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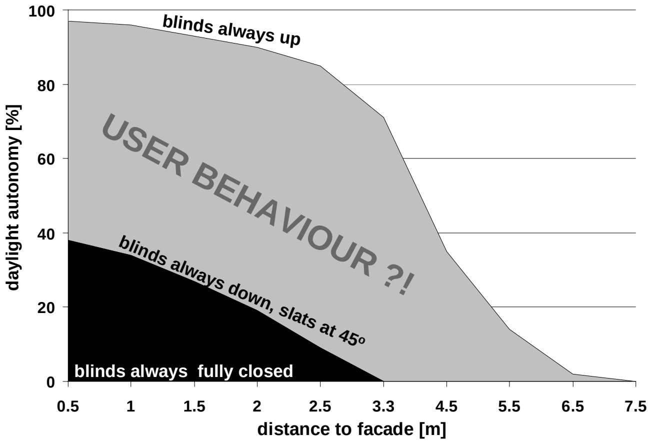

The Annual Daylight Availability in peripheral Offices in Canada – a Simulation Study

1st out of 4 reports for the project:

Towards Realistic Daylighting Energy Savings in Office Buildings

Submitted to:

Francois Dubrous
The Buildings Group – CANMET Energy Technology Centre
Natural Resources Canada, Ottawa, Ont., K1A 0E4, Canada

Submitted by:

Dr. Christoph F. Reinhart
The Lighting Group – Institute for Research in Construction
National Research Council Canada, Ottawa, Ont., K1A 0R6, Canada

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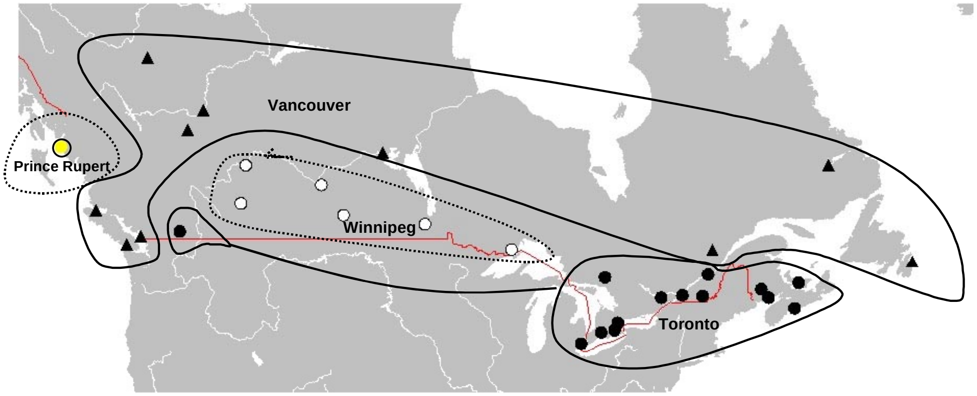
The Annual Daylight Availability in peripheral offices in Canada – a Simulation Study

Executive Summary

This report is the first out of a series of four within the project *Towards Realistic Daylighting Energy Savings in Office Buildings.* The objective of the report is to quantify and analyze the amount of daylight that is available in peripheral offices in Canada assuming that the blinds are kept in the same position throughout the year. Occupant behavior is still neglected at this point in the project.

An extensive simulation study of the *daylight autonomy distribution* in offices of varying building location, external shading situation, facade orientation, glazing type and occupancy schedule has been carried for 31 Canadian weather stations. All simulations were carried out with the dynamic daylight simulation method DAYSIM which uses the RADIANCE raytracing algorithm. The daylight autonomy is a new measure of the annual daylight availability in a space. It is defined as the percentage of the working year that a minimum illuminance threshold at a work place of 500 lx (as measured on the work plane) can be maintained by daylight alone. The charm of this performance parameter is that it simultaneously considers building design *and* user occupancy. The selected stations cover all of Canada's 25 Census Metropolitan Areas which house 62.5% of the Canadian population. The sites have been clustered into zones of similar daylighting potential. The population-weighted, climatic centers of these zones are Winnipeg MB, Toronto ON, Vancouver BC and Prince Rupert BC.

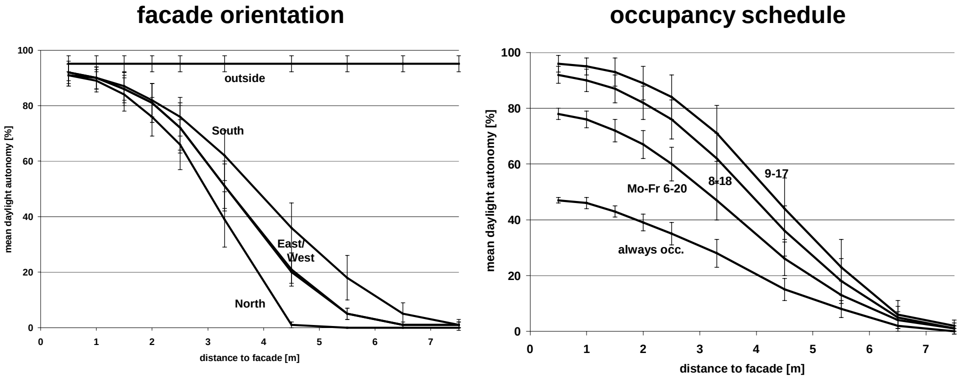
four Canadian daylighting zones



In the absence of blinds the daylight autonomy at a work place in the *Winnipeg*-zone can be more than 20 percentage points higher than at an identical work place in the *Vancouver*-zone. Assuming an occupancy schedule of weekdays 8 AM to 6pm (i.e., 10 hours per day), an increase of the daylight autonomy of 10 percentage points translates into one extra hour per day of interior daylight levels over 500lx.

Simulation results further yield that the geographical location, surrounding objects, facade orientation and glazing type all influence the interior daylight autonomy distribution in the critical range between 1 and 5m away from the facade. This range marks where work places in peripheral offices are usually situated.

The facade orientation determines how deep daylight can penetrate into the building. An office facing South has a higher daylighting autonomy distribution than a Western/Eastern or Northern office if the blinds are permanently retracted. In contrast to this, changing the occupancy schedule of an office introduces a constant scaling factor to the interior daylight autonomy distribution without affecting its overall shape.

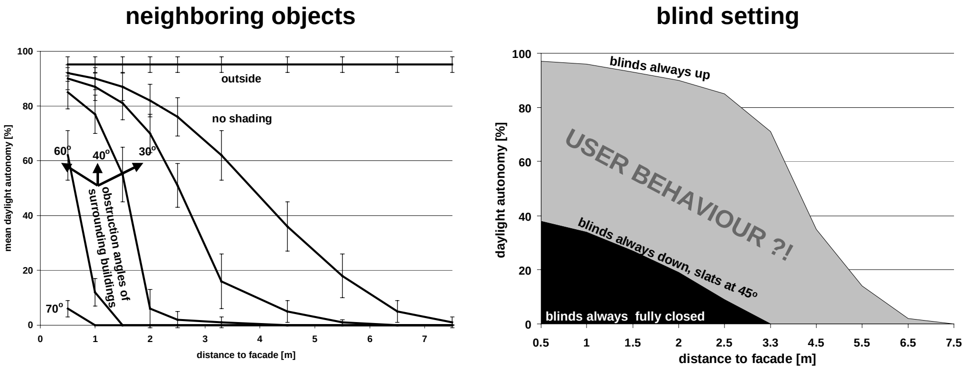

facade orientation

occupancy schedule

mean daylight autonomy distribution for 31 Canadian locations for varying facade orientation and user occupancy

Shading due to surrounding objects can seriously reduce the daylit area in an office, especially if the considered office building and the opposing facade form an “urban canyon” that only admits light from the near zenith region of the celestial hemisphere. The effect is smaller if the office building is a low rise.

The setting of the blinds ultimately determines the amount of daylight in an office. Having the blinds permanently retracted defines a physical upper limit of the daylight availability, but is unrealistic for most offices due to glare considerations and overheating. On the other hand, fully lowering the blinds and closing the slats leads to the absence of any daylight in a space. Lowered blinds with a slat angle of 45° exclude all direct sunlight while admitting diffuse daylight. This blind setting provides a more realistic lower limit of the amount of daylight in a space even though the *true* daylight availability depends on the actual user behavior, i.e. how individuals operate their blinds.


neighboring objects

blind setting

mean daylight autonomy distribution for 31 Canadian locations for varying external shading situations and blind settings

Future simulations will combine the results from this report with user occupancy profiles and behavioral switching patterns in order to yield more realistic predictions of the temporary status of manually operated blinds.

Table of Contents

1 Introduction

background

Daylighting is the immediate exploitation of solar energy in buildings. It summarizes all building design measures which strive to optimize the availability of *glare-free* natural daylight in a building's interior in order to create spaces of high visual quality and/or to reduce the energy demand for artificial lighting and cooling. Daylighting is of particular interest to commercial buildings in which the times of daylight availability and building occupation largely overlap.

To include daylighting credits in building codes and regulations it is important to ensure that savings can be guaranteed. Field studies reveal that anticipated energy savings due to daylight tend to be overoptimistic. One reason for unrealistic expectations is that daylight evaluation methods usually assume that the shading device is retracted throughout the year, i.e. they fail to acknowledge how occupants manage their venetian blinds.

