2001) can be used.
2 This *direct* glare criterion for closing blinds has been first identified by Inoue *et al.* (Inoue 1988).
3 The work station is modeled by 12 sensors distributed over the desk and near the occupant's head (Fig. 1).

3. manually controlled blinds: blinds are manually fully lowered (slat angle of 45^{o}) as soon as outside direct solar irradiance above $50Wm^{-2}$ hits the work station adjacent to the facade. The blinds are re-opened once a day in the morning upon arrival[4].
4. blinds permanently closed (slat angle of 45^{o}): this scenario defines a lower limit of how much daylight is available. It can be used to model the manual blind control of a user who does not operate the blinds on a daily basis.

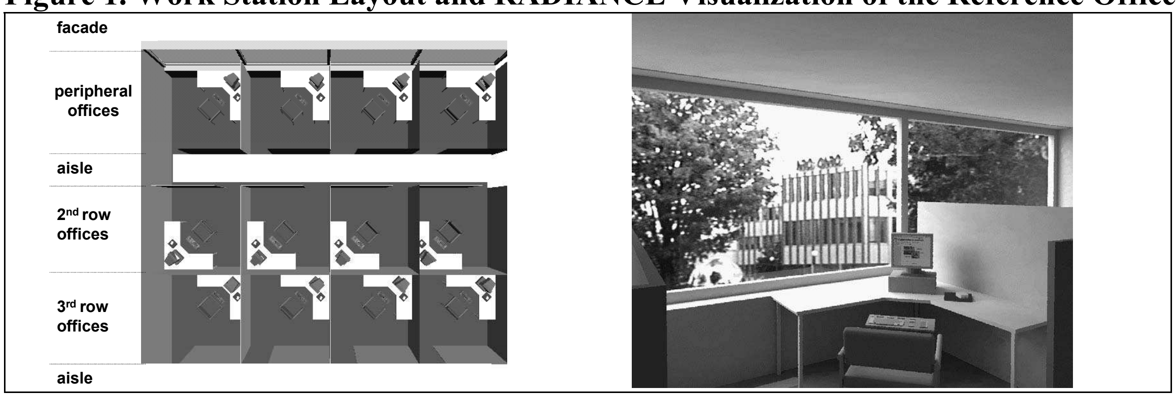
Investigated Office Geometries

Several hundred raytracing calculations have been carried out. To maintain comparability between the different simulations the same set of RADIANCE simulation parameters has been used throughout the whole study[5].

Reference Geometry

Figure 1 shows the reference work station layout relative to which design changes have been introduced. Only the first three rows of work stations adjacent to a facade have been considered. Geometrical details of the work station layout are provided in Table 1.

Figure 1. Work Station Layout and RADIANCE Visualization of the Reference Office



Investigated Office Geometries

Building location. To account for varying building locations, five climatic centers which represent the ambient daylight conditions of 186 North American Metropolitan Areas have been identified in a preparatory simulation study. For these five climatic centers over 1000 open plan office settings have been investigated.

4 This re-opening criteria has been proposed by Newsham (Newsham 1994) and is supported by data collected from Lindsay (Lindsay 1993). On the other hand, it stands in contrast to findings from Rubin (Rubin 1978) who reported that blinds are manually adjusted for periods ranging from weeks to months (blind strategy no.4).

5 Non-default *rtrace* simulation parameters were: ab=7, ad=1500, as=200, aa=0.1, ar=300, lr=9 and st=0.2.

Interior design variables. Table 2 lists all space design variables which have been varied with respect to the reference office design. The gray fields mark the values for the reference design.

Table 1. Details of the Reference Workstation Layout

Interior Design Variables		Building Envelope	
Variable	**Size**	**Variable**	**Size**
workstation size	10x10ft	$\tau_{visible}$ of windows	35%
partition height	64"	window width	equals work station width
floor-ceiling height	9ft	window height	0.75m above floor
aisle width	4ft	external obstructions	none
ceiling reflectance	80%	window frame width	10cm
VDT position	45^o towards window	facade orientation	4 cardinal directions
partition reflectance	50%		
floor reflectance	20%		

Table 2. Interior Design Variables

Variable	Range			Unit	#
workstation size	10 x 10	8 x 8	6 x 6	ft^2	**3**
partition height	72	64	48	in	**3**
floor to ceiling height	9	8		ft	**2**
aisle width	4			ft	**1**
ceiling reflectance	80	90		%	**2**
partition reflectance	50	35	20	%	**3**
floor reflectance	20			%	**1**

External variables. For each of these different office designs over 600 different settings have been considered, i.e. four facade orientations, three blind control strategies, two glazing types and five climatic centers.

