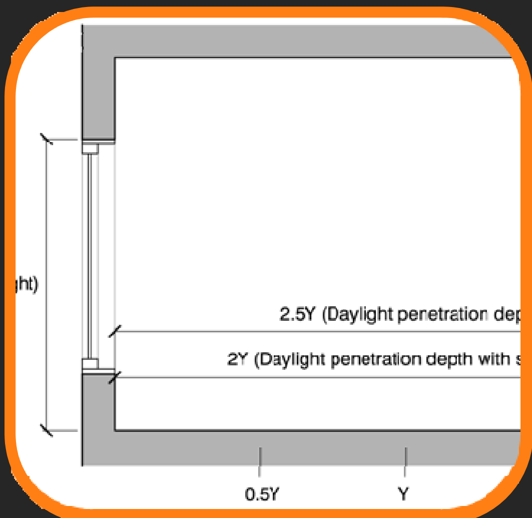
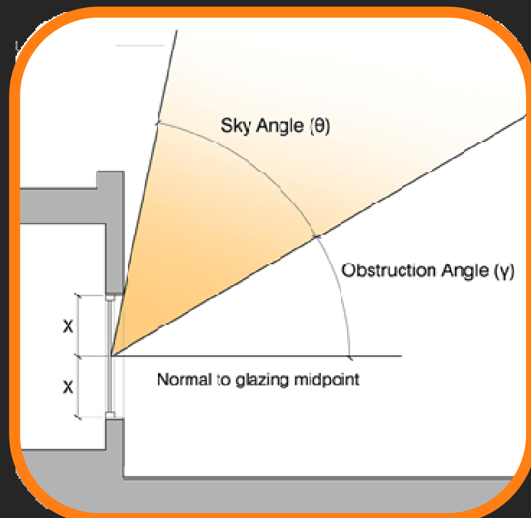
Harvard University
Graduate School of Design

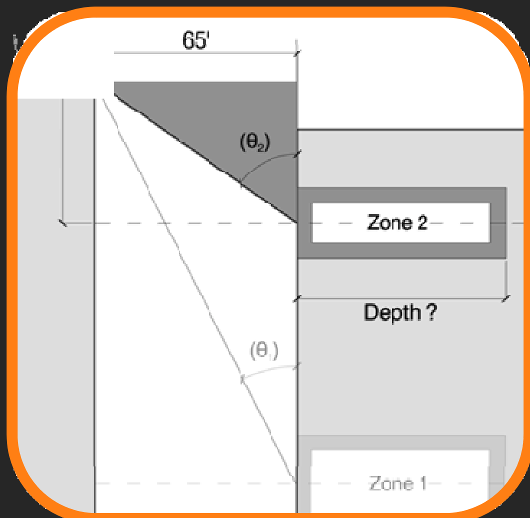
version: 3/16/2009

A Design Sequence for Diffuse Daylighting

'DAYLIGHTING RULES OF THUMB'







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WHAT IS IT?

- This document presents a sequence of simple equations (rules of thumb) which can be used to identify potentially daylit zones in a building and to assign them dimensions and glazing areas.

- The sequence is meant to be applied during the preliminary phases of building design (initial massing and programming).

- Its ease of application means that a daylighting concept can be formed for an entire building while it is still being designed and that the building's daylighting scheme can be quickly re-evaluated as the design evolves.

INFO

The design sequence is based on a recent paper which compares design sequence predictions to more advanced daylight simulations using Radiance. It can be read under www.gsd.harvard.edu/people/faculty/reinhart/documents/DiffuseDaylightingDesignSequence.pdf

WHEN?

- The method presented in this guide has been developed for buildings that are either located in a climate with mostly overcast (cloudy) sky conditions or in an urban environment whose spaces primarily receive diffuse daylight.

- It must be stressed that the repercussions of direct sunlight are effectively ignored by the design sequence. I.e. the resulting spaces should be adequately lit under overcast sky conditions, but may be 'overlit', overheated and/or 'glary' in the presence of direct sunlight.

INFO

It is recommended that you carry out an initial evaluation of your site to using a sun path diagram and local climate file to quantify the importance of direct versus diffuse radiation for your site.

DESIGN SEQUENCE

(1) How much daylight is the space receiving?

Calculate effective sky angle.

(2) How much light does the space need?

Set target mean daylight factor desired for the space.

(3) Can the target level be achieved?

Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

(4) What dimensional constraints does the target level impose?

Calculate suitable room depths and surface reflectances.

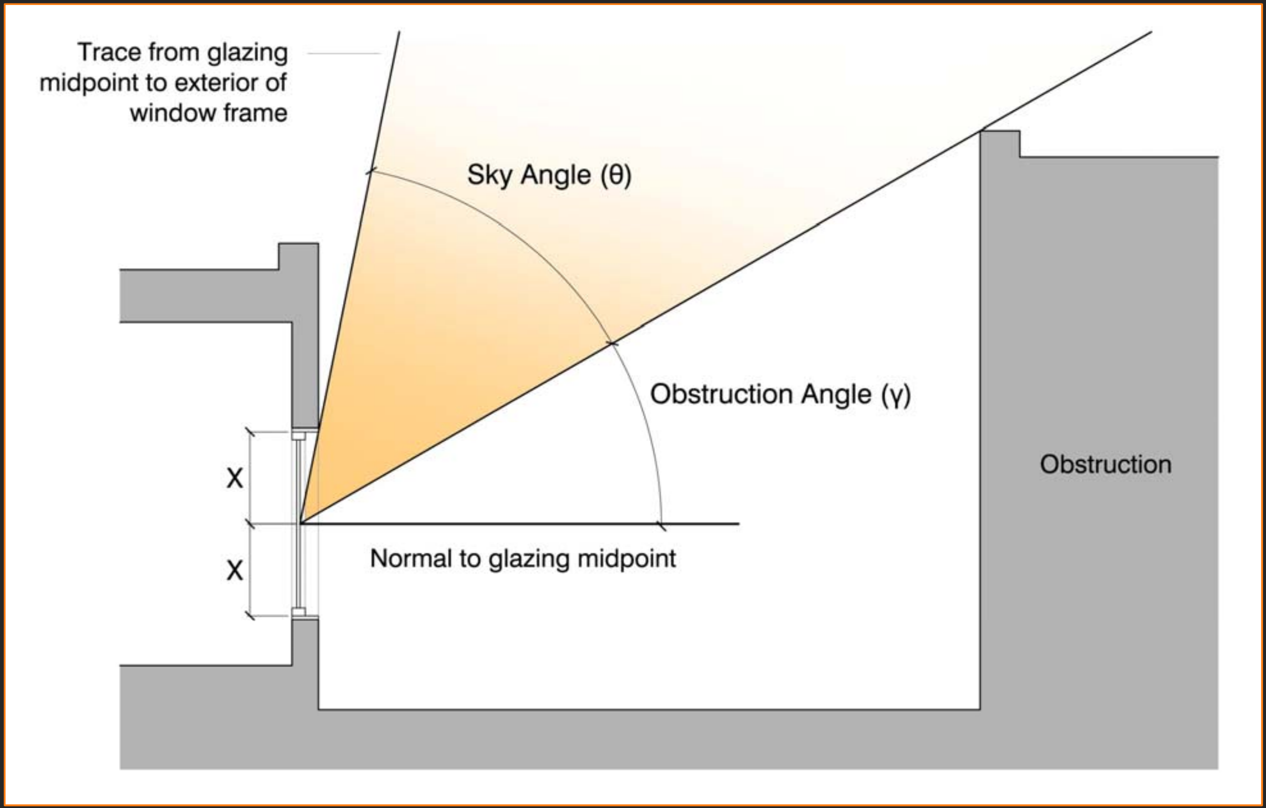
(5) What quantity of openings are required to achieve the target level in a space with these dimensions?