This report is the first out of a series of four within the project *Towards Realistic Daylighting Energy Savings in Office Buildings* that has been initiated by Natural Resources Canada and the National Research Council*.* The goals of the project are to

- establish a realistic *baseline* of the actual daylight availability in buildings, a baseline which incorporates occupant behavior and to
- explore the benefits of typical energy saving design measures compared to this baseline.

objectives of this study

The objective of this first report is to quantify and analyze the amount of daylight that is available in peripheral offices in Canada assuming that the blinds are kept in the same position throughout the year. Occupant behavior is still neglected at this point in the project. Instead, the following three static settings of an interior venetian blind system are considered:

(a) blinds are permanently retracted

(b) blinds are permanently lowered with a slat angle of 45^o

(c) blinds are permanently lowered with the slats fully closed

For these scenarios the daylight autonomy distribution has been simulated in sidelit offices with varying geographical locations, shading situations due to surrounding objects, facade orientations, glazing types and user occupancy profiles. The daylight autonomy is a new measure of the annual daylight availability in a space. It is defined as the percentage of the working year that a minimum illuminance threshold at a work place of 500lx (as measured on the work plane) can be maintained by daylight alone. The results for scenarios (a) and (c) define the physical upper and lower limits of the annual daylight availability in a given office whereas (b) provides a more realistic lower limit.

Future simulations will link the results from this report with user occupancy profiles and behavioral control patterns in order to yield more realistic predictions of the temporary status of manually operated blinds, i.e. a *baseline* of the actual daylight availability in buildings.

The following questions have been addressed:

(1) What are the necessary “physical boundary conditions” for good daylighting in a peripheral office, i.e. what combinations of building location, height of surrounding objects, facade orientation and glazing type yield non-vanishing interior daylight autonomies?

(2) How does the occupancy schedule influence a building's daylighting potential?

overview of the report

The utilized daylight simulation method, investigated building geometries, user occupancy profiles and radiation data sets are described in Chapter 2. Chapter 3 presents and analyzes the simulation results. Questions (1) and (2) are discussed in Chapter 4.

2 Methodology

An extensive simulation study has been carried out to quantify the annual daylight availability in sidelit, perimeter offices in Canada. The use of daylighting through skylights has not been investigated in this study[1].

An important difference between daylight and electric lighting is that the former is highly dynamic. To account for the daily and seasonal dynamics of daylight, the RADIANCE-based simulation method DAYSIM has been chosen as it can calculate indoor illuminances and luminances under all appearing sky conditions throughout a year. The method is briefly described in section 2.1. Ambient daylight conditions were simulated based on irradiance data from 31 Canadian weather stations as explained in section 2.2. The investigated buildings and user occupancy schedules are presented in sections 2.3 and 2.4. The utilized daylight performance metric – the *daylight autonomy* – is discussed in 2.5. A clustering algorithm has been used to group geographical locations of comparable daylighting potential into daylighting zones. The algorithm is shortly described in section 2.6.

2.1 Annual Daylight Simulations

The daylight simulation method DAYSIM can reliably and efficiently model indoor illuminance distributions in complex building geometries under arbitrary sky conditions. It uses the calculation algorithm of the backward-raytracer RADIANCE (Ward G & Rubinstein F, 1988) combined with a daylight coefficient approach (Reinhart C F & Herkel S, 2000). The underlying sky model to predict sky luminous efficacies and sky luminous distributions from widely available irradiance data is the Perez sky model (Perez R, Ineichen P, Seals R et al., 1990; Perez R, Seals R, & Michalsky J, 1993). DAYSIM simulation results have been validated for a range of sky conditions and advanced building geometries including venetian blinds (Reinhart C F & Walkenhorst O, 2001). Fig. 2-1 sketches the input data required to carry out a daylight simulation.

All simulations in this study were carried out on the CRAY/SGI Origin 2000/108 of the Steacie Institute for Molecular Sciences of the National Research Council of Canada. To maintain comparability between the different simulations the same set of RADIANCE simulation parameters has been used throughout the whole study. These parameters are listed below (Table 2-1).

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[1] The necessary skylight simulation tools -e.g. (Laouadi A & Atif M , 2000)- have not been sufficiently validated as of yet.

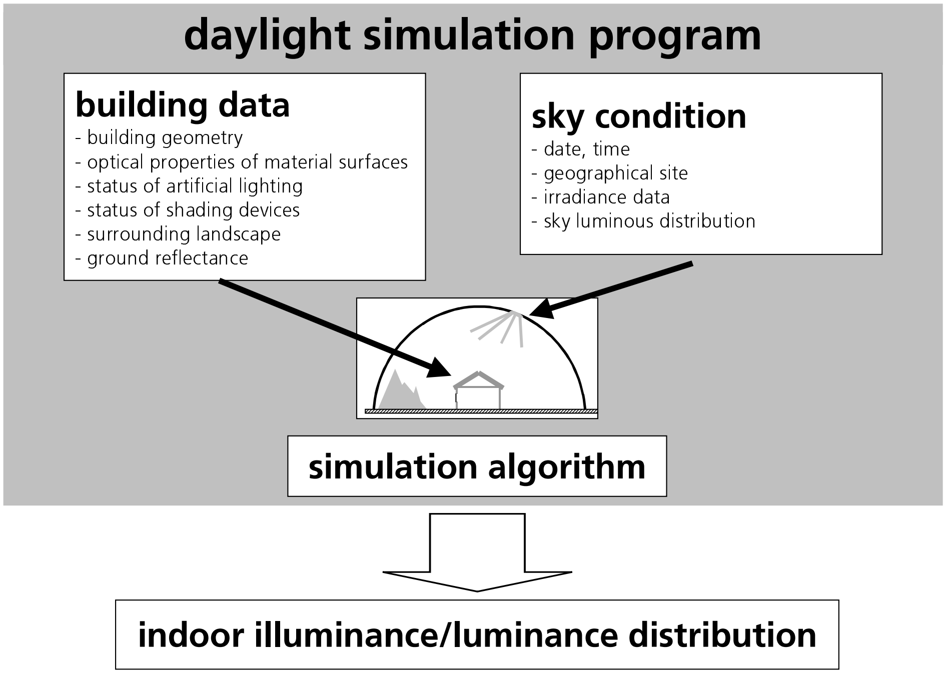

Fig. 2-1: A daylight simulation tool requires information on the building and the prevailing sky conditions to calculate indoor illuminance or luminance distributions.

Table 2-1: Utilized RADIANCE simulation parameters (only non-default values are listed).

ambient calculation	ambient bounces	ambient division	ambient sampling	ambient accuracy	ambient resolution
	7	1500	100	0.1	400
direct calculation	specular threshold	limit reflection	direct threshold	direct sub-sampling	
	0.2	9	0	0	

2.2 Irradiance Data

Hourly mean direct and diffuse irradiances from 31 Canadian weather stations have been taken from the Environment Canada database CWEEDS (Environment Canada, 1996) for the year 1990. The data set contains long term records for a number of Canadian locations of hourly weather observations specifically designed for use in building energy calculations. The selected weather stations cover all of Canada’s 25 Census Metropolitan Areas (CMA) which house 62.5%[2] of the Canadian population (Statistics Canada, 2001). The additional sites have been selected based on their population and geographical distance from any CMA. The geographical distribution of all stations is shown in Fig 2-2. Details of all sites are provided in Appendix A.

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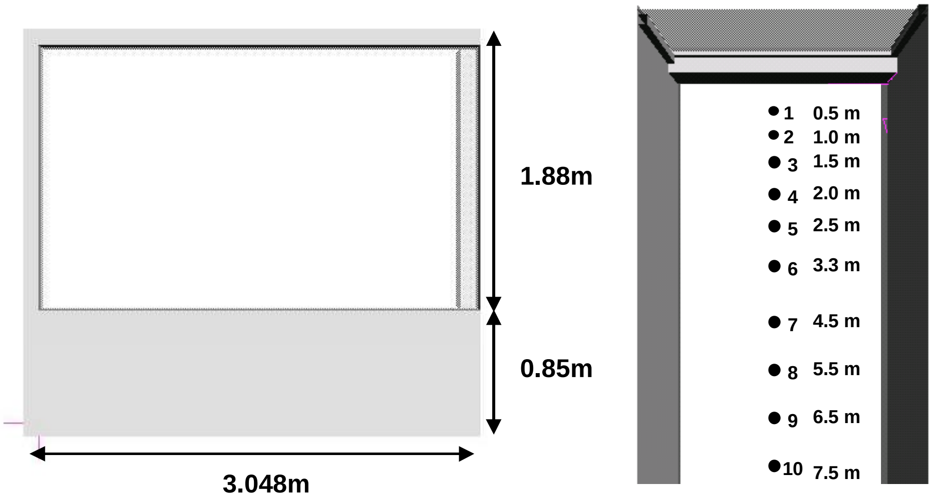
[2] Statistics Canada 2001: “On July 1, 2000, 62.5 % of the population of Canada, or nearly 19.3 million people, resided in one of the 25 census metropolitan areas (CMAs). One third were concentrated in the three main CMAs: Toronto (4.8 million), Montreal (3.5 million) and Vancouver (2.0 million)."

Fig. 2-2: Geographical distribution of the investigated Canadian locations.

2.3 Building Description

2.3.1 Building Geometry

A standard rectangular peripheral office space has been chosen as the basic room geometry. The facade has been endowed with a large glazing of varying visual transmittance (Fig. 2-3(a)) and the facade orientation has been varied in all four principal sky directions. Corner offices have not been explicitly addressed in this study. The daylight situation in a corner office can be approximated by choosing the higher of the two corresponding facade orientations. Figure 2-3 shows a view of the facade and a floor plan of the peripheral office. A depicted sensor positions are located at work plane height (0.85 cm) facing upwards. Table 2-2 provides further details.



(a) (b)

Fig. 2-3: Facade view (a) and floor plan (b) of the peripheral office geometry.

Table 2–2: Details of the peripheral office.