Table 3. Building Envelope Variables

Variable	Range					#
facade orientation	North	South	West	East		**4**
blind control	always open	automated	manual	always closed		**4**
$\tau_{visible}$ of windows	35	75				**2**
external obstructions	no obstruction	obstruction 30^o	obstruction 30^o	obstruction 60^o		**4**
climates centers	Daytona Beach, FL	Los Angeles, CA	New York, NY	Vancouver, BC	Winnipeg, MB	**5**

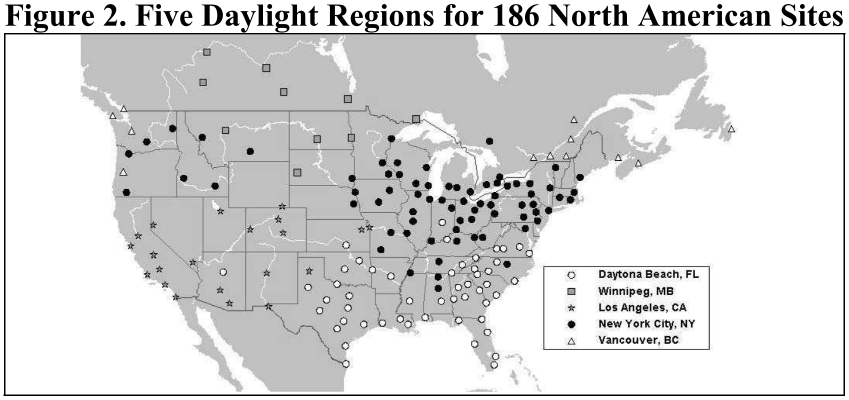
Simulation Results

Daylighting Regions for North America

The parameter study was carried out in two phases. In the first phase daylight autonomy distributions were calculated for 25 Canadian and 161 US-American Standard Metropolitan Areas. These 186 sites represent 62.5% of the Canadian and 74% of the US-American population. Hourly mean direct and diffuse irradiances were taken from the Environment Canada database CWEEDS (Environment Canada 1992) and the US database SAMSON (NCDC 1996) for the year 1990. The investigated office geometries correspond to the reference geometry with four different facade orientations, two glazing transmittances and with and without interior partitions. The resulting daylight autonomy distributions were clustered in five groups with comparable daylighting potential using the clustering approach suggested by Andersson, Carroll and Martin (Andersson, Carroll & Martin 1986). The approach uses the concept of a *climatic distance,* D, between two sites to identify regions of similar daylight potential. D was defined as the generalized Euclidean square root of the sum of the squared differences of the daylight autonomies for two sites. Based on this measure, the clustering of the 186 sites into *n* regions becomes an optimization problem which aims at finding the partition that minimizes the sum of the climatic distances of all sites from their pertaining climatic center [Späth 1980]. A *population-weighted climatic center* was chosen to represent each cluster. The idea behind weighing different sites within a daylighting region according to their population was to concentrate the further-going analysis on the most densely populated area within a region.

Clustering results. The 186 sites were clustered into 5 regions (Figure 2). This somewhat arbitrary number of clusters has been found to reflect the climatic diversities within North America without being too large to be handled in the second simulation phase. The population-weighted climatic centers of the five daylight regions are Daytona Beach FL, Los Angeles CA, New York City NY, Winnipeg MB and Vancouver BC.

Figure 2. Five Daylight Regions for 186 North American Sites



The regions are a result of clustering daylight autonomy distributions for 16 office geometries for each of these regions.