Determine the required glazing area.

SKY ANGLE

(1) How much daylight is the space receiving?

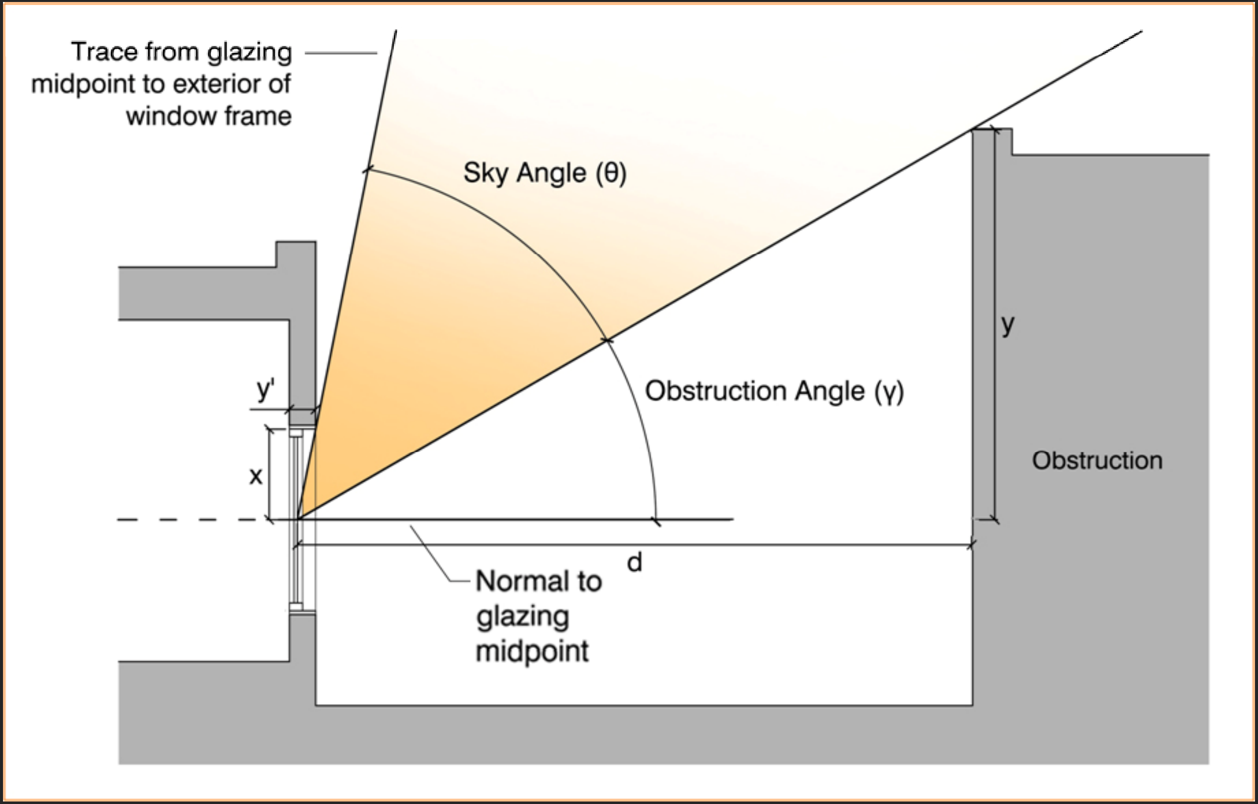
Calculate effective sky angle.



SKY ANGLE

(1) How much daylight is the space receiving?

Sky angle (θ) = 90º – arctan(y’/x) – arctan(y/d)



INFO

In case you do not know yet where to place your window just pick the center of the face for your sky angle calculation. Please note that more complex obstruction conditions can be analyzed using a 3D model and a raytracer.

DAYLIGHT FACTOR

(2) How much light does the space need?

Set target mean daylight factor desired for the space.

- The daylight factor (DF) is a metric used to quantify the amount of diffuse daylight in a space. (Diffuse daylight is light that has been scattered in the atmosphere before reaching the Earth's surface).

- It is usually measured at the height of the workplane (i.e. a desktop), under a standardized CIE overcast sky. It is defined as the ratio of the illuminance of a point in a building and the illuminance at an unshaded outside point facing upwards:

$$DF = (E_{in} / E_{ext}) \times 100$$

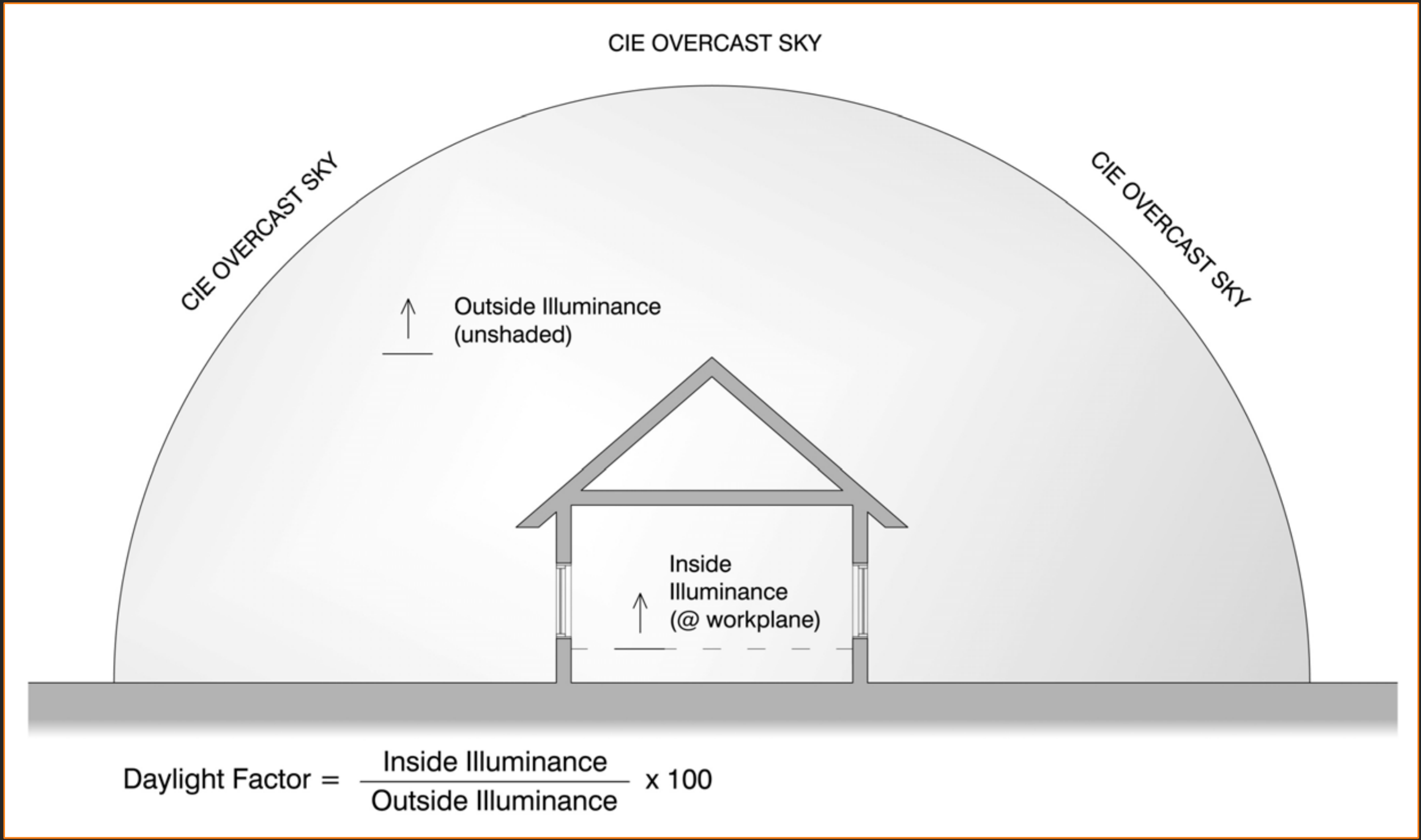
E_{in} : Interior illuminance at a fixed point on the workplane.
E_{ext} : Exterior illuminance under an overcast sky.