Variable	Size	Variable	Size
office width	10ft	$\tau_{visible}$ of windows	35 % to 75%
office depth[3]	30ft	window width	equals room width
office height	9ft	window height	0.75m above floor to ceiling
ceiling reflectance	80%	window frame width	10cm
wall reflectance	50%	facade orientation	4 principal sky directions
floor reflectance	20%	height of neighboring buildings	variable (see 2.3.2)
wall reflectance	50%	reflectance of neighboring buildings	40% (Ng E, 2001)
floor reflectance	20%	external ground reflection	20%
daylight savings time	April 1st to October 31st		

2.3.2 Shading Situation due to Surrounding Objects

The amount of daylight at a work place is significantly influenced by surrounding objects like landscape and other buildings. Several obstruction angles have been considered for different facade orientations. As shown in Fig. 2-4 and 2-5, an obstruction angle for an office is defined as the smallest altitude at which the celestial hemisphere can be seen from the center of the facade of the office. Surrounding objects were modeled by three polygons as shown in Fig. 2.5.

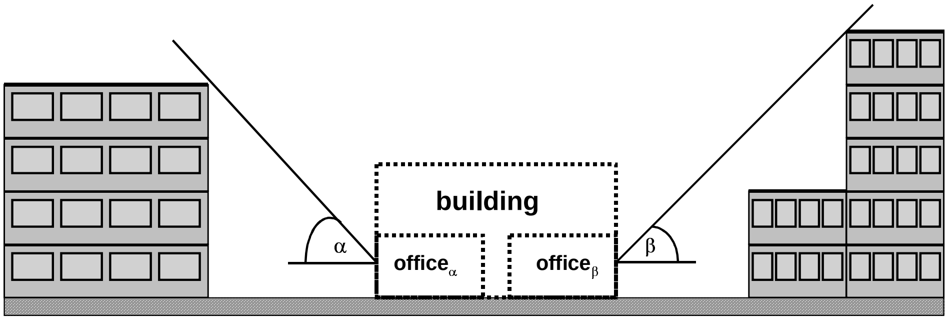


Fig 2-4: Each facade of a building has a different obstruction angle which is defined by surrounding landscape and buildings.

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[3] The large office depth of 30ft has been chosen to determine how deep daylight can penetrate into the building. Simulation results for an office of smaller depth would yield similar values within the confinement of the reduced space.

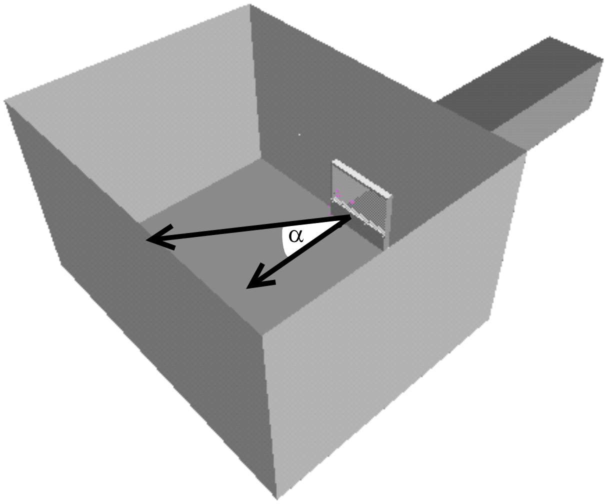


Fig 2-5: RADIANCE-scene of the obstruction scenario 40°. An urban canyon formed by two opposing high rises (see Table 2-3).

The following obstruction angels have been considered:

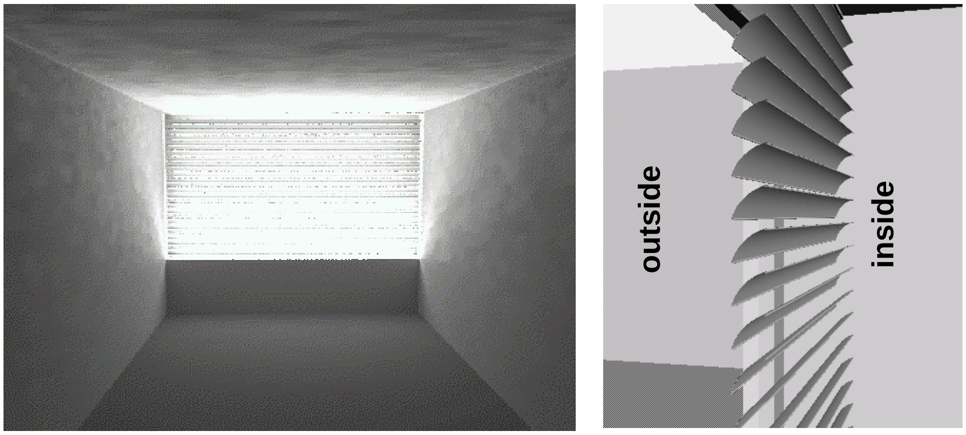
Table 2–3: Investigated obstruction angles.

obstruction scenario	**description**
0°	no external obstructions
30°	This obstruction scenario corresponds to an office in a *single story* building which is shaded by a 4 story building (building height 13.5m) on the other side of a 20m wide street.
40°	This obstruction scenario corresponds to an office bordering an urban canyon. The office is located on the first floor of a *5 story* office building (building height 16.8m) which is facing another 5 story building on the other side of a 20m wide street.
60°	This obstruction scenario corresponds to an office bordering an urban canyon. The office is located on the first floor of a *10 story* office building (building height 36.5m) which is facing another 10 story building on the other side of a 20m wide street.
70°	This obstruction scenario corresponds to an office bordering an urban canyon. The office is located on the first floor of a *17 story* office building (building height 56.8m) which is facing another 17 story building on the other side of a 20m wide street. This very high obstruction angle corresponds to the maximum building density that is allowed for residential buildings in Hong Kong (Ng E, 2001)

2.3.3 Venetian Blinds

An internal venetian blind system has been chosen as a shading device that is commonly found throughout North America. The diffuse reflectance of the slats was modeled to be 52% with a specularity of 15% (Ward G & Shakespeare R, 1998). The blinds were modeled and simulated in RADIANCE with the same set of simulation parameters as in the DAYSIM validation study (Reinhart C F & Walkenhorst O, 2001) (Fig.2-6).

The blinds were modeled either fully retracted or fully lowered with a slat angle of 45^o tilted downwards (Fig. 2-6(b)). A third scenario with the blinds down and the slat angle fully closed has not been explicitly simulated as such a setting ideally leads to the absence of any daylight in a space. The blind setting with the slats tilted downwards by 45^o has been chosen as a more realistic lower limit of the available daylight, as all direct sunlight is blocked in this setting whereas unobtrusive diffuse daylight can still enter the office.



(a) (b)

Fig. 2-6: RADIANCE simulation of the blinds down and a slat angle of 45^o (a) and detail of the blind model (b).

2.4 Occupancy Schedules

The daylighting potential of a building strongly depends on the occupancy schedule of the users. The following occupancy schedules have been considered.

Table 2–4: Occupancy schedules.

schedule	description
weekdays from 9 AM to 5 PM	common office working hours
weekdays from 8 AM to 6 PM	common office working hours including one hour arrival and one hour departure time
weekdays from 6 AM to 8 PM	hours of occupancy for an open space office with different occupants arriving early or leaving late
always occupied	this occupancy schedule is more relevant in hospitals or production sites than in offices

2.5 Daylight Autonomy

Annual daylight simulations yield indoor illuminance distributions for each hour of the year. This large amount of data needs to be further processed to yield a measure of the daylight performance of a given work place in a building. The Canadian Labor Codes (CLC Canadian Labor Code , 1991) states that for task positions in offices where “continuous reading or writing is performed” the minimum illuminance shall not be less than 500lx". Based on these legal requirements, the *daylight autonomy* at a sensor point is defined as the percentage of the working year when the illuminance due to daylight lies above 500lx, i.e. when office work at this point could principally be carried out by daylight alone.

The charm of the daylight autonomy as a performance parameter is that it takes facade orientation and user occupancy profiles into account and considers all possible sky conditions throughout the year. It is therefore a holistic approach to describe the annual daylight availability at a work place. While the daylight autonomy neglects lighting quality aspects, it is a suitable performance metric to resolve when and where daylight is principally available to replace artificial lighting.

Dimmed electric lighting system can save energy at work place without full daylight autonomy, i.e. with interior daylight illuminances below 500lx. This saving potential will be considered in future reports.

2.6 Clustering Algorithm

A clustering algorithm has been used to group the 31 Canadian weather stations into regions of similar daylighting potential. The usefulness of aggregating highly populated centers into groups with comparable climatic conditions has originally been identified and addressed by Andersson, Carroll and Martin at Lawrence Berkeley National Laboratory (Andersson B , Carroll W K, & Martin M R, 1986). The researchers used 125 US-based standard metropolitan areas and grouped them according to their pertaining heating and cooling degree days, clearness indices (a measure of solar radiation) and latent enthalpy hours. In this study indoor daylight autonomy distributions were used instead to characterize the daylighting potential of a given site. The utilized clustering algorithm consists of 4 steps:

- definition of the *climatic distance* and the *climatic center*
- *ad hoc* construction of clusters
- repartitioning using an optimization algorithm
- identification of *population-weighted climatic centers*

<u>(1) definition of the climatic distance and center:</u> to identify regions of similar daylight potential based on the simulated daylight autonomy distributions it is necessary to define a measure to describe "similarity" between different sites. A useful measure which has been proposed by Andersson *et al.* is the so-called *climatic distance*, D, between two sites,

which is a generalized Euclidean square root of the sum of the weighted squares:

$$D_{1,2} = \sqrt{\sum\nolimits_{i=\text{orientation,geometry}} a_i^2 \left(DA_{i,1} - DA_{i,2}\right)^2} \qquad \text{equ. 2-1}$$

where a_i = normalization factor for variable i and
$DA_{i,j}$ = i^{th} daylight autonomy of the j^{th} site

In this application all normalization factors, a_i, have been set to unity as only one physical quantity, i.e. daylight autonomies, has been considered. The climatic variables $DA_{i,j}$ correspond to the daylight autonomies for the j^{th} site at different orientations, distances to the facade and for different office geometries.