Reference Geometry

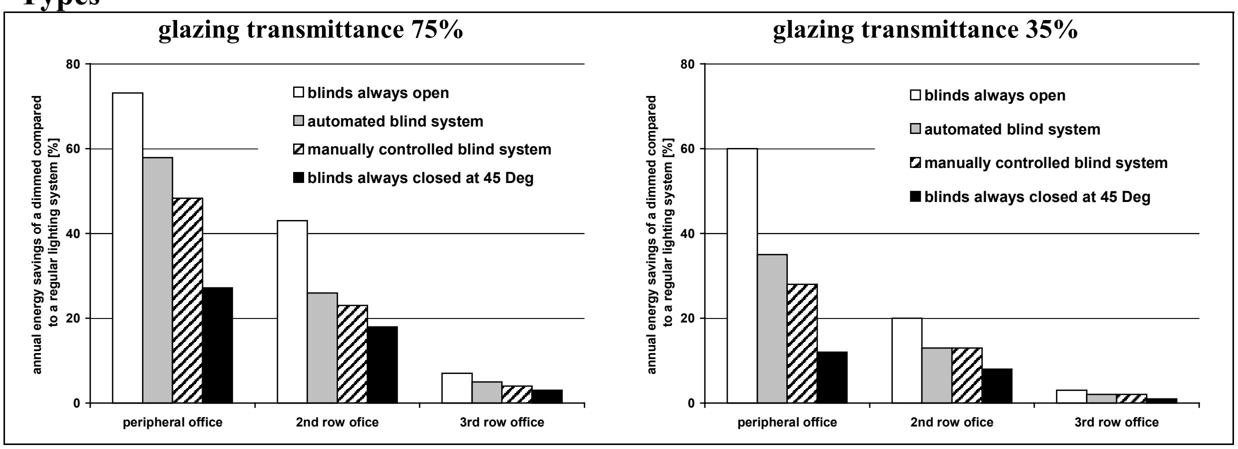
In the second phase of the parameter study daylight simulations were carried out for the above described office geometries and the five climatic centers. In this section the daylight situation in the reference office is described for different facade orientations, glazing types, blind control strategies, orientations, external obstructions and climate regions.

Figure 3 shows lighting energy savings of a dimmed compared to a regular lighting system for the reference office with a southern facade located in New York City (NYC). Four blind control strategies and two glazing types are considered. The figure reveals a significant impact of the blind usage with savings in the peripheral office ranging from 27% for *always closed* to 73% for *always opened*. Real energy savings probably lie somewhere between the *automated* and the *always closed* scenario. Changing from a high to a low transmittance glazing reduces energy savings by about 20 percentage points for the peripheral office. Care has to be taken that such energy savings on the electric lighting side are not compromised by additional cooling loads. Therefore, an "adequate" blind control strategy has to be chosen[6].

The figure suggests that a dimmed lighting systems can yield substantial energy savings for peripheral work places in an open plan office. Energy savings in 2nd row offices are more moderate and therefore harder to economically justify with today's dimming controls. On the other hand, as sensors are expected to become cheaper, better integrated and easier to commission, dimming the lighting in 2nd row offices might become a viable design option in the near future. No considerable savings can be recuperated for 3rd row offices.

An analysis of the daylight autonomy distribution in the reference office with a high transmittance glazing showed that while the peripheral office boosts values between 70% and 85% for manual and automated blind control, the daylight autonomy vanishes for internal work stations. Therefore, an automated on/off switch would only yield any savings in peripheral offices.

Figure 3. Electric Lighting Energy Savings for the Reference Office with a Southern Orientation Situated in NYC for Various Blind Control Strategies and Two Glazing Types