- The 'mean daylight factor' of a room is the average daylight factor value of a grid of sensors at work plane height that extends across the room.

DAYLIGHT FACTOR

(2) How much light does the space need?

Daylight factor calculation diagram:



DAYLIGHT FACTOR

(2) How much light does the space need?

- According to the British Standards Institution, BS 8206 part 2 CIBSE a space with an mean daylight factor between 2% and 5% is considered well lit and requires little or no additional lighting during daytime. A space with a daylight factor of less than 2% appears dimly lit.

Some examples of daylight factor requirements in different space types are listed below:

Space Type	Target
Office/Retail	2%
Classroom/Conference Room	3%
Circulation Area	1%

DAYLIGHT FEASIBILITY TEST

(3) Can the target level be achieved?

Calculate the window to wall ratio (WWR) required to achieve the set daylight factor and choose to continue or abandon daylighting of the space.

- To determine which parts of the building can be daylit.
- To slate zones for abandonment or for further analysis.

The window to wall ratio (WWR) corresponds to:

$$WWR = \frac{\text{Area of Exterior Openings (excluding mullions and window frames)}}{\text{Total Wall Area of Exterior Façade (width} \times \text{floor to ceiling height)}}$$

INFO

"How satisfactory the daylight within a space actually ends up being is further dependent on the specific lighting requirements of the space as well as the uniformity of the daylight throughout the space. Daylight quantity and uniformity both depend on interior space dimensions and surface reflectances."

DAYLIGHT FEASIBILITY TEST

(3) Can the target level be achieved?

The equation below (called the daylight feasibility test) correlates the severity of external obstructions, glazing type and target mean daylight factor to the minimum window to wall ratio required for a sidelit space.

$$WWR > \frac{0.088 \cdot DF}{\tau_{vis}} \cdot \frac{90^{\circ}}{\theta}$$

DF: Targeted daylight factor in %
θ: Sky angle in º
τ_{vis}: Glazing visual transmittance

- A space within a building 'passes' the daylight feasibility test if the required WWR is below 80%. A pass suggests that can be 'easily' daylit.
- Spaces with a minimum WWR above 80% cannot be easily daylit meaning either that the usage of this space should not require frequent use of daylight or that the use of more advanced daylight techniques such as light redirecting façade elements and highly reflective surfaces should be considered. These techniques cannot be evaluated using this simple design sequence.

INFO

A 'simple' way to lower the minimum WWR is to increase the visual transmittance of the glazings (Tvis).

LIMITING DEPTH

(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

In addition to the daylight factor requirement, three factors which limit room depth should be considered in daylight design:

- **DAYLIGHT UNIFORMITY**
  Distance at which the uniformity of daylighting levels throughout the space drops.
- **NO SKY LINE DEPTH**
  Distance away from the windows at which the sky is no longer visible.
- **DEPTH OF DAYLIGHT AREA**
  Distance to which 'meaningful' levels of daylight extend throughout the space.

INFO

A further discussion of the 'depth of the daylight area' can be found here.

LIMITING DEPTH

(4) What dimensional constraints does the target level impose?

DAYLIGHT UNIFORMITY:

The mean daylight factor becomes a poor representation of the daylighting levels in spaces under overcast sky conditions in the case of deep rooms, since they have very high daylight levels near the windows and very low values at the rear. The maximum acceptable depth of a space as far as daylight uniformity is concerned can be approximated by:

$$\text{Limiting depth} = \frac{2}{1-R_{mean}} \Bigg/ \frac{1}{w} + \frac{1}{h_{window\text{-}head\text{-}height}}$$

R_{mean}: Mean surface reflectance
w: Room width in meters

Spaces with depths lower than this limiting depth usually exhibit relatively uniform levels of daylighting throughout.

LIMITING DEPTH

(4) What dimensional constraints does the target level impose?

NO SKY LINE DEPTH:

The room depth (at the height of the working plane) past which there is no direct view of the sky. It is defined as:

$$\text{Limiting Depth} = (\text{window head height} - \text{workplane height}) \cdot \tan(\alpha)$$

Where, α (No sky line angle) ~ θ (Sky angle)

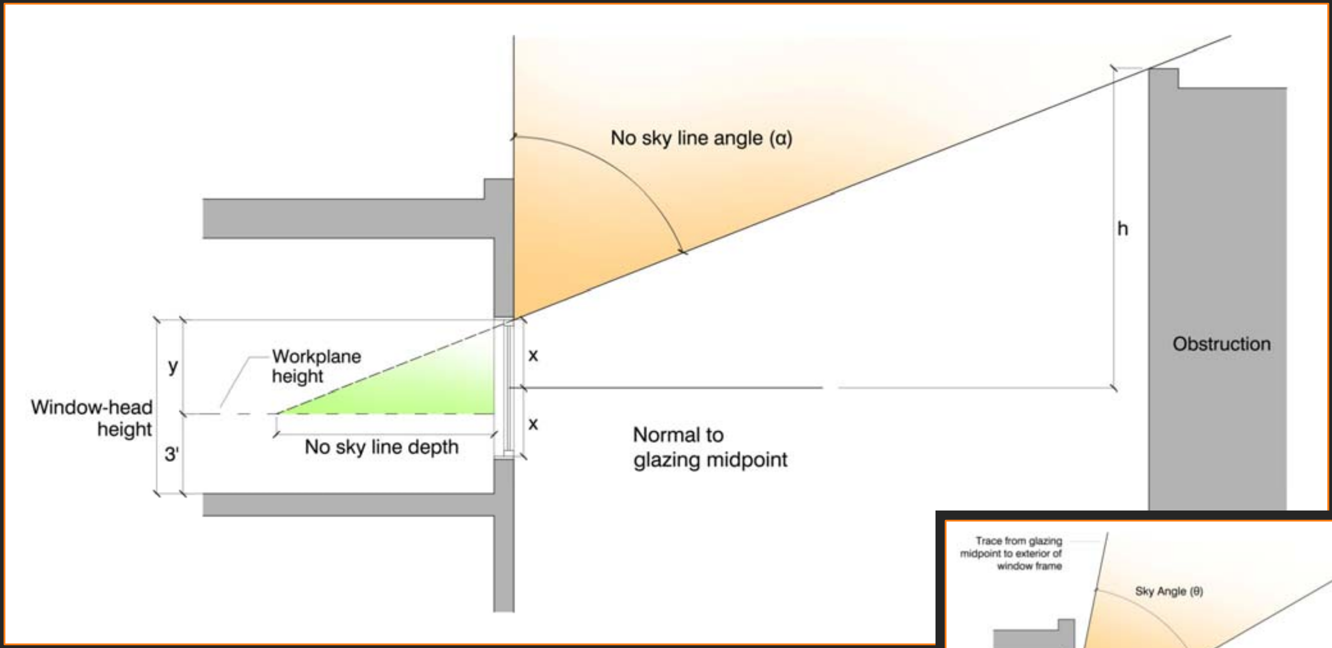
Staying within this limiting depth allows for a space whose work surfaces all 'see' as least some part of the sky.