Another useful definition by Andersson *et al*. is the *climatic center* of a region. The *climatic center* is defined as the mean of the climatic variables of the members of a region. It resembles a “center of gravity” for the region.

Based on these two definitions, the clustering of the 31 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, i.e.:

$$\text{MIN}\left|\sum\nolimits_{j=31\,\text{stations}} \sum\nolimits_{i=\text{orientation,geometry}} \left(X_{i,j} - DA_{i,j}\right)^2\right|_{\text{all possible partitions}} \qquad \text{equ. 2-2}$$

where $X_{i,\,j}$ i^{th} daylight autonomy variable of the climatic center of the j^{th} site.

This optimization problem has been solved in two steps according to an algorithm described by Späth (Späth H, 1980).

<u>(2) *ad hoc* construction of clusters:</u> in a first step the 31 stations are grouped into *n* clusters. This grouping is carried out *ad hoc* by the `joiner`– algorithm by Späth (Späth H, 1980), i.e. it does generally not even locally satisfy the minimum requirement from equation 2-2.

<u>(3) repartitioning with an optimization algorithm:</u> in the second calculation step the `kmeans`–algorithm by Späth is used to ensure that equation 2-2 is at least locally satisfied. Starting from a given partition each site is in turn transferred experimentally from its cluster to all other clusters. If this results in a reduced sum in equation 2-2, the station is permanently moved into the different cluster. The algorithm maintains the original number of clusters.

<u>(4) identification of the *population-weighted climatic centers*:</u> once the clustering has been finished, a representative member of each climatic region is identified. In accordance with Andersson a *population-weighted climatic center* is chosen. The idea behind weighing different sites within a class according to their population is to concentrate the further-going analysis on the densely populated sites within a region.

3 Results and Analysis

In this chapter, daylight autonomy distributions of the above described office settings are compared and analyzed. Section 3.1 provides an overview of the annual amount of daylight available at an unshaded outside point. In sections 3.2 and 3.3 daylight autonomy distributions in peripheral offices with and without blinds are presented. Four Canadian daylighting zones are identifies in section 3.4.

3.1 Exterior Daylight Conditions

The daylight availability at an outside point provides a theoretical upper limit of how much daylight can be harvested in a building. Fig. 3-1 compares annual direct and diffuse horizontal solar irradiances of the considered 31 weather stations for 1990. The sites are ordered according to their geographical longitudes starting at Prince Rupert, BC, (130W) and moving East to St. John’s, NF (53W). The figure reveals that 44% to 66% of the total solar radiation at these locations stem from diffuse daylight with an average of 52%. The amount of solar radiation is lowest at the coasts and highest in the Prairies.

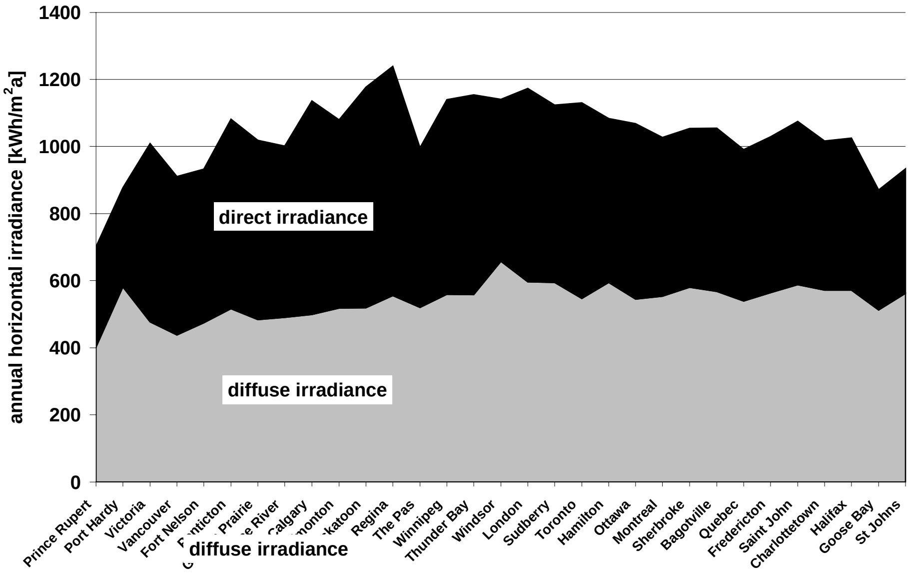


Fig.3-1: Annual horizontal irradiances for an unshaded horizontal point for different Canadian locations.

Fig. 3-2 shows how the annual solar radiations from Fig. 3-1 translate into annual daylight autonomies for an unshaded exterior point for different building occupancy profiles and a minimum threshold of 500lx. A brief analysis showed that varying the threshold from 150lx to 1500lx changes the values in Fig. 3-2 by less that 2 percentage points. For example, an exterior unshaded sensor point in Winnipeg has an outside daylight autonomy of 87% for an occupancy schedule of Monday to Friday (Mo-Fr) 6AM to 8PM.

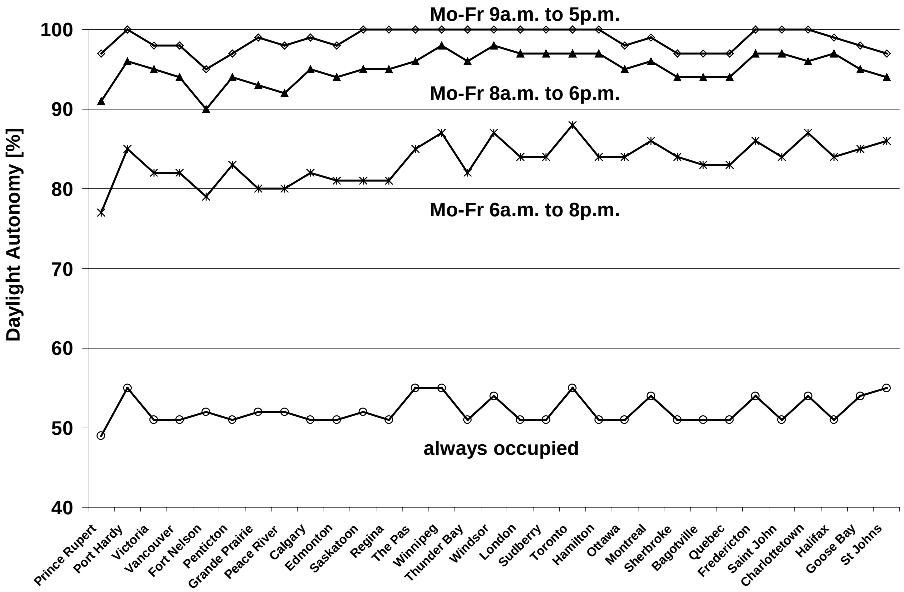


Fig.3-2: Daylight autonomy for an unshaded outside horizontal point (minimum threshold=500lx).

While the 31 total solar irradiances in Fig. 3-1 vary with a relative standard deviation of 9%, the same quantity lies below 3% for the outside daylight autonomies. The reason for the small variation of the outside daylight autonomy between sites is that it only considers *how often* during occupied hours the minimum illuminance threshold is surpassed by natural daylight and not by *how much*.

Fig. 3-2 reveals how closely the daylighting concept of a building is entangled with the user occupancy pattern: Allowing two extra hours for arrival and departure (Mo-Fr 8 AM to 6 PM) reduces the daylight autonomy by some 4% compared to a schedule of Mo-Fr 9 AM to 5 PM. If the occupancy is further increased to Mo-Fr 6 AM to 8 PM, outside daylight autonomies falls around 15%. In the extreme case of 24h-occupancy the daylight autonomy lies around 52%, which roughly corresponds to the annual times when the sun is above the horizon.

Fig. 3-3 shows the effect of surrounding objects on the outside daylight autonomy for an occupancy schedule of Mo-Fr 8 AM to 6 PM. The impact of shading scenario 30^o is negligible and of scenario 40^o small. However, for very high obstruction angles of 60^o and 70^o the average outside daylight autonomy falls from 95% to 91% and 82%, respectively. The reason for the limited effect of external shading on the outside daylight autonomy is that an outside point facing upwards receives most daylight from the near-zenith part of the celestial hemisphere which is not shaded by an urban canyon. The effect of external shading on a sidelit office is considerably larger (see section 3.2).

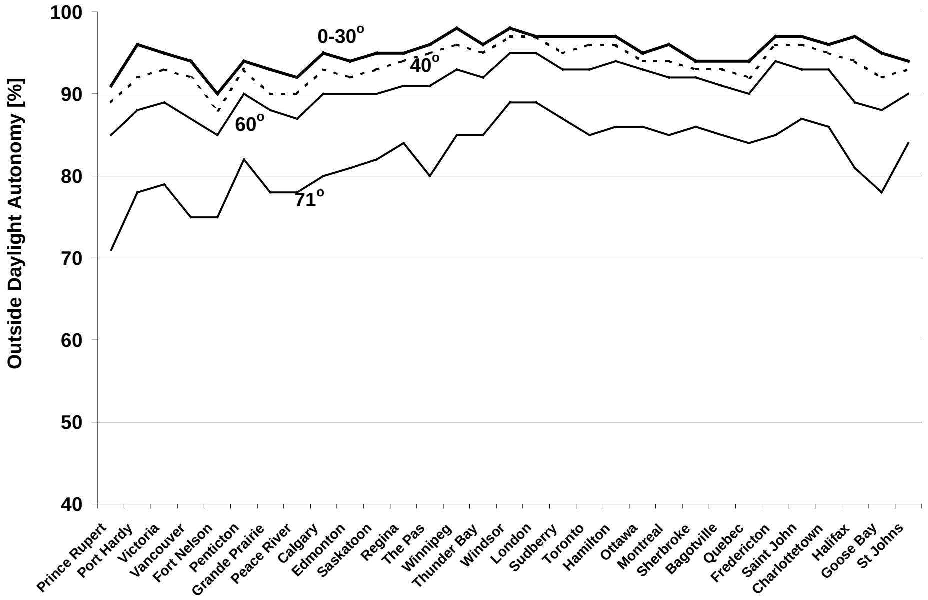


Fig. 3-3: Daylight autonomy for an outside horizontal sensor for various shading situations. The assumed occupancy profile is weekdays 8am to 6 PMand the minimum illuminance threshold is 500lx.