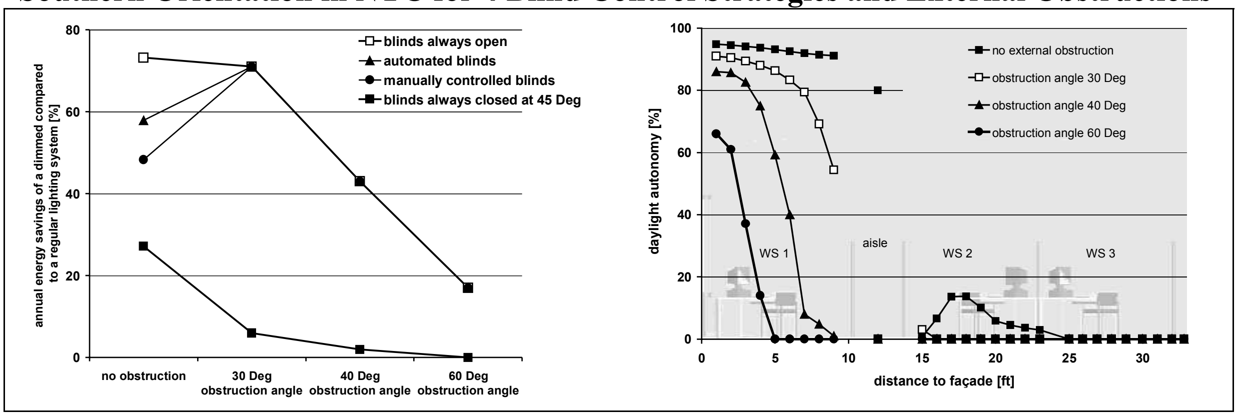


External Obstruction. The shading situation due to surrounding buildings and landscape can seriously reduce the available daylight especially in densely populated metropolitan areas. Figure 4 presents energy savings and daylight autonomies for the reference geometry in NYC with a southern facade for three different obstruction angles. The obstruction angle is here defined as the smallest angle with the horizontal under which the sky can be seen from the lower edge of a window. An obstruction angle of 30^o describes the shading situation of an office that is bordering an urban canyon (40% reflectance) formed by buildings that are about 4 stories higher than the considered office. Figure 4 shows that energy savings of *automated*, *manual* and *always open* are identical for non vanishing obstructions angles, as direct sunlight never hits the facade. For a 30^o obstruction angle the obstructing building actually

[6] "Adequacy" depends on the considered climate. In a cooling dominated climate automated blinds effectively avoid unwanted solar gains even during user absence. In a more temperate climate the urgency to avoid solar gains can be less pressing and does not always justify the investment in an automated blind system.

seems to act as a more efficient shading device than the blinds. These results have to be treated with care as the blind model does not consider privacy issues which might motivate the closing of the blinds in such a dense urban setting. If the blinds are *always closed*, this has a devastating effect on the expected energy savings. The daylight autonomy distribution shows that rising obstruction angles lead to an increasingly narrow strip of daylight near the facade, i.e. a less and less uniform distribution of daylight throughout the space.

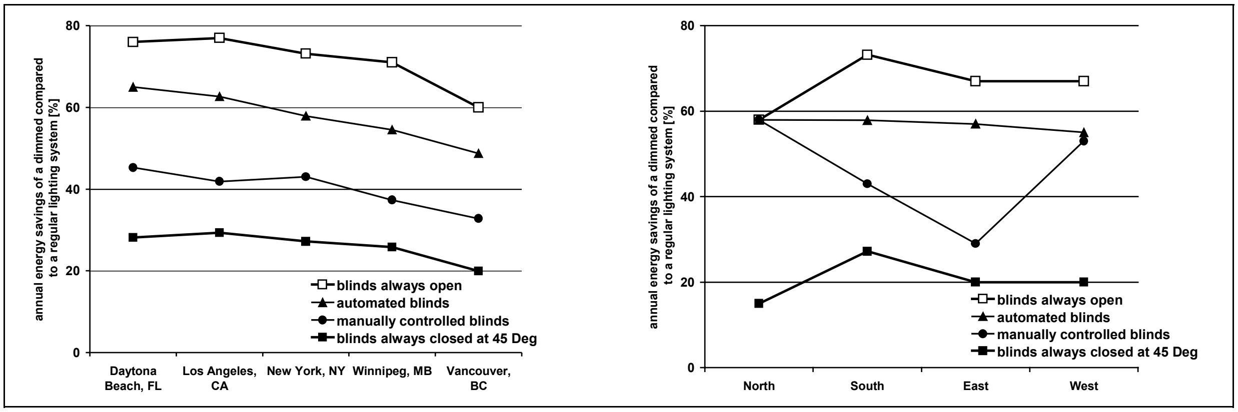
Figure 4. Electric Lighting Energy Savings for a Peripheral Reference Office with a Southern Orientation in NYC for 4 Blind Control Strategies and External Obstructions



Building site. Figure 5 (left) shows energy savings for the reference geometry with a southern facade orientation for the five climatic centers that have been identified above. Energy savings are falling with rising latitude and total annual solar radiation. An analysis of the monthly energy savings for the five sites showed that most differences appear in the winter months due to shorter day lengths in the North. In particular, the Vancouver region is characterized by dark overcasts winter skies. The savings vary by 16 percentage points for blinds *always open* to 8 percentage points for *always closed*, revealing that the blinds moderate the difference between sites by excluding direct sunlight from the interior.