INFO

Note: α = θ is an approximation and is only valid if Δheight(top of obstructing building - centre of window) is substantially larger than Δheight(window head - centre of window).

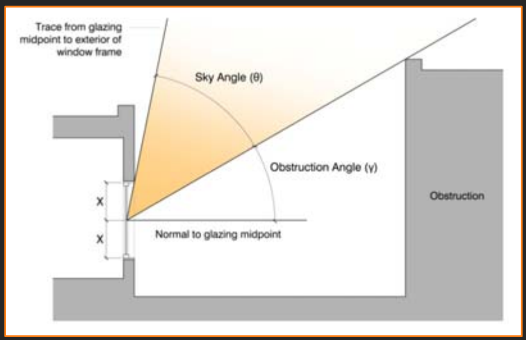
LIMITING DEPTH

(4) What dimensional constraints does the target level impose?



No sky line depth = $\tan(\alpha) \cdot y$

Approximation $\alpha = \theta$ valid when $h >> x$



INFO

A comparison between the two diagrams illustrates that when taking $\alpha = \theta$ in the no sky line depth calculation the distance from the window-head height to the centre of the glazing (x) is ignored.

LIMITING DEPTH

(4) What dimensional constraints does the target level impose?

DEPTH OF DAYLIGHT AREA:

Daylight penetration in a space varies linearly with window head height.

The relationship factor varies depending on whether or not a shading device is used (also see next slide).

With no shading device:

$$\text{Limiting depth} = 2.5 \cdot h_{\text{window-head height}}$$

With a shading device:

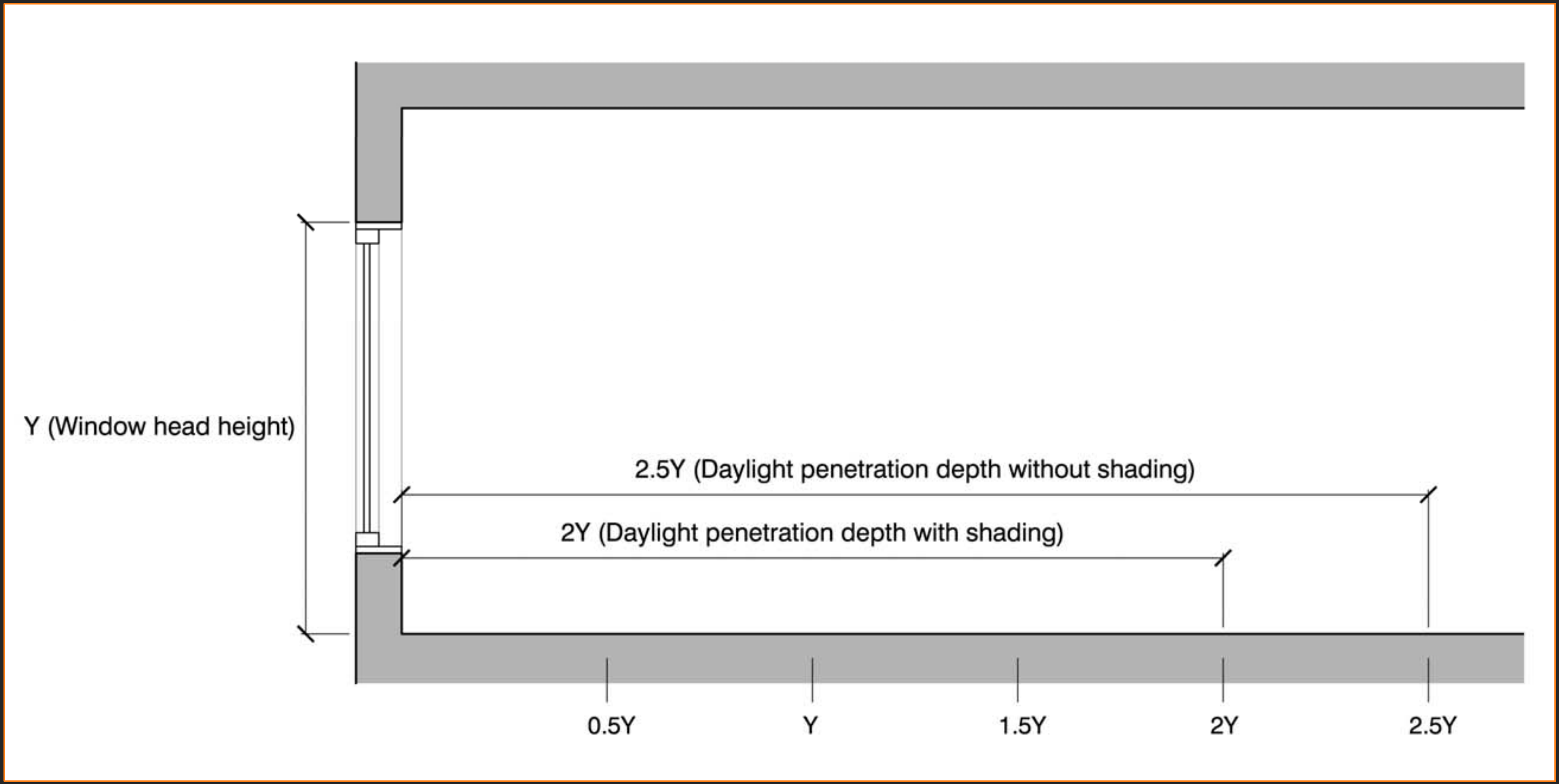
$$\text{Limiting depth} = 2.0 \cdot h_{\text{window-head height}}$$

This limiting depth allows for a space with an operable level of daylight throughout.

LIMITING DEPTH

(4) What dimensional constraints does the target level impose?

DEPTH OF DAYLIGHT AREA:



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LIMITING DEPTH

(4) What dimensional constraints does the target level impose?

Considered together, the three limiting factors yield the following equation for determining the constraint on room depth:

$$\text{Room Depth} < \text{Minimum}\left(\begin{array}{ll} \dfrac{2}{1-R_{mean}} \Big/ \left(\dfrac{1}{w}+\dfrac{1}{h_{window\text{-}head\text{-}height}}\right) & \\ (h_{window\text{-}head\text{-}height} - \text{work plane height}) \cdot \tan(\theta) & \\ 2.0 \cdot h_{window\text{-}head\text{-}height} & \text{if a shading device is required} \\ 2.5 \cdot h_{window\text{-}head\text{-}height} & \text{if no shading device is required} \end{array}\right)$$

The greatest room depth that can be used for daylighting is the smallest of the three values prescribed by the daylight uniformity, no sky line depth and the depth of daylight equations.

GLAZING AREA

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?

Determine the required glazing area.