3.2 Daylight Availability in Offices without Blinds

In this section daylight autonomies in peripheral offices without blinds are presented.

3.2.1 Building Location

Fig. 3-4 shows outdoor and indoor daylight autonomies for an office with a Southern facade orientation and a high transmittance glazing (τ_{vis}=75%). An occupancy schedule of weekdays 8am to 6 PMhas been chosen. The figure shows that the daylight autonomy falls with rising distance to the facade and that the impact of the geographical location of the office on the daylight autonomy is largest between 2 m and 5.5 m away from the facade. This is the range in which the office occupants are usually seated. In accordance with Fig. 3-2 interior daylight autonomies tend to be lowest near the coasts and highest in the Prairies.

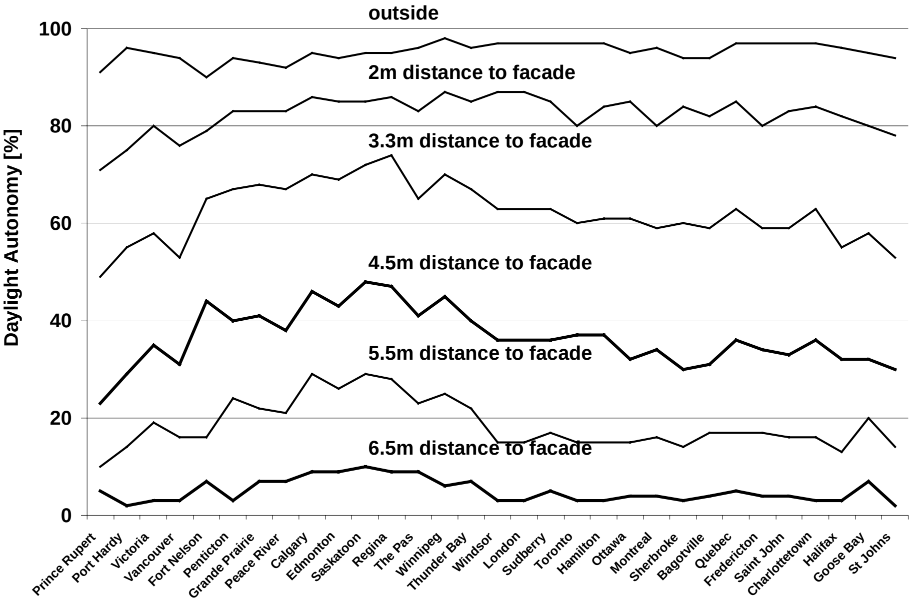


Fig.3-4: Daylight autonomy for various sensor points inside an office with a southern facade and an high transmittance glazing (τ_{vis}=75%). The assumed occupancy profile is weekdays 8am to 6 PMand the minimum illuminance threshold is 500lx.

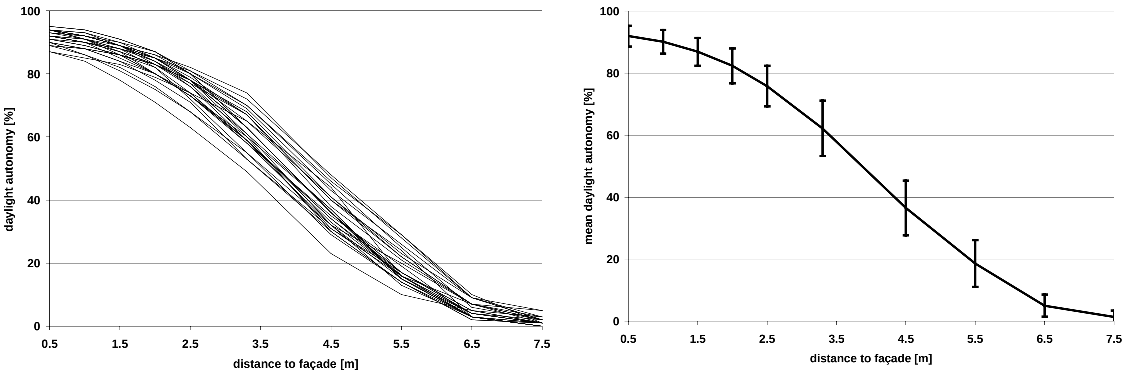
Fig. 3-5(a) shows the indoor daylight autonomy distributions for the same offices as Fig. 3-4. The lowest line corresponds to Prince Rupert, BC. This geographical location is characterized by dark overcast skies throughout most of December and January which cause the low daylight autonomies (*see also* Fig. 3-2 and 3-3). Fig. 3-5(b) summarizes 3-5(a). The plot shows the mean of the 31 daylight autonomy distributions. The error bars correspond to 1.5 times the standard derivation of the daylight autonomies for a particular sensor point. The standard deviation is a measure of how widely values are dispersed from the average value (the mean). It is defined as

$$\sqrt{\frac{n\left(\sum x^2\right)-\left(\sum x\right)^2}{n(n-1)}} \qquad \text{equ. 3-1}$$

where n=number of sites and

x=daylight autonomy at a sensor point

This graphical presentation will be used in the following to compare daylight autonomies for varying facade orientations, occupancy schedules, external shading situations and glazing types.



(a) (b)

Fig. 3-5: (a) Daylight autonomy distributions for the 31 weather stations for an office with a Southern facade, a high transmittance glazing and a user occupancy on weekdays 8AM to 6pm; (b) mean daylight autonomy distribution from the 31 sites. The error bars correspond to 1.5 times the standard derivation of the daylight autonomies of the particular sensor points.

3.2.2 Facade Orientation

Fig. 3-6 shows mean daylight autonomy distributions in correspondence to Fig. 3-5(b) for four facade orientations. The outside daylight autonomy is plotted as a reference. All four daylight autonomies are nearly identical within the first 2m distance from the facade. Between 2 and 5m the graphs diverge and the daylight orientation for the South penetrates roughly 1m deeper into the space than North and 0.5m deeper than East and West. The latter two basically coincide throughout the space.

While the figure shows how much more daylight a Southern office receives compared to a Western/Eastern or a Northern office, one should remember that the graphs merely provide a physical upper limit of the daylight availability in the offices in the absence of blinds. The true daylight potential of Southern, Eastern and Western facades is considerably lower as direct sunlight causes glare and requires a (partly) closing of the blinds. An estimate of how much the daylighting is left in real offices will be one of the major outcomes of this project.

The results for the Northern facade can be directly compared to the results from a simulation study in which the daylight simulation program DeLight was used to calculate the daylight autonomy for a office geometry with a Northern facade located in Paris (48^o 67’ N) (Vartiainen, 2001). The study yielded a daylight autonomy of 91% at 1.25 m distance from the facade which lies within the range of the daylight autonomy of a Northern offices shown in Fig. 3-6.

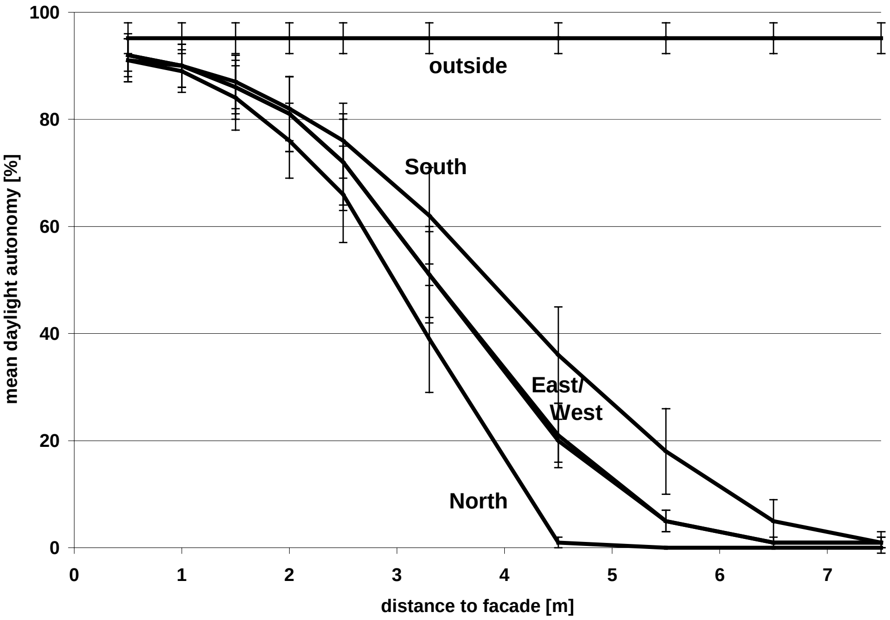


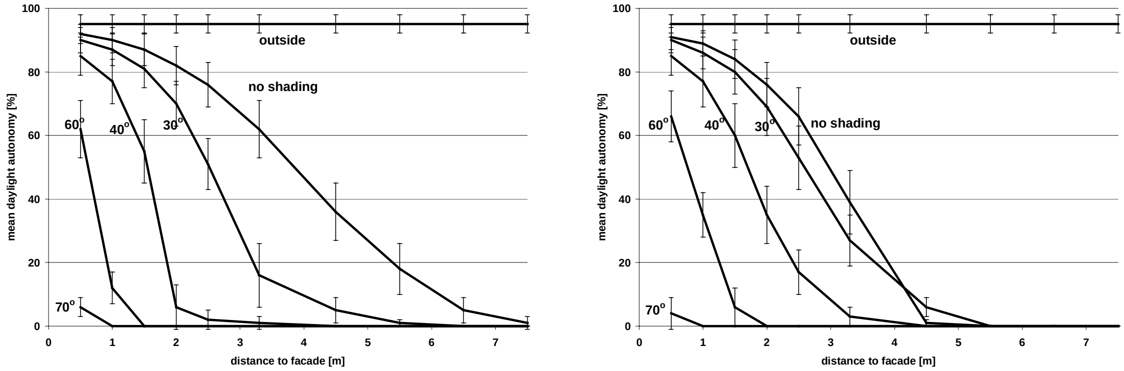
Fig.3-6: Mean daylight autonomy distributions in offices with a high transmittance glazing (τ_{vis}=75%) and varying facade orientations. The blinds are retracted throughout the year. The assumed occupancy profile is weekdays 8 AM to 6pm and the minimum illuminance threshold is 500lx.