Facade orientation. The right diagram in Figure 5 illustrates the influence of facade orientation on energy savings. The figure demonstrates a strong dependence of these savings on the underlying blind control. If the blinds are permanently retracted, a northern facade has the lowest energy savings due to the absence of direct sunlight. On the other hand, as an automated system excludes direct sunlight, it yields very similar savings for all facade orientations. As hardly any direct sunlight is ever incident on a northern facade, *automated* and *manual* are nearly identical for this orientation. *Manual blind control* predicts considerably higher energy savings for a northern and western than for a southern or eastern facade. These results are due to the re-opening mechanism of the model that is only triggered upon arrival in the morning. As past field studies tended to concentrate on southern and southwestern facades, further work will be necessary to generalize the manual blind control model to for eastern and northern facades.

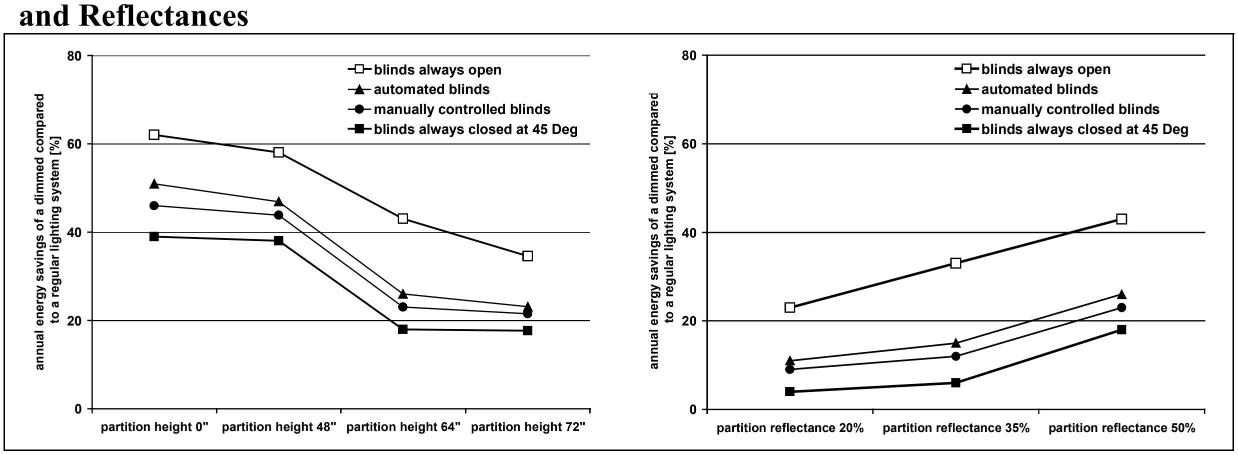
Figure 5. Electric Lighting Energy Savings for a Peripheral Reference Office with a South Orientation Situated in NYC for 4 Blind Control Strategies and Facade Orientations



Interior Design Variables

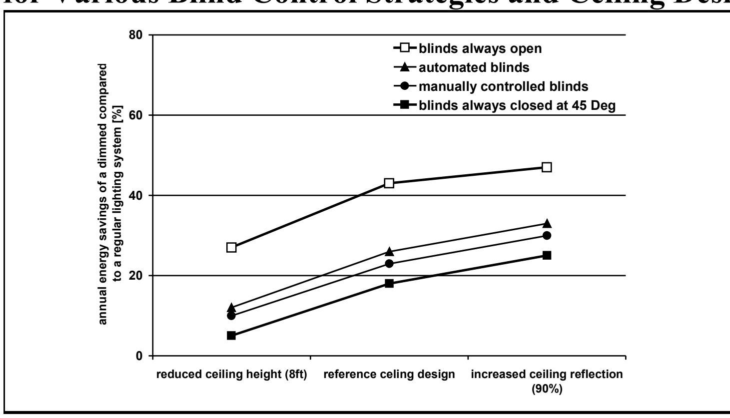
Partition design. The impact of interior design variables on energy savings due to daylight is larger in interior than in peripheral work spaces. Accordingly, Figure 6 presents energy savings for a 2nd row office for various partition heights (left) and reflectances (right). Lowering partition heights from 64" (reference geometry) to 48" nearly doubles energy savings for the automated and manually controlled blind scenario. Another benefit of reduced partition heights between peripheral and 2nd row offices is the latter get some of the amenities of the former, i.e. a partial view outside. On the other hand, lower partitions reduce the acoustical separation between two work spaces. A smart design option might be to group work places that require intense communication between co-workers in peripheral and 2nd row offices and reserve inner spaces with higher partitions for more noise sensitive tasks. Reducing partition reflectance seriously reduces the amount of daylight at 2nd row offices and should be avoided if daylighting is desired.