One final calculation to get the net glazing area ($A_{glazing}$) required for a space with dimensions according to the pervious four steps is:

$$A_{glazing} = \frac{DF \cdot 2A_{total}(1 - R_{mean})}{\tau_{vis} \cdot \theta}$$

DF: Targeted daylight factor in %

A_{total}: Total area of all interior surfaces (including windows) in sq.ft.

R_{mean}: Mean surface reflectance

τ_{vis}: Glazing transmittance

θ: Sky angle in º

INFO

Note: $A_{glazing2}$ and τ_{vis} must be realistic and in line with solar gain, glare and other daylighting considerations.

EXAMPLE APPLICATION

In this simple example of an urban setting, two zones in a new building are being considered for daylighting: Zone 1 (retail) and Zone 2 (office).

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?
Calculate effective sky angle.

(2) How much light does the space need?
Set target mean daylight factor desired for the space.

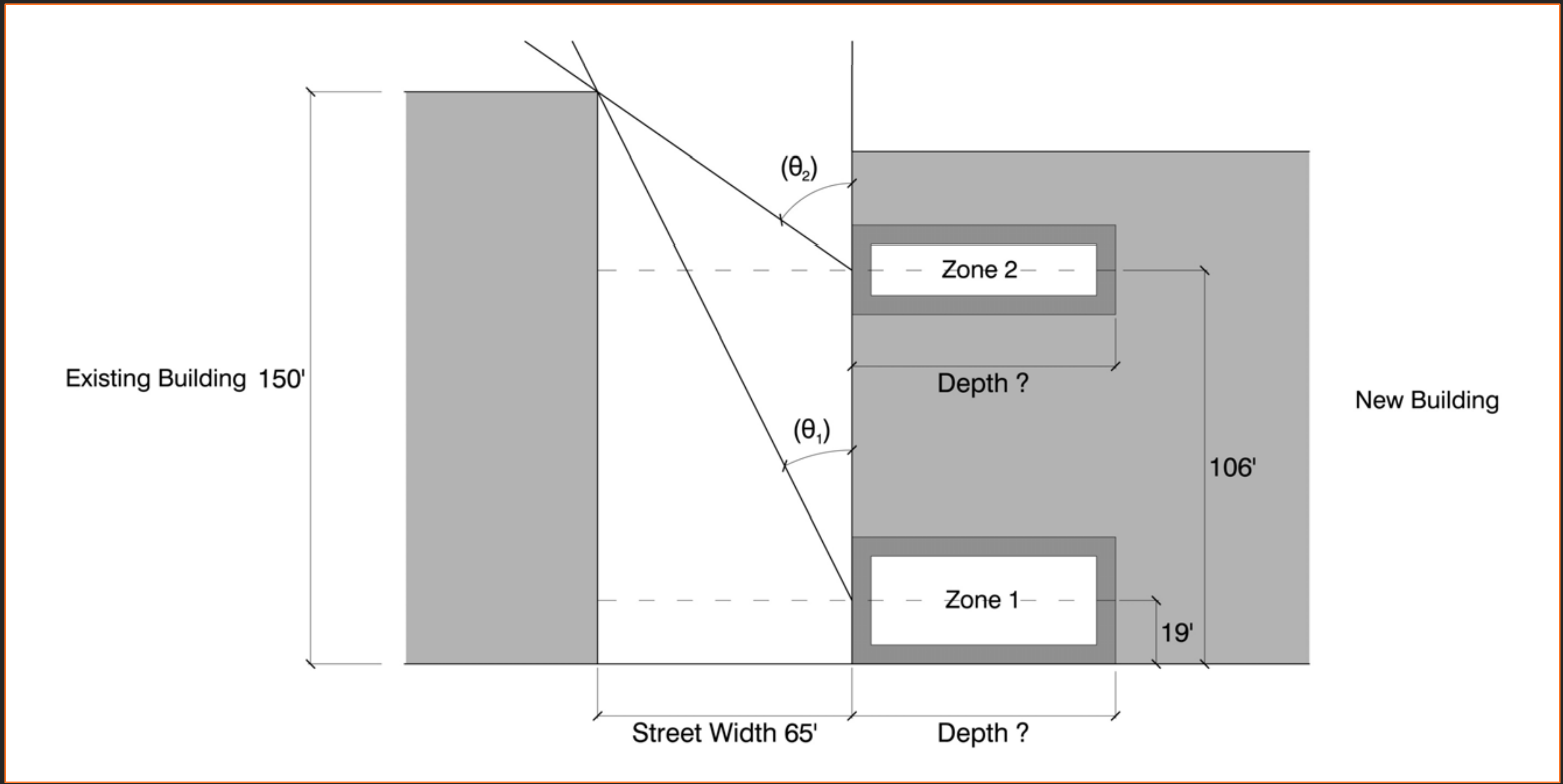
(3) Can the target level be achieved?
Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?
Determine the required glazing area.

EXAMPLE APPLICATION

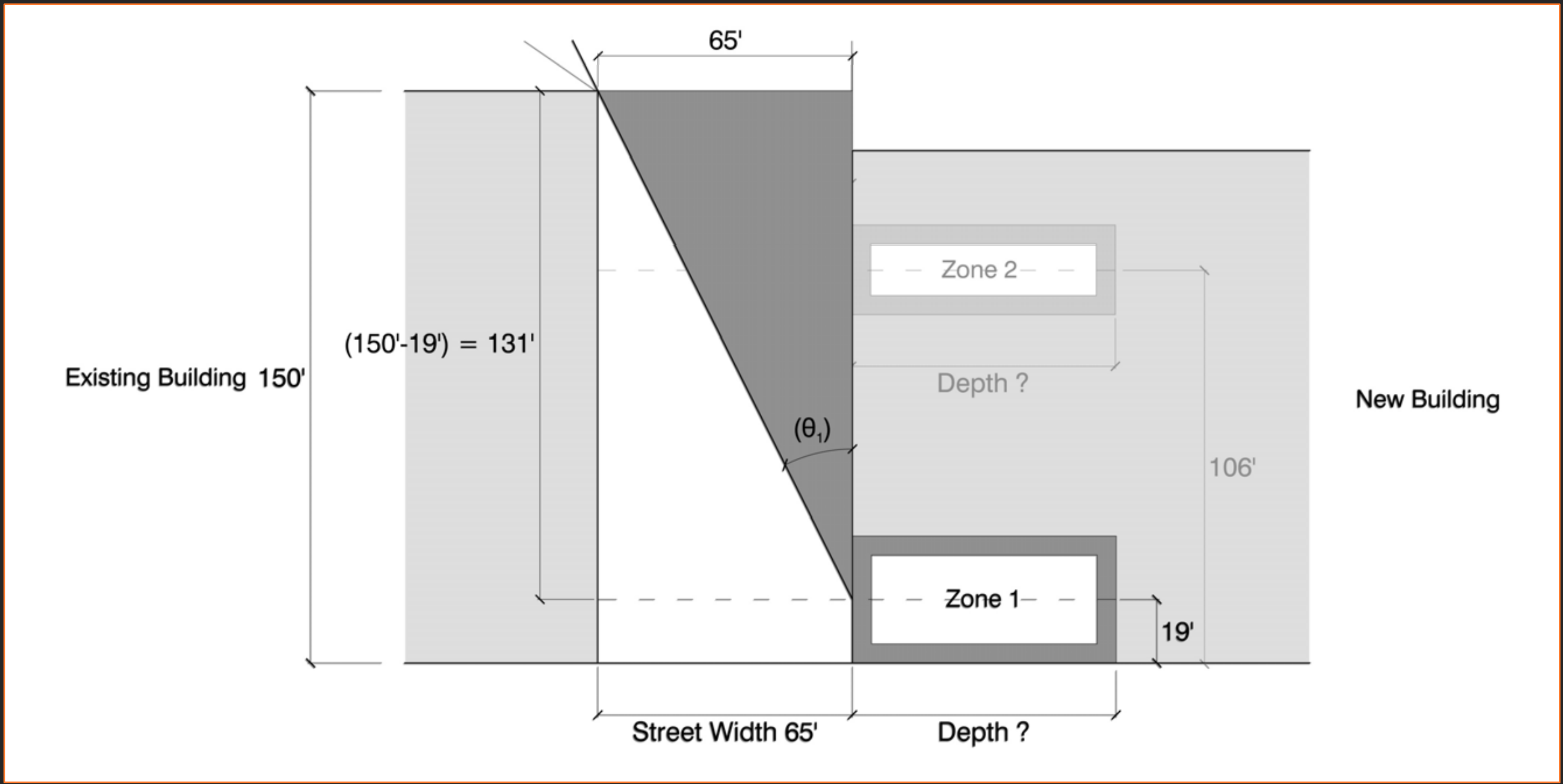
(1) How much daylight is the space receiving?