3.2.3 Surrounding Objects

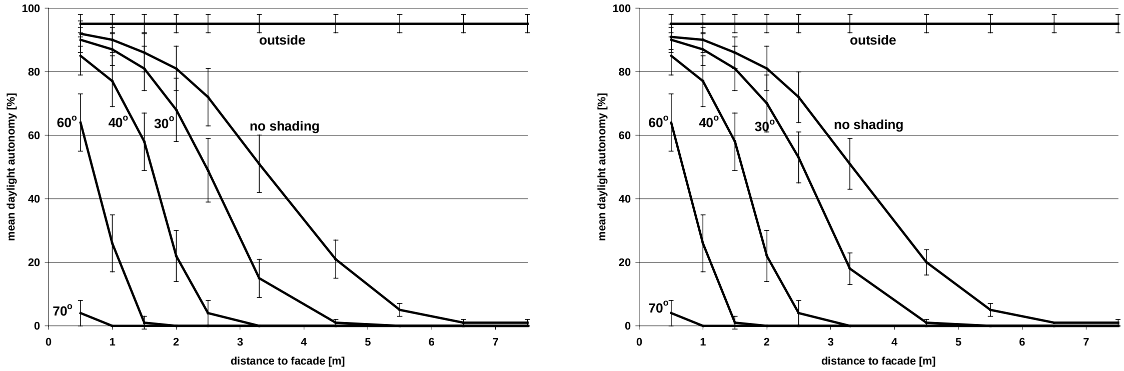
Fig. 3-7 shows mean daylight autonomy distributions for all principal sky directions under varying external shading scenarios. The figure shows that the distance daylight can penetrate into a building falls with rising obstruction angle. The effect is strongest for the Southern and weakest for the Northern office which has a low daylight penetration depth even in the absence of external obstructions. It is surprising to note that for the Northern facade orientation the daylight autonomy at 4.5m for the shading scenario 30^o is actually higher than in the absence of an external shading. The effect has been reported before and stems from the fact that the southern facade of a neighboring building can act as a diffuse reflector of direct sunlight which is redirected onto the Northern facade (Mwaniki Wa-Gichia, 1998).

For an obstruction angle above 30^o most direct sunlight is blocked from entering an office and the daylight autonomies for the different orientations become nearly identical. The reason for this is that most incoming daylight is reflected at least once before reaching the offices. While there is a considerable amount of daylight available in an office with shading scenario 30^o, the daylight potential for a lower story office bordering an urban canyon (40^o) is seriously impeded. The reason for this is that a facade opposing a low rise “sees” nearly half of the celestial hemisphere whereas in an urban canyon most incoming daylight stems from a narrow near-zenith region of the celestial hemisphere. For the latter shading scenarios the area with daylight autonomies above 40% lies within 2m distance from the facade.

The quality of daylight that is reflected from an opposing facade depends on whether the facade features any specular surfaces which can trigger glare (Mwaniki Wa-Gichia, 1998; Littlefair P, 2001).



(a) South (b) North

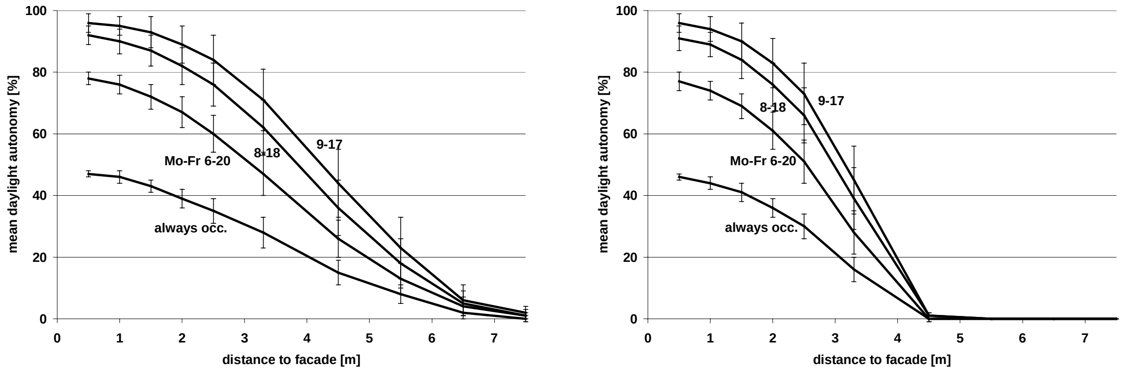


(c) West (d) East

Fig. 3-7: Mean daylight autonomy distributions in offices with a high transmittance glazing (τ_{vis}=75%), varying obstruction angles and varying facade orientations (a-d). The blinds are retracted throughout the year. The assumed occupancy profile is weekdays 8 AM to 6pm and the minimum illuminance threshold is 500lx.

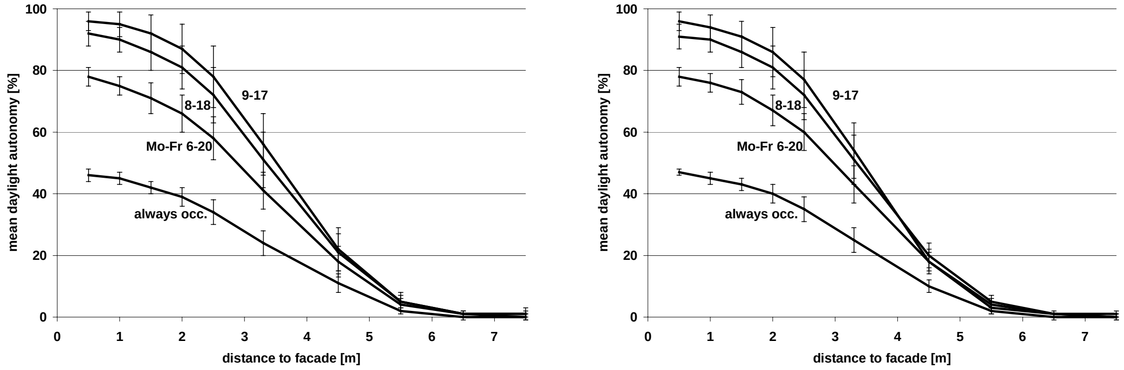
3.2.4 Occupancy Schedules

Fig. 3-8 shows indoor daylight autonomy distributions for all principal sky directions and various occupancy schedules. The facade has a high transmittance glazing and is not shaded by surrounding buildings. As for an unshaded outside point the daylight autonomies fall with rising occupancy times even though the solar penetration depth is not affected for varying facade orientations. Instead changing the occupancy schedule corresponds for all facade orientations to scaling the daylight autonomy distribution with a constant factor.



(a) South

(b) North



(c) West

(d) East

Fig. 3-8: Mean daylight autonomy distributions in offices with a high transmittance glazing (τ_{vis}=75%) and varying facade orientations (a-d) for different occupancy profiles. The blinds are retracted throughout the year. The minimum illuminance threshold is 500lx.

This simple relationship is depicted in Fig. 3-9. The points in the graph represent all indoor points in Fig. 3-8 with daylight autonomies above 40%. The coordinates of the points were determined as follows:

$$\text{x coordinate:} \quad \frac{\textbf{outside daylight autonomy}_{\text{schedule 1}}}{\textbf{outside daylight autonomy}_{\text{schedule Mo-Fr 9-5}}}$$

$$\text{y coordinate:} \quad \frac{\textbf{inside daylight autonomy}_{\text{schedule 1}}}{\textbf{inside daylight autonomy}_{\text{schedule Mo-Fr 9-5}}}$$

A linear fit through the data in Fig. 3-9 yields y = 1.0525x - 0.0873 (R^2 = 0.98) which is very close to the unity plot y=x. This finding leads to the following conclusions:

- changing the occupancy schedule for an office directly scales the daylight autonomy distribution without changing its overall shape.
- for an unshaded office with a large glazing this scaling factor roughly corresponds to the ratio of the outside horizontal daylight autonomies for both schedules.

The latter conclusion offers a straightforward way to estimate the effect of changing occupancy profiles on peripheral offices without blinds. This simple rule applies to offices whose indoor illuminance profile is mainly determined by daylight that directly enters the facade without being reflected from the ground or from surrounding objects.