Figure 6. Electric Lighting Energy Savings for a 2nd Row Office with a South Orientation Situated in NYC for Various Blind Control Strategies, Partitions Heights and Reflectances



Ceiling design. The ceiling is a crucial design element for daylighting as the majority of daylight that penetrates into a building beyond the 1st work station is reflected from the ceiling at least once. Figure 7 depicts energy savings in a 2nd row office in NYC City for a ceiling with a reduced height of 8ft and a high reflectance ceiling. Reducing the ceiling height from 9ft to 8ft cuts the energy savings in half. On the other hand, increasing the ceiling reflectivity has a positive effect on energy savings and leads to a more uniform distribution of daylight throughout the space. As enhancing the ceiling reflectivity is a low-cost design measures, it can be highly recommended. The danger of reflective glare caused by glossy ceilings will probably disappear with the foreseeable shift from conventional monitors to flat screens.

Figure 7. Electric Lighting Energy Savings for a 2nd Row Office with a South Orientation Situated in NYC for Various Blind Control Strategies and Ceiling Designs



Work station sizes. This section briefly discusses the effect of reducing the individual work station size in an open plan office from 10ft x 10ft. For peripheral offices this has basically no effect on the daylight autonomy and energy savings. For 2nd row offices the effect could in principal be positive, as the work places move closer to the facade and therefore receive more daylight. On the other hand, in such a densely populated office it is possible that the blinds will be permanently lowered because nobody perceives ownership over them and because the number of individuals that might experience glare rises.

Discussion and Conclusion

To the author's knowledge, this study presents the first systematic application of dynamic daylight simulations in standard, non-daylight optimized open plan offices which are the focus of the COPE project. The predicted electric lighting energy savings describe the effect of replacing an ideally commissioned, dimmed lighting system with a regular lighting system for different interior design settings. These energy savings could be further enhanced by also optimizing the facade for daylighting, e.g. through light shelves, split blinds etc.. Such design option have not been investigated since COPE concentrates on interior design refurbishments.

Navvab and Siminovitch investigated the effect of internal partitions on the daylight factor using scale models and Superlite simulations and concluded that “ceiling and partition surface properties and their positions greatly affect the lighting conditions of a space” and that “the shading control system should be fully integrated into an open plan office design” (Navvab & Siminovitch 1987). While the present study agrees on the physical size of daylight factors for interior offices that have been reported by Navvab and Siminovitch, it extends their analysis by using indices which are based on *annual* daylight simulations. Vartiainen also simulated daylight autonomies in peripheral offices of varying orientation, building site and facade design using the DeLight simulation tool (Vartiainen 2000). To model blinds Vartiainen excluded all direct sunlight and scaled down diffuse daylight with a constant factor. Where applicable Vartiainen's results are in agreement with the conclusions of this study:

Which Design Parameters Influence the Daylight Situation in a Typical Open Plan Office?

1. Electric lighting energy savings for a dimmed lighting system in an open plan office decisively depend on the underlying blind control strategy. For automated or manually controlled blinds savings lie around 50% to 60% for a peripheral office with a southern orientation in NYC. For various sites in North America these values vary by ±8 percentage points. While the facade orientation has a minor impact for the automated blind control, savings for manually controlled blinds vary dramatically and predictions are less reliable. If thermal and lighting usage were considered simultaneously, an automated blind control system might yield even more energy savings over a manually controlled system.
2. Electric lighting energy savings in 2^{nd} row offices are usually modest even though they can be doubled by various interior design measures like reducing the partition height to 48" and increasing the ceiling reflectance. If daylighting a 2^{nd} row office is desired, the facade necessarily needs to feature a high transmittance glazing.
3. External obstructions up to an obstruction angle of 30^o do not seem to seriously impede the daylight availability in an office as the neighboring buildings act as static shading devices. On the other hand, this seemingly positive effect might be compromised by privacy issues in a dense urban setting which lead to regularly lowered blinds.

How Relevant are these Results for Existing Open Plan Offices?

The field studies from the COPE project were carried out in three standard, deep-plan North American office buildings. An analysis of the work place arrangement in these buildings showed that between 40% and 60% of open plan work places were peripheral or 2^{nd} row, i.e. could benefit from daylight. While a sample of three buildings is clearly too low to draw any general conclusions, this finding at least hints a significant energy saving potential of dimmed lighting systems in open plan offices.

Acknowledgement

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