Effective sky angles θ_1 and θ_2 beginning at centre of glazing.

EXAMPLE APPLICATION

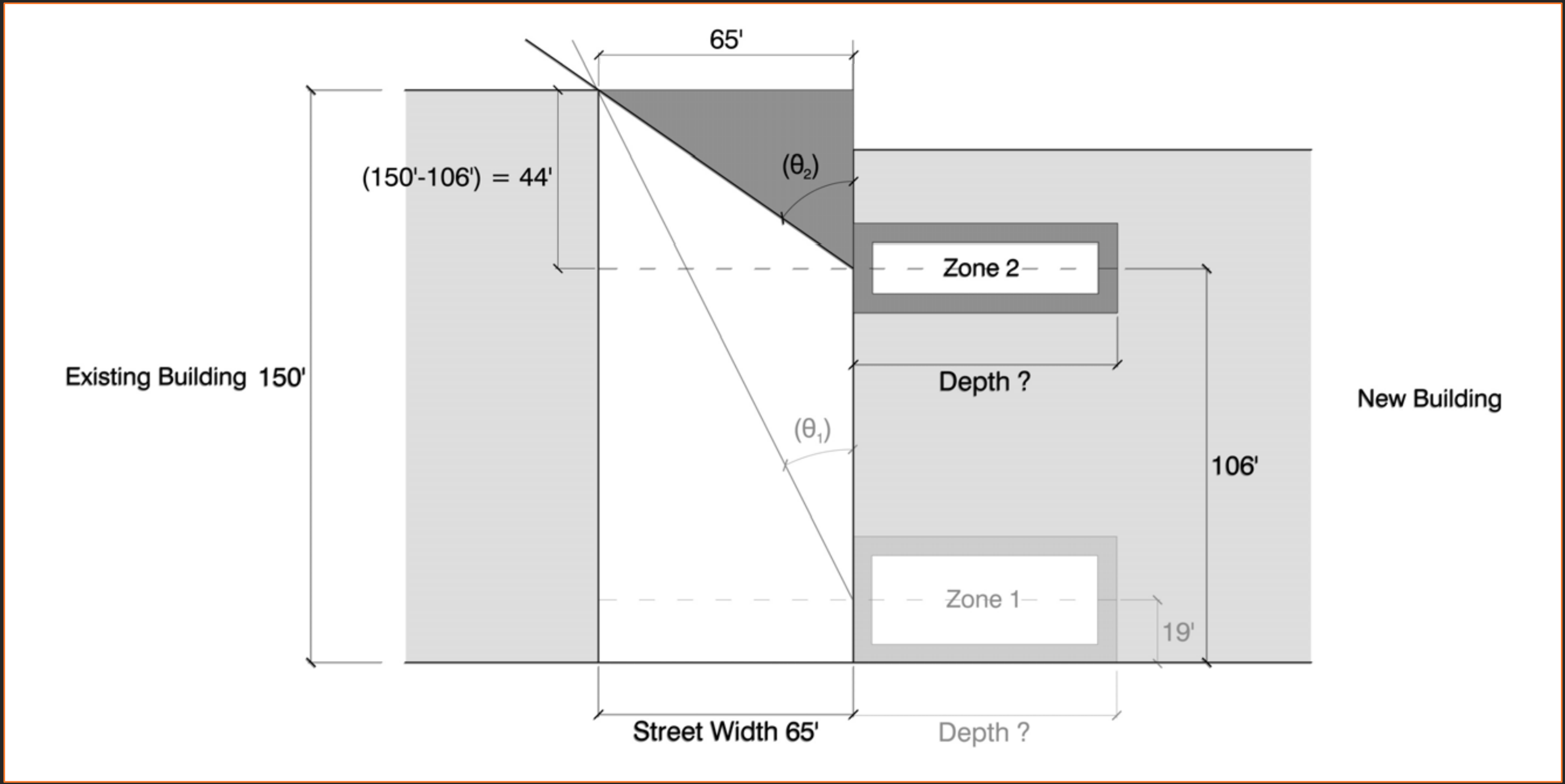
(1) How much daylight is the space receiving?



θ_1 = arctan(65’/131’) ~ 27º

EXAMPLE APPLICATION

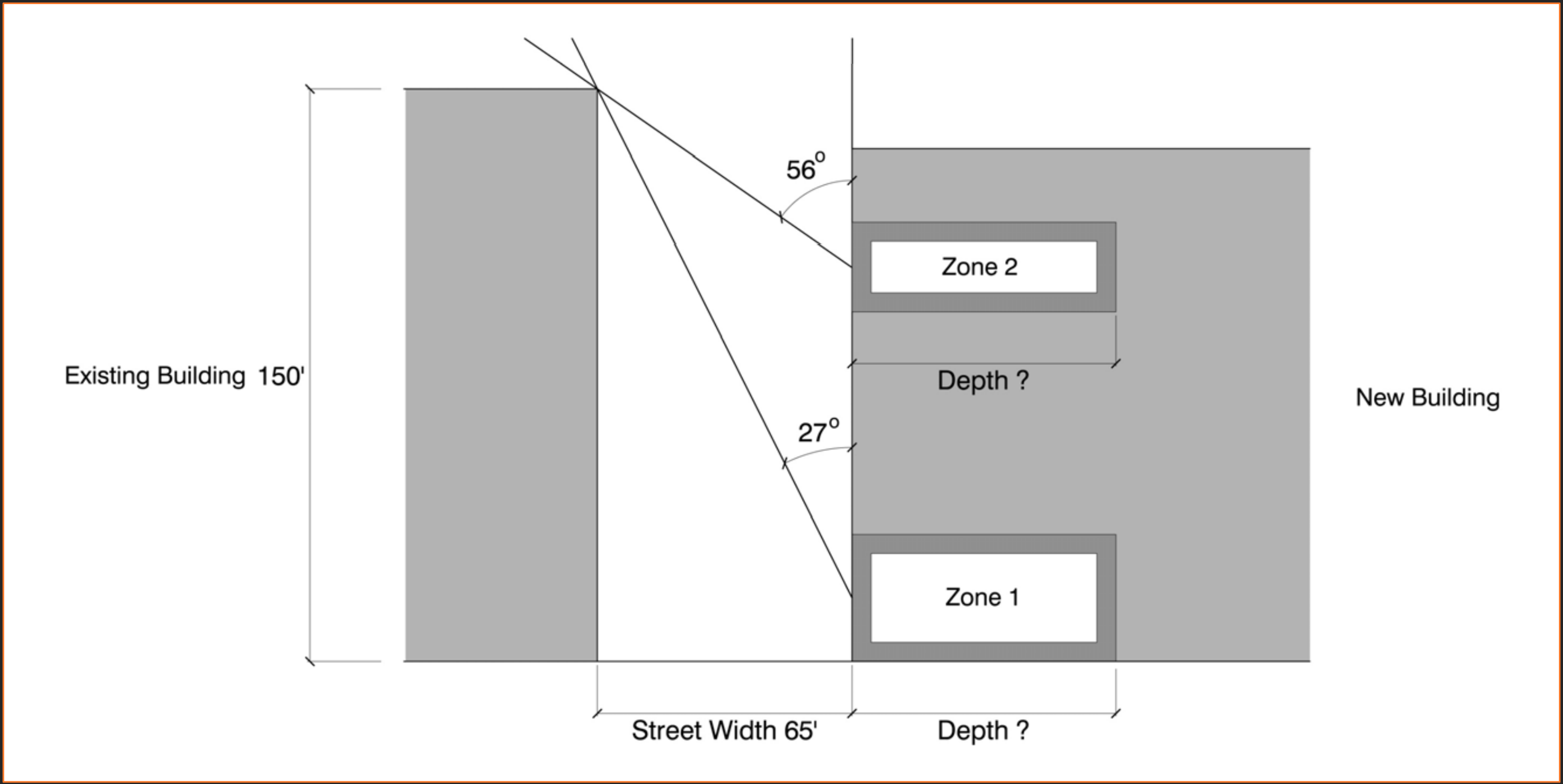
(1) How much daylight is the space receiving?