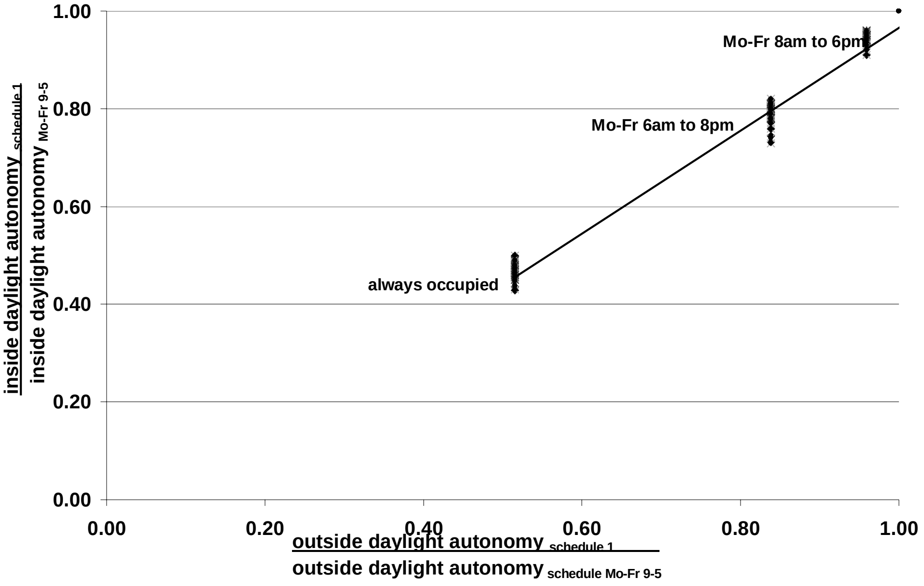


Fig. 3-9: Relationship between the ratios of inside and outside the daylight autonomies for two occupancy schedules.

3.3 Daylight Availability in Offices with Blinds

In this section, internal daylight autonomies in the presence of blinds are discussed. As explained in the introduction, three static settings of an internal venetian blind system have been considered:

(a) blinds are permanently retracted (results from previous section)

(b) blinds are permanently lowered with a slat angle of 45^o

(c) blinds are permanently lowered with the slats fully closed (no daylight)

Fig. 3-10 provides an overview of the daylight autonomy distribution for all three blind settings for offices situated in Toronto. The considered offices have varying facade orientations with a high or low transmittance glazing. The gray areas are framed by blind settings (a) and (b). The black areas are bordered by blind settings (b) and (c). The figure clearly shows that keeping the blinds constantly lowered with the slat angles at a 45^o angle to avoid glare from direct sunlight seriously reduces the daylight autonomy for all facade orientations and glazing types. In fact, the daylight autonomies for all but a Southern facade with a high transmittance glazing lie below 10% for distances from the facade larger than 1.5 m. While the results for blind setting (a) are too optimistic, the results for setting (b) are probably too low for most offices. The daylight autonomy should usually lie somewhere within the gray areas in Fig. 3-10 with absolute values depending on how the users interact with their blinds.

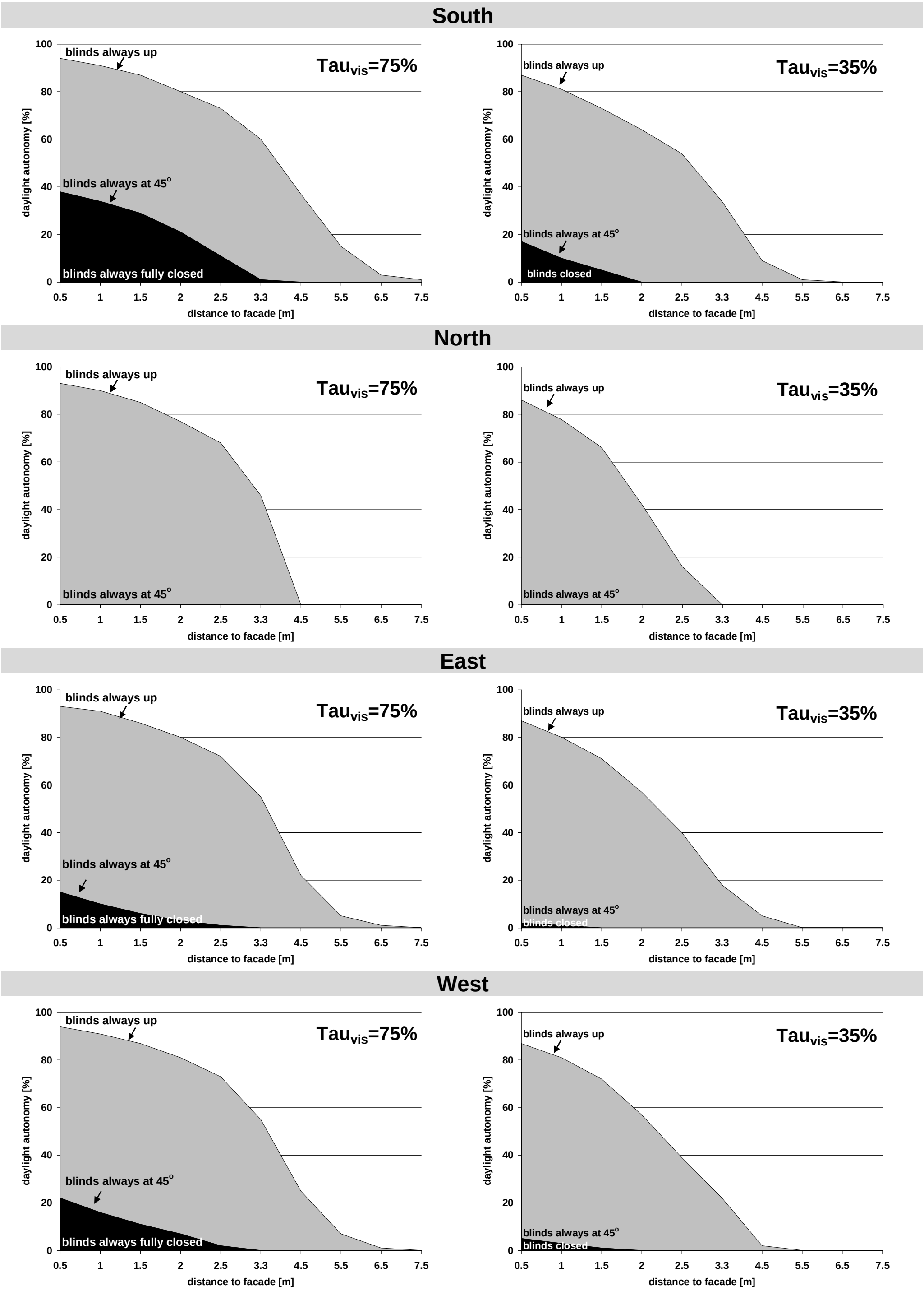


Fig. 3-10: Daylight autonomy distribution for an office in Toronto with the blinds permanently retracted (gray area) or lowered with a slat angle of 45^o (black area). Results are shown for four facade orientations and two glazing types. The assumed occupancy profile is weekdays 8 AM to 6pm and the minimum illuminance threshold is 500lx.

Comparing the results for a Northern facade with the blinds permanently retracted with a Southern facade with the blinds permanently down at a 45° angle reveals that the “true” daylight availability in a Northern office that is not subject to glare might actually be higher than in a Southern office. This type of questions will be addressed in the next phase of the project.

Fig. 3-11 corresponds to the previous figure for a southern office with a high transmittance glazing for various occupancy schedules. As in Fig. 3-8 changing the occupancy schedule for an office with the blinds permanently lowered leads to a scaling of the daylight autonomy distribution by a constant factor. The size of the factor in the presence of blinds is different to the ratio of the outside daylight autonomies for the two schedules (section 3.2.4). The reason for this is that any daylight that enters a building through a lowered blind system with the slats at 45° has been reflected at least once from the ground or surrounding objects. Therefore, the scaling factor depends on the reflectivity of these ambient surfaces.

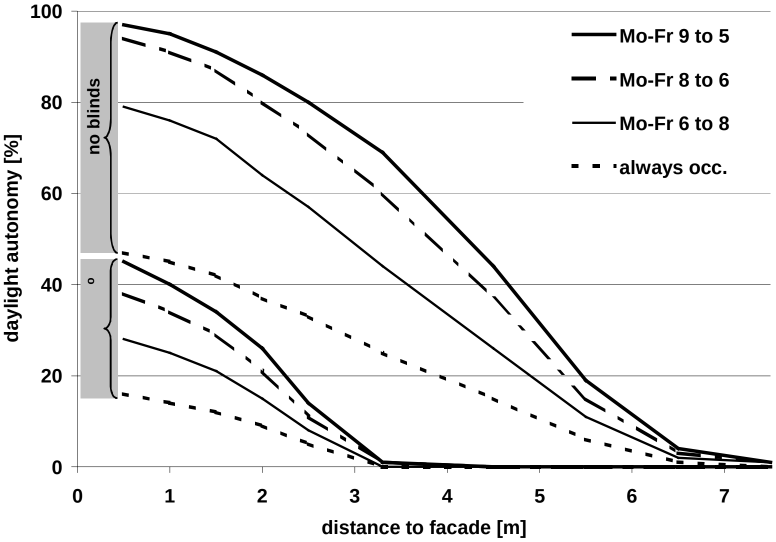


Fig. 3-11: Daylight autonomy distribution for an southern office in Toronto with the blinds permanently retracted or lowered with a slat angle of 45°. Results are shown for various occupancy schedules. The minimum illuminance threshold is 500lx.

3.4 Canadian Daylighting Zones

In this section, the results from the proceeding section are used to group the 31 weather stations into zones of comparable daylighting potential. Fig. 3-12 shows the results of the clustering algorithm described in section 2.6. For each weather station 32 interior daylight autonomy distributions for offices with varying facade orientations, glazing types, occupancy schedules and obstruction angles have been considered. The population weighted climatic centers of the resulting zones are -ordered by falling daylighting potential- are Winnipeg MB, Toronto ON, Vancouver BC and Prince Rupert BC.

The Prince Rupert zone only comprises a single location with a particular low daylight availability in the winter months. The Vancouver zone covers the coastal regions as well as sites with higher latitudes that receive less daylight during winter months. The Toronto zone comprises sites of lower latitude with an average ratio of 47% direct to total solar irradiance. The Winnipeg zone covers the remaining low latitude weather stations. These sites that are characterized by a high percentage of direct solar radiation of 54%.