θ_2 = arctan(65'/44') ~ 56º

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?



Effective sky angles θ_1 and θ_2.

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?
Calculate effective sky angle.

(2) How much light does the space need?
Set target mean daylight factor desired for the space.

(3) Can the target level be achieved?
Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?
Determine the required glazing area.

EXAMPLE APPLICATION

(2) How much light does the space need?

- Based on standard guidelines a target mean daylight factor of 2% is chosen for both the office and retail spaces.

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?
Calculate effective sky angle.

(2) How much light does the space need?
Set target mean daylight factor desired for the space.

(3) Can the target level be achieved?
Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?
Determine the required glazing area.

EXAMPLE APPLICATION

(3) Can the target level be achieved?

Given:

DF:	Targeted daylight factor:	2%
θ_1:	Sky angle for zone 1 :	27º
θ_2:	Sky angle for zone 2 :	56º
T_{vis}:	Visual transmittance of double glazing:	0.8

$$\text{Zone 1 WWR} = \frac{0.088 \cdot 2}{0.8} \cdot \frac{90^\circ}{27^\circ} = 73\%$$

$$\text{Zone 2 WWR} = \frac{0.088 \cdot 2}{0.8} \cdot \frac{90^\circ}{56^\circ} = 35\%$$

- Both WWRs are below 80%, indicating that both spaces have potential for daylighting.

- Continue with analysis of both zones.

INFO

Note that the daylight factor is entered into the formula as 2 and not 0.02

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?
Calculate effective sky angle.

(2) How much light does the space need?
Set target mean daylight factor desired for the space.

(3) Can the target level be achieved?
Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?
Determine the required glazing area.

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EXAMPLE APPLICATION

(4) What dimensional constraints does the target level impose?

Given ZONE 1 (retail):

Window-head height: 11’
Space width: 32’
Sky angle: 27º

Mean surface reflectance: 0.5 (50%)
Workplane height: 3’
No shading device

DAYLIGHT UNIFORMITY

$$\text{Limiting Depth} = \frac{2}{1 - 0.5} \Big/ \left(\frac{1}{32'} + \frac{1}{11'}\right) = 33'\text{-}9''$$

NO SKY LINE DEPTH

$$\text{Limiting Depth} = (11' - 3') \cdot \tan(27^\circ) = 4'\text{-}0''$$

DEPTH OF DAYLIGHT AREA

$$\text{Limiting Depth} = 2.5 \cdot 11' = 27'\text{-}6''$$

INFO

Note: In this particular example we are using window-head-height and space width as ‘independent’ variables in order to determine a suitable space depth. You could also start with a ‘target depth’ and work you way backwards towards a suitable window-head-height and space width.

EXAMPLE APPLICATION

(4) What dimensional constraints does the target level impose?

Given ZONE 2 (office):

Window-head height:	9’	Mean surface reflectance:	0.5 (50%)
Space width:	10’	Workplane height:	3’
Sky angle:	56º	Shading device required	

DAYLIGHT UNIFORMITY

$$\text{Limiting Depth} = \frac{2}{1 - 0.5} \Big/ \frac{1}{10'} + \frac{1}{9'} = 19'\text{-}0''$$

NO SKY LINE DEPTH

$$\text{Limiting Depth} = (9' - 3') \cdot \tan(56^\circ) = 8'\text{-}10''$$

DEPTH OF DAYLIGHT AREA

$$\text{Limiting Depth} = 2.0 \cdot 9' = 18'\text{-}0''$$

EXAMPLE APPLICATION

(4) What dimensional constraints does the target level impose?

$$\text{Room Depth Zone 1} = \text{Minimum of} \begin{pmatrix} \frac{2}{1-0.5} \Big/ \frac{1}{32'} + \frac{1}{11'} = 33'\text{-}9' \\ (11' - 3') \cdot \tan(27^\circ) = 4'\text{-}0'' \\ 2.5 \cdot 11' = 27'\text{-}6'' \end{pmatrix} = 4' - 0''$$

$$\text{Room Depth Zone 2} = \text{Minimum of} \begin{pmatrix} \frac{2}{1-0.5} \Big/ \frac{1}{10'} + \frac{1}{9'} = 19'\text{-}0'' \\ (9' - 3') \cdot \tan(56^\circ) = 8'\text{-}10'' \\ 2.0 \cdot 9' = 18'\text{-}0'' \end{pmatrix} = 8' - 10''$$

INFO

Important: This “limiting room depth” result is not meant to prescribe wall positions in a room, but merely to indicate where the level of usable daylight falls off. For example, in the case of Zone 2 (office), desks should be positioned within the 8’-10” boundary, but additional depth may be used for circulation, services, etc.

EXAMPLE APPLICATION

(1) How much daylight is the space receiving?
Calculate effective sky angle.

(2) How much light does the space need?
Set target mean daylight factor desired for the space.

(3) Can the target level be achieved?
Calculate the window to wall ratio required to achieve the set daylight factor and choose to continue or abandon daylighting of the space. (Daylight Feasibility Test)

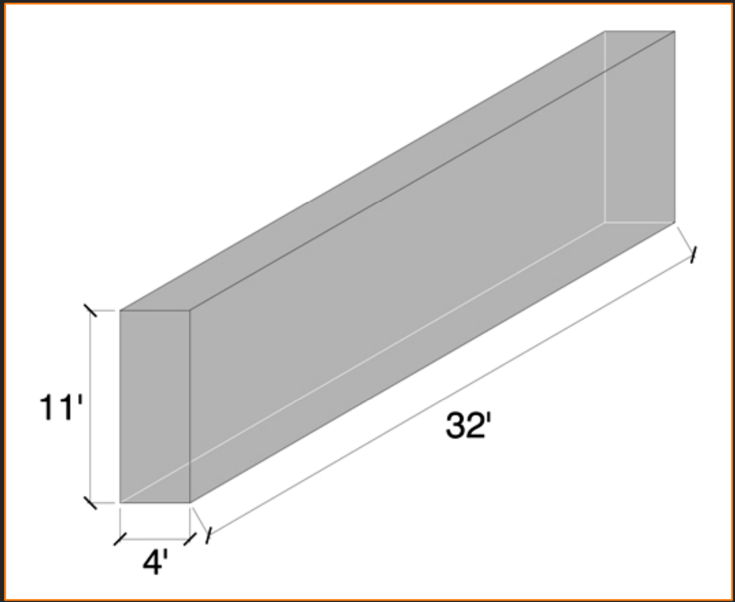
(4) What dimensional constraints does the target level impose?
Calculate suitable room depths and surface reflectances.

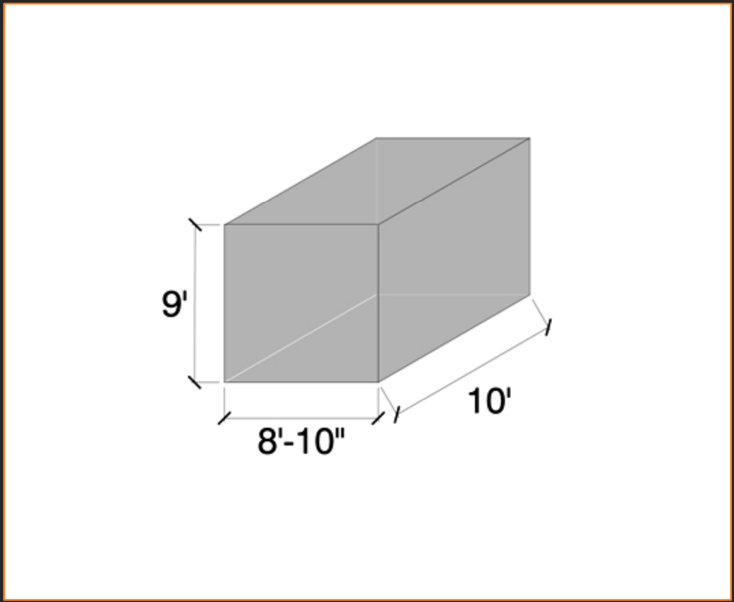
(5) What quantity of openings are required to achieve the target level in a space with these dimensions?
Determine the required glazing area.

EXAMPLE APPLICATION

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?

Calculate the interior surface area of the two zones, assuming (for this example) window-head height = ceiling height and using the limiting dimension found in (4). The two spaces have the following measurements:





A_{total}zone1: 1 048 sq.ft.

2(4’×11’ + 11’×32’ + 4’×32’)

A_{total}zone2: 515.5 sq.ft.

2(9’×8.83’ + 9’×10’ + 8.83’×10’)

EXAMPLE APPLICATION

(5) What quantity of openings are required to achieve the target level in a space with these dimensions?

For zone 1:

$$A_{glazing} = \frac{2 \cdot 2(1048)(1-0.5)}{0.8 \cdot 27^{o}} = 97.0 \text{ sq.ft}$$

Resulting WWR: [97/(11x32)] x 100 ~ 28%

For zone 2:

$$A_{glazing} = \frac{2 \cdot 2(515.5)(1-0.5)}{0.8 \cdot 56^{o}} = 23.0 \text{ sq.ft}$$

Resulting WWR: [23/(9x10)] x 100 ~ 26%

INFO

- The daylight factor is entered into the formula as 2 and not 0.02
- Remember that WWR = Area of Exterior Openings **/** Total Wall Area of Exterior Façade

CONCLUSIONS

- The WWRs of zones 1 and 2 lie close to 30%, which is good daylighting practice.

- After completing the analysis, the proportion of required glazing for zone 1 fell from 73% to 28%. This is due to the low space depth (4') that was introduced in the glazing area equation (step 4) due to the NO SKY LINE DEPTH criterion that determined that really only a 4' wide band near the façade can be adequately daylit. As a consequence, only a WWR of 28% is required to daylight this narrow band. In practice, one would likely work with a larger glazing for a retail space. In that case 'more daylight' would enter 'further' into the space. This daylight could be integrated with the electric lighting system (e.g. through an indirect photocell controlled lighting system that 'mixes' the daylight and the electric light at the ceiling). In order to design such a more complicated daylighting/lighting concept the designer would have to go beyond the rules of thumb and use simulations and/or other more advanced design techniques.

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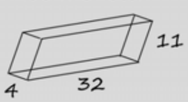
SAMPLE WORKSHEET

Daylight Feasibility Test		
(0.088 DF / T_{vis}) · (90 / θ)	WWR	Below 80%?
(0.88 x 2 / 0.8) x (90 / 27)	73%	no

Limiting Depth		
Daylight Uniformity (2 / 1 - R_{mean}) / [(1 / w) + (1 / $h_{window\ head\ height}$)]	Depth	Limiting Depth
(2 / 1-0.5) / ((1/32) + (1/11))	33'-9"	
No Sky Line Depth ($h_{window\ head\ height}$ - workplane height) · tan (θ)	Depth	
(11-3) x tan 27	4'	4'
Depth of Daylight Area (2.5 **OR** 2.0 · $h_{window\ head\ height}$)	Depth	
2.5 x 11	27'-6"	

Glazing Area		
Room Sketch	2 [(h · $d_{limiting}$) + ($d_{limiting}$ · w) + (w · h)]	A_{total}
	2 x (11x4) + (4x32) + (32x11)	1 048

A good tool for keeping track of information!

The worksheet can be downloaded from:
http://www.gsd.harvard.edu/people/faculty/reinhart/documents/worksheet.pdf

CONSIDERATIONS

- Again note that as a metric, the daylight factor does not take into account: direct sunlight, local climate, façade orientation nor movable shading.

- The sequence does provide quite accurate results in the case of buildings where the climate is temperate and mostly overcast or where the urban fabric is dense.

- Simulations are able to deal with the more complex situations mentioned. However, in the case where simulations aren't possible or justifiable due to time constraints, applying the daylighting design sequence is preferable to conducting no analysis at all.

REFERENCES

The scientific basis of the daylighting design sequence as described in this document is provided under:
http://isites.harvard.edu/fs/docs/icb.topic466783.files/Daylighting%20design%20sequence.v1.pdf

Free online references:

Tips for Daylighting with Windows: http://windows.lbl.gov/pub/designguide/default.html

Daylighting Guide for Canadian Commercial Buildings:
www.enermodal.com/Canadian/pdf/DaylightingGuideforCanadianBuildingsFinal6.pdf

Daylighting Schools:
http://www.innovativedesign.net/pdf/daylightguide_8511.pdf

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Harvard Graduate School of Design:

The GSD has been putting special attention to the advancement of environmental building performance, supporting a number of researches in the matter. www.gsd.harvard.edu

The Presidential Instructional Technology Fellows:

The Presidential Instructional Technology Fellows (PITFs) program was established to recruit and train fellows in conjunction with the Schools to work with faculty to develop digital course materials with immediate educational benefits. PITFs leverage existing software tools developed here at Harvard and provide outreach. www.provost.harvard.edu/funding