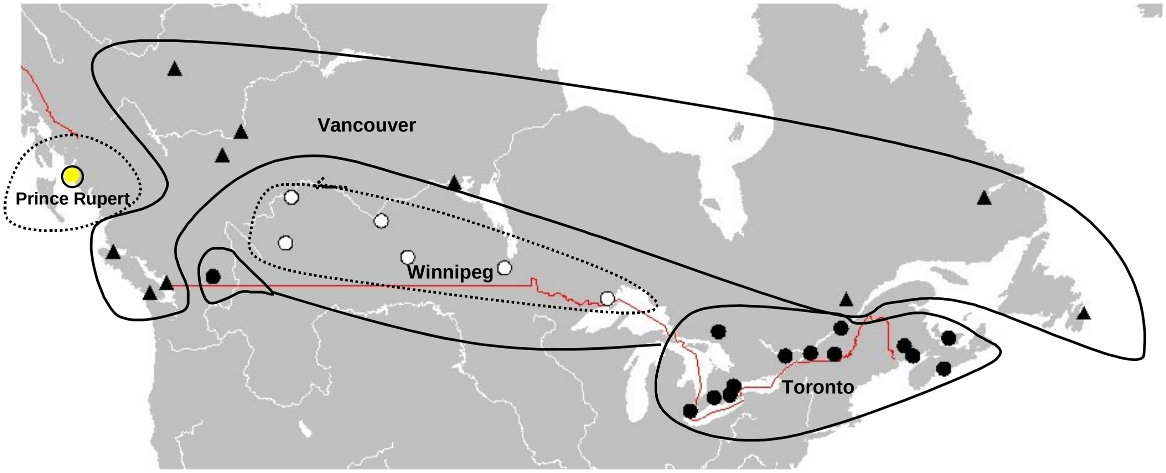


Fig. 3-12: Based on the clustering algorithm from chapter 2 four Canadian daylighting zones are identified. The clustering is based on daylight autonomy distributions for offices with varying facade orientations, glazing types, occupancy schedules and external shading situations.

4 Discussion and Conclusion

In this chapter, the answers to the two questions formulated in the introduction are summarized. The questions were:

(1) *What are the necessary "physical boundary conditions" for good daylighting in a peripheral office, i.e. what combinations of building location, height of surrounding objects, facade orientation and glazing type yield non-vanishing interior daylight autonomies?*

The preceding chapter has shown that building location, height of surrounding objects, facade orientation and glazing type all influence the interior daylight autonomy distribution in the critical range between 1.5 and 5 m away from the facade. This range marks where work places in peripheral offices are usually situated. In the following the above listed quantities are ranked according to the impact they have on the daylighting potential of a peripheral office.

external objects

Figures 3-3 and 3-7 show that the presence of surrounding objects may seriously impede outside and inside daylight autonomies. In the case where a low rise is facing a high rise with an obstruction angle below 30^o, the opposing facade may temporarily enhance the daylight availability at deeper room depths -especially for an office with a northern facade. The overall effect of the opposing facade is usually still negative but daylight is still possible in the low story building. If on the other hand two neighboring high-rises form an *urban canyon* which only admits near-zenith daylight, the daylit region in a low story office bordering the canyon collapses to a narrow strip of less than 1.5 m width. The resulting high illuminance gradient across the work plane makes such a work place unfavorable for daylighting. These results are in qualitative agreement with Mwaniki who used RADIANCE to simulate interior illuminances under as range of clear sky conditions (Mwaniki Wa-Gichia, 1998).

building location

Given that the obstruction angle of an office lies below 30^o the building location has a significant impact on the daylight autonomy. An office located in the *Winnipeg*-area may actually have an over 20% percentage points higher daylight autonomy than an identical office in the *Vancouver*-area at 3.3 m distance to the facade. To help the reader judge the significance of this effect, it is important to note that an increase of the daylight autonomy of 10 percentage points for an occupancy schedule of weekdays 8 AM to 6pm corresponds to one extra hour per day during which the minimum illuminance threshold is maintained by daylight alone.

facade orientation and glazing type

Fig. 3-6 shows that a Southern facade receives more daylight than other facade orientations. As a considerable part of this daylight is direct sunlight which is accompanied by glare and mostly unwanted solar gains in the cooling period, the choice of a suitable shading device is crucial to control glare and heat gains. Fig. 3-10 shows that choosing a solar protective glazing (τ_{vis}=35%) is a viable option for unshaded South, West and East facing facades to reduce solar gains without reducing the daylight availability too seriously. On the other hand, a low transmittance glazing on a North facing facade reduces the daylit region into a narrow strip within 1.5 to 2m distance from the facade.

blind setting

Fig. 3-10 highlights that independent of all the other design parameters the setting of the blinds ultimately defines the daylight autonomy in an office. It is trivial to note that a fully lowered blind systems with the slats fully closed excludes all incoming daylight. But it is interesting to realize that even if the slats are at a 45^o angle, i.e. in a position where direct sunlight is blocked but diffuse daylight can still enter, the minimum illuminance is rarely (if at all) met my daylight alone. This result stresses the need to understand how office occupants interact with their blind systems.

(2) How does the occupancy schedule influence a building's daylighting potential?

Figures 3-8 and 3-11 depict that changing the occupancy schedule introduces a constant scaling factor for the interior daylight autonomy distribution. This factor corresponds to the ratio of the outside daylight autonomies for the different occupancy schedules, if most incoming daylight is directly incident onto the facade without being reflected from neighboring objects of the surrounding ground. The figures highlight that the energy saving potential of a daylighting concept highly depends on the occupancy pattern of a building.

Summing up, the results from the simulation study help to define under which physical boundary conditions daylighting becomes a viable design option in peripheral offices. All presented interior daylight autonomies are preliminary results, as user behavior has not been considered so far. The static minimum illuminance threshold of 500lx will not be used throughout the whole project as a dimmed lighting system can also save energy if the daylight levels in a room lie below this value.

Acknowledgement

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Appendix A: Considered Canadian Metropolitan Areas

Metropolitan Area	**population**	**Station Name**	**ID**	**TZn**	**La (º)**	**Lo (º)**	**Elev (m)**
Toronto (Ontario)	4,751,400.00	TORONTO	04714	-5	43.67	79.63	173
Montréal (Quebec)	3,480,300.00	MONTREAL	94792	-5	45.47	73.75	31
Vancouver (B.C.)	2,048,800.00	VANCOUVER	24287	-8	49.18	123.17	3
Ottawa–Hull (Ontario–Quebec)	1,081,000.00	OTTAWA	04772	-5	45.32	75.67	116
Calgary (Alberta)	953000	CALGARY	25110	-7	51.12	114.02	1077
Edmonton (Alberta)	944200	EDMONTON	25142	-7	53.3	113.58	715
Québec (Quebec)	689700	QUEBEC	04708	-5	46.8	71.38	70
Winnipeg (Manitoba)	681100	WINNIPEG	14996	-6	49.9	97.23	237
Hamilton (Ontario)	671700	HAMILTON	04797	-5	43.17	79.93	237
Kitchener (Ontario)	421800	LONDON	94805	-5	43.03	81.15	278
London (Ontario)	421300	LONDON	94805	-5	43.03	81.15	278
St. Catharines–Niagara (Ontario)	390000	HAMILTON	04797	-5	43.17	79.93	237
Halifax (Nova Scotia)	356000	HALIFAX	14673	-4	44.63	63.5	126
Victoria (B.C.)	317500	VICTORIA	24297	-8	48.65	124.43	20
Windsor (Ontario)	304400	DETROIT	94847	-5	42.27	82.97	191
Oshawa (Ontario)	297900	TORONTO	04714	-5	43.67	79.63	173
Saskatoon (Saskatchewan)	232600	SASKATOON	25015	-6	52.17	106.68	501
Regina (Saskatchewan)	200500	REGINA	25005	-6	50.43	104.67	578
St. John's (Newfoundland)	175100	ST_JOHNS	14521	-4	47.62	52.73	136
Chicoutimi–Jonquière (Quebec)	160100	BAGOTVILLE	94795	-5	48.33	71	159
Sudbury (Ontario)	157100	SUDBURY	94828	-5	46.62	80.8	347
Sherbrooke (Quebec)	152900	SHERBROOKE	04785	-5	45.42	71.9	522
Trois-Rivières (Quebec)	141800	MONTREAL	94792	-5	45.47	73.75	31
Kelowna (B.C.)	136500	Penticton	94116	-8	49.47	119.6	376
Saint John (New Brunswick)	127700	SAINT_JOHN	14643	-4	45.32	65.88	109
Thunder Bay (Ontario)	126300	THUNDER_BAY	94804	-5	48.37	89.32	199
Fredericton (New Brunswick)	78950	Fredericton	14670	-4	45.87	66.53	18
Charlottetown (P.E.I.)	57200	Charlottetown	14688	-4	46.28	63.13	50
Penticton (B.C.)	41200	Penticton	94116	-8	49.47	119.6	376
Grande_Prairie (Alberta)	31100	Grande_Prairie	25115	-7	55.18	118.88	655
Prince_Rupert (B. C.A1)	17400	Prince_Rupert	25353	-8	54.3	130.43	33
Dawson_Creek (B.C.)	11100	Grand_Prarie	25115	-7	55.18	118.88	655
Goose_Bay (New Foundland)	8600	Goose_Bay	15601	-4	53.32	60.42	50
The_Pas (Manitoba)	5900	The_PAS	25004	-6	53.97	101.1	296
Peace River (Alberta)	5600	Peace_River	25101	-7	56.23	117.43	560
Port_Hardy (B.C.)	5200	Port_Hardy	25223	-8	50.68	127.23	20
Fort_Nelson (B.C.)	4400	Fort_Nelson	25218	-8	58.83	122.56	376

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